ROBUST BIRD-STRIKE MODELING USING LS-DYNA

by

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Abstract

Throughout this work, bird-strike events are studied using three approaches in LS-DYNA: Lagrangian, Arbitrary Lagrange Eulerian (ALE), and Smooth Particle Hydrodynamics (SPH). A simple one-dimensional beam centered impact problem was solved analytically to validate the results produced by LS-DYNA using the three mentioned methods. All three approaches in LS-DYNA produced results within 7% error when compared with the analytical solution. Bird-strike events, soft-body impact problems, are divided into three separate problems: frontal impact on rigid flat plate, 0 degree impact on deformable tapered plate, and 30 degree impact on deformable tapered plate. The bird model is modeled as a cylinder. Throughout the study, the most influencing parameters have been identified and peak pressures and forces are compared to those results available in the literature. The case for 0 degrees tapered plate impact shows little bird-plate interaction because the bird is sliced in two parts and the results from all three methods employed are within 10% difference from the test data available in the literature. For the frontal impact on rigid plate, all three methods are validated with the test data within 10% error. Overall, Lagrangia, ALE and SPH methods can be used for the analysis of bird-strike events.
Resumen

A través de este trabajo, el impacto de aves es estudiado utilizando tres formulaciones en LS-DYNA: Lagrangiano, Lagrange-Euler Arbitrario (ALE), e Hidrodinámica de Partículas Suavizadas (SPH) por sus siglas en inglés. Un problema simple uni-dimensional del impacto central en una viga fue resuelto analíticamente para validar los resultados producidos por LS-DYNA usando los tres métodos mencionados. Los tres métodos en LS-DYNA dieron resultados dentro de un margen de error del 7% al compararlo con la solución analítica. Los impactos de ave, problema de impacto de cuerpos blandos, son divididos en tres problemas separados: Impacto frontal contra placas planas rígidas, impacto a 0 grados en placas afiladas deformables e impacto a 30 grados en placas afiladas deformables. El ave es modelada como un cilindro. A lo largo del presente estudio, los parámetros con más influencia fueron identificados y las presiones y fuerzas picos fueron comparados con las disponibles en la literatura. En el caso de impacto a 0 grados en una placa afilada la placa presenta muy poca interacción con el ave debido a que el ave es dividida en dos partes y los resultados de los tres métodos utilizados están dentro del 10% de diferencia comparada con los datos experimentales disponibles en la literatura. Para el impacto frontal contra placas rígidas, los tres métodos fueron validados con los resultados experimentales dentro de un margen de error del 10%. En general, los métodos de Lagrange, ALE y SPH pueden ser utilizados en el análisis de impacto de aves.
Dedication

To my Lord Jesus, my family and close friends.
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During my graduate studies at the University of Puerto Rico at Mayagüez, several persons have collaborated direct and indirectly with my thesis. Without their help it would have been impossible to complete this work. First and foremost, I would like to begin by expressing my sincere gratitude to my advisor, Dr. Vijay K. Goyal, for giving me the opportunity to conduct my master’s degree under his guidance and supervision. Dr. Goyal has provided motivation, encouragement, and support throughout my studies.

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Chapter 1.
Preliminary Remarks

Collisions between a bird and an aircraft, known as bird-strike events, are very common and dangerous. According to the Federal Aviation Administration (FAA), wildlife strikes cost the U.S. civil aviation industry over $300 million and more than 500,000 downtime hours each year (Metrisin and Potter, 2001). Also, people have died due to aircraft malfunctions after bird-strikes which make it imperative to design aircraft components capable of withstanding these impacts.

To obtain certification from the FAA, an aircraft must be able to land after an impact with a 4 pound bird at any point in the aircraft. For new jet engines designs, the FAA certification requires tests for medium and large bird ingestion. For the medium or flocking bird requirement, an engine must be capable of operating for five minutes with less than 25% thrust loss after impacting several 1.5 pound or 2.5 pound birds. For the large bird ingestion test, the engine must be able to ingest a 6 pound or 8 pound bird and achieve safe shutdown. These tests take hours of planning to execute and cost millions of dollars to the jet engine manufacturing companies. Due to this, it is very important to be able to predict damage caused by a bird-strike impact on new engine designs to save money and time.

In order to predict the damage of the components of a fan blade during a bird-strike event, it is necessary to create an appropriate model for the blade and the bird. This model must be able to reproduce both impact and loads generated in a bird-strike event. A good
approximation for the model is the finite element method because of its ability to analyze complex geometries, material and load non-linearity, and study the interaction between the bird and the target. Various finite element methods are used to model the impact phenomena. The typical Lagrangian method is the most commonly used in designing fan blades. This Lagrangian description has been widely used to model the bird and the fan blade, which has to comply with the requirements for bird ingestion. However, a Lagrangian description of this problem may result in loss of bird mass due to the fluid behavior of the bird which causes large distortions in the bird. These excessive distortions cause failure due to volumetric strain in some elements of the modeled bird. The loss of mass may reduce the real loads applied to the fan blade, which is the reason why other descriptions such as the Arbitrary Lagrangian Eulerian (ALE) and the Smoothed Particle Hydrodynamics (SPH) are being used in this work. LS-DYNA, a high and low impact dynamics finite element software, has implemented these formulations to model fluid-structure interaction problems. In this work, ALE and SPH methods are being studies in an attempt to provide standard procedures to model bird-strike events.

1.1 Literature Review

The impact event is not a new topic and it has been studied by various authors. Parkes (1955) was the first to analyze the transversal impact of a mass against a cantilever beam. Stronge et al. (1993) also discuss the theory involving irreversible or plastic deformation of structural elements composed of relatively thin ductile materials. The description of these deformations in a context of impact damage was also discussed.
The impact phenomenon was also analyzed theoretically by Goldsmith (2001). Goldsmith (2001) included the theory of colliding solids and also analyzed a transverse impact of a mass on a beam assuming a equivalent system in which the beam is modeled by a massless spring. Goldsmith (2001) used energy method and the Lagrangian equations of motion to obtain a relation between the static and dynamic deflections of the beam.

A more complex impact problem is that involving a soft body impact against a rigid plate. Cassenti (1979) developed the governing equations for this kind of impact. Cassenti (1979) related the conservation equations with the constitutive equation of the impacting material to obtain analytically the Hugoniot pressure or the pressure generated in the beginning of the impact.

A bird-strike can be considered as a soft body impact problem. The characterization of birds impacting a rigid plate was studied by Barber et al. (1975). Barber et al. (1975) found that peak pressures were generated in the impact of the bird against a rigid circular plate. This peak pressures were independent of the bird size and proportional to the square of the impact velocity. Four steps concerning the impact pressures were found: initial shock (Hugonniot Pressure), impact shock decay, a steady state phase and the final decay of the pressure. This pressure plots were used as a reference to compare the obtained pressures in the LS-DYNA simulation of the bird-strike event.
Bird-strike events have been analyzed using Lagrangian and ALE methods in different finite element codes. Neiring (1988) used the current Lagrange model of the bird as the basis. His work shows different methods of computer simulation for the bird-strike event but states that an improvement is necessary due to large distortions experienced by the bird in the Lagrange model.

Martin (2004) studied a transient, material, and geometric nonlinear finite element based impact analysis using PW/WHAM. His work consisted in simulating soft body impact over stainless steel disc, a deformable flat plate, and a tapered plate. The formulation employed was very similar to the concept of the meshless finite element technique SPH.

Moffat and Cleghorn (2001) developed a bird model using the MSC/DYTRAN code for an ALE description. They reproduced the impacts of the bird in rigid and flexible targets. The data obtained from the model and the experimental test performed by Barber et al. (1975) was close in results to the simulations in MSC/DYTRAN.

A very extensive description of the ALE method was presented by Stoker (1999). Stoker studied applications of the ALE method in the forming processes. To explain the ALE method, Stoker included a section with fundamentals of continuum mechanics, followed by a derivation of the ALE motion description, and a mathematical formulation used for calculations. The main benefit of the ALE method is the significant reduction of mesh distortions during the simulation. This is a significant error in the Lagrangian method which caused inaccuracy in the results and even resulted in stopping some simulations. To reduce this error, remeshing must be performed, which results in longer processing time. The ALE
Linder (2003) explained in great detail the ALE method including the description of movement and the numerical iteration process. The method was implemented to Finite Strain Plasticity problems. The ALE method combines the advantages of the Lagrangian and Eulerian methods without the disadvantages associated to each method.

Linder (2003) explained the description of motion for the three methods (Lagrangian, Eulerian and ALE). For the Lagrangian method, the reference is taken in the material such that the physical motion in the material is equal to the mesh motion. In the Eulerian method, the mesh is referenced with spatial configuration of the body (the material flows through the stationary mesh). This method does not need remeshing and is used for fluid dynamics simulations. The major disadvantages of the method are that the resolution of flow definition and interface definition is less than in other approaches. In the ALE method, the reference is chosen arbitrarily to use the optimal method for each step of the simulation. For the ALE method, the simulation is split into a Lagrangian phase, an Eulerian phase and a smoothing phase in between. Because of this, greater distortions of the material can be handled than those allowed by the Lagrangian method with higher resolution and the Eulerian approach.

Donea et al. (2004) used the Lagrangian and Eulerian descriptions as fundamentals for the better understanding of the ALE method. The ALE method takes a reference coordinate to better describe the motion of the mesh and material. That reference configuration depends on the material domain defined as $\Phi$ and the spatial domain defined as $\Psi$. An extensive
description of the Eulerian method for an ideal fluid has been presented by Karamchetti (1980). The author provides a detailed explanation of fluid dynamics for an ideal fluid.

Birnbaum et al. (1997) used coupling techniques for numerical methods applied to solve structural and impact simulation problems. The authors provided examples of applications of the coupling of Eulerian, Lagrangian, ALE, Structural and SPH techniques applied to general fluid interaction and impact problems. To compare the methods described (Lagrangian, Eulerian, ALE, SPH), Birnbaum et al. created three simulations of a Lagrange projectile impacting a concrete target (modeled in SPH, Lagrange and Euler). The Lagrange-SPH combination produced the best results, for the visualization of the impact. The three methods provided an adequate prediction of the deceleration of the projectile when compared to test results, although the average peak deceleration of the projectile was under-predicted by 20-30%.

Souli and Olovsson (2000) presented two ALE-mesh motion methods defined in LS-DYNA: the predefined load curve motion and the automatic motion of elements in order to adapt to the current location of the material. They included results of bird-strike simulations using these methods. For the bird-strike simulation, they created three simulations using a multi-material ALE model, a multi-material Eulerian model and a constraint based coupling method. The best method for the simulations performed was the multi-material ALE method since the bird deformation was acceptable and the energy loss was the smallest of the three methods used.
Shultz and Peters (2002) used ALE models for bird-strike events in LS-DYNA. They presented a bird-strike simulation (bird impacting the inlet fan blades of a jet engine) using LS-DYNA and ANSYS software. The model consisted of shell elements for the blades, rigid elements for the hub and solid ALE elements for the Euler mesh to transport the bird materials. The bird was simulated with an Euler Mesh, while the blades were simulated with a Lagrangian Mesh. When these meshes collided, the computer calculated the momentum transfer between the two bodies, creating the simulation of the bird-strike event. The first step of the simulation was to input the desired rotational velocity to the fan; this was done within the LS-DYNA software. The authors provided various recommendations for the modeling of bird-strike events.

Many authors have presented basic equations related with the SPH approach. Commonwealth Scientific & Industrial Research Organization (CSIRO) (2002) provided the equations for the SPH approximation using the smoothing kernel function. Lacome (2000) described the conventions used for the selection of the smoothing length. This is a very important parameter because the spatial resolution of the model depends on the smoothing length and the characteristic length of the meshed particle. Lacome (2001) also provided important information regarding the SPH process, the process of the neighbor search in the interpolation and the SPH approximations for the equations of energy and mass conservation.

A general description of the SPH method was presented by Hut et al. (1997). The authors presented applications of the method as well as information about the computational parameters for the SPH method and the expectations for accelerating processing time with the implementation of faster computers.
Randall Perrine (2003) applied the SPH method to an astrophysical problem. The author emphasized that a significant problem with the SPH method was the loss of energy due to the approximation.

Ubels et al. (2003) created a SPH model to simulate a bird-strike event (bird striking the front edge of an airplane wing). The PAM-CRASH software was used for this simulation. This model was used to determine the initial impact velocity to be used for a bird-strike test on three prototypes. The leading edges (front edge of the wing) were modeled as single layered shell elements; the bird was modeled using the SPH method to simulate a synthetic gelatin bird. The result of the models determined that 100 m/s was the critical impact velocity at which the tests should be done.

Carney et al. (2002) presented a simulation of a blade-out event using the LS-DYNA software. Metrisin and Potter (2001) predicted the bird-strike event using a sequential implicit/explicit solution. Engineers from Florida Turbine Technologies used an ANSYS linear static analysis for the implicit solution, since this was faster than using LS-DYNA. This implicit solution was used to pre-stress the blades due to the centrifugal force. The second phase of the analysis, called explicit analysis or transient phase, consisted of the simulation of the bird-strike in combination with the blade root nodes rotating with the angular velocity from the first phase.
Melis (2003) created a simulation that consisted of analyzing the impact of the landing of a Space Shuttle Rocket Booster Aft Skirt in a volume of water (the ocean). Tutt and Taylor (2004) created simulations of spacecraft water impact loads using LS-DYNA. These simulations were created to provide validation for the code. The simulation results were compared to the test results from NASA experiments. The method provided accurate results. Tutt and Taylor created a Lagrangian mesh to simulate the solid structure (Apollo Command Module) and an Eulerian mesh to simulate the water. This approach was similar to the one used by Melis (2003) for a similar problem of a solid impacting water. This type of mesh arrangement can be applied to bird-strike simulations were the bird is simulated with an Euler mesh and the compressor fan blades are simulated with a Lagrangian mesh. This method has proved useful for both of the simulations presented; therefore this type ALE arrangement is a good option for the future simulations to be created.

1.2 Objectives of the present work

The objectives of this work are summarized in the following three points:

1. First of all, investigate the computational approach for modeling bird-strike event using the LS-DYNA analysis code.

2. The second task consisted to evaluate ALE and SPH approaches in LS-DYNA. Simple ALE and SPH flat plate target analysis using LS-DYNA was performed to understand the implementation of the methods in the finite element code. Another important point in this task was to analyze flat plate target using the ALE and SPH approaches and compare it to the Lagrange and test data, obtained from the work in impacting birds on rigid and flexible plates by Barber et al. (1975) and Moffat and
Cleghorn (2001). In this task, it was necessary to conduct parametric studies on selected input parameters and mesh density to understand their influence on input load and response.

3. Finally, standard work to analyze ALE and SPH simulations of bird-strike events will be presented. This will include documentation on effects of selected input parameters and mesh density studies to input load and target response.

1.3 Outline of the Thesis

We first include in Chapter 2 a description of the impact problem summarizing the continuum approach used for soft body impact events. A simple supported beam example was solved analytically and contrasted to LS-DYNA simulations. Also the description of the bird-strike problem, the literature test data used for this work and a general model used for the bird are shown in Chapter 2. Then the pre-processing, processing and post-processing of the modeled bird-strike event in LS-DYNA using the Lagrange method is developed in Chapter 3. Then on Chapter 4 is discussed the Smooth Particle Hydrodynamics (SPH) formulation, the LS-DYNA capabilities and simulations of the bird-strike using the SPH formulation. In addition this chapter presents the comparison with the current Lagrangian model. Chapter 5 deals with the modeling and simulation of the bird-strike using Arbitrary Lagrange Eulerian (ALE) formulation and its comparison to the Lagrangian and SPH simulation. Conclusions are presented in Chapter 6.
Chapter 2. Impact Analysis

When we talk about the bird-strike event in this work we are referring to the impact of a bird against an aircraft component. The bird-strike events are considered as soft body impact in structural analysis because the yield point of the bird is far smaller when compared with that of the target. Thus, the bird at the impact can be considered as a fluid material. The soft body impact results in damage over a larger area if compared with ballistic impacts. Now, to better understand, bird-strike events let us first understand the impact problem and then apply it to the bird-strike event being studied in this work.

2.1 A Continuum Approach

Let us begin by discussing the continuum approach used to solve the soft body impact problem. There major equations are solved by LS-DYNA to obtain the velocity, density, and pressure of the fluid for a specific position and time. These equations are: conservation of mass, conservation of momentum, and constitutive relationship of the material. The most important information in an impact analysis is the pressure generated by the body on the target. Thus, we proceed to explain the basic equations used to find the pressure generated at the beginning of the impact as developed in Cassenti (1979).
2.1.1 Governing Equations

Let us begin with the general form of the conservation of momentum, which can be stated as follows:

\[
\vec{V} \cdot \sigma + \rho \vec{b} = \frac{D(\rho \vec{V})}{Dt} \tag{2.1}
\]

where \( \sigma \) is the stress matrix, \( \vec{b} \) the body forces per unit mass, \( \rho \) the density, and \( \vec{V} \) the velocity vector. For the impact problem, no body forces are considered: thus, \( \vec{b} = 0 \). Further, it is assumed that for equilibrium the normal compressive stress acting in the contact interface balance the normal pressure exerted for the body over the target within the contact area. Also, it is assumed that the shear stresses are neglected. Thus, the stress tensor can be expressed as follows

\[
\vec{\sigma} = -\vec{P} \tag{2.2}
\]

where \( \vec{P} \) is a diagonal matrix containing only normal pressure components. Thus, the conservation of momentum becomes

\[
-\vec{V} \cdot \vec{P} = \frac{D(\rho \vec{V})}{Dt} \tag{2.3}
\]

Shear stresses are neglected, and thus Eq. (2.3) may be expanded for the three orthogonal directions \( x_1, x_2 \) and \( x_3 \) as follows

\[
x_1 \text{ direction: } -\frac{\partial P_{11}}{\partial x_1} = \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_1} + v \frac{\partial u}{\partial x_2} + w \frac{\partial u}{\partial x_3} \right)
\]

\[
x_2 \text{ direction: } -\frac{\partial P_{22}}{\partial x_2} = \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x_1} + v \frac{\partial v}{\partial x_2} + w \frac{\partial v}{\partial x_3} \right)
\]
\[
\frac{\partial P_{33}}{\partial x_3} = \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x_1} + v \frac{\partial w}{\partial x_2} + w \frac{\partial w}{\partial x_3} \right)
\]

where \(u\), \(v\) and \(w\) are the velocities in the \(x_1\), \(x_2\) and \(x_3\) directions. The unknowns are the pressure, the velocity and the density of the body.

The second equation used in the analysis is the conservation of mass and it is written as per unit volume as follows:

\[
\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{V} = 0
\]

Equation (2.4) is expanded as follows:

\[
-\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x_1} + v \frac{\partial \rho}{\partial x_2} + w \frac{\partial \rho}{\partial x_3} + \rho \left( \frac{\partial u}{\partial x_1} + \frac{\partial v}{\partial x_2} + \frac{\partial w}{\partial x_3} \right) = 0
\]

Equations (2.3) and (2.4) consist of four independent equations involving seven unknowns. The unknowns are three components of the pressure \(P_{11}, P_{22}\) and \(P_{33}\), three velocities \(u\), \(v\) and \(w\); and the density \(\rho\). A third equation which will relate the pressure and density is the constitutive relationship. This reduces the seven unknowns to five and the system of equations can be solved. For this work different materials are used to model the impact analysis. The material model will depend on the three different methods used here: Lagrangian, Smooth Particle Hydrodynamic and Arbitrary Lagrange Eulerian. The corresponding constitutive equations or equations of state used for each method are discussed in the next section. However, we can express constitutive relation in its general form as follows:

\[
P = P(\rho)
\]
Now, the substitution of Eq. (2.5) into Eq. (2.3) leads to:

\[- \nabla \cdot \mathbf{P}(\rho) = \frac{D(\rho \mathbf{V})}{Dt} \rightarrow \frac{D(\rho \mathbf{V})}{Dt} + \frac{\partial \mathbf{P}}{\partial \rho} \cdot (\nabla \rho) = 0 \]  

(2.6)

To better understand this coupling, let us consider a one-dimensional soft body impact. This case is representative of the work done in this thesis. Figure 2.1 shows the one-dimensional soft body impact against a rigid plate in which a compressive shock wave propagates at speed \( v \) through the fluid. The pressure corresponding to the zone between the impact surface and the shock wave is commonly known as Hugoniot pressure. The fluid will move in this zone with zero velocity and will have an increased density. Equation (2.3) of the one-dimensional conservation of momentum simplifies to

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_1} \right) = - \frac{\partial P_{xx}}{\partial x_1} \]  

(2.7)

where \( P_{11} \) is the pressure inside the impact body in the \( x_1 \) direction, \( t \) is the time and \( x_1 \) is the distance from the surface.

The conservation of mass, Eq. (2.4), simplifies to

\[
\frac{\partial \rho}{\partial t} + u \frac{\partial P_{xx}}{\partial x_1} = -\rho \frac{\partial u}{\partial x_1} \]  

(2.8)
For a one-dimensional case there are three unknowns: the velocity $u$, the pressure $P_{xx}$, and the density $\rho$. Now, Eq. (2.5) is simplified by using a constitutive relation in which the hydrostatic pressure is expressed as a function of the density:

$$P_{xx} = P_{xx}(\rho)$$  \hspace{1cm} (2.9)

and the substitution of Eq. (2.9) into Eq. (2.7) leads to

$$\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x_x} \right) + P_{xx}'(\rho) \frac{\partial \rho}{\partial x} = 0$$  \hspace{1cm} (2.10)

where

$$P_{xx}'(\rho) = \frac{dP_{xx}}{d\rho}$$  \hspace{1cm} (2.11)
Equations (2.8) and (2.10) will be used to solve the two unknown density and speed. From Fig. 2.1 it can be observed that an additional $X_1$ coordinate is included. The fluid included in the region where $X_1$ is greater than zero has not been affected by the impact, however in the region where $X_1$ is less than zero the pressure and density are higher than the nominal values.

The shock wave is located in the fluid at a distance of:

$$x_1 = v_S \cdot t$$

where, $v_S$ is the propagation velocity of the shock front. The coordinate $X_1$, that is the same as the distance from the front shock, can be expressed as:

$$X_1 = x_1 - v_S \cdot t$$

Let $U$ be the fluid speed in the reference $X_1$. The fluid velocity can then be expressed as

$$u = U + v_S$$

Both the density $\rho$ and the velocity $U$ are function of the coordinate $X_1$ as shown in Eqs. (2.15) and (2.16).

$$U = U(X_1)$$

$$\rho = \rho(X_1)$$

Substituting Eqs. (2.14), (2.15) and (2.16) in Eq. (2.8) results in:

$$\rho U = C_1$$

Substituting Eqs. (2.14), (2.15) and (2.16) in Eq. (2.10) results in:

$$\frac{1}{2} \rho U^2 + P(\rho) = C_2$$

where $C_1$ and $C_2$ are constants and
\[
P(\rho) = \int \frac{P_{xx}'(\rho)}{\rho} d\rho
\]  
(2.19)

The constants \(C_1\) and \(C_2\) can be obtained considering the region beyond the shock front where:

\[
U = -u_o - v_S
\]  
(2.20)

\[
\rho = \rho_b
\]  
(2.21)

The nominal speed \(u_o\) is in the negative \(X_1\) direction. Substituting Eqs. (2.20) and (2.21) into Eqs. (2.17) and (2.18) defines \(C_1\) and \(C_2\). Thus, Eqs. (2.17) and (2.18) become:

\[
\frac{1}{2} \rho U^2 + P(\rho) = \frac{1}{2} \rho (u_o + v_S)^2 + P(\rho_o)
\]  
(2.22)

\[
\rho U = -\rho_o (u_o + v_S)
\]  
(2.23)

Also for the region between the shock front and the surface of impact:

\[
U = -v_S
\]  
(2.24)

\[
\rho = \rho_h
\]  
(2.25)

Substituting Eqs. (2.24) and (2.25) into Eq. (2.23) results in:

\[
\rho_h = \rho_o \left(1 + \frac{u_o}{v_S}\right)
\]  
(2.26)

Substituting Eqs. (2.24) thru (2.26) in Eq. (2.22) results in one equation (Eq. 2.27) in which the only unknown is the front propagation speed, \(v_S\).

\[
\frac{1}{2} \rho v_S^2 + P\left[\rho_o \left(1 + \frac{u_o}{v_S}\right)\right] = \frac{1}{2} \rho (u_o + v_S)^2 + P(\rho_o)
\]  
(2.27)
Then Eq. (2.27) is solved for $v_s$. Note that $\rho_h$ is found from Eq. (2.26) and the corresponding Hugoniot pressure, $p_h$ is found using Eq. (2.9). The Hugoniot pressure is that corresponding to the peak pressure generated at the beginning of the impact and different finite element formulations will be used to compute this pressure. The normal stress generated in the structure of the target will be equal to the Hugoniot pressure at the beginning of the impact as depicted in Fig. 2.2.

![Figure 2.2: Pressure evaluation model](image)

The next sections will include a brief discussion of the different methods used for the solution of the bird-strike equations discussed before using LS-DYNA. First the current Lagrangian formulation will be discussed followed by the two new methods studied in this work, the Arbitrary Lagrange Eulerian (ALE) method and the Smooth Particle Hydrodynamic (SPH) method.
2.1.2 Lagrangian Approach

The various formulations existent for the finite element analysis differ in the reference coordinates used to describe the motion and the governing equations. The Lagrangian method uses material coordinates (also known as Lagrangian coordinates) as the reference; these coordinates are generally denoted as $X$. The nodes of the Lagrangian mesh are associated to particles in the material under examination; therefore, each node of the mesh follows an individual particle in motion, this can be observed in Fig. 2.3. This formulation is used mostly to describe solid materials. The imposition of boundary conditions is simplified since the boundary nodes remain on the material boundary. Another advantage of the Lagrangian method is the ability to easily track history dependant materials. The main disadvantage of the Lagrangian method is the possibility of inaccurate results and the need of remeshing due to mesh deformations. Since in this method the material moves with the mesh, if the material suffers large deformations as observed in Fig. 2.4, the mesh will also suffer equal deformation and this leads to inaccurate results.

![Initial Position (t = 0) Final Position (t = t_f)](image)

**Figure 2.3:** Lagrangian mesh.
Figure 2.4: Example of Lagrangian mesh deformation

Figure 2.5: Description of motion for Lagrange formulation
The reference coordinates for the Lagrange method are the material coordinates, $X$. Let us define RM as the material domain (reference for the Lagrangian domain) and RS as the spatial domain. The motion description for the Lagrangian formulation is:

$$ x = \varphi(X, t) \quad (2.28) $$

where $\varphi(X, t)$ is the mapping between the current position and the initial position, as shown in Fig. 2.5.

The displacement $u$ of a material point is defined as the difference between the current position and the initial position:

$$ u(X, t) = \varphi(X, t) - X = x - X \quad (2.29) $$

To minimize the mesh deformations present in the Lagrangian meshes, two formulations exist. The first formulation is known as the Updated Lagrangian (UL) formulation, where the desired quantities are calculated with respect to the referential coordinates ($X$) for each time step. At the end of the time step, the referential coordinates are updated. In other words, the new reference is the current state. This formulation is expressed in terms of Eulerian measures of stress and strain. The derivatives and integrals for this formulation are with respect to the Eulerian (spatial) coordinates $x$.

The second formulation is known as the Total Lagrangian (TL) formulation, which is in terms of the Lagrangian measures of stress and strains. The derivatives and integrals of this formulation are with respect to the material coordinates $X$. Unlike the UL formulation, the reference for the TL formulation is the initial state, when $t = 0$. 

22
Two types of materials were used for the bird model: material null and the elastic fluid. The material null considers a fluid material composed of 90% of water and 10% of air. This material allows considering the equation of state without computing deviatoric stresses. The equation of state used with this material was the equation of state tabulated. This equation of state defines the pressure $P$ as follows

$$P = C(\varepsilon_V) + \gamma T(\varepsilon_V)E$$

where $C$ represents the constant array and $T$ the temperature constants that depend on the volumetric strain. For the type of impact problems studied in this work, temperature does not play a big role. In this context, the term $\gamma T(\varepsilon_V)E$ vanishes because $T(\varepsilon_V)$ is zero and thus the equation of state becomes as follows

$$P = C(\varepsilon_V)$$  \hspace{1cm} (2.30)

The volumetric strain $\varepsilon_V$ is given by the natural logarithm of the relative volume. The elastic fluid material was also used for the Lagrangian model. This material is described in the next section with details.

In the Lagrangian simulations performed in this work, Eq. (2.30) is expressed in terms of the constitutive equation expressed in Eq. (2.5), and needs to solve for velocities, density and pressure of the problem of impact. Figure 2.6 shows an example of the deformation obtained during the impact using a Lagrange model of the soft body.
The second type of material is the elastic fluid material. This material is an isotropic elastic material. The bulk modulus, $K$, is defined as a function of the young modulus and the Poisson’s ratio as follows

$$K = \frac{E}{3(1-2v)}$$

(2.31)

The constitutive relationship used here is based on the final Hugoniot pressures and is expressed as follows

$$\dot{P} = -K \dot{\varepsilon}$$

(2.32)

where $\dot{P}$ is the pressure rate and $\dot{\varepsilon}$ the deviatoric strain rate. In contrast with the material null the elastic fluid material considers the computation of the deviatoric stresses which are the stresses that will cause deformation to the element.

A state of stress $\boldsymbol{\sigma}$ can be split in two parts, one called the hydrostatic part and the other the deviatoric part. The hydrostatic stress can be defined as:
\[ \sigma_m = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \]

where \( \sigma_1 \), \( \sigma_2 \) and \( \sigma_3 \) are the principal stresses. Then the principal deviatoric state of stress are expressed as follows:

\[
\sigma_d = \begin{bmatrix}
\sigma_1 - \sigma_m & 0 & 0 \\
0 & \sigma_2 - \sigma_m & 0 \\
0 & 0 & \sigma_3 - \sigma_m
\end{bmatrix}
\]

(2.33)
2.1.3 ALE Approach

Eulerian Formulation

Before explaining the Arbitrary Lagrange Eulerian (ALE) method it is necessary to describe the Eulerian method for a better understanding of the ALE formulation. In the Eulerian formulation, the mesh remains fixed and the material under study flows through the mesh, as shown in Fig. 2.7. Since the mesh does not move, there is no possibility of mesh deformation, which is a major disadvantage of the Lagrangian method in which the mesh moves and distorts with the material. This method is applied mostly to the simulation of fluid behavior, although it has been applied to solid simulation. The major disadvantage of this method is difficult in tracking material interfaces and the history of the materials. This required more computations than in the Lagrangian methods, which leads to longer simulation time.

Figure 2.7: Description of motion for Eulerian formulation
The Eulerian motion description can be expressed as an inverse map of the Lagrangian motion as in Eq. (2.34). Figure 2.8 shows the mapping between the material and spatial domain for the Eulerian method. This method expresses the material coordinates in terms of the spatial coordinates as follows:

$$X = \phi^{-1}(x, t)$$ (2.34)

**ALE Approach**

The Arbitrary Lagrange-Eulerian (ALE) formulation is a combination of the Lagrange and Eulerian formulations in which the reference is set arbitrarily by the user in order to capture the advantages of the methods while minimizing the disadvantages, as shown in Fig. 2.9. The user must set the mesh motion that best suite the problem in order to minimize the mesh distortions and obtain the best results. This is the main disadvantage of the method, is that the user must be experienced in order to select the best method, and interpret the results obtained.
In this method, the referential domain is denoted as RR and the reference coordinates are denoted as $X$. The position of the particle may be defined as $\chi = \varphi(X,t)$, and the mesh motion as $x = \phi(\chi,t)$.

The mesh displacement is defined as

$$\vec{u}(\chi,t) = x - X$$

(2.35)

The relationship between material coordinates and ALE coordinates, as shown in Fig. 2.10, is given by

$$\chi = \phi^{-1}(\varphi(X,t),t) = \Psi(X,t)$$

(2.36)

where $\Psi(X,t) = \phi^{-1} \circ \varphi$. 

**Figure 2.9**: Description of motion for Arbitrary Lagrange Eulerian formulation
Figure 2.10: Maps between material, spatial and referential domains.

Figure 2.11 shows how an ALE simulated soft body interacts with a rigid plate. Instead of defining a contact between the target and the soft body a coupling occurs in which the loads are computed as a function of the penetration of the soft body in the target. The material used for the ALE bird was the elastic fluid material, previously explained.

Figure 2.11: Soft body impact using ALE.
2.1.4 SPH Formulation

Smooth Particle Hydrodynamics (SPH) formulation is a meshless Lagrangian technique used to model the fluid equations of motion using a pseudo-particle interpolation method to compute smooth hydrodynamic variables. Initially this method was used to simulate astrophysical phenomenon, but recently it has been used to resolve other physics problems in continuum mechanics, crash simulations, brittle and ductile fracture in solids. Due to the absence of a grid, this method allows solving many problems that are hardly reproducible in other classical methods discarding the problem of large mesh deformations or tangling. Another advantage of the SPH method is that due to the absence of a mesh, problems with irregular geometry can be solved.

In this formulation, the fluid is represented as a set of moving particles, each one representing an interpolation point, where all the fluid properties are known. Then, with a regular interpolation function called smoothing length the solution of the desired quantities can be calculated for all the particles.

A real fluid can be modeled as many fluid particles provided that the particles are small compared to the scale over which macroscopic properties of the fluid varies, but large enough to contain many molecules so macroscopic properties can be defined sensibly. A large number of particles are needed for the SPH calculations, since the continuum limit is recovered when the number of particles goes to infinity.
Particles in the SPH method carry information about their hydrodynamic and thermodynamic information, this in addition to the mass needed to specify the evolution of the fluid. Nodes in SPH are similar to nodes in a mesh, the difference is that these nodes are continuously deformable and distort automatically to put more of the computational effort in regions of relatively high density.

One disadvantage in SPH is that this method is computationally demanding, both in memory and in CPU time. This can be overcome using a parallel analysis with more than one CPU. There is also the difficulty of establishing the boundary condition when using the SPH method. Another disadvantage is that particles may penetrate the boundaries and causing loss of smoothness and accuracy.

The moving particles are described by

$$\left( x_i(t), m_i(t) \right)_{i \in P}$$  \hspace{1cm} (2.37)

where $P$ is the set of moving particles, $x_i(t)$ the location of particle $i$, and $m_i(t)$ the weight of the particle. Lacome (2001) presented the movement of each particle and the change of the weight, given by

$$\frac{dm_i}{dt} = \nabla \cdot \mathbf{V}(x_i, t)m_i$$  \hspace{1cm} (2.38)

The quadrature formula can be written as:

$$\int_{\Omega} f(x)dx \approx \sum_{j \in P} m_j(t)f(x_j(t))$$  \hspace{1cm} (2.39)
A useful concept in SPH is the smoothing kernel. It is necessary first to introduce the auxiliary cubic B-spline function which has some good properties of regularity.

\[
\theta(y) = \alpha_1 \times \begin{cases} 
1 - \frac{3}{2} y^2 + \frac{3}{4} y^3 & \text{for } y \leq 1 \\
\frac{1}{4} (2 - y)^3 & \text{for } 1 \leq y \leq 2 \\
0 & \text{for } y \geq 2 
\end{cases}
\]  

(2.40)

Where, \( \alpha_1 \) is a constant that depends on the dimension and the shape of the kernel function. In two dimensions:

\[
\alpha_1 = \frac{10}{7\pi} 
\]  

(2.41)

Lacome (2001) also suggested the smoothing kernel as:

\[
W(x_i - x_j, \bar{h}) = \frac{1}{h} \theta \left( \frac{x_i - x_j}{\bar{h}} \right) 
\]  

(2.42)

where \( \bar{h} \) is the smoothing length of the kernel. Generally, a property \( A(x_i) \) is represented by its smooth particle approximation \( A^h(x_i) \) of the function, and by approximating the integral in Eq. (2.39):

\[
A^h(x_i) = \sum_{j=1}^{N} m_j \frac{A(x_j)}{\rho(x_j)} W(x_i - x_j, \bar{h}) 
\]  

(2.43)

The gradient of the function is obtained by applying the operator of derivation on the smoothing length.
Initially in the SPH method, the smoothing length was chosen as constant during the entire simulation. However, it was shown that it is better for each particle to have its own smoothing length, depending on the local number of particles. The current method used for the smoothing length is the gather formulation. In this method, 

\[ \bar{h} = h(x_i) \]

is defined and the neighboring particles of a defined particle are the particles inside of a sphere centered in \( x_i \) with a radius of \( h(x_i) \).

The equations for the SPH formulation presented in this section have been described by Monaghan (1989). The mass density has been defined as

\[ \rho(x) = \sum_{j=1}^{N} m_j W(x_i - x_j, \bar{h}) \]  

(2.45)
The equation of conservation of the mass in a Lagrangian form is:

\[
\frac{d\rho}{dt}(x_i) = -\rho \nabla V
\]  

(2.46)

The SPH approximation for the conservation of mass can be written in two different ways:

\[
\frac{d\rho}{dt}(x_i) = \sum_{j=1}^{N} m_j \left( v(x_j) - v(x_i) \right) \nabla W_{ij}
\]  

(2.47)

or

\[
\frac{d\rho}{dt}(x_i) = \sum_{j=1}^{N} m_j \frac{\rho_j}{\rho} \left( v(x_j) \right) \nabla W_{ij}
\]  

(2.48)

The SPH momentum equation may be written as:

\[
\frac{dv}{dt}(x_i) = \sum_{j=1}^{N} m_j \left( \frac{P(x_i)}{\rho^2} \nabla W_{ij} - \frac{P(x_j)}{\rho_j^2} \nabla W_{ji} \right)
\]  

(2.49)

**Figure 2.12:** Integration cycle in time of the SPH computation process.
Figure 2.12 illustrates an integration cycle in time of the SPH computation process Lacome, (2001). In the SPH analysis, it is important to know which particle will interact with its neighbors because the interpolation depends on these interactions. Therefore, a neighboring search technique has been developed Lacome (2001). The influence of a particle is established inside of a sphere of radius of $2h$, where $h$ is the smoothing length. In the neighboring search, it is also important to list, for each time step, the particles that are inside that sphere. If we have $N$ particles, then it is required $(N-1)$ distance comparison. If this comparison is done for each particle, then the total amount of comparisons will be $N(N-1)$.

For the neighboring search, the bucket sort algorithm is used. The domain covered by the particles is split in several boxes of a given size. First the algorithm searches for neighbors, for each particle inside the main box and the neighbor boxes contained in the domain of influence of the particle. A scheme of this neighbor search is shown in Fig. 2.13 (Lacome, 2001).

It is better to have a variable smoothing length to avoid problems related with expansion and compression of material. The concept of a variable smoothing length was developed by W. Benz. The main idea of this concept is that it is necessary to keep enough particles in the neighborhood to validate the approximation of continuum variables. The smoothing is allowed to vary in time and space. For a constant smoothing length, a material expansion can lead to numerical fracture and a material compression can slow down the calculation significantly.
The time rate of change for the smoothing length is given by the following equation:

$$\frac{dh}{dt} = \frac{1}{3} h \nabla \cdot \mathbf{V}$$  \hspace{1cm} (2.50)$$

The mass has to be kept constant in the neighborhood to achieve this equation. The total mass of n particles inside a sphere of radius $2h$ is:

$$M = n \cdot m = n \cdot (\rho V) = n \cdot \rho \cdot \frac{4}{3} \pi 8h^3$$

Then we have the time rate of change of the mass:

$$\frac{dM}{dt} = n \cdot \frac{d\rho}{dt} \cdot \frac{32}{3} \pi h^3 + n \rho \cdot \frac{32}{3} \pi \frac{dh^3}{dt}$$

Since the mass is constant in time, the left hand of the equation is equal to zero. Thus the equation is simplified to:

$$\frac{dh}{dt} = \frac{1}{3} h \nabla \cdot \mathbf{V}$$  \hspace{1cm} (2.51)$$
Due to computational efficiency a minimum of 0.2 times the initial smoothing length and a maximum value for the smoothing length twice the initial smoothing length are required. The value of the smoothing length is then between those minimum and maximum values.

The same example for soft body impact developed using Lagrange and ALE was solved using SPH method. The material type and the definition of the contact used in SPH were the same as in the Lagrange case. Figure 2.14 shows an example of the deformation obtained during the impact using a Lagrange model of the soft body.

Figure 2.14: SPH simulation for a soft body impact.
2.2 Beam Centered Impact Problem

Before studying bird-strike events, we proceeded to solve a beam centered impact problem (Goyal and Huertas, 2006c). The problem consisted in taking a simply supported beam of length, $L$, of 100 mm over which a rigid object of mass, $m_A$, of $2.233 \times 10^{-3}$ kg impacts at a constant initial velocity of, $(v_A)_1$, 100 m/s. The beam has a solid squared cross section of length 4 mm, modulus of elasticity, $E_B$, of 205 GPa, and a density, $\rho_B$, of 3,925 kg/m$^3$. Figure 2.15 shows a schematic of the problem. The goal of this problem is to obtain the pressure maximum peak pressure exerted at the moment of impact. The problem is solve analytically and then compared to the corresponding outputs from LS-DYNA for the Lagrange, SPH, and ALE, methods.

![Beam impact problem diagram](image)

**Figure 2.15:** Beam impact problem.
2.2.1 Analytical solution

Figure 2.16: Beam impact problem simplification.

Since the impact occurs at only one point, the problem can be solved by concentrating all the mass of the beam at the point of impact, i.e., at the center of the beam. Thus will simply the problem to a problem of central impact between two masses, as shown in Fig. 2.16.

The solution is a split in two stages. The first stage is the impact between the two masses with its respective initial velocities. At this stage an impact force occurs in the beam that is exactly the same as that generated by the beam against the projectile. The second stage is when both masses stick together with a common velocity, experiencing a perfectly plastic impact. In other words the coefficient of restitution for this problem is considered as $e=0$. This coefficient of restitution may be expressed as:

$$e = \frac{\left\{v_B\right\}_2 - \left\{v_A\right\}_2}{\left\{v_B\right\}_1 - \left\{v_A\right\}_1}$$  \hspace{1cm} (2.52)
If the object would have been dropped from a height $h$, the velocity of the projectile can be derived applying conservation of energy:

$$T_0 + V_0 = T_1 + V_2$$

$$0 + m_A g h = m_A v_A^2/2 + 0$$

Thus,

$$m_A g h = m_A v_A^2/2 \rightarrow (v_A)_1 = \sqrt{2gh}$$  \hspace{1cm} (2.53)

Now we apply the principle of linear impulse and momentum. This is obtained by integrating the equation of motion with respect to time. The equation of motion may be written using Newton’s second law:

$$\sum F = m \cdot a = m \cdot \frac{dv}{dt}$$  \hspace{1cm} (2.54)

Multiplying $dt$ on both sides and integrating between the limits $v = v_1$ at $t = t_1$ and $v = v_2$ at $t = t_2$ results in:
The particle’s initial momentum plus the sum of all the impulses applied from $t_1$ to $t_2$ is equal to the particle’s final momentum. The principle of linear impulse and momentum in vector form may be written in its general form as follows

$$\sum_{j} m_j \mathbf{v}_{o_j} + \sum_{t_1}^{t_2} \mathbf{F}_d t = \sum_{j} m_j \mathbf{v}_{f_j}$$  \hspace{1cm} (2.56)$$

where $\mathbf{v}_{o}$ is the initial vector of velocity (SI units: m/s) for a specific mass $j$, $\mathbf{v}_{f}$ the final vector of velocity (SI units: m/s) for the mass $j$ after the impact and $\mathbf{F}$ the force vector (SI units: N) generated during the impact. The impulse is a vector quantity having a magnitude equal to the area under the force-time curve as described in Fig. 2.18.

Figure 2.18: Impulse for a given force time history.
Figure 2.19: Average impact force.

The impact force will, in general, vary in time. However, the impact time is very short and the force may be considered constant, as show in Fig. 2.19. For this reason a time-averaged force $F_{ave}$ is defined as:

$$F_{ave} = \frac{1}{\Delta t} \int_{t_1}^{t_2} F dt$$

(2.57)

where $\Delta t = t_2 - t_1$. Thus the impulse is expressed as follows

$$I = \vec{F} \cdot \Delta t$$

(2.58)

For this problem, the theorem of impulse and momentum may be divided into two parts, as shown in Fig. 2.20:

Figure 2.20: Visualization of the theorem of impulse and momentum.
The diagrams indicate direction and magnitude of the particle’s initial and final momentum. The particle’s initial momentum plus the sum of all the impulses applied from \( t_1 \) to \( t_2 \) is equal to the particle’s final momentum.

\[
\sum m_j(v_j)_1 + \sum \int_{0}^{t} \vec{F} dt = \sum m_j(v_j)_2
\]  

(2.59)

where the sub-indices 1 and 2 correspond for the instants before and after the impact respectively. For our problem:

\[
m_A(v_A)_1 + 0 + 0 = (m_A + m_B) \cdot (v_A)_2
\]  

(2.60)

The final velocity of the projectile A and that of the concentrated mass of the beam B will be the same after the impact because a restitution coefficient of zero was assumed for this problem. Then this final velocity can be calculated as:

\[
(v_A)_2 = \frac{m_A}{(m_A + m_B)} \cdot (v_A)_1
\]  

(2.61)

Now, as a consequence of concentrating all the mass at the center of the beam, the model is similar to that of a one degree of freedom damped vibrating system, as shown in Fig. 2.21.

The principle of impulse and momentum for the system described in Fig. 2.21 is written as:

\[
\int_{0}^{t_0} F(t) dt - \int_{0}^{t_0} kudt - \int_{0}^{t_0} c_iudt = (m_A + m_B) \cdot (v_A)_2
\]  

(2.62)
where, \( t_o \) is the duration of the impact. Since the impact time is infinitesimal, we take the limit as \( t_o \) approaches zero in Eq. (2.62). The function \( F(t) \) is assumed as an impulsive time-average constant force \( F_{ave} \) acting during the time of the impact as observed in Fig. 2.19. The integrals containing the damping and the stiffness terms, during the infinitesimal time, tend to zero. Thus the Eq. (2.62) becomes

\[
F_{ave} \cdot t_o - 0 - 0 = (m_A + m_B) \cdot (v_A)_2 \quad \rightarrow \quad F_{ave} = \frac{(m_A + m_B) \cdot (v_A)_2}{t_o} \tag{2.63}
\]

Substituting the final system velocity \((v_A)_2\) from Eq. (2.61) in Eq. (2.63) leads to:

\[
F_{ave} = \frac{m_A}{t_o} (v_A)_2 \tag{2.64}
\]

Now Eq. (2.64) has two unknowns, the average force and the impact time. The impact time is taken to match the impact time given by LS-DYNA, and thus perform a fair comparison. Once the impact time is known, the force is obtained straightforward using Eq. (2.64).
Figure 2.22: Considering the continuous beam impact problem.

This example is modeled using LS-DYNA from which the impact time is extracted and the forces are compared to the analytical force. This force will be compared with that obtained using the Lagrange, SPH and ALE description in LS-DYNA.

Another approximation for this problem is to use a continuum model of the beam in which only a fraction of the beam is considered for the impact as shown in Fig. 2.22. Applying the principle of impulse and linear momentum for this case only a finite section is considered near the impact point. Also an equivalent elastic force \( V_e(t) \) and a damping force \( V_d(t) \) is considered for the finite element. Now applying the principle of impulse and linear momentum we get

\[
\int_0^{t_o} F(t) dt - 2 \int_0^{t_o} V_e dt - 2 \int_0^{t_o} V_d dt = m \cdot v_f
\]

(2.65)
Since the integration is computed for an infinitesimal time $t_0$, the second and third terms on
the left hand side of Eq. (2.65) vanish. Since the impulsive force is assumed as constant,
expression leads to the same results obtained in Eq. (2.63).

The properties of the beam and the projectile for our problem are summarized as:

\[
\begin{align*}
\text{Projectile} & \\
E_A &= 400 \text{ GPa} \\
\rho_A &= 1.787 \times 10^{-5} \frac{\text{kg}}{\text{mm}^3} \\
m_A &= 2.233 \times 10^{-3} \text{ kg} \\
\sigma_{yB} &= 1035 \text{ MPa} \\
\text{Beam} & \\
E_B &= 205 \text{ GPa} \\
\rho_B &= 3.925 \times 10^{-6} \frac{\text{kg}}{\text{mm}^3} \\
m_B &= 6.28 \times 10^{-3} \text{ kg}
\end{align*}
\]

Applying Eq. (2.61) to this problem, the final projectile-beam system velocity is:

\[
\left( v_A \right)_2 = \frac{m_A}{(m_A + m_B)} \cdot \left( v_A \right)_1 = 26.23 \frac{m}{s}
\]

### 2.2.2 Lagrange simulation

First, we solve this problem using the Lagrange description in LS-DYNA. From this
simulation the impact time was obtained. Fig. 2.23 shows the Lagrange simulation of this
impact and Fig 2.24 shows the plot for the impact force in this simulation.
Figure 2.23: Lagrange simulation of transversal beam impact

Figure 2.24: Impact force for the Lagrangian simulation
The impact time measured from Fig. 2.24 was $t_o = 8.08 \, \mu s$. Only the initial impact pulse was considered for effects of comparison because we are trying to compare a simple model discarding the possibility that the Lagrange simulation produced a not completely plastic impact.

Substituting the value of $t_o = 8.08 \, \mu s$ and $(v_A)_2 = 100 \, m/s$ in Eq. (2.64), the analytical impact force is 27.6 kN and the pressure 1.106 GPa. In impact problems, we are mostly interested in the highest impact force; all other information is not relevant. Thus, there is 2.4% difference when comparing the peak force with the Lagrangian simulation to the analytical solution. Table 2.1 summarizes these results.

<table>
<thead>
<tr>
<th>Beam impact</th>
<th>Peak force (kN)</th>
<th>Peak pressure (GPa)</th>
<th>ERROR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytically</td>
<td>27.65</td>
<td>1.105</td>
<td></td>
</tr>
<tr>
<td>Lagrange</td>
<td>26.98</td>
<td>1.079</td>
<td>2.4</td>
</tr>
</tbody>
</table>
2.2.3 ALE simulation of the beam centered impact

The problem is also solved using the Arbitrary Lagrange Eulerian (ALE) description. The major challenge in this ALE model is that LS-DYNA does not allow the use of rigid material for the bird and the creation of a reference void mesh around it. As discussed earlier the constitutive relation for this material varies from that used in the Lagrange case. Figure 2.25 shows the progression and the deformation obtained in this simulation.

![Figure 2.25: ALE simulation of transversal beam impact](image)

The impulse time for this simulation was similar to that obtained using Lagrangian approach and was \( t_o = 8.10 \ \mu s \). Using Eq. (2.65), the analytical impact force was 27.58 kN. The force plot for the ALE simulation is shown in Fig. 2.26. From the simulation and analytical values the results are within 6.2%. Table 2.2 summarizes these results.
Table 2.2: Comparison of the impulsive pressure for ALE

<table>
<thead>
<tr>
<th>Beam impact</th>
<th>Peak force (kN)</th>
<th>Peak pressure (GPa)</th>
<th>% ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytically</td>
<td>27.65</td>
<td>1.105</td>
<td></td>
</tr>
<tr>
<td>ALE</td>
<td>25.94</td>
<td>1.037</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Figure 2.26: Force plot for ALE simulation
2.2.4 SPH simulation of the beam centered impact

Lastly, the problem is simulated using the SPH formulation. In this case the projectile was composed of SPH particles. Figure 2.27 shows that the projectile suffered a deformation after the impact, which may affect the results for the computed impact force.

![SPH simulation of transversal beam impact](image)

**Figure 2.27:** SPH simulation of transversal beam impact

The impulse time was $t_0 = 8.03 \mu s$. Using this value in Eq. (2.64) the analytical impact force is found as 29.02 kN and the pressure as 1.161 GPa. From Fig. 2.28 it can be observed that the peak force in this SPH simulation was 27.84 kN which is 4.06 % lower than the theoretically value. The comparison for the force and pressure of this case with the analytical solution is shown in Table 2.3. It should be noted that the results converge to the analytical model. It was necessary to assign a high value of young modulus to the material of the bird in order to simulate it as a rigid body.
Figure 2.28: Force plot for SPH simulation

Table 2.3: Comparison of the impulsive pressure

<table>
<thead>
<tr>
<th>Beam impact</th>
<th>Peak force (kN)</th>
<th>Peak pressure (GPa)</th>
<th>% ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytically</td>
<td>29.02</td>
<td>1.161</td>
<td></td>
</tr>
<tr>
<td>SPH</td>
<td>27.84</td>
<td>1.11</td>
<td>4.06</td>
</tr>
</tbody>
</table>
2.3 Bird-Strike Impact Problem

The beam impact problem was based on rigid body impact in which the analytical load computation is relatively easily taking. The results obtained from this example provided us confidence in the methods being used and thus we proceeded to analyze the bird-strike impact problem. The bird-strike impact problem is a soft body impact which is different from the rigid body impact. It is a soft body impact problem because the bird is deformable and is composed of fluid and air, and the yield stress is far smaller when compared to that of the target.

Although the characterization for soft body impact is a complex problem, researchers have studied this problem using test data. Barber et al. (1975) performed an experimental characterization of bird-strike events. A bird-strike event may occur in different parts of an aircraft; however, the scope of this work is to study bird-strike against fan-blades. Figure 2.29(a) shows the damage caused by bird impact on the turbine fan blades. This only shows us that this problem is crucial and that by predicting the impact pressure will help us design better fan blades. Furthermore, a fan blade is composed of both flat and tapered sections. Thus, we focus our attention on analyzing bird-strikes against flat and tapered plate using Lagrange, SPH and ALE formulations in LS-DYNA. We use the work by Barber et al. (1975) as a mean of comparison. The results should be within 10% for the simulation to be useful.
Currently, the Lagrange formulation is being used to model bird-strike events in fan blades. However, some disadvantages were found in the simulation. The main disadvantage of this was that some element deletions occurs which can cause a loss of accuracy when computing the impact forces and pressures. For this reason two new finite element formulations are studied—the Smooth Particle Hydrodynamic (SPH) and the Arbitrary Lagrange Eulerian (ALE) methods—, in an attempt to create standard procedures.

### 2.3.1 LS-DYNA for Bird-Strike Events

The work done throughout this research is based on bird-strike simulations using LS-DYNA. Before we continue, let us briefly explain the advantages, disadvantages and features of this software. The main advantages of LS-DYNA is that it is one of the most robust programs currently available when simulating problems of nonlinear loading, which includes fluid-structure interaction and impact problems. LS-DYNA has the capabilities to stand non-
linearity of the impact problem and possesses a wide database with different kinds of material formulations. Also, it has the ability to work with different kinematic descriptions and element types for dynamic analysis (Hallquist, 1998). The main disadvantage of this code is that it is not user-friendly and used a large number of variables and parameters to build a model.

LS-DYNA uses keywords or cards which are flexible and locally organized database that groups together similar functions. For an example, under the keyword or card *ELEMENT are included solid, beam, shell SPH or ALE elements. The philosophy of LS-DYNA and its variables and keywords are explained in detail in Appendix A. Throughout this work different cards will be used, depending on the description considered. One of the goals is to identify the most influencing parameters in the determination of the force and pressures. The various parameters used in the analysis are the factors that will affect the computational time-step, the material-type used for both the bird and the target, the various contact type between the bird and the target, and the finite element properties. The contact type is one of the most important parameters in Lagrange because it sets the interaction between the bird and the target.

For each parameter considered in a keyword there are some specific variables. The values or flags determine how each parameter is handled by LS-DYNA. For the bird-strike event, it is intended to perform some parametrical studies to determine the most influential parameters in the analysis using the Lagrangian, ALE and SPH approaches.
2.3.2 General Bird and Target Model Properties

**Bird-Model**

How to model a bird is quite challenging and a model that best meets the testing bird properties must be used. The model considered in this work is that of a cylinder, as suggested by IBRG (2004). It has been shown that this model of bird produce close results to real birds. In addition, the bird model is assumed isotropic, symmetric and homogeneous. An approximate aspect ratio ($L/D$) of 2.03 was used for our bird model. The dimensions vary depending on the mass of the bird, and are selected from the test data by Barber et al. (1975). The material properties of the bird were similar to a gelatin material with 90% water and 10% air mixture. It is important to highlight that the mass of the testing birds plays an important role in the computer simulation because the pressure distribution greatly depends on the density of the impacting object. Table 2.4 summarizes the main properties used for modeling the bird.

**Table 2.4:** Properties for the model of bird

<table>
<thead>
<tr>
<th>Bird Property:</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>912.61 kg/m$^3$</td>
</tr>
<tr>
<td>Pressure Cutoff</td>
<td>0.09974 MPa</td>
</tr>
<tr>
<td>*Diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>*Length</td>
<td>90 mm</td>
</tr>
<tr>
<td>Impact Velocity</td>
<td>198 m/s (442.9 mph)</td>
</tr>
<tr>
<td></td>
<td>Rigid flat plate</td>
</tr>
<tr>
<td></td>
<td>477.4 m/s (1067 mph)</td>
</tr>
<tr>
<td></td>
<td>Tapered Plate</td>
</tr>
</tbody>
</table>
**Rigid Flat Plate Target**

In this research we use a rigid flat plate target and a deformable tapered plate target. The purpose of using a rigid flat plate target is to compare the simulations with the experimental data obtained from Barber et al. (1975). Barber et al. used a rigid flat plate for their experiments which can be modeled as a circular rigid plate with dimensions of 1 mm thickness and 15.25 cm of diameter. The material of the target disk was 4340 steel, with a yield strength of 1035 MPa, Rockwell surface hardness of C45, modulus of elasticity modulus of 205 GPa, and a Poisson’s ratio of 0.29. These properties of the material will be used in LS-DYNA to model the flat rigid plate.

The units used for all LS-DYNA simulations are in millimeters for the length, tons for the mass, seconds for the time, and newtons for the force. All pressure plots will be expressed in MPa.

**Deformable Tapered Plate Target**

The deformable tapered plate target properties were taken from the work by Moffat et al. (2001), who simulated the impacting bird (as a sphere) on a tapered plate using MSC/DYTRAN software. The properties for the tapered plate are given in Table 2.5.
Table 2.5: Tapered plate properties (fixed at the two shortest sides)

<table>
<thead>
<tr>
<th>Tapered Plate Property:</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Titanium 6-4 plate</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>828.0 MPa (1.20091×10^5 psi)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>105.0 GPa (15.228×10^6 psi)</td>
</tr>
<tr>
<td>Density</td>
<td>4410 kg/m³ (0.1593 lb/in³)</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.31</td>
</tr>
<tr>
<td>Effective Length</td>
<td>22.86 cm (9.0 in)</td>
</tr>
<tr>
<td>Width</td>
<td>7.62 cm (3.0 in)</td>
</tr>
<tr>
<td>Tapered angle</td>
<td>4.0°</td>
</tr>
<tr>
<td>Leading edge thickness</td>
<td>0.051 cm (0.0200787 in) Blended uniformly up to 0.160 cm (0.06299 in)</td>
</tr>
</tbody>
</table>
2.3.3 Test Data for Bird-Strike Event

The characterization of impacting birds on a rigid plate was done by Barber et al. (1975). Barber et al. (1975) determined experimentally the pressure-time variations generated by small birds impacting a flat rigid plate. Barber obtained the pressure data by recording the output of pressure sensors on the target plate. Barber identified each bird impact with a specific shot number followed by a letter. The letter indicated the place in the rigid plate at which the pressure was measured using a transducer. Barber varied the mass of the bird and the velocity of the bird for each classified shot.

The birds used in the tests (Barber et al., 1975) were of approximately from 70g to 125g, and were fired at velocities ranging from 60 to 350 m/s (134.2 to 782.9 mph). For a better simulation of bird-strike events, the density of the bird model is obtained based on the data.

Data Selection

For purposes of this work, we did not run simulations for each test data but for the data representative of all the experiments put together. Thus, in order to choose the adequate bird model dimensions and properties used in this work, we created frequency distribution plots for both the masses and the velocities. Figures 2.30 thru 2.32 summarize this test data frequency of the bird-strike event provided by Barber et al. (1975).
Figure 2.30: Histogram for the bird masses of the Barber et al. (1975) bird impact research.

Figure 2.31: Histogram for the bird velocities of the Barber et al. (1975) bird impact research.
Figure 2.32: Histogram for the bird impact peak pressures of the Barber et al. (1975) bird impact research.

All simulations are based on the data obtained from the histograms in Figs. 2.30 thru 2.32. We chose the most frequent range of bird masses and velocities. We chose shot 5126A because it satisfies the chosen bird mass of 0.071 kg and velocity 198 m/s. Thus all flat plate analysis is based on this particular test data. It is important to highlight that all plots were reproduced for means of comparison. Now we will explain the procedure how we reproduce the graphical results of the pressure transducers provided by Barber et al. (1975). These plots will permit a point to point comparison of the experimental and computer simulation data.

**Barber Graph Manipulation**

For a fair comparison between the results obtained using LS-DYNA and those obtained by Barber et al. (1975), we reproduced the experimental data from their tests by scanning Barber et al. (1975) and scaling them using the MatLab 7.1. As an example, let us
choose shot 4992-B. First, the graph was scanned, as shown in Fig. 2.33. After inverting the colors, the graph was embossed to clearly expose the edges of the data lines, this was done because the data representation lines were thick and it would be difficult to be consistent in the selection of the desired points. The file was saved as a picture file recognizable by MatLab 7.1. The resulting plot is shown in Fig. 2.34. The next paragraphs explain how the code for graph interpretation interface works (Simon Brewer, 1999). The MatLab code output data for the scanned graph is given in matrix form of form $n \times 2$, where $n$ are the number of selected points of the manipulated graph. These matrix values were imported into a spreadsheet where they are plotted, as shown in Fig. 2.35. Figures 2.35 thru 2.41 show the files for all other pressure plot, including that of shot 5126A.

Figure 2.33: Pressure – Time oscillograph for shot 4992-B (Barber et al., 1975)
Figure 2.34: Manipulation of the Pressure-Time oscillograph for shot 4992-B analyzed in MatLab (Barber et al., 1975)

Figure 2.35: Pressure vs. time distribution for Shot 4992B (Barber et al., 1975)
Figure 2.36: Pressure vs. time distribution for Shot 5181C (Barber et al., 1975)

Figure 2.37: Pressure vs. time distribution for Shot 5126A (Barber et al., 1975)
Figure 2.38: Pressure vs. time distribution for Shot 5172C

Figure 2.39: Pressure vs. time distribution for Shot 5127A
Figure 2.40: Pressure vs. time distribution for Shot 5113A

Figure 2.41: Pressure vs. time distribution for Shot 5129A
Plots for Bird Impacts on a Rigid Plate

All the approximate data plots show the same behavior and thus we must identify the stages in the loading observed by Barber et al. (1975). The pressure measured in the test data shows three different stages as seen in Fig. 2.35 thru 2.41. The first stage, and is the most important one, is where the peak pressure is generated at the beginning of the impact. The second stage shows that the bird exerts a steady pressure over the plate and occurs for a short period of time (150 to 400 µs). In this stage, there are some high frequency variations of the pressure which influence on the target and will depend in on the geometric characteristic of the same. The final stage is the fall of the pressure.
Chapter 3.
Bird-Strike Modeling Based on Lagrangian Formulation

3.1 Lagrangian Bird Model

A Lagrangian approach is used for the bird-strike impact problem. Some of the typical parameters used to model Lagrangian simulations of bird-strike events are studied in the following sections. First, we validated the Lagrangian approach with the test data and, since it is the most common technique being used; we use it as a mean of comparison to the Smooth Particle Hydrodynamics and ALE models.

3.1.1 Pre-processing variables for the Lagrangian model

The definition and meaning of each variables and functions in the various the cards are described in section A.2. The initial time step scale factor, TSSFAC, inside the *CONTROL_TIMESTEP card has a default value of 0.9. This value was changed to 0.7 to avoid contact instabilities. Also the value of the variable ERODE, inside the mentioned card, was set to 1.0 to allow element erosion when the minimum time-step (TSMIN) is reached. For the *CONTROL_TERMINATION card, the value of the DTMIN variable was set to 0.25, which means that the minimum time-step is equal to 0.25 times the initial time-step (DTSTART).

\[ TSMIN = 0.25 \times DTSTART \] (3.1)
The current Lagrangian bird was modeled using the parameters of Table 3.1. A solid element with single integration point constant stress formulation was selected. Two different types of materials for the bird were considered: material NULL simulates a fluid material with 90% water and 10% air, and material ELASTIC_FLUID. The constants used for the *EOS_TABULATED were taken from the current Lagrangian model of the bird and are given in Table 3.2. The $\varepsilon_V$ stands for the values of the volumetric strains, $T$ and $C$ are the constants considered in Eq. (2.30). These values are useful to compute the pressure for the bird using Eq. (2.30).

### Table 3.1 Bird model used for the Lagrangian simulations in this project.

<table>
<thead>
<tr>
<th>Element Type</th>
<th>8-node solid element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Formulation</td>
<td>Single integration point constant stress element (type 1)</td>
</tr>
<tr>
<td>Mesh Density</td>
<td>Cube elements with edge length of 2.5 mm</td>
</tr>
<tr>
<td>Contact</td>
<td>ERODING_NODE_TO_SURFACE</td>
</tr>
<tr>
<td></td>
<td>Slave Nodes: defined in a set using the complete set of bird nodes</td>
</tr>
<tr>
<td></td>
<td>Master Surface is defined with segments that point toward the bird</td>
</tr>
<tr>
<td></td>
<td>No Friction (FS=FD=VC=VDC=0.0)</td>
</tr>
<tr>
<td>Material Model 1</td>
<td>*MAT_NULL (type 9)</td>
</tr>
<tr>
<td></td>
<td>Density (no bloat) = $9.1261 \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>Pressure Cutoff (PC) = -0.09974</td>
</tr>
<tr>
<td></td>
<td>Dynamic Viscosity Coefficient (MU) = $2.7 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>Erosion in Tension (TEROD) = 1.1 and $(1.8026 \times 10^4)$</td>
</tr>
<tr>
<td></td>
<td>Erosion in Compression (CEROD) = 0.80 and $(1.3110 \times 10^4)$</td>
</tr>
<tr>
<td>Material Model 2</td>
<td>*MAT_ELASTIC_FLUID (type 1)</td>
</tr>
<tr>
<td></td>
<td>Density (no bloat) = 912 kg/m$^3$</td>
</tr>
<tr>
<td></td>
<td>Young Modulus = 23.94 MPa</td>
</tr>
<tr>
<td></td>
<td>Bulk modulus = 2200 MPa</td>
</tr>
<tr>
<td>Bulk Viscosity</td>
<td>*CONTROL_BULK_VISCOSITY</td>
</tr>
<tr>
<td></td>
<td>Quadratic Coefficient (Q1) = 2.0</td>
</tr>
<tr>
<td></td>
<td>Linear Coefficient (Q2) = 0.25</td>
</tr>
<tr>
<td></td>
<td>Standard (TYPE) = 1</td>
</tr>
<tr>
<td>Hourglass</td>
<td>*HOURGLASS</td>
</tr>
<tr>
<td></td>
<td>Flanagan-Belytschko viscous form (IHQ=2)</td>
</tr>
<tr>
<td></td>
<td>Coefficient (QM) = 0.14</td>
</tr>
<tr>
<td>Equation of State</td>
<td>*EOS_TABULATED (form 9)</td>
</tr>
<tr>
<td></td>
<td>GAMMA = 1.0</td>
</tr>
<tr>
<td></td>
<td>Initial Internal Energy (E0) = 0.0</td>
</tr>
<tr>
<td></td>
<td>Initial Relative Volume (V0) = 1.0</td>
</tr>
</tbody>
</table>

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Table 3.2: Constants for the *EOS_TABULATED equation of state.

<table>
<thead>
<tr>
<th>$\varepsilon_V$</th>
<th>C</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>-5000.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.09529999644</td>
<td>294.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.104399994</td>
<td>1470.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.1123999953</td>
<td>2940.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.1177999973</td>
<td>4410.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.1257999986</td>
<td>5880.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.1310000122</td>
<td>7350.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.1483999938</td>
<td>14700.0</td>
<td>0.0</td>
</tr>
<tr>
<td>-0.2326999903</td>
<td>73500.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 3.1(a) shows the pattern used for the Lagrangian bird-model and Fig. 3.1(b) the rigid flat plate target model for the frontal bird impact. The rigid flat plate target dimensions and properties are the same for all the three formulations (Lagrangian, ALE and SPH) throughout in this work. The Lagrangian bird is modeled as a uniform cylinder and meshed using solid elements. The shell-type elements are used for the rigid flat plate target of with constant thickness of 1 mm (0.0393 in). All the nodes of the shell target were constrained in translation and rotation trying to represent the rigid plate used by Barber et al. (1975). The *BOUNDARY_SPC card adds translation and rotation constraints to the nodes. Constraints in rotation and translation in the three $x$, $y$ and $z$ directions were applied to all the nodes in the shell target and to the thickness of the shell element.
3.2 Bird Impact against a Flat Rigid Plate

3.2.1 Using *MAT_NULL

*Eroding Nodes to Surface Contact Type*

First we studied the different types of contacts, starting with the *CONTACT_EROding_NODES_TO_SURFACE*. This contact type is a one-way contact which allows for compression loads to be transferred between the slave nodes to the master surface and it is recommended when the surface orientation is known throughout the analysis. The erosion contact type allows the removal of the elements due to failure criteria to make the calculation more stable. This contact type contains logic that allows the contact surface to be updated as the external elements are deleted. The deformation for this simulation is shown in Fig. 3.2 and the force plot generated by LS-DYNA is shown in Fig. 3.3. The maximum value of force obtained from the simulation was 0.114 MN (25628 lbf). Additionally, the pressure was calculated using an approximate area at the impact time, which is measured as 1300 mm². Thus the peak pressure obtained is 87.6 MPa, which is 117% higher than the peak pressure found by Barber et al. (1975).
Figure 3.2: Deformation of the bird model for the Lagrangian simulation using the ERODING_NODES_TO_SURFACE contact.

Figure 3.3: Force plot for the Lagrangian simulation using the ERODING_NODES_TO_SURFACE contact.
Figure 3.4: Global change in mass for the Lagrangian simulation.

Also, it should be highlighted that during the simulation some elements were deleted, therefore there is a loss in the bird’s mass, as shown in Fig. 3.4.

The simulation using *CONTACT_ERODING_NODES_TO_SURFACE was taken as reference because the parameters used in the model are those corresponding to the current Lagrangian model (Vasko, 2000).

When the values of the relative volume in tension and compression were changed to 1.1 and 0.8 the resultant force obtained was 0.523 MN as seen in Fig. 3.5. Therefore, this parameter is extremely sensitive for the Lagrange simulation.
Figure 3.5: Resultant force in the interface for the Lagrange frontal impact on a rigid flat plate.

Forming Nodes to Surface Contact Type

Now we consider the *CONTACT_FORMING_NODES_TO_SURFACE to define the contact between the bird model and the target. The deformation was not as smooth as it was when using the *CONTACT_ERODING_NODES_TO_SURFACE. It can be seen in Fig. 3.6 that at the final deformation, a considerable amount of the bird model actually penetrates the target. The main reason is that this contact type is suitable for metal stamping and not for rigid structures. Figure 3.7 presents the force plot generated by LS-DYNA for this simulation.
Figure 3.6: Deformation of the bird model for the Lagrangian simulation using the FORMING_NODES_TO_SURFACE contact

Figure 3.7: Force plot for the Lagrangian simulation using the FORMING_NODES_TO_SURFACE contact
Figure 3.7 shows that the maximum force value obtained for this simulation was 0.0404 MN. This value was 64.63% lower than the maximum value obtained in the previous Lagrangian simulation. The fact that the deformation shows errors and that the behavior of the force was very different when compared to force plots of previous simulations leads to the conclusion that this simulation does not provide accurate results.

**Nodes to Surface Contact Type**

Lastly, we change the contact type to *CONTACT_NODES_TO_SURFACE. This is a constraint based contact in which the forces are computed to keep the slave nodes in the master surface. The deformation of this simulation presented instability error. This error was similar to that observed in the simulation performed using *CONTACT_FORMING_NODES_TO_SURFACE, as shown in Fig. 3.8. The force plot from this simulation (see Fig. 3.9) was exactly the same as the force plot from the previous simulation. This force plot is the same as Fig. 3.7, resulting in a maximum force value was the same as in the previous simulation, 0.0404 MN, 64.63% lower than the peak force in the simulation using the *CONTACT_ERODING_NODE_TO_SURFACE.
**Figure 3.8:** Deformation of the bird model for the Lagrangian simulation using the NODES_TO_SURFACE contact

**Figure 3.9:** Force plot for the Lagrangian simulation using the NODES_TO_SURFACE contact.
3.2.2 Using *MAT_ELASTIC_FLUID

For this simulation we changed the bird material from *MAT_NULL to *MAT_ELASTIC_FLUID. Since the results produced using *MAT_NULL are not acceptable due to the large margins of error, we decided to study to change the material model for the bird. The same three types of contacts are studied for this material as well. First, *CONTACT_ERODING_NODE_TO_SURFACE was used. A different outcome is expected because the equation of state for this material is different and it is described in section 2.1.2.

*CONTACT_ERODING_NODE_TO_SURFACE

Figure 3.10 shows how the bird deforms after the impact and the force plot is show in Fig. 3.12. The maximum impact force obtained from this simulation was 0.0581 MN and it was obtained at 44.9 µs. Since the pressure is needed in order to compare these results with the test data provided by Barber et al. (1975), we calculated the impact area by measuring the diameter of impact at the same time in which the peak force occurred. This area was only an approximation to compute the maximum peak pressure. It was calculated measuring the diameter of the impact area as shown in Figure 3.11. The diameter was 41.18 mm therefore the approximated area was 1331.8 mm². Thus the peak pressure is 43.66 MPa, which is has 9.15% difference when compared to that obtained by Barber et al. (1975).

![Figure 3.10: Lagrangian bird deformation when using *MAT_ELASTIC_FLUID](image-url)
Figure 3.11: Diameter in the peak force impact time.

Figure 3.12: Force plot for the Lagrangian case using elastic fluid material.
*CONTACT_FORMING_NODE_TO_SURFACE*

Using the material elastic fluid the contact was changed to a forming contact type. The peak force obtained in this simulation was 0.0403 MN and the diameter of the impact area was 43.9 mm. Using this values the peak pressure was calculated to be 26.67 MPa. Figure 3.13 shows the deformation of the bird for this simulation. Again we can see that the final deformation penetrates the rigid plate and thus it is not recommended.

![Figure 3.13: Force plot for the Lagrangian case using elastic fluid material.](image)

**CONTACT_NODE_TO_SURFACE**

The last contact used was the contact node to surface. The curve for the force obtained for this case was the similar to the one using forming contact type. The maximum force was 0.0403 MN and the impact diameter was the same as in the previous case. The deformation was different as observed in Fig. 3.14. A comparison of the force obtained in the last three simulations is show in Fig. 3.16
3.2.3 Comparison of the Lagrangian Simulations

Three Lagrangian simulations were performed varying contact cards and bird material types. The contact cards used were: *CONTACT_ERODING_NODES_TO_SURFACE, *CONTACT_FORMING_NODES_TO_SURFACE and *CONTACT_NODES_TO_SURFACE. The materials used were *MAT_NULL and *MAT_ELASTIC_FLUID. There is no difference between the results of the simulations using the *CONTACT_FORMING_NODES_TO_SURFACE and *CONTACT_NODES_TO_SURFACE cards. Figures 3.6 and 3.8 show that simulations with these contacts do not provide a smooth deformation of the bird. Since a significant amount of the bird actually penetrates through the target causes errors in the force and thus pressure values. As a consequence, the peak force values obtained for these simulations were 64.63% lower than the values obtained in the Lagrangian simulations using an eroding contact type.

On the other hand, the Lagrangian simulation performed using the *CONTACT_ERODING_NODES_TO_SURFACE contact card provided the best deformation and the force plots. Thus eroding contact type is the contact type recommended for the Lagrangian bird model for bird-strike events against fan blades. In addition, the results for this simulation
are reliable and, thus, recommended as a standard. Figure 3.15 shows the results of the Lagrangian simulations using *MAT_NULL superimposed on one plot.

![Figure 3.15: Comparison of the Lagrangian simulations using *MAT_NULL](image)

The peak pressure obtained using the eroding contact with MATERIAL_NULL was 117% when compared with the test data. When using MATERIAL_ELASTIC_FLUID the approximate pressure was 9.15% higher to that value obtained by Barber et al. (1975). Thus, the bird with this material type is recommended and thus used as a reference to compare the pressure values obtained with both SPH and ALE approaches. Table 3.3 shows the comparison of the peak pressure for the different Lagrangian simulations. As observed when using the material elastic fluid a higher convergence is was found with the test data. Therefore, this simulation is used as a reference for comparison with ALE and SPH methods. All the pressures were calculated using the approximate impact area calculated using the diameter at the impact time.
Table 3.3: Peak impact pressure comparison for Lagrange simulations

<table>
<thead>
<tr>
<th>Simulation Description</th>
<th>Peak pressure (MPa)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barber et al. (1975)</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Lagrange MAT ELASTIC FLUID eroding</td>
<td>43.66</td>
<td>9.15</td>
</tr>
<tr>
<td>Lagrangian MAT NULL and eroding node to surface contact</td>
<td>87</td>
<td>117</td>
</tr>
<tr>
<td>Lagrangian MAT NULL Nodes to surface</td>
<td>26.43</td>
<td>33.9</td>
</tr>
<tr>
<td>Lagrangian MAT NULL Forming</td>
<td>26.43</td>
<td>33.9</td>
</tr>
<tr>
<td>Lagrangian MAT ELASTIC FLUID and forming contact</td>
<td>26.6</td>
<td>33.5</td>
</tr>
<tr>
<td>Lagrangian MAT ELASTIC FLUID and node to surface contact</td>
<td>26.6</td>
<td>33.5</td>
</tr>
</tbody>
</table>

In addition, if we compare the force plots of the Lagrangian simulations using material elastic fluid, as shown in Fig. 3.16, we observe that the highest value corresponds to the eroding contact type. The contact forming and nodes to surface have an error of 33.5 % when compared with the experimental value of 40 from Barber et al. (1975). Thus, for the Lagrangian model we recommend a bird-model with material elastic fluid and an eroding node to surface contact type. Since the results for the Lagrange simulation are within 10% error with the experimental data, the results can be used as a mean of comparison for other methods, such as the SPH and ALE. Note that these errors could be due to the fact that we do not have a clear description of the test-layout of Barber et al. (1975).

Now, in the next sections we are going to use the previously described bird-model to study tapered plate impacts at 0 and 30 degrees.
3.2.4 Impact for a Tapered Plate (Impact at 30º)

Now we explain the simulation of a cylindrical bird impacting a tapered plate along the thinnest side. The model of the bird and the target used for this simulation are those explained in section 2.3.2 and in the previous sections of this chapter. The deflection of the leading edge and the loads generated in the impact were computed for LS-DYNA.

The results are compared to those provided by Moffat et al. (2001) by modeling the bird as sphere. Here, however, our bird model is a cylindrical-type projectile. The cylindrical form was chosen to be consistent to the worked performed here. In the Lagrangian approach, the sphere model creates problems because of the node superimposition due to the mesh type. These variations in density and overall solid dimensions of the bird should not produce huge differences to the results obtained by Moffat et al. (2001). The cylinder dimensions and
properties are same as those used in the flat plate impact (Table 2.4) with the difference that the impact velocity is 477.4 m/s (1067 mph).

The boundary nodes of the plate corresponding to both sides were fixed with *SPC_BOUNDARY card. The tapered section of the plate was simulated by increasing the mesh and assigning different parts with different *SECTION_SHELL cards. The cards differ from each other in the thickness of the elemental nodes. Five different parts were created for the tapered section of the plate. The thickness of these different parts is shown in Table 3.3. Parts are illustrated with different colors in the plate shell in Fig. 3.17.

Table 3.4: Thickness for each part for the tapered plate.

<table>
<thead>
<tr>
<th>Part</th>
<th>Thickness for the four different nodes of the shell element (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>1.382</td>
</tr>
<tr>
<td>8</td>
<td>1.164</td>
</tr>
<tr>
<td>9</td>
<td>0.946</td>
</tr>
<tr>
<td>10</td>
<td>0.728</td>
</tr>
<tr>
<td>11</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Moffat et al. (2001) found that the maximum deflection in the leading edge was 1.05 in when a bird impacts the simulated tapered plate at 30 degrees. The impact angle of the bird was 30 degrees and was measured between the axis of the cylinder and the plane of the tapered plate as showed in Fig. 3.17. The mesh of the cylinder was the same as previously described.
Figure 3.17: Lagrangian bird model impacting the tapered plate at 30°.

Using *MAT_NULL

Figure 3.20 shows the resultant force in the contact interface. The maximum value obtained was of 0.0538 MN. The maximum deflection was measured to be 1.36 in; this can be observed in Fig. 3.19. This deflection was measured using LS-PREPOST. Again, this type of material is not recommended for the bird-model.

Figure 3.18: Bird impacting a tapered plate at 30° and at different time intervals.
Figure 3.19: Top view of the deformed tapered plate leading edge after the impact of the Lagrangian bird at 30°.

Figure 3.20: Resultant force for the Lagrange simulation of the impact of a bird against a tapered plate with an angle of 30 degrees.
Using *MAT_ELASTIC_FLUID

Figure 3.21 shows the deformation of the tapered plate during the impact when the bird is modeled using *MAT_ELASTIC_FLUID. As observed some elements are eliminated during calculations due to negative volumetric strains failure. Figure 3.22 shows the top view of the tapered plate leading edge deflection.

The maximum deflection was found to be 1.19 in as seen in Fig 3.22. This deflection was measured using the tool of the LS-PREPOST to measure the change in coordinates using as point of reference the position of the corner of the plate which is constrained in translation and rotation in the x, y and z directions. In addition, Fig. 3.23 shows the resultant force in the contact interface and the maximum value was 0.056 MN.

Figure 3.21: Bird impacting a tapered plate at 30º and at different time intervals.
**Figure 3.22:** Top view of the deformed tapered plate leading edge after the impact of the Lagrangian bird at 30°.

**Figure 3.23:** Resultant force for the Lagrange simulation of the impact of a bird against a tapered plate with an angle of 30 degrees.
Table 3.5: Maximum normal deflection comparison.

<table>
<thead>
<tr>
<th>Tapered impact simulation at 30 degrees</th>
<th>Maximum normal deflection (in)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moffat et al. (2001)</td>
<td>1.05</td>
<td>-----</td>
</tr>
<tr>
<td>Lagrange using *MAT_NULL</td>
<td>1.36</td>
<td>29.8</td>
</tr>
<tr>
<td>Lagrange Using *MAT_ELASTIC_FLUID</td>
<td>1.19</td>
<td>13.3</td>
</tr>
</tbody>
</table>

The simulation using material elastic fluid and eroding node to surface gave us acceptable results when comparing to the work done by Moffat. Only a 13.3 % of error, taking in consideration that the shape of the bird used in our case was different from that used by Moffat. Thus, the force generated in this case can be used as reference to compare the results using both SPH and ALE methods. One reason why the better approximation is the Lagrange simulation using the material elastic fluid could be because the material elastic fluid computes the stresses that cause the deformation in the bird or the deviatoric stresses. Also, the material null does not take account for this stresses the energy in the impact will be absorbed by the target resulting in a higher force produced.

### 3.2.5 Impact Simulation for a Tapered Plate (at 0°)

In this simulation the angle of impact was varied to 0 degrees. The bird and plate properties were the same as the used in the 30 degrees impact. Figure 3.24 shows the geometrical model for this case.
**Figure 3.24:** Model of the tapered plate for the Lagrangian impact simulation.

**USING *MAT_NULL**

Figure 3.25 shows the deformation of the bird impacting the tapered plate at different times. The deformation pattern of the tapered plate obtained during this simulation was small because the bird was sliced in two parts (Moffat et al., 2001). During simulations, some elements of the bird were deleted which were produced due to failing in the negative tensile or compressive volumetric strains. Figure 3.26 shows the tapered plate leading edge deformation seen from top.

**Figure 3.25:** Deformation of the tapered plate at different time intervals for the Lagrange description.
The maximum resultant force on the impacting surface is approximately 0.0142 MN as shown in Fig. 3.27. This graph is not as smooth as that obtained in the flat-plate impact simulation. The interaction that produced the eroding contact type caused several decays and increases of the pressure.
Using **MAT_ELASTIC_FLUID**

As observed in Fig. 3.28 the bird and target slightly interact and no deformation of the tapered plate was obtained. This is expected since the bird impact occurs from the thinnest edge of the tapered plate and the bird is basically sliced in two parts. This occurs as we change the material type from *MAT_NULL to *MAT_ELASTIC_FLUID. All the remaining parameters were holding constant. As seen in Fig. 3.29 the maximum force obtained was 0.01411 MN.

![Figure 3.28: Interaction of the bird and the tapered plate for 0 degrees impact using mat elastic fluid.](image)

![Figure 3.29: Force plot for the Lagrange tapered plate impact at 0 using *MAT_ELASTIC_FLUID](image)
Table 3.6: Maximum force comparison for 0 degrees impact using Lagrange.

<table>
<thead>
<tr>
<th>Tapered impact simulation at 30 degrees</th>
<th>Maximum force (MN)</th>
<th>Error % from material elastic fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagrange using *MAT_NULL</td>
<td>0.0142</td>
<td>0.637</td>
</tr>
<tr>
<td>Lagrange Using *MAT_ELASTIC_FLUID</td>
<td>0.01411</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 3.6 shows that using material null and elastic fluid produce very similar force values for bird-strike events on tapered plates. There is 0.637% difference for the force between the two material models (material null and material elastic fluid). The material null which considers a fluid material with 90% water and 10% air and the material elastic fluid which model an isotropic fluid material can be used for 0 degrees impact analysis to calculate the force but for the bird deformation, as shown in Fig. 3.21, cannot be used. The reason is that the deviatoric stresses are not computed. The similitude in the results for the 0 degrees impact can be explained because in the case in which the material elastic fluid is used there was very little deformation of the bird and therefore there was no computation of the deviatoric stresses. However, material elastic fluid produces better results in the tapered plate impact at 30 degrees, 13.3% of error in the deflection when compared with Moffat et al. (2001), and thus it is recommended to use material elastic fluid for the bird when simulating tapered plate bird-strike events.
Chapter 4.
Bird-Strike Modeling Based on SPH Formulation

The Lagrangian method is the most commonly used when designing fan blades. This Lagrangian description has been used to create models for both the bird and fan blades. However, this description causes losses of the bird mass due to the fluid behavior of the bird, which causes large distortions in the bird model. This mass loss may reduce the real loads applied to the fan blade, which is the reason why the Smoothed Particle Hydrodynamics (SPH) is being studied in this work. LS-DYNA, an impact-dynamic finite element software, has integrated the SPH formulation to model this fluid-structure interaction problem. In this work, the SPH method is going to be evaluated and further developed into a standard approach to modeling bird-strike events.

In the Lagrangian model, the numerical mesh moves and distorts with the physical material, allowing to accurately and efficiently tracking material interfaces and the incorporate complex material models. One disadvantage of this method is the negative volume error which occurs as a result of mesh tangling do to its sensitivity to distortion, resulting in small time steps and sometimes loss of accuracy.

The SPH is a mesh-less or griddles technique that does not suffer from the normal problems of grid tangling in large deformation problems. The major advantages of the SPH technique is that it does not require a numerical grid and, since it is a Lagrangian method by nature, it
allows efficient tracking of material deformations and history-dependent behavior. Because the SPH method has not been fully developed there remain some issues in the areas of stability, consistency, and conservation. Lagrangian motions of mass points or particles are really interpolation points, which are approximated by a cubic $B$-spline function. Unlike finite element representations for a structure, this finite element model does not exhibit a fixed connectivity between adjacent elements during the impact event. The determination of which elements are nearest neighbors is limited by the search radius. The search radius defines the maximum distance from the center node that an element may search for nearest neighbors and becomes in effect a measure of the fluid cohesive strength.

4.1 SPH Model for the Bird-Strike Event

4.1.1 Pre-processing variables for the SPH model

The dimensions and overall properties for the bird and the targets used here are provided in section 2.3.2. The target used in all the SPH simulation has a Lagrangian description, therefore the model of the flat rigid plate and the tapered plate are those used in the Lagrangian simulations, presented in chapter 3. The explanation of the construction of the SPH bird model is discussed in section 4.2.1. Table 4.1 summarizes the general parameters used for the SPH bird model.
### Table 4.1: SPH bird model

<table>
<thead>
<tr>
<th><strong>Element Type</strong></th>
<th><strong>SPH element</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant for Smoothing (CSLH)</td>
<td>1.2</td>
</tr>
<tr>
<td>Lumped mass</td>
<td>$2.9 \times 10^{-8}$ Ton</td>
</tr>
<tr>
<td>Contact</td>
<td></td>
</tr>
<tr>
<td>Slave Nodes: defined in a set using the complete set that includes the SPH particles</td>
<td></td>
</tr>
<tr>
<td>Master Surface is defined with segments that point toward the bird</td>
<td></td>
</tr>
<tr>
<td>No Friction (FS=FD=DC=VC=VDC=0.0)</td>
<td></td>
</tr>
<tr>
<td>Material Model</td>
<td></td>
</tr>
<tr>
<td><em>MAT_NULL</em> (type 9)</td>
<td></td>
</tr>
<tr>
<td>Density (no bloat) = 912.61 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>Pressure Cutoff (PC) = -0.09974</td>
<td></td>
</tr>
<tr>
<td>Dynamic Viscosity Coefficient (MU) = 0.027 N.s/m$^2$</td>
<td></td>
</tr>
<tr>
<td>Erosion in Tension (TEROD) = 1.1 and (1.8026×10$^4$)</td>
<td></td>
</tr>
<tr>
<td>Erosion in Compression (CEROD) = 0.80 (1.3110×10$^4$)</td>
<td></td>
</tr>
<tr>
<td>Bulk Viscosity</td>
<td></td>
</tr>
<tr>
<td><em>CONTROL_BULK_VISCOSITY</em></td>
<td></td>
</tr>
<tr>
<td>Quadratic Coefficient (Q1) = 2.0</td>
<td></td>
</tr>
<tr>
<td>Linear Coefficient (Q2) = 0.25</td>
<td></td>
</tr>
<tr>
<td>Standard (TYPE) = 1</td>
<td></td>
</tr>
<tr>
<td>Hourglass</td>
<td></td>
</tr>
<tr>
<td><em>HOURGLASS</em></td>
<td></td>
</tr>
<tr>
<td>Flanagan-Belytschko viscous form (IHQ=2)</td>
<td></td>
</tr>
<tr>
<td>Coefficient (QM) = 0.14</td>
<td></td>
</tr>
<tr>
<td>Equation of State</td>
<td></td>
</tr>
<tr>
<td><em>EOS_TABULATED</em> (form 9)</td>
<td></td>
</tr>
<tr>
<td>GAMMA = 1.0</td>
<td></td>
</tr>
<tr>
<td>Initial Internal Energy (E0) = 0.0</td>
<td></td>
</tr>
<tr>
<td>Initial Relative Volume (V0) = 1.0</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Bird-Strike Simulation

As in the Chapter 3, two different simulations were performed. The first simulation consisted in the bird strike event against solid rigid plates as done by Barber et al. (1975). The second simulation model was based in the work of Moffat et al. (2001), bird-strikes on tapered plates. All simulations using the SPH model are compared with their respective available test data and the Lagrangian models.

In the next sections we explain the SPH model and the results obtained by the simulations using LS-DYNA preprocessor and ETA-FEMB post processor. The bird will follow the parameters of the Lagrange Bird previously discussed and the target plate model is identical to the plate used in the Barber et al. (1975).

4.2.1 SPH element generation

In order to achieve a fair comparison with the Lagrange simulations, we kept the same bird properties as in the Lagrangian case. Because the SPH model is represented by a group of elements or small spheres, and is not continuous along the whole space they are occupying, it is necessary to calculate the physical properties for each element by taking into account that each element should have the same bird density. It is also important to highlight that the sum of masses of all small elements or spheres must be equal to the mass of the bird.
The rigid and tapered plates used for the SPH model have the same dimensions and properties as in the case of the Lagrangian simulation. To model the bird, first a square mesh with equivalent sides to the pre-calculated diameter are constructed, and then extruded to a length with different number of subdivisions, as seen in Fig. 4.1(a). The elements located in the square mesh are eliminated to approximate the mesh shape to that of the circular (cylindrical) mesh used in the Lagrangian simulation, as shown in Figs. 4.1(b) and 4.1(c). The remaining nodes are used to calculate the mass and dimensions of each spherical element, and the SPH particles were constructed in each remaining node (Goyal et al., 2006a).

Figure 4.1: SPH element generation for the bird model
The following equation shows how the lumped mass for each SPH element is calculated:

\[
Lumped \ mass = \frac{m_{total}}{\#\nodes}
\]  

Note that the number of nodes is equal to the number SPH elements. For the shot reproduced the dimensions of the bird (cylindrical representation) were:

\[
D = 41.4431 \ mm
\]

\[
L = 60 \ mm
\]

\[
\rho = 912.6 \ \frac{kg}{m^3}
\]

\[
V = \frac{\pi \cdot D^2 \cdot L}{4} = 80936.7 \ mm^3
\]

\[
m = \rho \cdot V = 0.073863 \ kg
\]

Three simulations were performed: rigid flat plate with frontal impact, and deformable tapered plate with 0 and 30 degree impact.

### 4.3 Bird-Strike Against Rigid Flat Plate

#### 4.3.1 Parameter Variation for SPH Modeling

Several simulations are performed in which the variables inside the *CONTROL_* SPH card, type of contact and number of SPH particles were changed in order to study their sensitivity on the impact loads and pressures. For all the contacts, the flat plate was assigned as the master part and the SPH bird as the slave part.
Here, we explain the variables that affect directly the output data for a bird-strike event modeled in LS-DYNA using the SPH approach. The two most important parameters that influenced the desired response are the type of contact between the SPH particles and the target surface, and the Particle Approximation Theory (keyword: FORM inside the SPH card *CONTROL_SPH). The contacts used for the simulations performed included only those that define contact between the SPH nodes to the surface of the Lagrangian target these types of contacts are one-way contact types.

It is important to note that the activation of the control card *CONTROL_HOURGLASS and assigning the parameters of energy in the *HOURGLASS card do not affected the output results. The obtained results are compared with the Lagrange simulations of a cylinder impacting a circular rigid flat plate.

The FORM parameter (Particle Approximation Theory parameter) inside the *CONTROL_SPH card can be changed and set to FORM=1 (remoralization approximation). This generates a deformation similar to that predicted by Wilbeck and Barber (1978) of the impacting cylinder reducing the effect of bouncing of the particles when entering in contact with the target. The parameter has a default value of FORM=0. By changing this parameter, a bounce-off effect is produced and thus it affects the interaction of the upcoming particles when entering in contact with the target and the particles already in contact with it.
Figure 4.2: Side view of the simulation for *CONTACT_AUTOMATIC_NODE_TO_SURFACE and FORM=0.

Figure 4.3: Simulation results for the SPH with FORM=0 and *CONTACT_AUTOMATIC_NODE_TO_SURFACE.
Figures 4.2 and 4.3 illustrates the interaction for FORM=0 and *CONTACT_ AUTOMATIC _NODE_TO_SURFACE_ID. Figures 4.4 and 4.5 shows the results for the simulation when the FORM=1. The maximum force obtained for this simulation was 0.048 MN which differs from the 0.0581 MN of the Lagrange simulation with a 17.38% of error.

The variable NCBS (Number of Cycles Between particle Sorting) of the *CONTROL_SPH card is varied between 2 and 5. The same force at the interface surface is used for each value for the NCBS variable. Figure 4.6 shows the deformation at different time intervals for the case when NCBS is equal to 2. The final deformation is in good agreement to that predicted by Wilbeck and Barber (1978). Figures 4.8 and 4.9 show the results for the SPH simulation by setting NCBS=5. By comparing Figs. 4.7 and 4.9, it is observed that there is no difference in the resultant force at the interface of the SPH bird and the Shell Target. Both simulations gave a peak force of 5.4 kN. Thus, NCBS is a nonaffecting variable in the simulation. The contact used for this simulation was *CONTACT_CONSTRAINT_NODE_TO_SURFACE contact type. The same simulation is included in the contact variation for 8700 SPH particles in section 4.3.2.

Figure 4.4: Sequence at different time intervals of deformation of the SPH bird (FORM=1 and *CONTACT_AUTOMATIC_NODE_TO_SURFACE).
Figure 4.5: Resultant force for SPH simulation with FORM=1 and *CONTACT_AUTOMATIC_NODE_TO_SURFACE.

Figure 4.6: Deformation of the SPH bird for different time intervals (NCBS= 2)
Figure 4.7: Resultant force in the interface for the SPH simulation of the bird-strike (NCBS=2) and Constraint contact type.

Figure 4.8: Deformation of the SPH bird for different time intervals (NCBS= 5)
Figure 4.9: Resultant force in the interface for the SPH simulation of the bird-strike (NCBS=5)

4.3.2 Contact Variation for 8700 SPH particles

Now, we study the effect of various contact types for the bird model composed of 8700 SPH particles. The goal is to determine the best contact type for bird-strike modeling. The final results are compared to those obtained using the Lagrangian simulation discussed in section 3.2.1, in which the eroding contact type was used in conjunction with the material elastic fluid.

For this simulation a new mesh pattern is created for the bird. Two different mesh densities are used. As observed in Fig. 4.10, the higher meshing resolution is placed at the center of the bird to allow impact of a larger amount of SPH particles with the simulated transducer.
**Figure 4.10:** Top view of the created SPH particles and the original solid mesh.

**Figure 4.11:** Side view of the cylinder impacting the plate at different time intervals (*CONTACT_EROADING_NODE_TO_SURFACE)*
**Eroding Node to Surface Contact Type**

The contact type for this simulation was changed to *ERODING_NODE_TO_SURFACE and FORM=1. As seen in Fig. 4.11, for this contact type, there exist a bounce-off effect higher than when using the *CONTACT_CONSTRAINT_NODE_TO_SURFACE and FORM=1 but lower than when using the *AUTOMATIC_NODE_TO_SURFACE and FORM=0. Figure 4.12 shows that the maximum force obtained in this case was of 0.489 MN approximately, which has an error of 741% when compared with the 0.0581 MN peak force obtained using the standard Lagrangian case for the same contact type. The reason for this difference is the difference in the material and the equation of state used in both simulations. Figure 4.13 shows that for this simulation there was no loss in the overall mass of the system.

![Resultant force for SPH simulation with *CONCTACT_ERODING_NODE_TO_SURFACE and FORM=1.](image)

**Figure 4.12:** Resultant force for SPH simulation with *CONCTACT_ERODING_NODE_TO_SURFACE and FORM=1.
Figure 4.13: Mass plot during the impact event with FORM=1 and *
CONTACT_ERODING_NODE_TO_SURFACE

Forming Node to Surface Contact Type

The contact type is changed to *CONTACT_FORMING_NODE_TO_SURFACE
and the particle approximation theory parameter (FORM) is set to one. Figure 4.14 shows the
interaction between the cylinder and the solid target for this simulation. There was a lot of
bouncing in this simulation and the force plot, shown in Fig. 4.15, does not represent the
behavior of a typical bird-strike event. Thus this contact type is not recommended.
Figure 4.14: Side view of the cylinder impacting the plate at different time intervals (*CONCTACT_FORMING_NODE_TO_SURFACE and FORM=1)

Figure 4.15: Force for SPH simulation using forming contact type.
Figure 4.16: SPH progression of the bird deformation for a rigid wall contact.

**Bird-Strike Event Using a Rigid Wall Contact**

Now we changed the contact from the *CONTACT_CONSTRAINT_NODE_TO_SURFACE to *RIGID_WALL_PLANAR_FORCE. This last card is used to define a rigid wall. Also, a segment was created for the shell elements of the target. It was necessary to define a *DATABASE_RWFORC card for the creation of the database for the forces generated in the segment set. The *BOUNDARY_SPC card was eliminated. Figure 4.16 shows the deformation of the SPH bird for this simulation. The deformation behavior may be acceptable because not much bouncing effect is observed.

The resultant force is presented in Fig. 4.17. This data was extracted from the *rwforc file created by LS-DYNA. The behavior was similar to the previous simulations. It was observed that there exists a short time interval after the peak force where the calculated force vanishes afterwards. Table 4.2 provides the force values compared with this and the Lagrangian simulation.
Figure 4.17: Resultant normal force using the rigid wall contact.

Table 4.2: Comparison between SPH and Lagrangian simulations using a rigid wall

<table>
<thead>
<tr>
<th>Simulation Description</th>
<th>Peak Force (MN)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Wall</td>
<td>0.34</td>
<td>261.53</td>
</tr>
<tr>
<td>Lagrangian Elastic Fluid</td>
<td>0.0581</td>
<td>----</td>
</tr>
</tbody>
</table>
It is observed that the peak value of the force for the SPH simulation using a rigid wall constraint on the target were 261.53% higher than the result obtained by the Lagrangian simulation. The behavior after the impact for the SPH Rigid Wall simulation was similar to the behavior of the Lagrangian simulation, although it had less peaks (the plot was smoother) and did not decrease to zero except after the initial impact. However, the peak value of the force using the rigid wall constraint was significantly different to the peak value from the Lagrangian simulation than the value obtained using two targets. Thus, this contact is not recommended for bird-strike events.

**Using Two Targets and Rigid Wall contact**

Now, we use the same SPH bird-model as in previous simulations but with two plates as the targets and a rigid wall contact type. The SPH model is built using 8,700 SPH particles and arranged in a cylindrical geometry. Two plates were used to allow movement to one of the plates. The top plate was not constrained to any degree of freedom, but the bottom plate was constrained using the *BOUNDARY_SPC card. The distance between the plates was 1 mm, allowing small displacement of the upper plate before any contact with the bottom plate. The purpose was to observe the change in forces and pressures generated between the SPH particles and the top plate. It was necessary to define two contacts, one between the bird and the upper target and other between the first target and the bottom and constraint target. If there is no definition of these contacts no force will be calculated in the interface. Figure 4.18 presents the interaction between the bird and the plates.
Figure 4.18: Deformation of the SPH Bird and the plates.

Figure 4.19: Resultant force in the interface of the bird and the targets. a) Bottom plate, b) Top plate
The *DATABASE_NCFORC card was also defined. This card stores the nodal interface forces and allows pressure plot for this interface. In order to create this database, the SPR and MPR variables from the contact card are changed to one. The force plot for selected nodes is shown in Fig. 4.19. The results show similar pattern from previous simulations: the force decreases to almost zero after the initial impact.

Figure 4.19 shows the resultant force values at the interface between the bird and the targets. It is observed that in both contact interfaces the behavior was similar although the peak value of the force varied. The peak force values were approximately 0.325 MN and 0.78 MN. The first value (0.325 MN) had an error of 459% if compared with the Lagrange simulation in which the peak force was 0.0581 MN when using TEROD=1.1. On the other hand, the value of 0.78 MN had an error of 1242% which was higher than the values obtained in other simulations and is the force generated in the top plate (which was not constrained). This force was higher because the plate was impacted by the bird-model and then impacted the bottom plate.

The force values were compared between this simulation and the Lagrangian simulation and the results are shown in Table 4.3. The huge differences between this method and the Lagrange make this approach an unacceptable one.
Table 4.3: Comparison of results between the SPH simulation with two targets and the Lagrangian simulation

<table>
<thead>
<tr>
<th>Simulation Description</th>
<th>Peak Force (MN)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Targets (SPH)</td>
<td>0.325</td>
<td>459</td>
</tr>
<tr>
<td></td>
<td>0.78</td>
<td>1242</td>
</tr>
<tr>
<td>Lagrangian MAT ELASTIC FLUID</td>
<td>0.0581</td>
<td></td>
</tr>
</tbody>
</table>

*MAT_Rigid Material Model for a Simulated Solid Transducer*

Now we use a solid transducer in the center of the target to measure the pressure in that region. The material of this solid transducer was varied from *MAT_PIECE_WISE_LINEAR_PLASTICITY* to *MAT_RIGID*. The contact used was *CONTACT_CONSTRAINED_NODE_TO_SURFACE*.

The deformation of the bird is shown in Fig. 4.20. The behavior of the deformation of the bird resembles the one predicted by Barber et al. (1975). In addition, there was not much bouncing of the particles after the impact. However, the resultant force in the interface of the bird and the solid transducer was almost 100% lower when compared to the Lagrangian case, as seen in Fig. 4.21. All the force values for previous simulations were of the order $10^6$ N and the results for this simulation were in the order of $10^3$ N. This simulation did not provide acceptable results and thus is not recommended.
Figure 4.20: Deformation of the SPH bird for *MAT_RIGID.

Figure 4.21: Resultant force in the interface of the bird and the target for *MAT_RIGID.
Figure 4.22: Deformation of the SPH bird at different time intervals.

**Constraint Node to Surface Contact Type**

For this simulation, we used *MAT_NULL and *CONTACT_CONSTRAINT_NODE_TO_SURFACE. Some solid elements are created in the center of the target to simulate a transducer. Using the area of these elements the pressure is calculated by dividing the resultant force generated in the contact between the bird and the transducer over the area of the transducer. Figure 4.22 shows the deformed SPH bird at different time intervals. Figure 4.23 shows the top view of the SPH particles impacting the simulated transducer. Approximately 81 columns of SPH particles impacted the transducer which is higher to the previous simulations.
**Figure 4.23:** Top view of the impact of the SPH particles against the transducer.

**Figure 4.24:** Resultant force in the interface for the SPH simulation.
Fig. 4.24 shows the resultant force at the interface when the SPH bird impacts the transducer. The area of the transducer was 12x12 mm (144 mm$^2$). The pressure is given in Fig. 4.25. The peak force obtained in this case was 0.0054 MN. Then, dividing this value over 144 mm$^2$ the pressure for this simulation was 37.23 MPa (5409.7 psi) which was 7.05% lower than the 40 MPa (5801.2 psi) measured by Barber et al. for shot 5126A. However the steady state phase of the simulation, as observed in the experimental test, is not captured. Note that this simulation was the same used in the previous section to study the influence of the NCBS parameter in the results.

![Pressure Vs Time graph](image)

**Figure 4.25:** Pressure in the interface for the SPH simulation.
Changing the contact to *CONTACT_CONSTRAINT_NODE_TO_SURFACE, produced a behavior of the deformation of the bird similar to the predicted by Wilbeck and Barber (1978) for the cylinder impacting the solid rigid plate. Bounce-off effect was reduced even more; first reduction was due to changing FORM to “1”. The reason is that when particles first bounce back they slow down the upcoming particles, causing the resultant force drop. After this inter-particles collision, the particles with higher kinetic energy, the ones that have not been in contact with the target, push the rebounded particles creating the second peak value. The elimination of this peak values generates a more uniform deformation of the cylinder impacting the plate. There was no loss in mass for this simulation as can be observed in Fig. 4.26.

![Mass variation plot during the impact event with FORM=1 and *CONTACT_CONSTRAINT_NODE_TO_SURFACE](image)

**Figure 4.26:** Mass variation plot during the impact event with FORM=1 and *CONTACT_CONSTRAINT_NODE_TO_SURFACE
Comparing SPH (8,700 Particles) and Lagrangian Simulations

Figure 4.27 shows the SPH simulation that best converged to the Lagrangian solution in term of the pressure generated was when using a *CONTACT_CONSTRAINT_NODE_TO_SURFACE contact type. As explained before, a simulated transducer was used to compute the pressure. The percentage of error in this method was 6.75% if compared with the test data and 14.4% if compared with the Lagrangian case. The pressure comparison for different SPH simulation with test data and the Lagrangian case is shown in Table 4.4.

Table 4.4: Pressure comparison between SPH and Lagrangian simulations
4.3.3 Changing the number of SPH particles

New simulations were performed in which the number of SPH particles is changed to observe their effect. In addition, one challenge with the data from previous simulations was that the force data obtained presented a peak value, but immediately decreased to a value of almost zero. The reason for this error is that there is a lot of space between the SPH particles. This causes the first SPH particles to absorb a part of the momentum of the following particles and cause the decrease in force found in the data plots.

The amount of particles of our bird model was increased to 22,000 particles. Also, a simulation of a solid transducer was also included in this model. Several contacts were tried for this simulation. The peak values and percentage of error for the Rigid wall, Lagrangian and the *CONTACT_NODES_TO_SURFACE simulations are presented in Table 4.5. The force was 0.667 MN, 96.4% higher than the peak force obtained in a 8,700 particle SPH simulation using rigid wall contact type.

Table 4.5: Comparison of peak force values for the simulations performed

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Peak Force (MN)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Wall SPH (8,700 particles)</td>
<td>0.336</td>
<td>485.19</td>
</tr>
<tr>
<td>Rigid Wall SPH (22,000 particles)</td>
<td>0.667</td>
<td>1049</td>
</tr>
<tr>
<td>Nodes To Surface Contact (22,000 particles)</td>
<td>0.343</td>
<td>34.4</td>
</tr>
<tr>
<td>Lagrangian</td>
<td>0.0581</td>
<td></td>
</tr>
</tbody>
</table>
Also a bird model using 5,000 SPH particles was constructed. The first contact used was the *CONTACT_ERODING_NODES_TO_SURFACE. The maximum force value obtained by this SPH simulation was 0.104 MN. Using an approximate impact area of 1300 mm² was obtained measuring the diameter of the impact area at the time of the peak force; the pressure was calculated to be 80MPa. This pressure was 100% higher than the experimental data from Barber et al. (1975).

Another contact used with the 5,000 SPH particles simulation was the *CONTACT_NODES_TO_SURFACE. The maximum peak force value obtained was 0.0665 MN. The pressure calculated for this case was 51.1 MPa which had an error of 27.75% compared with the 40 MPa from Barber et al. (1975).

Also the *CONTACT_FORMING_NODES_TO_SURFACE contact was used with the 5,000 SPH particle bird model. The results obtained were similar to the results obtained with the *CONTACT_NODES_TO_SURFACE SPH simulation. Both simulations presented a peak force of 0.0665 MN. The plots of the *CONTACT_NODES_TO_SURFACE and *CONTACT_FORMING_NODES_TO_SURFACE SPH simulations are identically the same. The same situation occurred in the Lagrangian simulations using these two contacts.

A new model of bird involving 10,000 SPH particles was created. The contact used in this case was the *CONTACT_NODES_TO_SURFACE. The maximum peak force value obtained was of 0.0774 MN. Using the area at the impact time, the pressure calculated was 59.5 MPa which is 48.75% larger than the value obtained by Barber et al. (1975).
comparison with the Lagrangian simulation the peak force obtained was 33.21% higher than the peak force of the Lagrange simulation using a eroding contact type and material elastic fluid. This force was 92% higher than the Lagrangian peak force using a node to surface contact type and a material null.

Another SPH model was created with 2,178 particles. This model was created to evaluate the trend that was found with the 5,000 and 10,000 SPH particle models (when the number of particles increased, the force at the impact also increased). The 2,000 SPH particle model was subjected to impact using the *CONTACT_NODES_TO_SURFACE contact card. The trend that was mentioned before seems to be true, because the peak force value obtained for the 2,000 SPH particle model was 0.0633 MN, 4.81% lower than the values obtained for the 5,000 SPH particle models and 18.21% lower than the results for the 10,000 SPH particle model.

Table 4.6: Pressure comparison for particle variation in the SPH simulations.

<table>
<thead>
<tr>
<th>Contact Contact</th>
<th>Material Type</th>
<th>Number of Particles</th>
<th>Peak Pressure Value (MPa)</th>
<th>% Error From Test Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barber et al. (1975)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>40</td>
</tr>
<tr>
<td>*CONTACT_ERODING_NODES_TO_SURFACE</td>
<td>Elastic Fluid</td>
<td>Lagrangian</td>
<td>N/A</td>
<td>43.6</td>
</tr>
<tr>
<td>*CONTACT_ERODING_NODES_TO_SURFACE</td>
<td>Null</td>
<td>Lagrangian</td>
<td>N/A</td>
<td>87.6</td>
</tr>
<tr>
<td>*CONTACT_ERODING_NODES_TO_SURFACE</td>
<td>Null</td>
<td>SPH</td>
<td>5,000</td>
<td>80</td>
</tr>
<tr>
<td>*CONTACT_NODES_TO_SURFACE</td>
<td>Null</td>
<td>Lagrangian</td>
<td>N/A</td>
<td>31.07</td>
</tr>
<tr>
<td>*CONTACT_NODES_TO_SURFACE</td>
<td>Null</td>
<td>SPH</td>
<td>2,000</td>
<td>48.7</td>
</tr>
<tr>
<td>*CONTACT_NODES_TO_SURFACE</td>
<td>Null</td>
<td>SPH</td>
<td>5,000</td>
<td>51.1</td>
</tr>
<tr>
<td>*CONTACT_NODES_TO_SURFACE</td>
<td>Null</td>
<td>SPH</td>
<td>10,000</td>
<td>59.5</td>
</tr>
</tbody>
</table>
From Table 4.6, it can be stated that for a constant contact for the simulations performed when the number of SPH particles was increased, the maximum pressure value obtained from the simulation also increased. All the pressures were calculated using the approximate area measured at the time in which the peak force occurs for each simulation. As observed there was no convergence of the pressure for any of the cases showed in Table 4.6.

![Figure 4.28: SPH simulations of shot 5126 A for different number of particles.](image)
Figure 4.28 shows different deformation plots for SPH simulations using different number of particles in the model. As explained, this variation in number is considered in order to study its influence in the stability of the model, in the deformation and in the resultant force plot along the whole simulation. The simulation obtained with 2464 particles was unstable, which could be caused by the non-uniform distribution of the particles across the entire model of the bird. All the other models were constructed with a more uniform distribution of the particles and with a distance between adjacent particles almost constant. These models produced deformations close to experimental data. Models with 4700, 8700 and 22,000 SPH particles showed deformation with a sliding behavior in the steady phase of the impact. In contrast, models using 5000 and 10000 SPH particles presented bouncing of the particles in the steady phase of the bird-strike. However this bouncing effect is more affected by the type of contact used than for the amount of SPH particles used for the creation of the model, as shown in Fig. 4.29.

It is observed in Fig. 4.29 that when the bouncing effect is reduced by the change of the contact type, the peak force tends to be increased. This may result because of the concentration as a continuum of the force exerted by the particles against the plate. There is one exception on the 8700 particles in which the simulation with less bouncing effect has lower peak force. This may be caused because of the use of *MAT_RIGID for the target instead of the *MAT_PIECEWISE_LINEAR_PLASTICITY used in each SPH simulation.
<table>
<thead>
<tr>
<th>Contact Type for 5000 SPH particles</th>
<th>Deformation of the bird</th>
<th>Peak Force (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*CONTACT_ERODING.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>1.04</td>
</tr>
<tr>
<td>*CONTACT.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>0.665</td>
</tr>
<tr>
<td>*CONTACT_FORMING.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>0.665</td>
</tr>
<tr>
<td>Contact Type for 8700 SPH particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*CONTACT_AUTOMATIC.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>0.0480</td>
</tr>
<tr>
<td>*CONTACT_CONSTRAINT.NODES_TO_SURFACE And *MAT_RIGID</td>
<td>![Deformation Image]</td>
<td>0.0054</td>
</tr>
<tr>
<td>*CONTACT_ERODING.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>0.450</td>
</tr>
<tr>
<td>Contact Type for 22,000 SPH particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*RIGIDWALL_PLANAR</td>
<td>![Deformation Image]</td>
<td>0.668</td>
</tr>
<tr>
<td>*CONTACT.NODES_TO_SURFACE</td>
<td>![Deformation Image]</td>
<td>0.3436</td>
</tr>
</tbody>
</table>

**Figure 4.29:** SPH simulations of shot 5126 A for different number of particles.

**Figure 4.30:** Force plot comparison of different SPH simulations using a rigid wall contact type.
It can be observed from Figs. 4.30(a) that the results for the peak force in the SPH simulation with 22,000 particles were 96.5% higher than the SPH (8,700 particles) simulation. However, the behavior after the initial impact is similar in both SPH simulations, reaching a value close to zero. The high value of force obtained from the 22,000 particle simulation could be because by adding more particles to the SPH simulation the results in more bounce off effect, and the momentum of the first particles that impact the surface increase when impacting the upcoming particles.

**Figure 4.31:** Comparison of peak pressure obtained in Lagrangian and SPH simulation using the nodes to surface contact TEROD=1.1
Figure 4.31 shows a comparison between peak force for different number of particles and type of contact used. It can be observed that the *CONTACT_ERODING_NODE_TO_SURFACE and the in the *CONTACT_NODE_TO_SURFACE simulation with 8,700 particles have a peak pressure close to the peak pressure obtained in the Lagrangian simulation (6.5% lower than the Lagrangian case). These contact types are then one of the indicated to be used in SPH simulation of bird-strike because of its capability of reproduce the loads in the impact close to the Lagrange model and to the test data.

Using the results obtained it is observed that the mesh density affects the simulation. Simulated transducers make possible getting the pressure distribution graph. When two different mesh resolutions are used, the results are more accurate with respect to the maximum pressure obtained.

4.4 Impact for a Tapered Plate Impact at 0º

Now, we verify our model with the simulations provided by Moffat et al. (2001). As in the case of Lagrange simulation, we considered to different bird impact angles: 0º and 30º. The dimension and properties of the tapered plate are identical to those of previous simulations. The number of SPH particles created for this simulation was 26195 and its distribution was arranged to form the cylinder. The contact type used for this simulation was *CONTACT_ERODING_NODE_TO_SURFACE. The impact angle was 0º, as shown in Fig. 4.32.
Figure 4.32: Cross section of the model for tapered plate impact using a higher density of SPH particles.

Using Material Null

Figure 4.33 shows that the resultant force for this SPH simulation is approximately 0.0153 MN which represents an error of 7.74% if compared with the 0.0142 MN of the Lagrangian case. The reason is that there is little interaction between the tapered plate and the bird which is sliced in two parts. This is the same behavior observed in the Lagrangian approach. Only few particles are involved in the impact for the SPH simulation. The results for the 0 degrees of impact simulation show that there is an only slight deformation in the tapered plate. Also, there was no appreciable deformation of the leading edge as can be observed in Figs. 4.34 to 4.36. Figure 4.34 shows that the particles aligned with the plate were the ones suffering deflection while the other particles continued their trajectory. In short, for cases in which the impact-event occurs in the thinnest side of a plate, the SPH model can be used to simulate impact events.
Figure 4.33: Resultant force for the SPH simulation at 0 degrees using material null.

Figure 4.34: Result of the interaction for the SPH simulation of the tapered plate impact using material null.
Figure 4.35: Deformed plate after the 0 degrees impact of the SPH bird.

Figure 4.36: Front view of the deformed plate after the 0 degrees impact of the SPH bird using material null.
**Using Material Elastic Fluid**

The type of material for the bird-strike on a tapered plate at 0 degree was varied to an elastic fluid material. The contact used in this simulation as that used in the previous simulation was an eroding node to surface contact type. Figures 4.37 and 4.38 show that there was interaction of the plate and the bird, but as the impact is a 0 degrees the plate slices the bird in two parts. This occurs because the bird impacts at the narrowest side of the plate. Figure 4.37 shows that the maximum peak force computed for this case was 0.001694 MN. This force is 88.66% lower than the computed for the Lagrangian case. One reason for this is that the elastic fluid accounts for the deviatoric stresses, computing the stresses that cause deformation in the solid elements of the bird. The impact energy therefore will be absorbed for the material of the bird, decreasing the force generated in the impact.

![Figure 4.37: Result of the interaction for the SPH simulation of the tapered plate](image)

**Figure 4.37:** Result of the interaction for the SPH simulation of the tapered plate
Figure 4.38: Front view of the deformed plate after the 0 degrees impact of the SPH bird using material elastic fluid.

Figure 4.39: Resultant force for the SPH simulation at 0 degrees using material elastic fluid.
**Table 4.7:** Peak force comparison for various SPH tapered plate impact at 0 degrees.

<table>
<thead>
<tr>
<th>Tapered plate impact at 30 degrees</th>
<th>Bird Material</th>
<th>Contact Type</th>
<th>Number of Particles</th>
<th>Peak Force Value (MN)</th>
<th>% Error From Lagrange and Elastic Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagrange Null Eroding</td>
<td>N/A</td>
<td>0.0142</td>
<td>0.637</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lagrange Elastic Fluid Eroding</td>
<td>N/A</td>
<td>0.01411</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPH Elastic Fluid Eroding</td>
<td>26,000</td>
<td>0.00161</td>
<td>88.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPH Null Eroding</td>
<td>26,000</td>
<td>0.0153</td>
<td>7.74</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7 lists the peak forces obtained for the Lagrange and SPH simulations of the bird-strike on tapered plates impacting at an angle of 0 degrees. The simulation that best converges to the Lagrangian case is the SPH simulation using the material null for a SPH model with 26,000 particles.
4.5 Impact for a Tapered Plate at 30°

The bird, simulated with the cylinder, was rotated by an angle of 30° as shown in Fig. 4.40. The variables and parameter were the same as in the simulation of section 4.4. The contact used in this case was the *ERODING_NODE_TO_SURFACE. The influence of the type of material used on the final force and deflection was studied. The materials used were the null material and the elastic fluid material type.

**Using Null material**

The same model used in the impact at 0 degrees in which the amount of particles was 26,000 was used here. The type of material was the *MAT_NULL. Figure 4.41 shows the deformation of the tapered plate at different times of the simulation. In this case, the maximum normal deflection was 1.12 in which was 6.96% higher than the value obtained by Moffat et al. (2001). This deflection is show in Fig. 4.42. The side view is shown in Fig. 4.43.

![Figure 4.40: Side view of the SPH simulation for the bird impacting a plate at 30°.](image)
**Figure 4.41:** Deformation of the tapered plate using material null and 26195 SPH particles.

**Figure 4.42:** Top view of the deformed plate after the impact of the bird with an angle of 30 degrees.
Figure 4.43: Side view of the tapered plate leading edge.

Figure 4.44: Resultant force in the interface for the impact of the bird on a tapered plate with an angle of 30 degrees (SPH simulation).
Figure 4.44 illustrates the plot of the resultant force in the interface as a function of time. The maximum value of the force had a value of 0.049 MN, 13.46% lower than the 0.0566 MN in the Lagrange simulation of the same impact which shows that a good convergence both for force and deflection occurs in this simulation.

8700 particles and material null

Another simulation using a bird model of 8700 particles was performed. The contact used was an eroding node to surface contact type and the material used was the *MAT_NULL. Figure 4.45 shows the interaction of the bird and the plate and Fig. 4.46 shows the final deformation for the leading edge. The maximum normal deflection obtained in this case was 1.14 in which is 8.57% higher than the value found by Moffat et al. (2001). However, the peak force obtained in this simulation was 0.1156 MN which was 104.22 % higher than the 0.0566 MN obtained in the Lagrange case.

Figure 4.45: Deformation of the tapered plate at different times of the simulation (30 degrees and 8,700 SPH particles).
26,000 SPH particles and Elastic Fluid material

For this simulation, the material type was changed in order to study its influence in the final deflection of the leading edge and the peak force generated in the impact. The interaction of the bird and the plate is depicted in Fig. 4.47. Figure 4.48 shows that the maximum normal deflection was 1.25 in which is 19.6% higher than the 1.05 in found by Moffat et al. (2001). Figure 4.49 shows that the peak force for this simulation was 0.109 MN and is 93.8 % higher than the value obtained in the Lagrangian case. This increase in the force means that changing the material type to an elastic fluid material will affect the value of the peak force, as the type of equation of state is different.
Figure 4.47: Deformation of the tapered plate at different times of the simulation (30 degrees and 8,700 SPH particles).

Figure 4.48: Top view of the deformed plate after the impact of the bird using mat null.
Figure 4.49: Resultant force in the interface for the impact of the bird on a tapered plate with an angle of 30 degrees (SPH simulation).

Table 4.8: Force and maximum normal deflection comparison for various SPH tapered plate impact at 30 degrees.

<table>
<thead>
<tr>
<th>Tapered plate impact at 30 degrees</th>
<th>Bird Material</th>
<th>Contact Type</th>
<th>Number of Particles</th>
<th>Maximum Normal Deflection (in)</th>
<th>% Error from Moffat</th>
<th>Peak Force Value (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moffat</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.05</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lagrange</td>
<td>Null</td>
<td>Eroding</td>
<td>N/A</td>
<td>1.36</td>
<td>29.84</td>
<td>0.0537</td>
</tr>
<tr>
<td>Lagrange</td>
<td>Elastic Fluid</td>
<td>Eroding</td>
<td>N/A</td>
<td>1.19</td>
<td>13.38</td>
<td>0.0566</td>
</tr>
<tr>
<td>SPH</td>
<td>Elastic Fluid</td>
<td>Eroding</td>
<td>26,000</td>
<td>1.25</td>
<td>19.61</td>
<td>0.1097</td>
</tr>
<tr>
<td>SPH</td>
<td>Null</td>
<td>Eroding</td>
<td>8,700</td>
<td>1.14</td>
<td>8.57</td>
<td>0.1156</td>
</tr>
<tr>
<td>SPH</td>
<td>Null</td>
<td>Eroding</td>
<td>26,000</td>
<td>1.12</td>
<td>6.96</td>
<td>0.0489</td>
</tr>
</tbody>
</table>
A observe in Table 4.8 the simulation that has better convergence to the maximum deflection found by Moffat is the SPH simulation using material null and 26,000 particles. In addition, for this model the peak force obtained was only 13.4% different from the one calculated using the Lagrange simulation with material elastic fluid. But if the peak force is compared with the Lagrangian case using the same null material the error is 8.93%. However, changing the material in the SPH simulation to the material elastic fluid does not result in a convergence of the force to the Lagrangian model using the same elastic fluid material.

4.6 Computational Time Employed

The time employed in the simulation of the bird-strike using the Lagrangian and SPH methods are presented in this chapter. Three different cases of impact were analyzed: Frontal bird-strike impact in a flat circular rigid plate, bird-strike in a tapered plate at an angle of 30 degrees and finally bird-strike impact in a tapered plate at an angle of 0 degrees. Fig. 4.50 show the elapsed time for the different methods and impacts simulated.

![Elapsed simulation time for Lagrange and SPH methods and impact types.](image)

**Figure 4.50:** Elapsed simulation time for Lagrange and SPH methods and impact types.
4.7 Comparison of the Total Energy

*Frontal Bird Strike Impact in a Flat Circular Rigid-Plate*

In order to further analyze the results obtained, energy plots were created in LS-DYNA for Lagrangian and SPH simulations. Figure 4.51 shows the superposition of the total, kinetic, and internal energy for the Lagrange and SPH simulation with the specified number of particles and types of contacts. It can be observed that the total energy increases for the SPH simulations while it decreases for the Lagrangian simulations. The reason is that in the Lagrangian simulation there is an energy loss due to the friction of the whole bird model with the plate. This friction can be observed in the deformation of the Lagrangian simulations.

![Figure 4.51: Plot of the total, internal, and kinetic energy for the SPH and Lagrangian simulations](image)
On the other hand, the energy increase of the SPH models during the impact may be due to the fact that there is not so much friction in the impact simulations. As it can be observed in the deformation of the SPH models, the particles in these simulations seem to rebound at the impact and collide with the particles that are coming next. The increase in energy is an error in these simulations and our theory is that it is occurring due to the rebound of the particles at the impact. However it can be observed that the simulation with the highest total energy was the 2,000 particle SPH simulation. The expected behavior was that the model with the most SPH particles would have the greatest increase in energy, but this was not the result obtained from the simulation.

Also, Fig. 4.51 suggests that the increase in internal energy of the SPH bird models was the biggest factor that contributed to the increase in energy. The kinetic energy only increased a small amount; however the internal energy had the greatest increase which caused the increase in total energy for the SPH simulations.

### 4.8 Advantages and Disadvantages

The following section presents the advantages and disadvantages of simulating a bird-strike event using the Lagrange and SPH approaches. The advantages and disadvantages are presented for both methods and are based on the following cases: a cylinder impacting frontally a circular rigid plate; and a cylindrical form impacting, at different angles of incidence, and a tapered plate. The material used to simulate the impacting cylinder was based on the current bird model, and the material for the circular plate was steel 4340, and Titanium 6-4 for the tapered plate.
Lagrangian Approach

The Lagrange FEA method presented the following advantages when compared to the SPH method:

1. Noticeable reduction in computational time
2. The development of the whole model (construction and assignation of variables) is simpler than the SPH and ALE method.
3. More defined shapes can be achieved when simulating an object.
4. Simulation variables are constant during different types of simulations, for example: This method permits the simulation of impact events in situations where the impacts occur in the narrowest part of a plate.
5. Material simulated is a continuum

The Lagrange FEA method presented the following disadvantages when compared to the SPH method:

1. Element (mass) loss during simulation
2. Noticeable loss on total energy
3. Deformation is not uniform due to the loss of elements
4. Resultant force graphs are not as uniform as those produced using the SPH method

Smoothing Particle Hydrodynamics Approach

The SPH method is a relatively a new finite element method. For studies involving impact events this method simulates the material, which has the largest deformation when the impact is occurring, as a mesh of individual particles that interact among them when a great
external force, that creates large deformations, acts on them. Following are some of the advantages for the SPH method:

1. In impact Events there is no loss or change in mass

2. Distribution of resultant force along time is more uniform and approaches the behavior observed in the Barber et al. (1975) research

3. The number of variables that affect the final result of the simulation is reduced to just contact variables and variables related to the SPH control card

4. In both methods total energy loss occurred, but the SPH method presents the lowest change

Following are some of the disadvantages for the SPH method:

1. Material is not continuous

2. Greater computational time compared with the Lagrange method

3. More complicated model development when compared to the Lagrange modeling, object shapes are more difficult to achieve

4. Impacts occurring on the narrowest part of the plate require a mesh with a great number of elements, increasing simulation time. The increasing in mesh density does not assure that particles interact with the plate; there could be no interaction because of the gap between the particles

5. Contact type changes depending on the impact event to be simulated
4.9 Best Approach for Bird-Strike Event Modeling

After studying the influence of various parameters involved in the SPH bird model, we compared the peak pressure and we are ready to make some recommendation on when is it best to use this approach. First and foremost, the SPH bird model is far more complex than the Lagrangian bird model and the number of variables influencing the SPH model is higher than for the Lagrangian one. For the SPH bird model, the mesh density or number of particles included has a strong influence in the peak impact pressure. This causes the selection of an optimum number of particles before beginning further simulations.

For the first case, the frontal impact against a flat rigid plate, a bird model with 8700 particles with one-way constraint contact type and a null material type can be used. The error obtained in the pressure after comparing with the experimental data is within 10%. For the Lagrangian model the error when using elastic fluid material and an eroding contact type produced an error of 9%. Therefore, the SPH model can successfully be used in this kind of frontal impacts.

For the second case, 0 and 30 degrees impact against a tapered plate, the SPH model validates the results obtained in the literature. The SPH model is recommended for angled impacts on tapered plates since the error of the maximum normal deflection in less than 7% when compared with the experimental data by Moffat et al. (2001). These results are validated using 26,000 SPH particles, a eroding contact type and a null material. If compared with the Lagrangian simulation in which the error was 13.3% when using an elastic fluid
material and an eroding contact type, the SPH can also be used successfully to simulate angle
bird-strike on tapered plates. For the 0 degree impact, neither the Lagrangian nor the SPH
provide any significant deformation. Results show very little interaction between the bird and
the tapered plate because the bird is being sliced in two parts, being the null material the best
approximation when using SPH.

Based on the results, the SPH method can be considered as a good alternative to simulate
bird-strike events although it is more complex in the model creation.
Chapter 5.
Bird-Strike Modeling Based on ALE Formulation

The Lagrangian method is the most commonly used when designing fan blades. This Lagrangian description has been used to create models for both the bird and fan blades. However, this description causes losses of the bird mass due to the fluid behavior of the bird, which causes large distortions in the bird model. This mass loss may reduce the real loads applied to the fan blade, which is the reason why the Arbitrary Lagrange Eulerian method (ALE) is being studied in this work. LS-DYNA, an impact-dynamic finite element software, has integrated the ALE formulation to model this fluid-structure interaction problem. In this work, the ALE method is going to be evaluated and further developed into a standard approach to modeling bird-strike events.

5.1 ALE Model for the Bird-Strike Event

Now, we proceed to study the ALE Approach for bird-strike events. Here we discuss the common variables used by LS-DYNA and a brief description of a typical ALE code used. The overall dimensions and physical properties of the bird are taken from the model of the bird explained in section 2.4.1. In addition the properties used for the targets were taken from the model presented in section 2.4.1.
**Table 5.1: Bird model used for the ALE simulation.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element Type</td>
<td>8-node solid ALE element</td>
</tr>
<tr>
<td>Element Formulation</td>
<td>1 point integration with single material and void (type 12)</td>
</tr>
<tr>
<td>Ambient Element Type</td>
<td>Not needed for the bird</td>
</tr>
<tr>
<td>Mesh Density</td>
<td>Cube elements with edge length of 2.5 mm</td>
</tr>
<tr>
<td>Coupling</td>
<td>CONSTRAINED_LAGRANGE_IN_SOLID</td>
</tr>
<tr>
<td>Slave Part</td>
<td>The part corresponding to the target. Must be Lagrangian.</td>
</tr>
<tr>
<td>Master</td>
<td>Defined in a Set part grouping the ALE parts(void and bird)</td>
</tr>
<tr>
<td>Material Model</td>
<td>*MAT_ELASTIC_FLUID (type 1)</td>
</tr>
<tr>
<td>Density (no bloat)</td>
<td>912 kg/m³</td>
</tr>
<tr>
<td>Young Modulus</td>
<td>23.94 MPa</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>2200 MPa</td>
</tr>
</tbody>
</table>
5.1.1 Pre-Processing in the ALE Formulation

When modeling a bird-strike event using the ALE description it is necessary to create a void mesh surrounding the bird. Both the void and the bird must be part of one computational domain and the elements do not have to overlap. Therefore, it is necessary to merge the common nodes of the bird and the surrounding mesh (Goyal et al., 2006b). The ALE bird model uses parameters in Table 5.1.

5.2 Bird Impact Against a Flat Plate

The bird-strike simulations in a flat rigid plate are based on the shot 5126A by the Barber et al. (1975), as previously discussed in Chapters 3 and 4. The purpose of the simulations performed here is an attempt to incorporate the ALE approach for bird-strike events, and thus validate results with the experimental data and the Lagrange model. LS-DYNA data output parameters such as *DATABASE_FSI are used to obtain the impact force and average pressure diagrams.

Two different simulations were performed: 2D and 3D ALE cases of the impact of a bird against a rigid plate. The first one is a 2D simulation based on the work done by Souli and Olovsson (2000), which has been validated and proven to be a reliable method. The second model is a 3D simulation to study the bird strike event in solid rigid plates studied by Barber et al (1975).
5.2.1 Bird Strike Simulation Using 2D ALE

Let us begin with the 2D ALE model. First, we varied the coupling and reference system parameters inside the *CONSTRAINT_LAGRANGE_IN_SOLID and *ALE_REFERENCE_SYSTEM_GROUP cards. By studying the deformations, the best results are achieved when we take a reference system type parameter of PRTYPE=5 and a coupling type parameter of CTYPE=5.

Here, we set the initial velocity of the model to 198 m/s (442.9 mph), which is the velocity used in the Lagrange simulation. This velocity is assigned to a node set containing the bird and the void mesh using the *INITIAL VELOCITY card. A node set containing all the nodes of the plate is created, where all degrees of freedom are constraints to model the flat rigid plate. A moving mesh was simulated without constraints of expansion. The material used for the target was the *MAT_PLASTIC_KINEMATIC and for the bird and void the *MAT_ELASTIC_FLUID. A penalty coupling was used to specify the type of coupling inside the *CONSTRAINED_LAGRANGE_IN_SOLID card. Figure 5.1 shows the interaction between the bird and the shell and the moving reference for the void mesh. The void has no constraints of rotation about the z axis.

The impacting progression for this simulation can be observed in Fig. 5.1. It can be observed that the modeled bird deforms to the sides although there is no a complete sliding of all of the bird material on the target. The mesh deforms as the bird impacts the target. The reference system follows an automatic mesh motion following a mass weighted average velocity in ALE.
**Figure 5.1:** Deformation of the shell target in the ALE description.

**Figure 5.2:** Average pressure for the 2D simulation in the ALE description.
As observed in Fig. 5.2, the maximum pressure obtained in this ALE simulation is approximately 3.5 MPa. The model used in this simulation has smaller dimensions than the dimensions of the bird tested by Barber in shot 5126A and for this reason it was not expected to produce the same results as in the test data. However, the behavior of the pressure between the fluid and the structure is similar to that observed in both Lagrange simulations and experimental data by Barber et al. (1975). Once again, the steady state for this case is not as well captured; instead the zero value is obtained after a short period of time.

The maximum force obtained for this ALE simulation is 0.080 MN in the negative $x$ direction. This result can not be compared with the Lagrange simulation because the geometrical models in both cases are not the same. The variables used in the ALE cards for this case will be used as reference to create an ALE model that fits the geometrical dimensions of a bird strike performed by Barber et al. (1975), specifically shot 5126 A.

### 5.2.2 2D ALE Simulation of Shot 5126A

By changing various bird parameters, a new deformation for the model bird is created. The deformation is shown in Fig. 5.3. The reference system composed by the surrounding void mesh translates following an automatic mesh motion using mass weighted average velocity. The NADV variable (Number of cycles between advections) was changed to the flag of 1 in the *CONTROL_ALE card.
Figure 5.3: Deformation of the 2D ALE bird impacting a rigid plate.

Figure 5.4: Average pressure (left) and force in the negative $x$ direction (right) for ALE simulation using NADV=1
Figure 5.4 shows the average pressure and force in the $x$ direction. The peak pressure is approximately 36 MPa, which is 10% lower than the 40 MPa measured by Barber et al. (1975) and 17.54% lower than the 43.66 MPa obtained from the Lagrangian formulation using the elastic fluid material. In this case there is almost no variation in the impact area when compared with the SPH and Lagrange methods. Also, in the ALE method there is no change in the global mass of the model as in the Lagrange method. This is observed in Fig. 5.5, which shows zero change in the mass, in contrast with the Lagrange model shown in Fig. 3.4. This suggests that the loads generated with the ALE method could be more accurate to the real loads generated in a bird-strike event. This also is supported by the fact that the peak pressure obtained in the ALE method was 10% of the test data obtained by Barber et al. (1975).

Figure 5.5: Change in mass for the 2D ALE simulation
Figure 5.6 shows the pressure contour progression for this simulation at different times of the impact. The fringe levels of pressure for the first impact of the bird are show in Fig. 5.6. The fringe levels changes from one plot to another in different time intervals. As observed in this figure, a shock pressure is generated at the moment of the impact. This shock pressure travels from the front to the back of the simulated ALE bird. The red elements represent the zone of higher pressure for each of the plots presented in Fig. 5.6. The highest value obtained was 278 MPa. This is the pressure calculated for one ALE element inside of the modeled bird and does not necessarily represent the pressure exerted on the target. The pressure contours confirm that the compressive shock waves, shown by Cassenti (1979), are also calculated by the 2D ALE simulation of a bird-strike.
5.2.3 Bird Strike Simulation Using ALE in 3D

A three dimensional ALE model in LS-DYNA of shot 5126A Barber et al. (1975) is also created. The simulation is performed by creating a void mesh inside of the bird. The dimensions and parameters were those corresponding to shot 5126 A. The material used for the bird was the *MAT_ELASTIC_FLUID and *MAT_PLASTIC_KINEMATIC for the plate. The formulation used for the ALE bird and surrounding void mesh simulation was the one-point integration with single material and void.

Figure 5.7 shows the meshing of the void material for this simulation. Also the merged nodes on the common boundaries of the void and the cylinder can be observed. This is a necessary condition to allow the bird material to flow through the void mesh. The number of cycles between advection (NADV) variable inside the *CONTROL_ALE was set to one. The continuum treatment used for this simulation was DCT = 2 (EULERIAN).

![Figure 5.7: Meshing of the ALE simulation of Shot 5126 A](image)
The void mesh and bird moved together with an initial velocity of 198 m/s (442.9 mph) against the rigid flat plate. The deformation of the bird and void mesh started when the ALE bird impacts the Lagrangian target. The penalty coupling was used to define the coupling. This means that the forces will be computed as a function of the penetration of the bird in the target.

### 5.2.4 Variation of the Coupling Type

Changes in the type of coupling used in the ALE model were performed in order to study the influence of this variable in the pressure calculated by LS-DYNA for the bird-strike simulation. The coupling type variable (CTYPE) is included in the *CONSTRAINED_LAGRANGE_IN_SOLID card.

**Using Acceleration Constraint Coupling**

For this case the type of coupling used was an acceleration constraint or CTYPE=1. This coupling was used to calculate the forces between the Lagrangian target and the ALE bird. Figure 5.8 shows the interaction between the ALE group and the Lagrangian flat plate and the average pressure for this simulation is depicted in Fig. 5.9. Although there was a deformation of the plate after the impact, no pressure was calculated when using acceleration constraint. The simulated ALE bird went through the flat plate without deformation. Therefore this type of coupling is not recommended for bird-strike modeling.
**Figure 5.8:** ALE simulation with acceleration constrain.

**Figure 5.9:** Average pressure for the ALE simulation using acceleration constrain for the coupling.
Using Constrained Acceleration Velocity

The next coupling used is the constrained acceleration velocity that is the default value used by LS-DYNA (CTYPE=2). Figure 5.10 shows that there is some interaction between the bird and the target. However, in Fig. 5.11 it can be observed that no pressure was computed for the fluid-structure database. Therefore, this coupling type does not produce good results for this type of problems.

Figure 5.10: ALE simulation with acceleration constrain.

Figure 5.11: Average pressure for the simulation of a bird-strike (CTYPE=2)
Figure 5.12: ALE simulation with an acceleration velocity constrain in the *CONSTRAINED_LAGRANGE_IN_SOLID card.

Using Constrained Acceleration Velocity in the Normal direction

For this simulation the coupling type used was an acceleration velocity constraint in normal direction only (CTYPE=3) for the coupling between the ALE bird and the Lagrangian target. As seen in Fig. 5.12 the bird went deforms after the coupling, however Fig.5.13 shows that there was no pressure in for the fluid-structure interaction database.

Figure 5.13: Average pressure for the simulation of a bird-strike (CTYPE =3)
Using Penalty Coupling without Erosion

The next coupling type used was the penalty coupling (CTYPE=4). The final shape of the deformed bird for this case encloses the same behavior to that obtained in the 2D ALE simulation as seen in Fig. 5.14. The deformation for this simulation was not as accurate as desired and as a consequence the pressure in the coupling interface registered an approximate value of 95 MPa as seen in Fig. 5.15. This value is 135% higher than the 40 MPa measured in the test data corresponding to shot 5126A from Barber et al. (1975) and 117% higher to the 43.6 MPa of the Lagrangian case. The reason is that the equation of state is a function of time and thus the time step scale factor (TSSFAC) needs to be changed.

Figure 5.14: Deformation of the bird for the ALE simulation.
Based on the results obtained, the recommended coupling type when simulating bird-strike events is the penalty based. For this coupling, the forces are computed as a function of the penetration of the ALE bird in the Lagrangian target. The acceleration and velocity constraint coupling did not produce desired results.

### 5.2.4 Variation of the Time Step Scale Factor

The Time Step Scale Factor (TSSFAC) inside the *CONTROL_TIMESTEP was modified in order to change the time step used for the ALE calculations. It is desired to study how this variation affects the final results in the time history force and pressure generated by the fluid structure database output.

The TSSFAC used in the previous 3D ALE simulation was 0.35 which produced a peak pressure of 95 MPa, as seen in Fig. 5.15. A value of TSSFAC of 0.58 produced similar
deformation however the pressure plot changed. Figure 5.16 shows the new peak pressure obtained in this simulation that was 44.85 MPa 12.25% higher than the experimental value of 40 MPa found by Barber et al. (1975), as seen in Fig. 2.37. Another value used was a TSSFAC of 0.90. The deformation obtained again was similar to previous 3D ALE simulation. Figure 5.17 shows that the peak pressure for this case is 19.4 MPa, which is 51.4% lower than the experimental value. When the TSSFAC was set to 0.58 the peak pressure obtained was 44.85 MPa which is 12.12 % higher than the experimental value of Barber. Figure 5.18 shows the influence of the time step scale factor on the maximum peak pressure at the impact time. The optimum value that for which a steady value is maintained. Thus a value of 0.58 is selected.

![Figure 5.16: Average pressure for the 3D ALE simulation of the bird-strike for TSSFAC=0.58.](image)

**Figure 5.16:** Average pressure for the 3D ALE simulation of the bird-strike for TSSFAC=0.58.
Figure 5.17: Average pressure for the 3D ALE simulation of the bird-strike for TSSFAC=0.90.

Figure 5.18: Average pressure for the 3D ALE simulation of the bird-strike
Table 5.2: Comparison of peak pressure for different Lagrange, SPH and ALE simulations.

<table>
<thead>
<tr>
<th>CONTACT</th>
<th>TYPE</th>
<th>TSSFAC</th>
<th>PEAK PRESSURE VALUE (MPa)</th>
<th>%ERROR from the TEST DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST DATA BY BARBER ET AL. (1975)</td>
<td>N/A</td>
<td>N/A</td>
<td>40</td>
<td>---</td>
</tr>
<tr>
<td>LAGRANGE MAT ELASTIC FLUID ERODING CONTACT</td>
<td>Lagrange</td>
<td>N/A</td>
<td>43.66</td>
<td>9.15</td>
</tr>
<tr>
<td>SPH CONSTRAINT Using Simulated Transducer</td>
<td>SPH</td>
<td>N/A</td>
<td>37.3</td>
<td>6.75</td>
</tr>
<tr>
<td>2D ALE (PENALTY COUPLING) SHOT 5126 A, NADV=1</td>
<td>ALE</td>
<td>0.35</td>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td>3D ALE MAT ELASTIC FLUID</td>
<td>ALE</td>
<td>0.35</td>
<td>95</td>
<td>135</td>
</tr>
<tr>
<td>3D ALE MAT ELASTIC FLUID</td>
<td>ALE</td>
<td>0.58</td>
<td>44.8</td>
<td>12</td>
</tr>
<tr>
<td>3D ALE MAT ELASTIC FLUID</td>
<td>ALE</td>
<td>0.67</td>
<td>26.5</td>
<td>33.7</td>
</tr>
<tr>
<td>3D ALE MAT ELASTIC FLUID</td>
<td>ALE</td>
<td>0.71</td>
<td>26.08</td>
<td>34.8</td>
</tr>
<tr>
<td>3D ALE MAT ELASTIC FLUID</td>
<td>ALE</td>
<td>0.90</td>
<td>19.44</td>
<td>51.4</td>
</tr>
</tbody>
</table>

Table 5.2 shows the comparison of the average peak pressure generated for each of the ALE simulation with the test data from Barber et al. (1975). As observed when the TSSFAC is increased from the original value of 0.35 it considerably decrease the error compared with the test data. The optimum value of the pressure in which the error was the lowest possible, 12%, was obtained when the TSSFAC was 0.58. Therefore, it can be concluded that for simulation of bird-strike using the ALE method in 3D a value of 0.58 should be used for the TSSFAC.
Figure 5.19 shows the comparison for the simulations performed using ALE, Lagrange and SPH methods. Only selected cases are shown in this plot. The values corresponding to the peak pressures are those shown in Table 5.2. The error for the Lagrange and SPH simulations are under 10% and for the 3D ALE simulation with TSSFAC the error obtained was 12%. The material used for the Lagrange and ALE is the elastic fluid and for the SPH was material null. The peak pressure using the 2D ALE case has a delay which is irrelevant because it only depends on the time that takes the bird to impact the plate which is a function of the distance in which the bird was placed initially.
5.3 Bird-strike simulation in tapered plate

5.3.1 Simulation for Tapered Plate Impact at 0°

Now, we model a bird striking a tapered plate as was in the case of the Lagrangian model and SPH model. The bird properties and the tapered plate are taken as the explained in section 2.3.2. Two different impact angles for tapered plate are considered: 0 degrees and 30 degrees. The material used for the bird model is *MAT_ELASTIC_FLUID with a penalty coupling. The variables for the *REFERENCE_SYSTEM_GROUP were kept the same as in previous simulations.

2D Simulation

First a 2D simulation of the impact of the bird against the tapered plate was performed. The coupling of the bird and the tapered plate needs to be calculated in all the directions. This can be obtained setting the value of the DIREC variable inside the *CONSTRAINT_LAGRANGE_IN_SOLID to 3. The type of coupling used in this simulation was the penalty coupling (CTYPE=4). Figure 5.20 shows the interaction of the bird and the plate. The peak force obtained was 0.01461 MN with an error of 1.4% if compared with the Lagrangian simulation of the same case. The force plot is depicted in Fig. 5.21. It can observed that the bird did not go through the plate but
Figure 5.20: Interaction of the bird and the plate for 2D impact at 0 degrees.

Figure 5.21: Force plot for the 2D ALE simulation of the tapered plate impact at 0 degrees.
3D Simulation

The results obtained in the ALE simulation of a bird-strike impact against a tapered plate at 0 degrees were similar to that of the Lagrange and SPH cases. Figure 5.22 shows the interaction of the bird and the plate. As expected, the bird was sliced in two parts and the plate was slightly deformed as seen in Fig. 5.23. However, the pressure plot generated by the *DATABASE_FSI shows that there were little interaction between the Lagrangian plate and the ALE bird. It was necessary to vary the penalty factor in this simulation in order to calibrate the value of the force calculated in the coupling. The penalty factor (PFAC) is used only when a penalty coupling type is included in the keyword. The PFAC variable scales the estimated stiffness of the interacting (coupling) system. A value of 860 was used in our case which was found to be the optimum value. Figure 5.24 shows the plot of the average pressure in which the maximum value was 0.0112 MN, 20.4% lower than the 0.0141 MN computed by the Lagrange case using material elastic fluid.

![Figure 5.22: ALE Bird impacting a tapered plate at 0 degrees at different time intervals and the top view of the tapered plate after the impact.](image)
Figure 5.23: Frontal view of the deformation of the tapered plate.

Figure 5.24: Force plot for the ALE simulation of a tapered plate bird-strike for a 0 degrees impact.
5.3.2 ALE Simulation for Tapered Plate Impact at 30°

2D Simulation

The same model of the 2D bird used in section 5.3.1 was used here with the difference that it was rotated an angle of 30 degrees as shown in Fig. 5.25. The maximum deflection for this case was measured to be 1.18 in, 11.9% higher than the value obtained by Moffat et al (2001). Figure 5.26 shows that the maximum force obtained in this simulation was 0.05319 MN which is 6.06% higher than the Lagrange case. This value was obtained using a penalty coupling with a penalty factor of 120.

Figure 5.25: ALE Bird impacting a tapered plate at 0 degrees at different time intervals
Figure 5.26: Force plot for the 2D ALE simulation of the tapered plate impact at 30 degrees.

3D Simulation

Here a 3D simulation of the bird impact at 30 degrees against the deformable tapered plate is performed. Figure 5.16 shows the interaction of the ALE bird with the Lagrangian plate for different time intervals. Comparing Fig. 3.19 and 5.27, we observe that the deformation in the ALE simulation has a similar behavior as in the Lagrangian case. The maximum normal deflection shown in Fig. 5.28 for this ALE simulation was 1.25 in which is 19.8 % higher than the value found by Moffat et al. (2001) and 5.65 % lower than the Lagrange case using elastic fluid material. In addition, the ALE bird suffered a little change in dimensions only without any loss of mass.
**Figure 5.27:** ALE Bird impacting a tapered plate at 30 degrees at different time intervals and the top view of the tapered plate after the impact.

**Figure 5.28:** Top view of the leading edge deformation.
Figure 5.29: Comparison of the resultant force for the Lagrange, ALE and SPH simulation of a tapered plate bird-strike for a 30 degrees impact.

Figure 5.29 shows the comparison among the SPH, ALE and Lagrange simulation in terms of the final impact force for a tapered plate impact at 30 degrees. The SPH curve was obtained from the simulation of the tapered plate impact at 30 degrees, 26,000 SPH particles and material null performed in Chapter 4. The peak force obtained in the ALE simulation was near the 0.04761 MN 15.9 % lower than 0.0566 MN obtained in the Lagrange simulation. For this simulation also was necessary to calibrate the value of the penalty factor PFAC to a value of 170, which was the optimum value. As previously stated, the main reason for the difference is the type of material used in the ALE method. Another reason for this could be that in the ALE simulation the bird did not presented any loss of mass as in the Lagrangian
case. Also, in Chapter 4 it was observed that not all the particles of the modeled SPH bird interact in the impact, which could be one of the causes of the low force obtained. The difference in the time in which the peak pressure occurs for each case is irrelevant because the time parameters and the distance from the initial position of the bird to the target were different for each formulation. The comparison for the peak force and the maximum normal deflection obtained in the simulations of the impact of a bird against a tapered plate using Lagrange, SPH and ALE formulations are shown in Table 5.3.

Table 5.3: Comparison of peak forces for different Lagrange, SPH and ALE tapered plate impact simulations at 0 degrees.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>MATERIAL</th>
<th>CONTACT/COUPLING</th>
<th>ANGLE OF IMPACT</th>
<th>PEAK FORCE VALUE (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lagrange</td>
<td>Elastic Fluid</td>
<td>Eroding</td>
<td>0</td>
<td>0.01411</td>
</tr>
<tr>
<td>SPH</td>
<td>Null</td>
<td>Eroding</td>
<td>0</td>
<td>0.0153</td>
</tr>
<tr>
<td>2D ALE</td>
<td>Elastic Fluid</td>
<td>Penalty coupling DIREC=3</td>
<td>0</td>
<td>0.0146</td>
</tr>
<tr>
<td>3D ALE</td>
<td>Elastic Fluid</td>
<td>Penalty coupling DIREC=3 PFAC=860</td>
<td>0</td>
<td>0.0112</td>
</tr>
</tbody>
</table>
Table 5.4: Comparison of peak forces for different Lagrange, SPH and ALE tapered plate impact simulations at 30 degrees.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>Material</th>
<th>CONTACT/COUPLING</th>
<th>ANGLE OF IMPACT</th>
<th>Maximum Normal Deflection (in)</th>
<th>Error % from Moffat</th>
<th>PEAK FORCE VALUE (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moffat et al (2001)</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
<td>1.05</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lagrangian</td>
<td>Elastic Fluid</td>
<td>Eroding</td>
<td>30</td>
<td>1.19</td>
<td>13.38</td>
<td>0.0566</td>
</tr>
<tr>
<td>SPH</td>
<td>Null</td>
<td>Eroding 26,000 PARTICLES</td>
<td>30</td>
<td>1.12</td>
<td>6.96</td>
<td>0.0489</td>
</tr>
<tr>
<td>2D ALE</td>
<td>Elastic Fluid</td>
<td>PENALTY COUPLING</td>
<td>30</td>
<td>1.18</td>
<td>11.96</td>
<td>0.0532</td>
</tr>
<tr>
<td>3D ALE</td>
<td>Elastic Fluid</td>
<td>PENALTY COUPLING</td>
<td>30</td>
<td>1.25</td>
<td>19.8</td>
<td>0.0476</td>
</tr>
</tbody>
</table>
Chapter 6.
Concluding Remarks

6.1 Conclusions

The three computational methods (Lagrangian, SPH and ALE) used in LS-DYNA have shown to be robust for the one-dimensional beam centered impact problem. The peak pressure from all three cases has an error smaller than 7% when compared to the analytical results. For the Lagrangian and SPH the error is less than 5%. Thus, the three methods can be used to study soft-body impact problems, such as bird-strike events.

For the frontal bird-strike impact against a flat rigid plate, the best contact was the eroding contact type and the best Lagrangian material was material elastic fluid, which is a material specialized to model a fluid-like behavior taking in consideration the deviatoric stresses which are not considered for the null material. The Lagrangian simulations show that the results are in within 10% when compared to already available experimental data in the literature. The 2D ALE simulation, using an automatic mesh motion following a mass weighted average velocity and a penalty coupling produced a peak pressure of 36 MPa, and the results where within 10% with the pressure measured by Barber et al. (1975). The peak pressure using the 3D ALE simulations showed sensibility to the time-step scale factor (TSSFAC). It was shown that the best time scaled parameter is that of TSSFAC=0.58 which produces an error of 12.12% when compared with that by Barber et al. (1975). Both Lagrangian and ALE models used the material elastic fluid which can explain the convergence in their results. For flat plate impact simulation using a SPH bird constructed
using two different mesh resolutions, if the contact *CONTACT_CONSTRAINT_NODE_TO_SURFACE the pressure obtained is 37.3 MPa with an error of 6.75% over the test data. Therefore, it is recommended to use the above type of contact when studying SPH bird-strike events against rigid flat plate impacts simulations because it better represents the deformations and pressure obtained with the test data.

For the 0 degree bird impact against a tapered plate, there was a small fluid-structure interaction because the bird is basically sliced in two parts. This behavior is observed by all three approaches.

For the 30 degrees bird impact against a tapered plate, the Lagrangian and SPH produce peak forces within 10% error and the maximum normal deflection are found within 13.3% when compared to the maximum normal deflection found by Moffat. However, the maximum normal deflection found in this ALE simulation was 1.25 in, 19.73% higher than the value found by Moffat et al. (2001). Therefore, based on these simulations the ALE approach can be used for bird-strike events in tapered plates.
6.2 Recommendations for Future work

Further work in ALE bird-strike simulation for three dimensional cases should be performed oriented to obtain a better deformation of the bird in the impact. For a 3 dimensional model of a bird strike, a study of the variables involved in the *CONSTRAINT_LAGRANGE_IN_SOLID card need to be developed in order to set the best combination of variables that produce a valid interaction between the Lagrangian and the ALE parts of the model.

It is recommended the use of new versions of the ETA Femb PC Pre-Processor of LS-DYNA or alternates software to create the models. This due to the fact that some of the features of the version 28.0 of the ETA Femb PC Pre-Processor does not work properly.

A statistical study of the peak forces and pressures generated in the impact has to be performed in order to better compare the results obtained using the three method Lagrange, SPH and ALE with the experimental data.
References


Appendix A.
LS-DYNA Overview

A.1 Features

LS-DYNA\(^1\) is a multifunctional finite element code used to model and analyze deformations and dynamic response of structures and interactions between fluids and structures. This software uses various finite element methods and explicit time integration to predict the behavior of the object. LS-DYNA also has implicit capabilities; it can be used to solve problems of structural analysis and heat transfer. The discretization of the finite elements can be done using two-node beam elements, three- and four-node shell element, eight-node solid elements and among other available elements within the code.

Some of the significant features in LS-DYNA are: full definition of contact areas, large library of constitutive models, large library of element types and others. Beside these features, there are different implicit solvers and capabilities for working with the Arbitrary Lagrange Eulerian (ALE) method, Smooth Particle Hydrodynamics (SPH) thermal solver and coupled fluid dynamics. These capabilities allow the user to solve different problems with fluids and structures. Some of the main applications of LS-DYNA are crashworthiness, metal forming, drop testing and bird-strike analysis.

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\(^{1}\) Software developed by LSTC, Livermore Software Technology Corporation in California, USA.
LS-DYNA uses a KEYWORD INPUT database to define the characteristics of the model and other important functions used in the simulation. One keyword can group many similar functions. Each keyword is followed by a card input format to input the numerical values. The keywords are described in the LS-DYNA Keyword User’s Manual (2003). To reset the LS-DYNA default settings the Control keywords can be used. Other important keywords in the LS-DYNS keyword input are the Material cards, Equation-of-state cards, the Element cards, the Part definition cards, among others. The keyword input is written in data blocks with the information pertaining to the keyword following it. The sign “*” must precede the keyword and must be written in column one.

All of the keywords used in the software are presented in the Keyword User’s Manual with explanations of the card input format for each keyword. One of the most important aspects of the keyword input format is the relationship between the variables of the different keywords, illustrated in Fig. 2.5. As it can be observed in the Fig. 2.5, the variables defined in the *PART keyword are referenced in the following keywords (*SECTION, *MAT), if these relationships are not defined carefully, an error could occur at the moment of the simulation.
Another tool for the data input is the ETA/FEMB PRE-PROCESSOR. This is a very useful software within LS-DYNA, which allows model construction and the keyword input using a graphical interface. With this software, the user is capable of creating the simulation in a user friendly manner.

The tools used to plot results are the POST-GL version 1.0 and the LSTC PRE/POST processor. These processors are also included within the LS-DYNA software and are used to create three-dimensional plots of the deformation, stresses and strains that the models suffer due to the impact. The LSTC PRE/POST also allows for the creation of graphs of the maximum stresses and strains for the elements as a function of time.
A.2 Lagrangian Approach in LS-DYNA

In this section a description of a typical code for a Lagrangian simulation is presented. The code is divided in sections depending on the function of each card. The first section of the code is the *KEYWORD card and the function of this card is to let the program know that the input of the data will be done in keyword format. Next is the *TITLE card, this card is used to state the name of the simulation (it is optional).

The next section of the code involves the control cards for the execution of the simulation.

*CONTROL_TERMINATION: Mandatory and is used to specify the time of termination of the program. With this card the user may specify the following variables.

- **ENDTIM**: Termination time of the program,
- **ENDCYC**: Termination cycle,
- **DTMIN**: Reduction (scale) factor for the initial time step used to determine the minimum time step.
- **ENDDEN**: Percent change in energy ratio for termination of calculations.
- **ENDMAS**: Percent change in total mass for termination of calculation which is only used if mass scaling is used to control the termination. For this code, the only factor specified was the termination time.
*CONTROL_TIMESTEP: Used to control the time step for the calculations. In this card, the user can specify the following variables:

DTINIT : Initial time step.

TSSFAC : Scale factor for computed time step. This variable will affect the time-step as indicated in Eq. (B.1)

\[ \Delta t^{n+1} = TSSFAC \cdot \min \{ \Delta t_1, \Delta t_2, ..., \Delta t_N \} \]  

(A.1)

Where, N is the number of elements. The time-step corresponds to the transient time of an acoustic wave through an element using the shortest characteristic distance.

ISDO : Basis of time size calculation for 4 node-shell elements, which is only valid for shell elements.

DT2MS : Time step size for mass scaled solutions.

ERODE : Erosion flag for solid and t-shell elements when TSMIN in the *CONTROL_TERMINATION card is reached. For the Lagrangian models used in this work we used ERODE=1 which mean that erosion is allowed.

The next section is that corresponding to the database controls for binary outputs. In this section the software created output files are selected.
*DATABASE_BINARY_D3PLOT: Used to create a 3D plot of the simulation observed in the Post-Processing software included in LS-DYNA.

   DT : Time interval between outputs.

   LCDT: Load curve ID. Specify time interval between dumps.

   For the Lagrangian simulations performed, only the time interval between outputs was specified.

For the output files also a section for database control for ASCII can be specified. In this section.

*DATABASE_GLSTAT: Used to obtain global data of the system.

   DT: Time interval between outputs

   BINARY: Option to select what type of file will be created. For the BINARY option, a “1” indicates that an ASCII file is written, a “2” indicates that a binary database will be created and a “3” indicates that both files will be created.

*DATABASE_RCFORC: This card was useful in this thesis. It is used to obtain the outputs for the interacting forces in the contact of Lagrangian parts. It is necessary to indicate the following variables:

   DT: Time interval of output of the database

   BINARY: Flag for binary output.
The code also provides a section to specify the parts, sections and material for the objects in the simulation. This is done using the *PART, *SECTION and *MAT cards.

*PART: Used to identify each part and is related to the *SECTION and *MAT cards, since the section and material ID are set by the user using this card. The *SECTION card is followed by the type of element. As for example to define a shell element the *SECTION_SHELL card is used. The *MAT card is used to specify the material properties of each part. These cards may vary for each part only if each part has a different material or the selected element is different.

In the *PART card, the user specifies the following values:

    PID: Part ID.
    SID: Section ID.
    MID: Material ID.
    EOSID: Equation of state defined in the *EOS card. This equation of state is assigned to the material of the indicated in MID.
    HGID: Hourglass identification.

Other options include the part initialization for gravity loading (GRAV) used for brick elements and an option to identify thermal material property (TMID). The format of this card is to identify the section ID (SID), which must be equal to the section ID defined in the *PART card. For the *SECTION_SHELL card the user has to specify the element formulation options (ELFORM), followed by the option to apply a shear correction factor (SHRF) used to scale the transverse shear stress. The number of through thickness iteration
points (NIP) can be specified. Next the user can specify the quadrature or integration rule (QR/IRID) followed by a card for composite materials (ICOMP). In the following line of this card the user must input the thickness for each of the four elements that compose the shell element (T1, T2, T3 and T4).

The material used in the Lagrangian simulations was the *MAT_NULL. This material allows equation of state to be computed without computing deviatoric stresses. Erosion in tension and compression is possible. When using the *MAT_NULL an equation of state, *EOS is required. The *EOS_TABULATED card is used for the bird-strike simulation of this project.

MID: Material identification.
RO: Mass density.
PC: Pressure cutoff.
MU: Dynamic viscosity coefficient.
TEROD: Relative volume, V/Vo, for erosion in tension.
CEROD: Relative volume, V/Vo, for compression.
YM: Young modulus.
PR: Poisson’s ratio.

*EOS_TABULATED: A tabulated equation of state linearly dependent on the internal energy.

EOSID: Indicates the characterizing number for the equation which is referred in the corresponding part.
EV1, EV2 …EVN: Natural logarithm of the relative volume.
C1, C2 …C3: Constants.
T1, T2 …T3: Temperature constants.

GAMMA: $\gamma$

E0: Initial internal energy.

V0: Initial relative volume.

*SECTION_SOLID: Used to define section properties for the solid elements corresponding to the bird. The type-1 element formulation corresponds to a constant stress solid formulation. These section properties are assigned to the bird indicating the section ID in its corresponding *PART card.

The ETA FEMB PC Preprocessor is used to edit some of the properties of the bird, renumber the nodes of the blade and bird. The *SET_NODE_LIST also is used. The node ID gathered in this node set list are those corresponding to the model of the bird. This set of nodes are used to assign an initial velocity to the bird using the *INITIAL_VELOCITY card. A node set can also be created to add constraint to the node set using the *BOUNDARY_SPC_SET_ID card.

Next, the contact has to be defined between the bird and the blade. As an example of a contact card, we chose the following contact type:

*CONTACT_SURFACE_TO_SURFACE_ID:

    CID: Single number that identifies the contact.
SSID: Slave segment ID. Used to indicate the node ID, part ID, partset ID or shell element ID that is going to slide in the master surface until a tensile force develops.

MSID: Master segment ID. Indicates the master node ID, part ID, partset ID or shell element ID.

SSTYP and MSTYP: Variables are used to indicate the type of entity to be assigned to the slave segment and the master segment.

BT : Birth time in the third card input is set to zero which means that the contact surface becomes active at time equal to zero.

DT : Default death time. The value in this card is set to 1.0e+20, which is the time at when the contact surface is deactivated.

In the fourth card input, the scale factor for penalty stiffness for the slave and master segments (SFS and SFM respectively) are set to one. In addition, the scale factors for the slave and master surface thickness (SFST and SFMT respectively) have a value of one. The Coulomb friction scale factor (FSF) and the viscous friction scale factor (VSF) are set also to one.

When the material constants of the surfaces that are in contact have a wide variation of the elastic bulk modulii, it may be necessary to use the soft constrain. When the value is zero, it means that a penalty formulation is used.

The node information in the *NODE card corresponds to the nodes of the blade and the bird. The nodes corresponding to the void were eliminated. As in the code showed for the ALE
simulation the elements are defined using the *ELEMENT_SHELL card for the blade part corresponding to the blade and *ELEMENT_SOLID for the part corresponding to the bird.

A.3 ALE Approach in LS-DYNA

Souli and Olovsson (2000) mentioned four types of definitions for the ALE-mesh motion:

1. Classical mesh smoothing
2. Motion following pre-defined load curves ahead of time
3. Automatic translation, rotation and stretching of elements in order to adapt to the current location of the material inside the mesh.
4. Automatically translate and rotate the mesh, following a coordinate system defined by three arbitrary nodes in the model.

The Pre-Defined Load Curve Motion as presented by Souli and Olovsson (2000) is presented next. For this method, 12 load curves must be specified to solve for the velocities with the Equation A.2:

\[
\begin{pmatrix}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{pmatrix}
= \begin{pmatrix}
f_1 \\
f_2 \\
f_3
\end{pmatrix}
+ \begin{pmatrix}
f_4 & f_5 & f_6 \\
f_7 & f_8 & f_9 \\
f_{10} & f_{11} & f_{12}
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
\]

(A.2)

In the above equation, \( f_i(t) \) for \( i = 1, \ldots, 12 \) are the loads defined by the user. LS-DYNA uses the keyword *ALE_REFERENCE_SYSTEM_CURVE to define the motion and deformation.
for a geometric entity. This keyword allows the user to enter the 12 load curves described above.

If the description of the motion of the material is unknown then the automatic motion can be used. Souli and Olovsson (2000) described the rigid body translation defining the nodal velocity as:

\[
\begin{align*}
\{\dot{x}_c, \dot{y}_c, \dot{z}_c\} &= \sum_{n=1}^{N} m_n \begin{bmatrix} u \\ v \\ w \end{bmatrix} \\
&= \sum_{n=1}^{N} m_n 
\end{align*}
\]  

(A.3)

where \( m_n \) for \( n = 1, \ldots, N \) are the nodal masses in the ALE mesh, \( (u, v, w)_n \) are the nodal mass flow velocities. The center of gravity of the ALE mesh is defined as:

\[
x_c = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \frac{\sum_{n=1}^{N} m_n \begin{bmatrix} x \\ y \\ z \end{bmatrix}}{\sum_{n=1}^{N} m_N} 
\]  

(A.4)

The node velocity can be written as:

\[
X_i = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} + \begin{bmatrix} x' - \sigma_z & \sigma_y \\ \sigma_z & y' - \sigma_x \\ -\sigma_y & \sigma_x \end{bmatrix} \begin{bmatrix} x_i - x_c \\ y_i - y_c \\ z_i - z_c \end{bmatrix} 
\]  

(A.5)
LS-DYNA includes many commands or keywords implemented for the use of the ALE simulation. For example, the *ALE_REFERENCE_SYSTEM_GROUP defines the type of reference system for any part, element or other geometric entity. A geometric entity may be moved, smoothed, expanded according to the reference system type defined. With the *CONTROL_ALE card, the user can set default control parameters for the ALE and Eulerian calculations. The velocity boundary conditions are defined automatically when using this option.

The following capabilities for ALE and Eulerian formulations are available in LS-DYNA: several smoothing algorithms, multi-material Eulerian elements, first and second order advection methods, void materials, automatic slip, stick or silent boundary conditions for the Eulerian simulations, acoustic pressure formulation, automatic to Lagrangian shell, brick or beam element. Also it is possible to input Eulerian-Lagrangian coupling in LS-DYNA. This could be done by defining two lists of Lagrangian and Eulerian materials coupled together. This coupling method has many industrial applications.

**A.3.2 Code explanation**

Here we provide a brief description of the keywords used for a typical ALE simulation in LS-DYNA. There some similarities with the Lagrangian formulation. The ALE code is divided in different sections following the functionality of the card for a better description. The following cards are same as for the Lagrangian description:

*KEYWORD
The card *DATABASE_FSI is used to obtain the output database of the interaction of the ALE and Lagrangian model.

To create the void, the part, section and material ID’s were set using the *PART card in the same way as the target. The section card for the ALE model differs from the Lagrange model.

In the ALE model the *SECTION_SOLID_ALE card is activated instead of using the *SECTION_SOLID card.

*SECTION_SOLID_ALE:

SID: Section ID.

ELFORM: Element formulation.

AET: Ambient element type. This card is used for options 7, 11 and 12 of the element formulation. For the bird, it is not necessary to enter a value for AET.

AFAC: Smoothing weight factor for simple average solution.

BFAC: Smoothing weight factor for volume weighting.

CFAC: Smoothing weight factor for isoparametric solutions.

DFAC: Smoothing weight factor for equipotential solutions.

START: Start time for smoothing.
END: End time for smoothing.

AAFAC: ALE advection factor. The smoothing weight factors are different algorithms used to calculate the solution for the desired simulation.

The material for the void is defined using the *MAT_ELASTIC_FLUID. For this we define the following values.

MID: Material ID.
RO: Density.
E: Modulus of elasticity.
PR: Poisson’s ratio.
DA: Axial damping factor.
DB: Bending damping factor.
K: Bulk modulus.
VC: Tensor viscosity coefficient.
CP: Cavitation pressure.

The Bulk modulus, viscosity coefficient and the cavitation pressure are only defined for fluids. In the example, since it was a fluid, the values of the modulus of elasticity, Poisson’s ratio, and the damping factors were all zeroes.

*INITIAL_VOID_PART: Here the user defines the part ID for the part which is the void.

The *PART card was used to define the part ID of the target, the bird and the void mesh. The section of the bird is defined using the *SECTION_SOLID_ALE (same as the void). The
material ID can also defined the same way as for the void, using the *MAT_ELASTIC_FLUID.

In the section corresponding to the set part cards a list of the parts of the void and the bird are grouped together using the keyword *SET_PART_LIST. This card is used to define a set of parts with optional attributes. A unique number corresponding to the part set ID is used to identify the set. It is necessary to indicate in the second card of the *SET_PART_LIST, which parts are going to be grouped by indicating its corresponding part ID.

*ALE_REFERENCE_SYSTEM_GROUP: Used to define the type of reference system that is being prescribed to a geometric entity (part, part set, node set, or segment set).

  SID: Set ID. Corresponds to the same set defined before using the *SET_PART_LIST card.

  STYPE: The type of entity for the set ID is specified in the variable for the card input format, the number “0” indicates that a part set is used.

  PRTYPE: Defines the reference system type. The number “4” corresponds to an automatic mesh motion following mass weighted average velocity in the ALE mesh.

  PRID: ID of switch list.

  BCTRAN, BCEXP and BCROT: Used to set the translational, expansion and rotation constraints for the ALE group the variables respectively are used. The center of the mesh expansion XC, YC and ZC is the point (0, 0, 0).
EXPLIM: Limit ratio for mesh expansion in this work, defined with the variable, is 1.3.

*INITIAL VELOCITY: Set the initial velocity for the grouped parts of the bird and the void is set with the card. This card is used to define the nodal point initial translational velocities using nodal set ID’s. The nodal set ID (NSID) is the same number assigned in the *SET_NODE_LIST keyword, where all the nodes of the void mesh and bird material are grouped.

*CONTROL_ALE: Sets the default control parameters for the arbitrary Lagrange-Eulerian calculations.

DCT: Default continuum treatment. This was set to “2” which means an Eulerian treatment. The method used for the advection is the Van Leer (VL) and the Half-Index-Shift of second order (HIS).

*CONSTRAINED_LAGRANGE_IN_SOLID: Provide the mechanism for coupling interaction between a slave Lagrangian geometric entity and a master ALE or Eulerian geometry entity the keyword is used.

SSTYPE: In the variable of its card input the value of “1” indicates that the type of the slave is a PID (Part ID), and then the indicated number for the slave refers to the part which is the blade target shell. This part has to be a Lagrangian part.
MSTYPE: The value of “0” indicates that the type of the master is a part set ID. Then the number assigned to the MASTER variable corresponds to the grouped ALE materials.

NQUAD: Cuadrature rule. The cuadrature rule states that there will be $n \times n$ coupling points distributed over each Lagrangian segment surface (NQUAD=n).

CTYPE: Coupling type. If the coupling type is equal to four (CTYPE=4), then a penalty coupling without erosion is used. The coupling direction is in normal direction, compression only.

MCOUP: The variable has a value of “1” that means a coupling with material with highest density.

PFAC: The penalty factor variable is set to zero. This value is used for scaling the estimated stiffness of the interacting system and computes the coupling forces to be distributed on the slave and master parts.

No friction is considered in the model (FRIC=0). By setting NORM=0, the normal vector orientation of the Lagrangian shell part are defined according to the right hand rule.

Another section is that corresponding to the node set cards. In this section of the code the nodes are grouped and the boundary nodes are specified. To group the nodes, *SET_NODE_LIST card is used. For this card the set ID (SID) is specified, followed by attributes that may be specified to the group (DA1, DA2, DA3, DA4). The next variables for this card are the node ID’s (NID1, NID2… NID8) of the nodes to be grouped together.
*BOUNDARY_SPC_NODE: Add the required translational or rotational constraints to the boundary nodes.

NID/NSID: The first variable is the node ID or nodal set ID. This specifies the boundary nodes. The next variable is the coordinate system ID (CID). Next, the translational and rotational constraints can be set for these nodes by the user.

DOFX, DOFY and DOFZ: Set the translational constraints in the x, y and z direction.

DOFRX, DOFRY and DOFRZ: Set the rotational constraints in the x, y and z axis.

The last section of the code describes the geometry and the list of the elements and nodes used in the model. The coordinates for each node are given and the nodes are set in the respective elements. The *NODE card define the nodes by their node ID (NID) and their x, y and z coordinates. Also the user may set the translational constraints (TC) and the rotational constraints (RC). With *ELEMENT_SOLID card the void mesh and the bird elements are defined. It is required to identify the node ID and their respective part ID. First, the element ID is set (EID), followed by the specification of the part ID (PID). Next, the nodes that compose the element are specified. The element is an 8 node hexahedron, therefore for each solid element 8-nodes must be specified (N1, N2… N8).

To define the element type for the blade target shell structure the *ELEMENT_SHELL keyword is used. In this card the element ID (EID) must be set. Next the part ID (PID) is set.
This is a four node shell element and corresponds to the part ID (PID) “1”. For each shell four nodes must be specified (N1, N2, N3, N4).

The last command of the code is the *END command which ends the simulation.

A.4 SPH Approach in LS-DYNA

For the Smooth Particle Hydrodynamics formulation, the initial particle masses, densities, constitutive laws and coordinates must be set. All the particles of a neighborhood need to have the same mass to make the particle mesh required regular enough. LS-DYNA has implemented new keywords for the SPH elements used for explicit applications. Some initials characteristics and properties for the SPH simulations have to be defined for the user.

The *CONTROL_SPH card is used to provide control parameters for computations involving SPH particles. Some of the variables used in this keyword are: The number of cycles between particle sorting, the BOXID that specified the box inside of which SPH particles are computed, Death time, etc.

The *SECTION_SPH card is used to define the section properties for SPH particles. With this keyword it is possible to define the constant applied to the smoothing length, the minimum and maximum scale factor for the smoothing length, the initial smoothing length and the start and stop time for the SPH approximation.
The *ELEMENT_SPH defines the particles in the nodes with its respective part ID and mass. Although SPH is an extra layer of LS-DYNA, it is possible to use the other capabilities and classical keywords of LS-DYNA.

It is necessary to use the SPH processor when there are SPH particles in the model. Some of the material types available for SPH in the 970 version of LS-DYNA are:

*MAT_ELASTIC
*MAT_PLASTIC_KINEMATIC
*MAT_VISCOELASTIC
*MAT_HIGH_EXPLOSIVE_BURN
*MAT_NULL
*MAT_ELASTIC_PLASTIC_HYDRO

There is no need to define contact between SPH parts. This contact will only be defined between two SPH materials when one particle of one material is inside the sphere of influence of the other SPH material (Lacome, 2001). On the other hand, if there are any brick or shell elements in the model, then it is necessary to use a NODE_TO_SURFACE contact.

The keywords *DATABASE_HISTORY_SPH and *DATABASE_SPHOUT generate a SPHOUT file. The information carried for this file includes the stress variables such as pressure, stresses, Von Misses and the strain variables.
A.4.1 SPH code explanation

A description of a typical SPH code for the bird-strike event simulation is now presented. The first keyword in the code is the *KEYWORD card, used to inform the program what will be the input. Next, the *TITLE card is used to input the title of the simulation. The next section of the code is the control section. The *CONTROL_TERMINATION keyword defines the termination time for the simulation. Also, the termination may be specified for a cycle by specifying the ENDCYC variable. The *CONTROL_TIMESTEP card is used to specify initial time step controls. The next control keyword used is the *CONTROL_SHELL card, used to control calculations for the shell elements. This keyword was used in this simulation to set the shell theory. The *CONTROL_ENERGY card was used to apply the Stonewall Energy dissipation option. Other controls that may be applied with this card are the Hourglass energy calculation, the Sliding interface energy dissipation and the Rayleigh energy dissipation option.

The *CONTROL_SPH card is used to specify controls for the SPH calculations. The number of cycles between particle sorting can be specified with the NCBS variable. The BOXID variable is used to specify a box within the SPH computations will be done; no computations will be made to the particles that move outside the specified box. The DT variable is used to specify the “Death time”, which is the time when the SPH calculations will be stopped. The IDIM variable is used to specify the dimensions of the problem (2D or 3D). The MEMORY variable is used to set the number of neighboring particles for the initial calculation. The FORM variable is used to input the particle approximation theory used. If a “0” is the input, the default theory will be used, if a “1” is the input, the renormalization approximation will
be used. The start variable is used to input the time when the SPH particle approximations will begin. The MAXV variable is used to identify the maximum velocity permitted for the particles, particles that have a higher velocity will be deactivated. For this simulation the values for the SPH controls were left as the default values.

The *DATABASE_BINARY_D3PLOT was used to specify the time for the time interval between the output to the database. This was set with the DT/CYCL variable. The next section of the code consisted of setting the parts, material and element definitions. The *MAT PIECEWISE_LINEAR_PLASTICITY card was used to define the material properties for the target. The *MAT PLASTIC_KINEMATIC card was used to define the material properties for the beam. The *EOS_GRUNEISEN was used to define the equation of state to be used for the calculations. The values for the variables used in this equation of state must be set by the user for this command to work properly. The next card used was the *SECTION_SPH used to define section properties for the SPH particles. The first variable (SID) is used to set the section ID, followed by the CSLH variable that is used to set the constant applied for the smoothing length of the particles.

The *PART commands are used to define the type of elements and material properties that are applied to the parts used in the simulation. The material and element type are set using the keywords explained before, they are applied to the respective parts by input of the section ID (SID) and the material ID (MID) specified in the *MAT and *SECTION keywords.
The next keyword was the *NODE card used to input the ID and coordinates for each node. The *ELEMENT_SOLID keyword was used to specify the nodes that composed the target, which was a solid element composed of nodes 1 thru 8. Also in this card, the user specifies the part ID for the solid element as defined in the *PART card. The *DEFINE_BOX keyword was used to define a box that included all the SPH particles. This box was used as a reference for the next keyword which is the *RIGIDWALL_PLANAR card. This card was used to define the contact between a rigid surface and the nodal points of the deforming body. The BOXID variable was used to specify that the nodes inside the “box 1” were the slave nodes to the rigid wall. The FRIC variable was set to a value of “1”, which indicates a constraint of no sliding after contact.

The *SET_NODE_LIST_GENERATE card was used to create a set node list consisting of all the nodes that compose the cylinder. This list is used as reference for the initialization of the velocity.

The next keyword was the *INITIAL_VELOCITY card, used to apply the initial velocity to the cylindrical beam. The node set ID 1 and the BOX ID 1 (defined above) were set as the part at which the initial velocity was applied, the initial velocity was $-100$ in the $z$ direction.

The *ELEMENT_SPH card was used to define the elements that compose the cylinder as a lumped mass element (Smooth Particles). The variables used for this card are the NID to set the node ID of the nodes that compose the element, the PID to define the part to which these elements are assigned and MASS to set the mass value for each particle.
The *END card was then used to finish the code.
Appendix B.
Keyword for the 3D Lagrangian Simulation

KEYWORD FOR THE 3 DIMENSIONAL LAGRANGIAN SIMULATION OF A BIRD-STRIKE

$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ LS-DYNA(970) DECK WRITTEN BY : eta/FEMB-PC version 28.0$
$ ENGINEER : CARLOS HUERTAS ORTECHO$
$ PROJECT : DEVELOPMENT OF ROBUST ANALYTICAL MODELS FOR BIRD STRIKE$
$ UNITS : IN, LB*SEC^2/IN, SEC, LB$
$ TIME : 06:09:56 PM$
$ DATE : Tuesday, October 11, 2005$

$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ KEYWORD$
$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ TITLE$
Lagrange

$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ CONTROL CARD$

$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ CONTROL_HOURGLASS$

$+---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ DATABASE_GLSTAT$
$ DATABASE_RCFORC$
$ DATABASE_NCFORC$
$ DATABASE_SPHOUT$
$ DATABASE_ELOUT$

214
DATABASE CONTROL FOR BINARY

*DATABASE_BINARY_D3PLOT

DT/CYCL  LCDT  BEAM  NPLTC
0.0000030  0  0  0

PART CARDS

*PART

SHEADING
PART-11

PID  SECID  MID  EOSID  HGID  GRAV  ADPOPT  TMID
11  5  2  0  0  0  0  0

PART

SHEADING
PART-22 BIRD

PID  SECID  MID  EOSID  HGID  GRAV  ADPOPT  TMID
37  6  1  1

SECTION CARDS

*SECTION_SHELL

SECID  ELFORM  SHRF  NIP  PROPT  QR/IRID  ICOMP  SETYP
5  2  1.0  2  0.0  0.0  0  1

T1  T2  T3  T4  NLOC  MAREA
0.03937008  0.03937008  0.03937008  0.03937008  0.03937008  0  0

*SECTION_SOLID

SECID  ELFORM  AET
6  1  0

MATERIAL CARDS

*MAT_NULL

M-1

MID  RO  PC  MU  TEROD  CEROD  YM  PR
18.5395E-05  -14.466  0.0  1.1  0.80  0.0  0.0

*MAT_PIECEWISE_LINEAR_PLASTICITY

M-2

MID  RO  E  PR  SIGY  ETAN  FAIL  TDEL
23.6727E-04  2.9733E+07  0.29  150114.0  0.010000E+21  0.0

C  P  LCSS  LCSR  VP
0.0  0.0  0.0  0.0

EPS1  EPS2  EPS3  EPS4  EPS5  EPS6  EPS7  EPS8
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0

ES1  ES2  ES3  ES4  ES5  ES6  ES7  ES8
0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0

215
$EOS CARDS$

*EOS TABULATED
$^EQUATION_1$
$EOSID  GAMA   E0   V0$

1  1.0  0.0  1.0

$^EQUATION_1

EV1  EV2  EV3  EV4  EV5
1.0  0.0  -0.0953  -0.1044  -0.1124

EV6  EV7  EV8  EV9  EV10
-0.1178  -0.1257  -0.1310001  -0.1483999  -0.2326999

C1  C2  C3  C4  C5
-5000.0  0.0  294.0  1470.0  2940.0

C6  C7  C8  C9  C10
4410.0  5880.0  7350.0  14700.0  73500.0

T1  T2  T3  T4  T5
0.0  0.0  0.0  0.0  0.0

T6  T7  T8  T9  T10
0.0  0.0  0.0  0.0  0.0

$HOURGLASS CARDS$

*HOURGLASS
$^HOURGLASS_1$

HGID  IHQ  QM  IBQ  Q1  Q2  QB  QW
1  2  0.14  0  1.5  0.060  0  0

$NODE SET CARDS$

*SET_NODE_LIST
$^NODE_SET 4$

SID  DA1  DA2  DA3  DA4
4  0.0  0.0  0.0  0.0

NID1  NID2  NID3  NID4  NID5  NID6  NID7  NID8
17522  17523  17524  17525  17526  17527  17528  17529
17531  17532  17533  17534  17535  17536  17537  17538
...
17280  17279  17278  17277  17260  17259  17258  17257
17256

*SET_NODE_LIST
$^NODE_SET 5$

SID  DA1  DA2  DA3  DA4
5  0.0  0.0  0.0  0.0

NID1  NID2  NID3  NID4  NID5  NID6  NID7  NID8
35044  84278  84284  35050  34748  150569  150570  34754
...
81273  81272  81279  81278  81285  81284  81290  32056
81296  32062  32068  32038  32044  32050  32140  32146
32152  32158  32164
PART SET CARDS

SET_PART_LIST

SID DA1 DA2 DA3 DA4
1 0.0 0.0 0.0 0.0

BOUNDARY SPC CARDS

BOUNDARY_SPC_SET_ID

ID
1

INITIAL VELOCITY CARDS

INITIAL_VELOCITY

VX VY VZ VXR VYR VZR
0.0 0.0 -7795.276 0.0 0.0 0.0

CONTACT CARDS

CONTACT_ERODING_NODES_TO_SURFACE_ID

CID
2

SSID MSID SSTYP MSTYP SBOXID MBOXID SPR MPR
5 11 4 3 1 1 1

SOFT SOFSCL LCIDAB MAXPAR SBLOPT DEPTH BSORT FRCFRQ
0 0.10 1.025 0.0 2.0 0 1

PENMAX THKOPT SHLTHK SNLOG ISYM I2D3D SLDTHK SLDSTF
0.0 0.0 0.0 0.0 0.0 0.0 0.0

IGAP IGNORE
2 0
BOX CARDS

*DEFINE_BOX

BOXID XMIN XMAX YMIN YMAX ZMIN ZMAX
1 -0.984252 0.984252 -0.984252 0.984252 0.0 2.480315

*NODE

NID X Y Z TC RC
17080 -1.181102 1.181102 -0.3937008 0.0 0.0
17081 -1.181102 1.062992 -0.3937008 0.0 0.0
...
152727 -0.5895815 -0.3978004 0.2362205 0.0 0.0

*ELEMENT_SHELL

EID PID NID1 NID2 NID3 NID4
20238 11 17080 17081 17102 17101
20239 11 17081 17082 17103 17102
...
21277 11 18266 17702 17520 17499

*ELEMENT_SOLID

EID PID NID1 NID2 NID3 NID4 NID5 NID6 NID7 NID8
78995 37 35044 84278 84284 35050 34748 150569 150570 34754
...
81234 37 32578 152653 152658 32584 32164 81398 81404 32170

*END
Appendix C.
Keyword for the 2D ALE Simulation

KEYWORD FOR THE 2 DIMENSIONAL ALE SIMULATION OF A BIRD-STRIKE

$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$ LS-DYNA(970) DECK WRITTEN BY: eta/FEMB-PC version 28.0
$ ENGINEER: CARLOS HUERTAS ORTECHO
$ PROJECT: DEVELOPMENT OF ROBUST ANALYTICAL MODELS FOR BIRD-STRIKE
$ UNITS: MM, TON, SEC, N
$ TIME: 07:23:08 PM
$ DATE: Saturday, December 10, 2005
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*KEYWORD 2000000
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*TITLE
LS-DYNA USER INPUT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$                                                                              $
$                                 CONTROL CARD                                 $
$                                                                              $
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*CONTROL_ALE
$     DCT      NADV      METH      AFAC      BFAC      CFAC      DFAC      EFAC
2      1      2      -1.0       0.0       0.0       0.0       0.0
$     START       END     AAFAC     VFACT      PRIT       EBC      PREF       NSIDEBC
0.0       0.0       0.0  0.000010
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*CONTROL_ENERGY
$     HGEN      RWEN    SLNTEN     RYLEN
2      2      1      1
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*CONTROL_TERMINATION
$     ENDTIM    ENDCYC     DTMIN    ENDENG    ENDMAS
0.001         0       0.0       0.0       0.0
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*CONTROL_TIMESTEP
$     DTINIT    TSSFAC      ISDO    TSLIMT     DT2MS      LCTM     ERODE     MS1ST
0.0      0.35         0       0.0       0.0         0         0         0
$     DT2MSF
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$                                                                              $
$                          DATABASE CONTROL FOR ASCII                          $
$                                                                              $
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DATABASE_GLSTAT
$       DT    BINARY
0.0000072         1
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DATABASE_MATSUM
$       DT    BINARY
0.0000072         2

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DATABASE CONTROL FOR BINARY

*DATABASE_BINARY_D3PLOT
$ DT/CYCL  LCDT  BEAM  NPLTC
0.0000072  0

*DATABASE_FSI
$ DT
0.0000072
$ DBFSI_ID  SID  SIDTYPE
1  1  1

*PART
$HEADING
PART-1
$ PID  SECID  MID  EOSID  HGID  GRAV  ADPOPT  TMID
1  1  1  0  0  0  0  0

*PART
$HEADING
PART-3
$ PID  SECID  MID  EOSID  HGID  GRAV  ADPOPT  TMID
3  2  2  0  0  0  0  0

*PART
$HEADING
PART-5
$ PID  SECID  MID  EOSID  HGID  GRAV  ADPOPT  TMID
5  2  2  0  0  0  0  0

*SECTION_SHELL
$ SECID  ELFORM  SHRF  NIP  PROPT  QR/IRID  ICOMP  SETYP
1  0.0  2  0.0  0.0  1
$ T1  T2  T3  T4  NLOC  MAREA
3.048  3.048  3.048  3.048  0

*SECTION_SOLID_ALE
$ SECID  ELFORM  AET
2  12
$ AFAC  BFAC  CFAC  DFAC  START  END  AAFAC
0.0  0.0  0.0  0.0  0.0  0.0
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ $  
$ MATERIAL CARDS $  
$ $  
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
*MAT PLASTIC_KINEMATIC
$*MAT PLASTIC_KINEMATIC$
$ MID  RO  E  PR  SIGY  ETAN  BETA$
13.9200E-09  205000.0  0.29  1035.0  0.99112  0.0  0.0  0.0  0.0
*MAT_ELASTIC_FLUID
$*MAT_ELASTIC_FLUID$
$ MID  RO  E  PR  DA  DB  K$
29.1200E-10  23.94  0.0  0.0  0.0  2200.0  0.30  239.4
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ $  
$ NODE SET CARDS $  
$ $  
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
*SET_NODE_LIST
$*NODE_SET 3$
$ SID  DA1  DA2  DA3  DA4$
3  0.0  0.0  0.0  0.0
$ NID1  NID2  NID3  NID4  NID5  NID6  NID7  NID8$
1  3  4  2  5  6  7  8
9 10 11 12 13 14 15 16
17 18 19 20 21 22 23 24
25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48
49 50 51 52 53 54 55 56
57 58 59 60 61 62
*SET_NODE_LIST
$*NODE_SET 1$
$ SID  DA1  DA2  DA3  DA4$
1  0.0  0.0  0.0  0.0
$ NID1  NID2  NID3  NID4  NID5  NID6  NID7  NID8$
63 64 81 80 352 355 354 353
65 82 357 356 66 83 359 358
663 698 664 699 667 702 668 703
669 704
*SET_NODE_LIST
$*NODE_SET 2$
$ SID  DA1  DA2  DA3  DA4$
2  0.0  0.0  0.0  0.0
$ NID1  NID2  NID3  NID4  NID5  NID6  NID7  NID8$
63 64 81 80 352 355 354 353
663 698 664 699 667 702 668 703
669 704
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8$
$ $
PART SET CARDS

*SET_PART_LIST

PART_SET 1

SID DA1 DA2 DA3 DA4
1 0.0 0.0 0.0 0.0

PID1 PID2 PID3 PID4 PID5 PID6 PID7 PID8
3 5

BOUNDARY SPC CARDS

BOUNDARY_SPC_SET_ID

ID
2

NSID CID DOFX DOFY DOFZ DOFRX DOFRY DOFRZ
3 0 1 1 1 1 1 1
1
2 0 0 0 1 0 0 0

CONSTRAINED LAGRANGE IN SOLID CARDS

LAGRANGIAN SOLID CARD 1

SLAVE MASTER SSTYP MSTYP NQUAD CTYPE DIREC MCOUP
1 1 0 2 4 2 1

START END PFAC FRIC FRCMIN NORM PNORM DAMP
0.0 0.0 0.0 0.0

CQ HMIN HMAX ILEAK PLEAK
0.0 0.0 0.0 0.0

INITIAL VELOCITY CARDS

INITIAL VOID CARDS

VOID CARD 1

PID
3

INITIAL VELOCITY

NSID NSIDEX BOXID IRIGID
1 0 0

VX VY VZ VXR VYR VZR
198000.0 0.0 0.0 0.0 0.0 0.0

INITIAL VOID PART

VOID CARD 1

PID
3
$  
$  ALE CARDS  
$  
$  
*ALE_REFERENCE_SYSTEM_GROUP  
$*ALE_1  
$ SID STYPE PRTYPE PRID BCTRAN BCEXP BCROT ICOORD  
  1 0 4 0 0 0 0 0  
$ XC YC ZC EXPLIM  
  0.0 0.0 0.0 1.3  
$  
$  
$  
$ NODE INFORMATION  
$  
$  
*NODE  
$ NID X Y Z TC RC  
  1 0.0 150.0 -20.0 0.0 0.0  
  2 0.0 150.0 0.0 0.0 0.0  
  704 -76.23333 -10.0 -20.0 0.0 0.0  
$  
$  
$ ELEMENTS INFORMATION  
$  
$  
*ELEMENT_SHELL  
$ EID PID NID1 NID2 NID3 NID4  
  1 1 1 3 4 2  
  2 1 3 5 6 4  
  30 1 59 61 62 60  
$  
$  
$ SOLID ELEMENTS  
$  
$  
*ELEMENT_SOLID  
$ EID PID NID1 NID2 NID3 NID4 NID5 NID6 NID7 NID8  
  287 3 63 64 81 80 352 355 354 353  
  288 3 64 65 82 81 355 357 356 354  
  590 5 669 243 260 259 704 532 549 548  
$  
$  
*END