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Finite Element Modelling For Bird Strike Analysis And Review Of Existing Numerical Methods

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Abstract

This paper reviews numerical methods that are currently available to simulate bird strike as well as the theory of the event. Finite element model of a 1.8kg homogenous bird model with a simplified geometrical shape is modeled using the SPH formulation. The reliability of the bird model is validated by comparing the numerical result with experimental results of a real bird of similar mass impacting normally at an impact velocity of 95m/s on to a flat rigid panel results are compared in terms of pressure profile, Hugoniot (Shock) and stagnation pressure.

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1. Introduction

During its life cycle an aircraft flies on the risk of impacting foreign objects. According to the aeronautical specifications, with the term “birdstrike” we mean the collision between a bird and an aircraft front facing component, which includes windshield, nacelles, wing leading edge and compressor blade. The probability of an accident is higher in the airport area during the take-off and landing phases, and especially in the early morning and late afternoon. In recent years the severity and importance of the birdstrike has grown because of the remarkable increase of the air traffic and airplane performances in term of velocity, followed by an increment of energy density and impulsive loads during the impact. The birdstrike is not only relative to the flight safety, but also to not negligible maintenance costs, which the companies must meet to repair possible damages in case of an accident. In order to better understand the nature of birdstrike and also prevent the hazard of an accident, they have been formed international committees, such as the birdstrike Committee.

Therefore more and more companies and government authorities have initiated advanced research and development programs to ensure that every structural part of an aircraft is able to withstand the loads due to a high velocity impact and at least guarantee the safe landing of the airplane, in according to the International Certification Standards.

This paper aims at summarizing the steps involved in creating the bird model, covers the theory of bird strikes and provides an analytical evaluation of the phenomenon. It is necessary to carry out the full scale bird strike experiments in order to determine the degree of damage after bird-strike and to evaluate the critical dynamic failure position. In this report explicit finite element analysis is carried out to predict the deformation pattern of the bird and comparison of numerical results is done. The reliability of the bird model is validated by comparing the numerical result with experimental results of a real bird of similar mass impacting normally on to a flat rigid panel, results are compared in terms of pressure profile. The Impact analysis is performed by the finite element method through Altair Hyper works version 10 package and LS-DYNA version 971. Finally, recommendations are made regarding the best suitable method.

2. Certification Specifications

Both Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) list regulations for the aircraft certification process to ensure that the front facing aircraft components should be capable of withstanding birdstrikes at critical flight speed to a certain degree. The certification specifications are as shown in the table 1.

2.1. Applicable FAR 25 Rrequirements

With reference to FAR regulations Part 25.571(e) (1), the Front hood must be capable of successfully completing a flight during which likely structural damage occurs as a result of: Impact with a 4-pound bird when the velocity of the airplane relative to the bird along the airplane's flight path is equal to Vc (which is 113 m/s in our case) at sea level or 0.85 Vc at 8,000 feet, whichever is more critical.

The requirements for the Front Hood in relation with potential bird strikes is that bird should not penetrate, debris should not come out or the debris should be within control surface and engine ingestion limits and there should not be a attachment failure.

Table 1. : FAR - Birdstrike Test Requirements

Aircraft Component	**Bird Weight**	**FAR Section**
Windshields and Frames	4lb	25.775 (b), 25.775(c)
Wing Leading Edges	4lb	25.571 (e)(1)
Empennage Leading Edges	8lb	25.631, 25.571 (e)(l)
Engine – Inlet Lip	4lb	25.571(e)(1)
Engine – Fan Integrity	4lb	33.77, 25.571(e)(l)
Engine – continued Operation	Up to 8 of 1.5 lb birds	33.77,25.571(e)(l)

3. Bird Strike Theory

3.1. Physics Overview

There are three categories of impact events:
- Elastic impact,
- Plastic impact,
- Hydrodynamic impact.

The elastic impacts are typically low speed events, and the stresses generated because of the collision are lower than the material yield stress. So the nature and duration of the impact depend on the elastic modulus and the elastic wave velocities of the material. In case of higher impact speeds the produced stresses cause a plastic deformation of the material target and this kind of collision constitute the plastic impact category. For those events, the material strength is still a dominating factor. Finally, for higher impact velocities again the stresses generated by deceleration of the projectile greatly exceed the yield stress. This is a hydrodynamic regime, for which the projectile can be treated as fluids, and it is the material density which dominates the behaviour of the parts instead of material strength.

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The bird strike fall into this category of impact, where the bird do not bounce and impact response is determined by the length of the bird and by the initial impact velocity but not by the material strength. A hydrodynamic event like this one is a non-steady fluid dynamic process that has four distinct phases:
1. Initial impact
2. Impact pressure decay
3. Steady flow
4. Flow termination

At the initial impact phase, the particles at front end are brought to rest instantaneously and the shock wave propagates through the projectile. As the shock wave propagates it brings the material behind the shock to rest. The pressure in the shock compressed region is reffered as Hugoniot pressure.

Although the magnitude of the pressure is very high it lasts only for few microseconds. There exists a pressure gradient at the edge of the projectile which makes the particle to flow steadily and in the outward direction. After several reflections of release waves, a steady flow condition is established. As the impact continues there will be decay process where the pressure reduces to zero and is the termination phase.

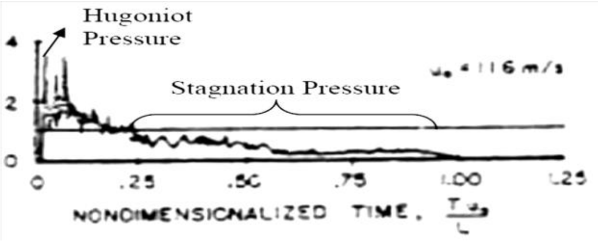

Fig 1. Pressure-Time Plot for Bird Impact

3.2. Reference Equations

In order to determine certain reference equations, let us consider an object of mass 'm' with length 'l' impacting the plate with velocity 'v' at an angle θ.

3.2.1. Impulse

In case of bird strike the impulse is the product of mass, velocity with sine of the impact angle.The final velocity will be zero in the process.

$$\textbf{Impulse, } I = m\, v \sin\theta \qquad (1.1)$$

3.2.2. Impact Duration

The impact duration is the time elapsed from the moment when the bird touches the target until there is no further bird material flowing onto the target. It is define as squash-up time Ts .The Squash time for the bird strike process is the time required for the entire bird to disintegrate. It is obtained by dividing length of the specimen with its impact velocity.

$$\textbf{Squash time, } T_s = l/v \qquad (1.2)$$

3.2.3 Effective length of the bird

The effective length of the bird is obtained by the sum of length of the bird and product of diameter with tangent of the impact angle.

$$l_{eff} = l + d \tan\theta \qquad (1.3)$$

3.2.4 Average Impact Force

A main effect of a birdstrike is the energy transfer to the airplane structure impacted, it can be estimated by approximately simple calculations. After the impact the change in a bird's kinetic energy can be defined by the equation.

$$F_{avg} = m v^2 \sin\theta / l_{eff} \qquad (1.4)$$

4. Bird Strike testing

Bird strike tests are done in accordance with FAR Parts 25, as shown in the table 1.1. A bird-cannon is used to shoot the euthanized birds at the target structure. The cannon is a tube, usually 5-10 inches in daimeter, connected to a large compressed air source. High air pressures are not needed, since even 40 psi, for example, will accelerate the bird to several hundred meters per second in a very short distance. Inside the cannon, the bird is loosely placed in a cylindrical, open-ended carrier, called a "sabot", that conforms to the shape of the tube and acts as a seal. The lightweight sabot greatly improves repeatability of the output speeds. It separates from the bird before impact. High speed cameras (10000-20000 fps) are placed to capture the details, at actual playback speeds bird shot shows nothing but sabot fragments fluttering down from the cannon. At slow playback speeds, the reply shows the fluid behaviour of the bird, high local deflections of the target.

The experimental proof tests are expensive and are often difficult to perform with the necessary accuracy and repeatability. The build and test procedure are quite expensive due to high tooling cost associated with each design iteration until the tests are successfully completed.

These costs, as well as the aggressive requirements to reduce design cycle time while minimizing the structural weight, make the possibilities of bird strike design and certification through analysis alone a very attractive proposition. Improved design methodologies, based on better analytical simulation procedures, will result in significantly shorter design cycles, and a reduced number of expensive, experimental proof tests.

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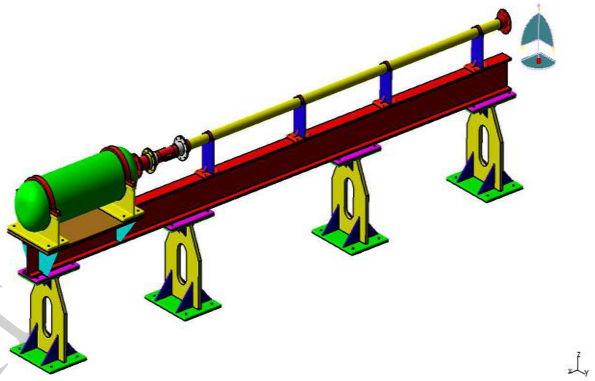

Fig 2. Air Pressure Gun

5. The Bird Strike Problem

The bird strike problem includes three principal elements- the bird,the target, and their dynamic impact interaction. The main technical limitation for using the real birds in tests is the issue of repeatability of results, primarily due to non-homogeneity of the bird material. This non-repeatability makes it very challenging to validate test results. Various researchers have studied wax, foam, emulsions and gelatin as the material for a substitute bird.

5.1. Modelling Approaches

There is no a unique numerical method to analyze the impact phenomenon, and in particular the fluid-structure interaction problems. During a single impact analysis it could be often useful to couple different numerical solvers in order to treat each domain of the problem more appropriately. For each methodology it can be described both strengths and weaknesses, for that many times the right choice of more suitable modelling approach is function of the user expertise.

The four main modelling methods that are currently available are: the Lagrangian mesh, the Eulerian mesh, the Arbitrary Lagrangian-Eulerian (ALE) mesh, and the Smooth Particle Hydrodynamic (SPH) method.

5.1.1. Lagrangian Formulation

The Lagrangian modelling method divides a volume into a large number of small geometries called elements, and it is generally well suited for the description of solid materials impact problems, for which the numerical mesh moves and distorts as shown in figure 3.1.

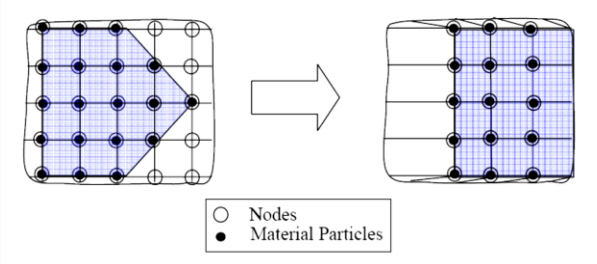

Fig 3.1. Lagrangian model

The main difference between the various formulations is the choice of the reference coordinates for the description of the motion. The Lagrangian method uses material coordinates as the reference. 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. Lagrangian approach is particularly well suited for the description of solid behaviour, its main drawback is that, due to the nature of the formulation for severe deformations, the numerical mesh may become overly distorted with a resulting small time-step and possible loss of accuracy. In that case the numerical solution can only be carried out to a certain point before the Lagrangian mesh distortions cause the analysis to be stopped due to a very small time-step.

5.1.2. Eulerian Formulation

In the Eulerian technique the mesh is basically treated as a control volume, i.e. the mesh remains fixed and the material under study flows through the mesh, as shown in figure 3.2.

Since the mesh does not move, there is no possibility of mesh deformation, which is a major disadvantage of the Lagrangian method. In addition, an Eulerian technique completely avoids the difficulties associated with the time step reduction required by the type of highly deformed domains encountered by the Lagrangian technique, when used in explicit time integration solutions.

This method is applied mostly to the simulation of fluid behaviour, such as water/fuel sloshing, although it has been applied to solid simulation too. The major disadvantage of this method is the difficulty to keep track of the material behaviour history, for which it is necessary the use of more sophisticated techniques.

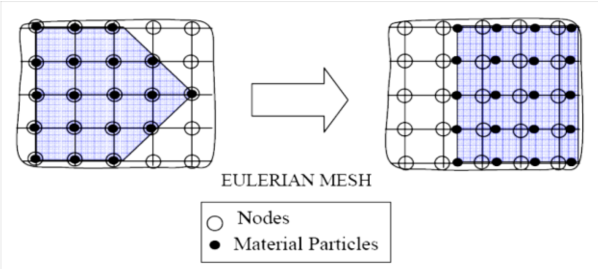

Fig 3.2. Eulerian model

5.1.3. ALE Formulation

The third modelling method is the Arbitrary Lagrangian-Eulerian (ALE) method. It can be considered like a combination of the Lagrangian and Eulerian formulation in which it is possible the advantages of both methods while also minimizing the disadvantages. Unlike the Eulerian method, for which the material moves through a fixed mesh, in the ALE modelling, the material flows in the mesh, but this last can move and stretch if needed, in order to follow the boundary motion and prevent the mesh tangling, as shown in the figure 3.3.
Due to a good set of the background mesh motion from the user, it is possible to minimize the mesh distortions and obtain the best results. In this way a large number of elements can be eliminated and calculating time reduced, thereby providing a computational time saving. In particular at each time step, it can evaluate the position of the material with respect to the nodes figure, and the coupling with the solid structure is done by tracking the relative displacements between the coupled Lagrangian nodes and the fluid.

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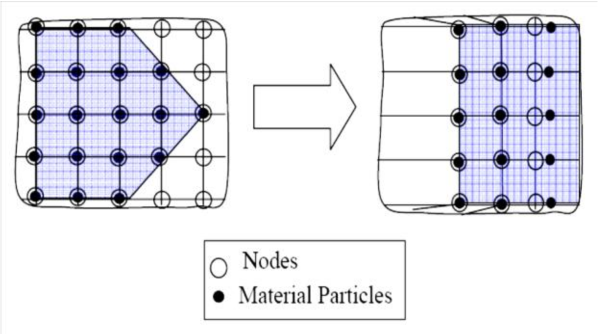

Fig 3.3. ALE model

5.1.4. SPH Formulation

The Smooth Particle Hydrodynamics is a Lagrangian mesh less technique and was developed by Monaghan in the late 1970’s for astrophysics problems with application to hypervelocity impacts (~10 km/s) where the material shatters upon impact. It is both effective and accurate at modelling material deformation as well as adaptable in terms of specific material models and besides to solve computational fluid dynamic problems, it can be also applied for continuum mechanics problems with large deformations, as crash simulations. In the SPH formulation the fluid is represented as a set of moving particles, each one representing an interpolation point, where all the fluid properties are known.

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The influence of each particle is established inside of a sphere of radius of 2h, called support domain Ωh, where h is the smoothing length, as shown in the figure 3.4.

The smoothing length of every particle changes with the time. When particles separate the smoothing length increases, while when they come close to each other, the smoothing length decreases accordingly.

It is necessary to keep enough particles in the neighbourhood to validate the approximation of continuum variables. Because of the grid less nature of the methodology, the SPH does not suffer from the usual disadvantage relative to mesh tangling in large deformation problems, like a pure Lagrangian formulation, and uses fewer elements than the ALE method, avoids the material interface problems associated with it.

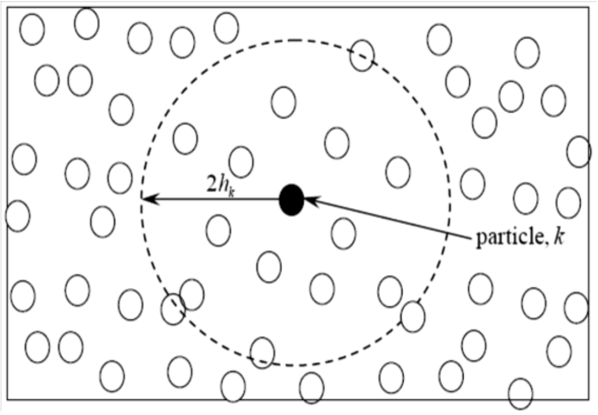


Fig 3.4. Single SPH particle representation.

6. FE Bird Model

SPH model of bird is taken to carry out numerical studies. The shape of the bird is chosen to be a cylindrical to represent an experimental Bird model. In conjunction with the certification standard required by the FAA for transport category aircraft, the mass of the bird model is chosen to be 1.82 kg. The density of the bird model on the other hand is chosen to be 935 kg/m3 after taking into consideration that avian tissue are composed mainly of water with a small percentage of internal cavities such as lungs. With a mass of 1.82 kg and a density of 935 kg/m^3, the dimensions of the bird is calculated and shown in figure 4**.** It has a length to diameter ratio of 2:1.Pitch distance of 4mm is maintained.

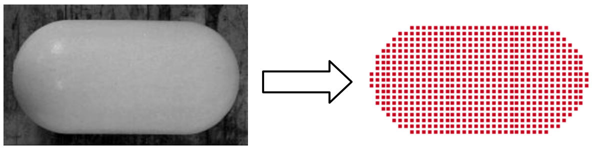


Fig 4. Bird model

Table 2. Input Properties for Bird model

G (GPa)	ρ (Kg/m^3)	SIGY	EH
2	935	20000	1000

7. Validation of Finite Element Model

7.1. Wilbeck's test results

Dr. James Wilbeck was one of the first researchers to investigate the experimental behaviour of a bird under impact [5]. His conclusions and results are very important to this day since they provide the shape and characteristics used for numerical bird models. By publishing his results he also provided useful information to validate the numerical models.

Substitutes such as gelatine, beef, RTV rubber, and neoprene were compared against data from a chicken projectile. Experiments showed that the most suitable substitute material is gelatine with a10% porosity and a density of 950 kg/m3. The tests also showed that the geometry of the projectile is of importance. The most suitable shape for the projectile is then a cylinder with hemispherical ends with a length to diameter ratio equal to 2, as illustrated in figure 5.1.

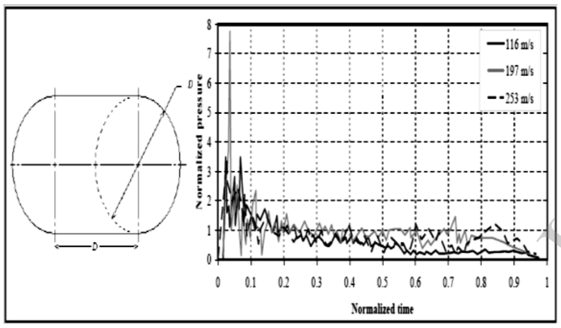


Fig 5.1. Bird model geometry and Wilbeck's results for the bird projectile.

7.2. Target plate

The bird impact test was performed on a square rigid target plate. It is an RHA steel plate of 0.305 m by 0.305 m (12" X 12") and 0.0127 m (1/2") thick. The purpose of having this geometry is that its behaviour is easily known and efforts can be focused on the behaviour of the bird during the impact. A video camera recorded the event with a sampling rate of 3000 frames per second. In addition, piezo-electric carbon gages were used to measure the pressure applied by the bird onto the rigid target.

Five carbon gages were glued to the target plate according to the pattern in which the centre of impact and centre of the target are coincident. The target plate had a dimension of 0.305 m by 0.305 m (12" X 12") with a thickness of 0.0127 m (1/2") and was clamped on the support along the edges. It was made of RHA steel and the legs of the gages were connected behind the plate so that the connections were protected from the impact. Moreover, a 0.0016 m (1/16") layer of Lexan was glued on top of the carbon gages in order to protect the gages. The frequency of the numerical simulations is of 100 kHz. Thus, a sampling rate of 1000 kHz was used to capture the event adequately.

The numerical model includes a rigid target modelled with 4 nodded shell elements and the bird was modelled as SPH particles. An automatic node to surface contact is established to control the interaction between the projectile and the target.

The mesh density chosen is arbitrary. The boundary of the rigid target is set by constraining the node's rotational and translational degree of freedoms at the edge of the plate.

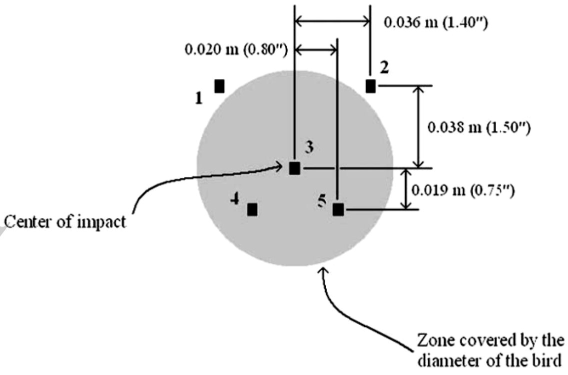


Fig 5.2. Carbon gages' position on target.

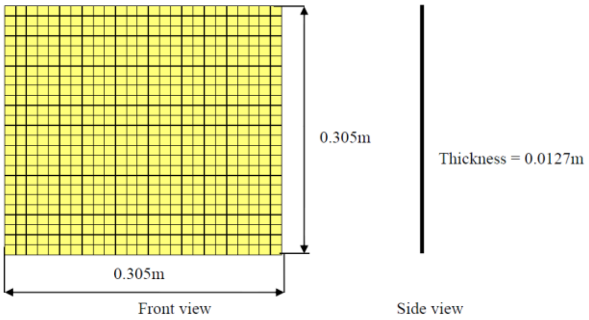


Fig 5.3. Geometry of the rigid target

Table 3. Rigid Plate properties

E (GPa)	ρ (Kg/m^3)	ν
207	7850	0.3

8. Results

8.1. Comparison of experimental test and simulation.

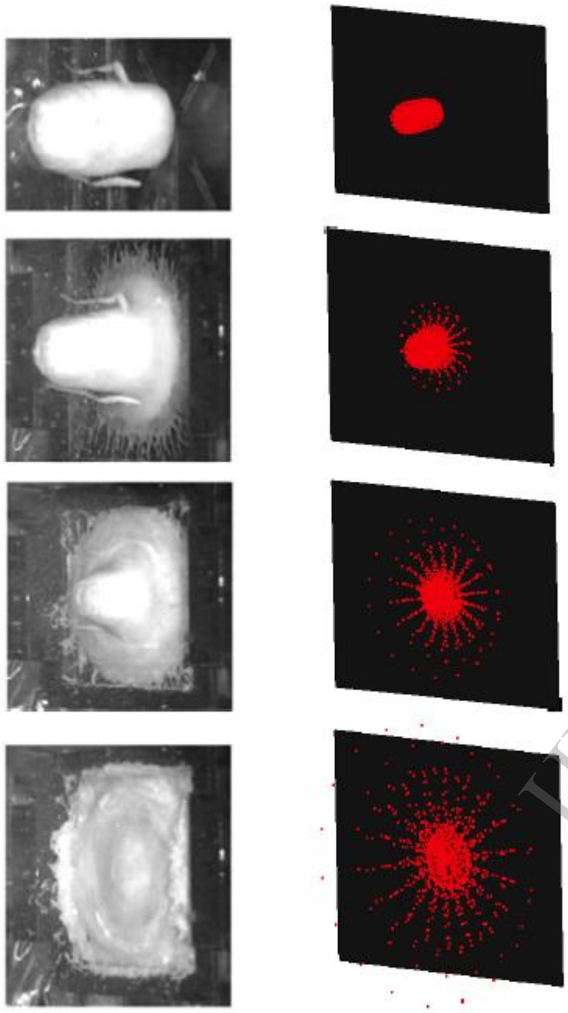
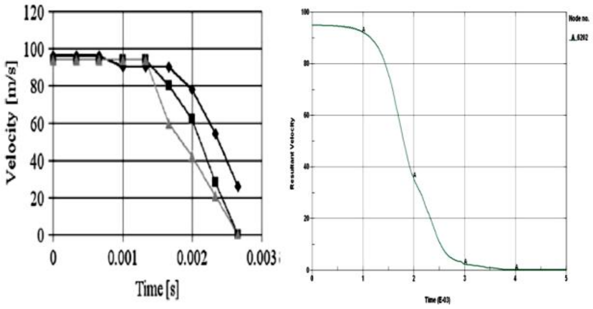


Fig 6. Comparison of Experimental test and simulation

8.2. Test and Simulation results



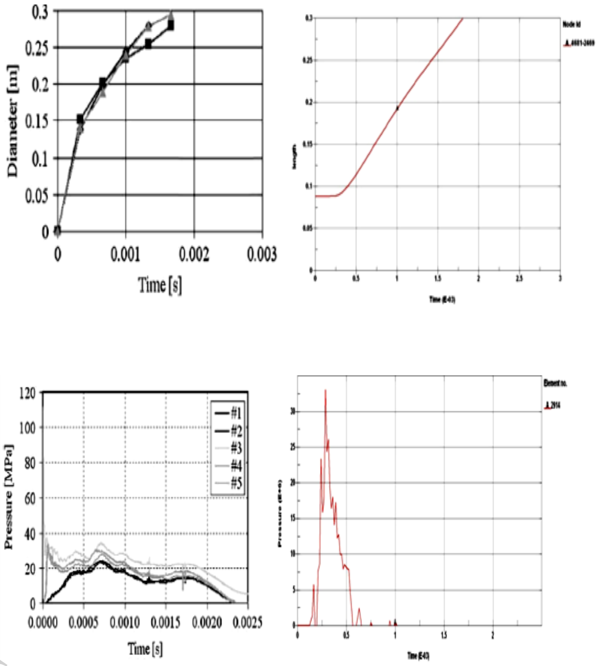


Fig 6.1. Test and Simulation results

The good correlation between the experimental data and the simulations confirms that the properties used for the simulations are appropriate.

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9. Conclusion

One of the safety concerns plaguing the aircraft industry since its inception has been bird strikes, or bird ingestion. These are increasing every year and are the major safety hazards to aircraft at take-off and landing. These have become more evident to the military as aircraft began flying at low-altitude, high-speed profiles. As a consequence, the airworthiness authorities require that none of the vital, forward-facing elements of aircraft structures should fail as a result of bird strike. Bird strike criteria shall be considered from the conceptual design phase itself.

Finite element modelling and simulation are performed fast enough so that the results can be incorporated into the normal design iteration process. The tests shall be conducted to ensure that the structural parts/engine are able to withstand bird impact or at least guarantee the safe landing of the aircraft after the bird strike occurs.

The SPH approach is considered to be the most suitable and feasible methodology to simulate the dynamics of an high speed impact phenomenon, like the birdstrike against an aircraft component. Both bird SPH and target FE model were prepared by the Hypermesh pre-processor software, while the numerical simulation was performed by using LSTC/LS-Dyna explicit solver.

A good correlation is observed between the experiment and the simulation results.

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