

**MULTIPLE STAGE TURBOFAN BIRD INGESTION ANALYSIS  
WITH ALE AND SPH METHODS**

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**Abstract**

This paper describes the application of the ALE and SPH methods for the numerical analysis of a 2.5 lb 'core' bird ingestion into the PW6000 turbofan engine.

The main intention was to predict the loading and the mechanical response of the HPC front stage. This requires an in-depth analysis of the fluid-structure interaction in the fan and in the LPC.

Two principle scenarios were considered - first, bird ingestion with a typical takeoff A/C velocity of 88 m/s and the engine running at SLTO conditions, and secondly, bird ingestion in a typical low altitude approach situation. The first situation creates high loading for the fan and the HPC front stage rotor blades. The second situation is the maximum loading case for the HPC variable inlet guide vanes, as the vane schedule is maximum closed. In both cases, the 'core' bird enters the fan inlet plane at 25% span.

The analytical predictions for the SLTO case are compared to the distribution of bird mass contamination, found in the HPC after a flocking bird engine ingestion test in 2004.

**Abbreviations**

A/C aircraft  
ALE arbitrary Lagrange Eulerian  
IBR integrally bladed rotor  
IGV inlet guide vane  
HPC high pressure compressor  
LPC low pressure compressor  
SLTO Sea level take off  
SPH smoothed particle hydrodynamics

**Introduction**

In the past two decades the simulation of bird ingestion on fan blades with a Lagrangian bird model has become an established process in aero engine companies. Here the description of the bird behavior with compressible fluid material models and the analysis of the response of the structure with strain rate dependent elastic-plastic material properties represents international standard (Ref. [1]-[3],[6]).

In recent years advanced numerical methods for the simulation of fluid-structure interaction, such as the ALE (Arbitrary Lagrange Eulerian) and the SPH (Smoothed Particle Hydrodynamics) method, are offered by the respective commercial codes. Details about specific features and the underlying numerical procedures can be found in Ref. [7]-[9]. Both methods allow to simulate the spreading of the bird fluid into separate isolated substructures. Compared to the Lagrangian description of the bird the numerical stability of both methods is substantially better with respect to effects like hourglassing

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or negative volume in brick elements.

Examples of recent applications of both methods to bird-strike problems are presented in Ref. [4]-[6].

Along with the numerical performance increase due to massive parallel processing techniques and advanced hardware platforms (e.g. Linux clusters), the simulation of bird slurry transition thru multiple compressor stages has become feasible.

At MTU Aero Engines the ALE and SPH method are used to analyze the transition of bird masses thru fan, LPC and transition duct into the front stage of the HPC. The investigated HP compressor has Titanium inlet guide vanes and highly swept forward IBR blades in the first stage. The calculations were performed with LS-DYNA version 970 SMP on Linux workstations.

#### Application of the ALE Method

The term Lagrangian formulation means, that the mesh is bound to the structure, i.e. the mesh distorts and moves with the structure. Eulerian formulation means, that the mesh is fixed in space and the material moves through this mesh. ALE is a combination of both formulations. In the current application the engine structures to be analyzed are represented by a Lagrangian formulation, while the propagation of the bird slurry is calculated within an Eulerian mesh. For the user this approach is rather convenient, as the Eulerian and Lagrangian meshes need not to be consistent at the interface surfaces.

Fig. 1 shows the Lagrangian mesh of the compressor structure model with the blading and casing walls of fan, LPC and transition duct struts. The aerodynamic shape of the airfoils is approximated with

plate geometries (i.e. no chordwise chamber). For the all-in-one SPH analysis a single airfoil of the HPC IGV and two blades of the HPC rotor 1 IBR are added to the base model - both HPC components with a fine mesh suitable for local stress analysis.

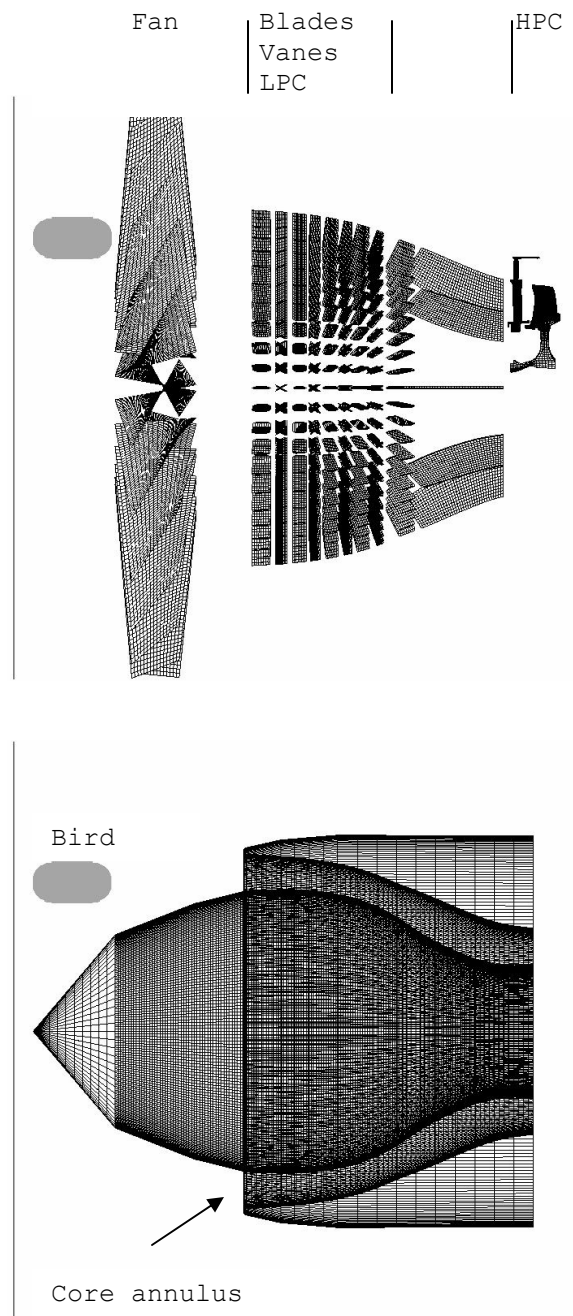


Fig.1: Finite Element Model of the blading and casing structures

The full structural model involves 314000 nodes, 113000 shell and 122500 brick elements. The LS-DYNA stability criterion determining the max allowable step size for the explicit time integration limits the initial step size to 0.007  $\mu$ s based on a brick element on the HPC rotor 1 airfoil trailing edge.

The Eulerian fluid mesh covers an 180° circumferential sector (see Fig. 2) and is discretized in radial, circumferential and axial direction by 60 x 200 x 75 elements.

Depending on the selected numerical advection scheme and the method for fluid-structure interaction (constraint method, penalty base method) the numerical analysis with the LS-DYNA version 970 is more or less dispersive and dissipative and numerical leakage may occur.

For the current investigation the ALE model is therefore only used to predict the slicing, circumferential deflection and disintegration of the bird in the fan, to determine how much of the bird slurry is ingested into the core engine and to track its spatial distribution through the various LPC stages.

In a second separate step this information is then used to define a substitute continuum for the bird slurry prior to the entry into the HPC and to calculate the response of the HPC front stage with the established method for single stage bird strike analysis.

#### SLTO low speed situation

Fig. 3 shows an example of the bird slicing and of its circumferential deflection for the SLTO condition with a bird entry velocity of 88 m/s. The void area of the Eulerian fluid mesh is not displayed.

For the fan blades, this is a 'lowspeed' impact situation with severe momentum exchange (i.e. the bird axial entry velocity is low compared to the blade rotational speed).

Bird part of mesh  
at simulation start

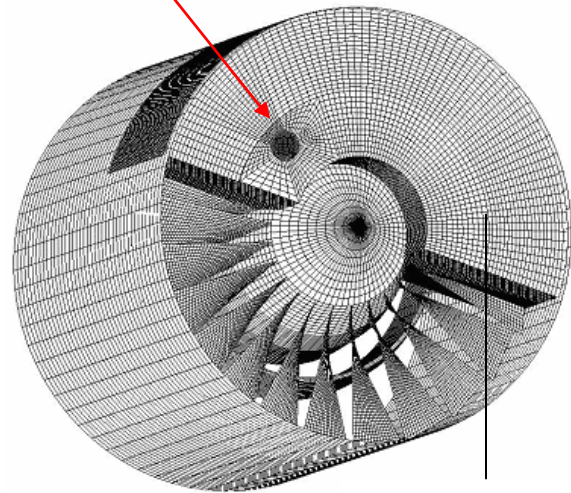


Fig. 2: Lagrangian engine model (Fan, Fan case, bypass splitter) and Eulerian fluid mesh

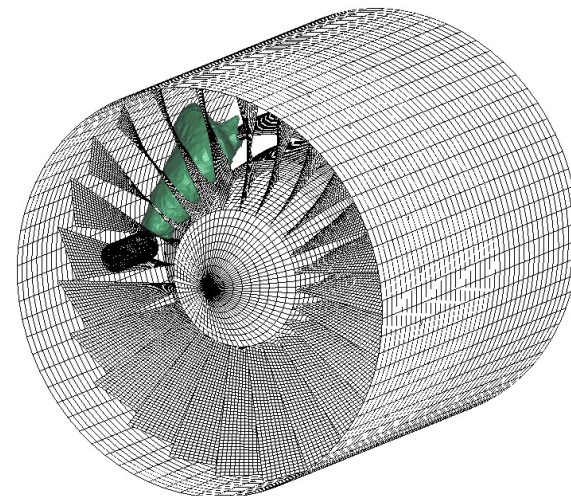
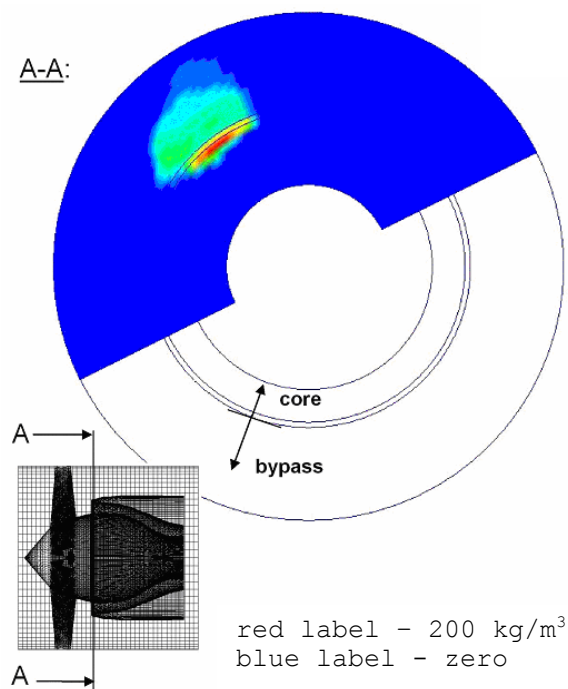
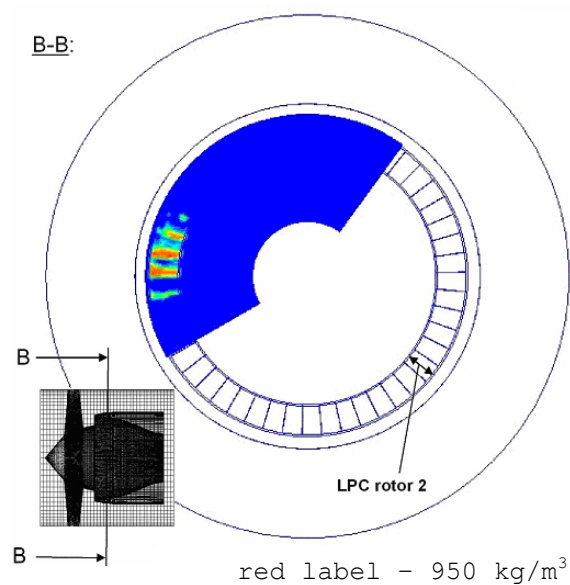


Fig. 3: Bird slicing and acceleration in the fan - 2.6 ms after bird entry into engine (SLTO low speed case) - bird starting volume in void is still displayed



SLTO low speed case - bypass  
splitter plane A-A  
3.6 ms after bird entry into engine



Approach case - LPC front rotor  
plane B-B  
3.9 ms after bird entry into engine

Fig. 4: Examples of bird slurry  
density distributions

The bird masses are accelerated in tangential direction, i.e. they move to greater radii. Mainly due to this effect only a fraction of the 2.5 lb bird mass is ingested into the core engine, although the initial bird target line (i.e. 25% fan span) is centered directly into the core engine

The LSTC/LSPOST postprocessor allows for density plots of arbitrary cutting planes at various time steps. The upper image of Fig. 4 gives an example for the splitter plane A-A at the time when half of the bird mass has passed through. The bird slurry fills a  $40^\circ$  circumferential sector with a maximum local density of  $200 \text{ kg/m}^3$  to be compared to an initial bird density of  $950 \text{ kg/m}^3$ . The core mass fraction is concentrated in the LPC blade tip regions.

For predefined control volumes, the resultant momentum of all fluid parts, contained in these volumes, can be tracked along with time. Fig. 5 shows the time histories for three such control volumes. The first one is the volume that defines the initial shape of the bird at the analysis start. The two other volumes extend from the fan inlet to the LPC exit and are divided into the core and bypass region. The outer diameter of the core engine inlet defines the radial boundary between the two volumes. The underlying analysis only includes the bird-blade interaction in the fan.

The initial total momentum of the bird mass is  $100 \text{ Ns}$  ( $1.135 \text{ kg} \times 88 \text{ m/s}$ ). During the first two milliseconds the bird masses move from their initial volume into the core volume. The interaction with the fan blades starts at  $t=0.8$  milliseconds. With the acceleration of the fluid particles the momentum content in the core volume rises. The peak value is reached after 2.5 milliseconds. At this time the total

momentum of all fluid parts has more than doubled.

From  $t=1.5$  milliseconds on the fluid parts start to move from the core volume into the bypass volume. After 4.5 milliseconds all fluid particles have passed through the splitter plane. The momentum stored in the core volume is 40 Ns while the bypass volume contains a total momentum of 200 Ns. Thus it is assumed that at least 17% of the total bird mass are ingested into the core engine.

The further divergence of the core mass fraction in the LPC is limited as the blade and vane airfoils of the LPC act as guiding boundaries. At the LPC exit the main extension of the bird slurry is  $60^\circ$  (compared to  $40^\circ$  at the LPC entry), which develops into a  $90^\circ$  sector (2 pitches of 8 transition duct struts) at the transition duct exit.

With the bird slurry moving thru the rear stages of the LPC numerically a massive increase of hourglass energy is recognized. The ingestion into the HPC and the response of the front stage therefore was done in a separate analysis.

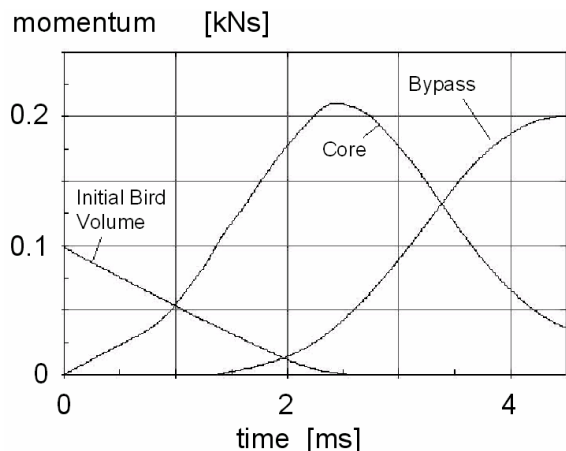


Fig. 5: Time histories of the fluid momentum distributions (SLTO low speed case)

Based on the results of the described ALE analysis a homogenized continuum of the bird slurry was modelled and the impact into the HPC front stage was calculated with an established procedure for single stage bird strike (i.e. Lagrangian description of bird slurry).

It is beyond the scope of this paper to discuss the results of this analysis in detail. For the SLTO low speed situation the main core engine momentum exchange occurs in the rotor stage of the HPC, as the IGV schedule is nominal (i.e. almost axially aligned).

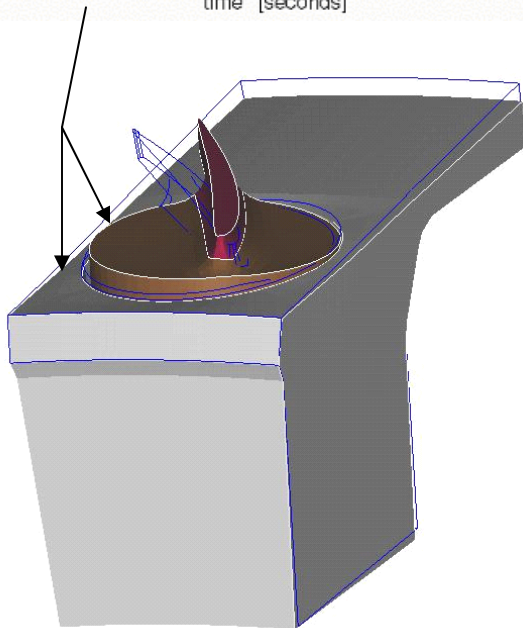
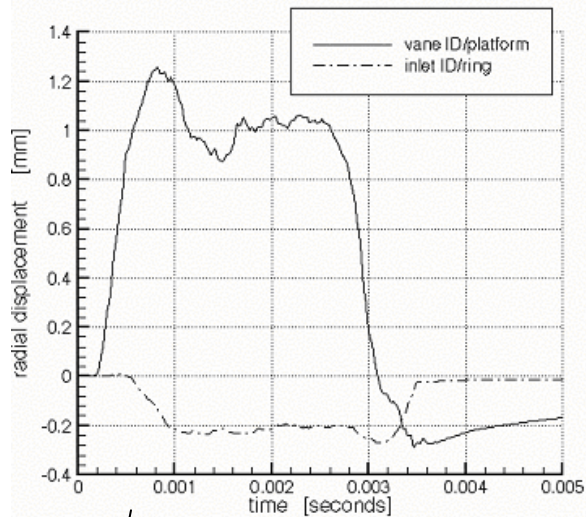
All blades of HPC rotor 1 are hit by the bird slurry. Elastic tip bending deflections of a few millimeters (without IGV or stator 1 clashing) and very slight plastifications at the airfoil roots are predicted. No visible damage, no tip curl of the swept forward tip leading edges are analyzed.

These analytical predictions correlate with the observations from the corresponding PW6000 engine ingestion test performed in 2004. The results are also consistent with experience from other turbofan programs, but even so cannot be generalized, as there also exists test evidence at MTU from military programs in which bird strike has caused severe damage in the HPC.

#### Low altitude approach situation

Bird ingestion under low altitude approach conditions may lead to a severe loading of the HPC inlet guide vanes. With the engine operating at flight idle speed and a typical A/C approach velocity of 130 m/s the direction of the relative velocity of bird particles ingested into the fan is almost parallel to the fan blade chordwise direction. Thus the bird will be sliced but not accelerated. The bird particles keep their radial position on their flight path into the core engine.

The corresponding LS-DYNA ALE analysis predicts that the 2.5 lb core bird at 25% fan span will be almost completely ingested into the core engine. The lower image of Fig. 4 shows the typical density distribution of the bird slurry when passing through the LPC front rotor. The maximum concentration is still  $950 \text{ kg/m}^3$ , which is almost the initial bird density, and the bird



deformed shape 1 ms after bird slurry entry into HPC

Fig. 6: Time histories of inner diameter HPC vane/ring radial displacements (maximum positions)

slurry is equally distributed from the hub to the tip.

The HPC IGV schedule is maximum closed at flight idle engine operation conditions and the ingested bird masses generate a significant loading, although the bird particle axial velocity is moderate low when leaving the LPC.

The analysis of the bird impact for the IGVs is performed the same way as described before - i.e. analysis of the bird transition through fan and LPC with the ALE approach, followed by a conventional single stage analysis with a newly defined homogenized continuum of the bird slurry prior to the entry into HPC.

For weight reduction purposes the HPC IGVs are made of Titanium. The analysis predicts an almost elastic bending-torsion response of the affected vane airfoils with just very slight, invisible residual plastification.

The short-time radial lifting of the vane ID platforms relative to the ID ring does not exceed a maximum value of 1.4 mm (see Fig. 6). This compares to a platform thickness of 3 mm and the geometric

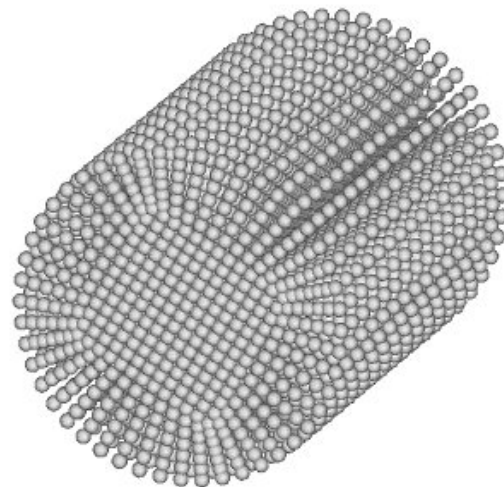


Fig. 7: General scheme of the SPH bird model

design tolerances of all contributing parts were reviewed to exclude the risk for the ID platforms for being pulled out of the ID ring and not to snap back.

#### Application of the SPH Method

The SPH method is an element free numerical method and thus completely avoids the problem of element hourglassing.

The bird model is discretized into a large number of interacting fluid point masses (see Fig. 7). In the current application a partition into 120000 SPH nodes is used.

Due to the large number of communicating particles the method is comparatively CPU-time intensive but, in return, numerically robust.

particle velocity [m/s]

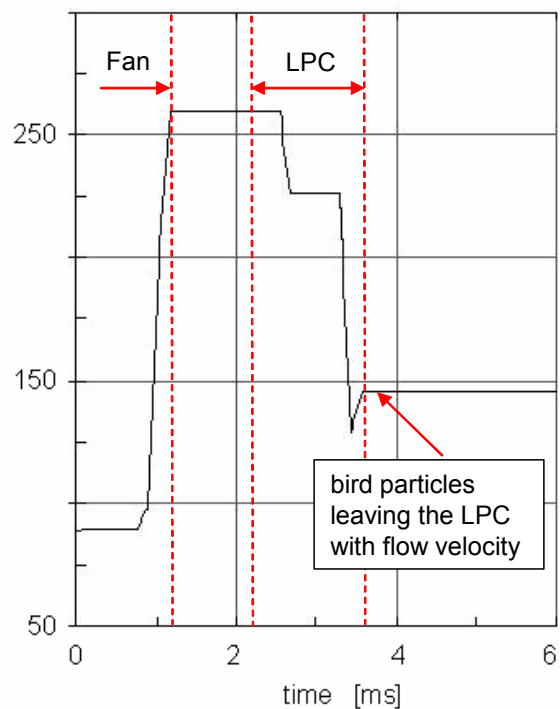


Fig. 8: Typical time histories of the calculated axial bird particle velocity (SLTO low speed case)



Vanes 10-12 with visible flow lines of contamination (concave sides)



Vanes 25-27 without visible flow lines of contamination (concave sides)

Fig. 9: Findings of bird mass contamination on the HPC IGVs after flocking bird engine ingestion test (SLTO low speed ingestion test)

The SPH approach is especially suited to track the velocity of individual particles on their way through the various compressor stages. Fig. 8 shows the typical acceleration in the fan (from 88 m/s to 260 m/s) and the stepwise deceleration in the LPC. The calculated axial particle velocity of 145 m/s at the LPC exit correlates well with what is expected from the aerodynamically predicted flow velocity (i.e. 152 m/s for SLTO operation).

Fig. 10 shows the distribution of the core particles for the time  $t=5$  ms when the first particles arrive at the end of the transition duct (SLTO low speed case). A  $90^\circ$  sector is filled from the inner to the outer diameter. The expansion from hub to tip is due to a substantial number of particles leaving the LPC with a non-zero angular velocity.

The main results of the SPH investigations are more or less consistent with the corresponding ALE analysis and can be substantiated with test evidence from the 2004 engine ingestion tests. Fig. 9 shows examples of bird mass contamination found on the IGV airfoils. Contamination with visible flow lines (see upper image) indicates primary contamination from the bird slurry, while contamination without flow lines (lower image) is interpreted as disordered secondary contamination from a compressor surge immediately after the bird mass ingestion into the HPC.

The response of the HPC front stage was analyzed with an all-in-one model by adding a single vane segment and two IBR blades of the first HPC stage to the base model (see Fig. 1). This approach reduces the influence of user dependent input, as the loading of the HPC is directly calculated in a single analysis without user interaction. Fig. 11 shows the calculated impact

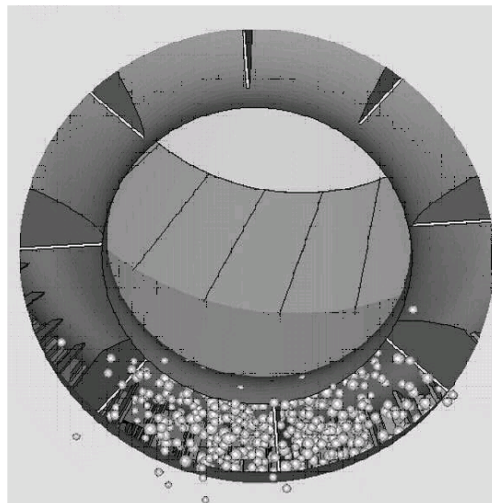


Fig. 10: Calculated particle distribution 5 ms after bird entry into engine - view upstream into the LPC-HPC transition duct (SLTO case)

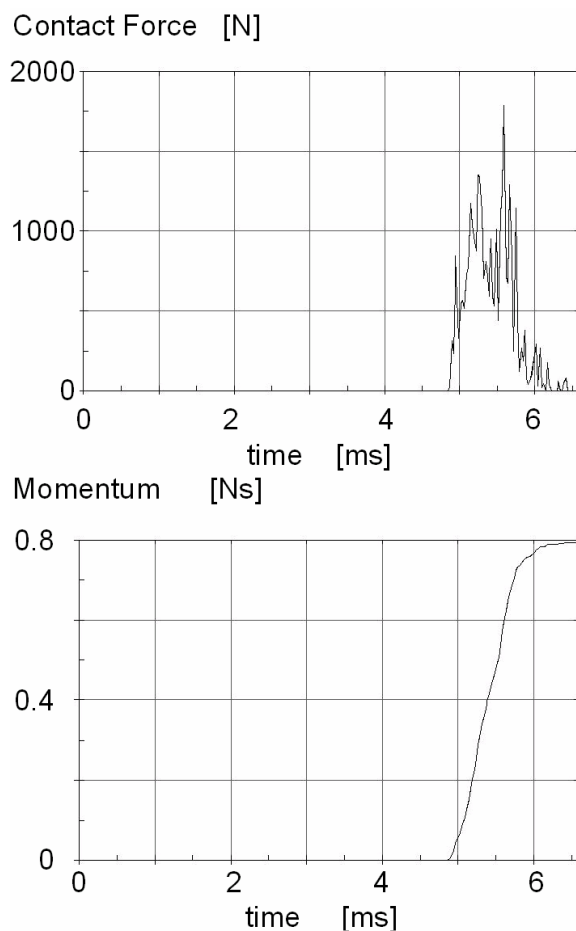


Fig. 11: Time histories of contact force and transferred momentum between the fluid and a single blade of the HPC front rotor (SLTO case)

force per blade and the corresponding transferred momentum for the SLTO low speed case. It is less than 1% of the initial total bird momentum.

A comparison of the results from the ALE 2-step analysis with those calculated with the all-in-one SPH model shows that the 2-step approach tends to substantially overpredict the HPC loading, if the user-subjective 'homogenization' of the bird slurry continuum for step 2 is made too conservative. A 15% error in each dimension of the step-2 bird substitute geometry turns into a more than 50% error for the average density.

#### **Concluding remarks**

Compared to the conventional Lagrangian description both the ALE and the SPH method offer substantially new capabilities for multiple stage aero engine bird ingestion analysis. Possible applications are investigations as described in this paper or just analysis of combined rotor-stator response within one model.

The present investigation and the ALE application in particular suffers from a considerable loss of accuracy with the fluid masses progressing far into the LPC. LS-DYNA offers various numerical control options for both the ALE and SPH method and future applications will need extensive sensitivity studies for method adjustment and validation.

#### **References**

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