Fan Blade Optimization Under Medium Bird Strike Load

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Abstract

The 3D non-linear transient dynamic analysis program MSC.Dytran is used to simulate and carry out an explicit time integration analysis of the dynamic non-linear behavior of the engine structure under medium bird strike.

For accurate prediction of the secondary damage, it is required to use a Eulerian method to modeling the bird. This is accomplished by using adaptive multiple Euler domains.

1.0 Introduction

In this paper a new approach to simulation of the medium bird ingestion test is presented. FAR Section 33.77 specifies the size and the number of the birds, which needs to be ingested. For 350 square inches of inlet area two birds need to be ingested. The birds should be ingested "In rapid sequence to simulate a flock encounter and aimed at the selected critical areas". One of the requirements to pass this test is to sustain more than 75% engine thrust after the event. The engine thrust loss is due to fan blade deformation, engine core damage and enlarged fan tip clearance. Additional complications appear due to fan blade stalling as a result of aerodynamic mismatch.
The test has to be performed on the certified production engine hardware. Ability to optimise the best engine response to bird strike can substantially reduce cost and time of developing a new engine.
The effect of the “splash” bird and a new technique to model its interaction to the engine structure will also be briefly discussed in this paper.

2.0 Model Description

Figure 1 depicts the finite element model of a typical P&WC engine used for an MSC.Dytran simulation. Engine parts are modelled using quadrilateral shell elements with Key-Hoff formulation and five layers (integration points) across the thickness. An isotropic elastoplastic material model (DYMAT24) is used for all plate elements.

The model contains 5 major systems:

- Fan blades
- Fan rotor assembly
- Low pressure shaft with LPT rotor
- #1 ball and #4 roller bearings
- Static structure with the engine mounts.

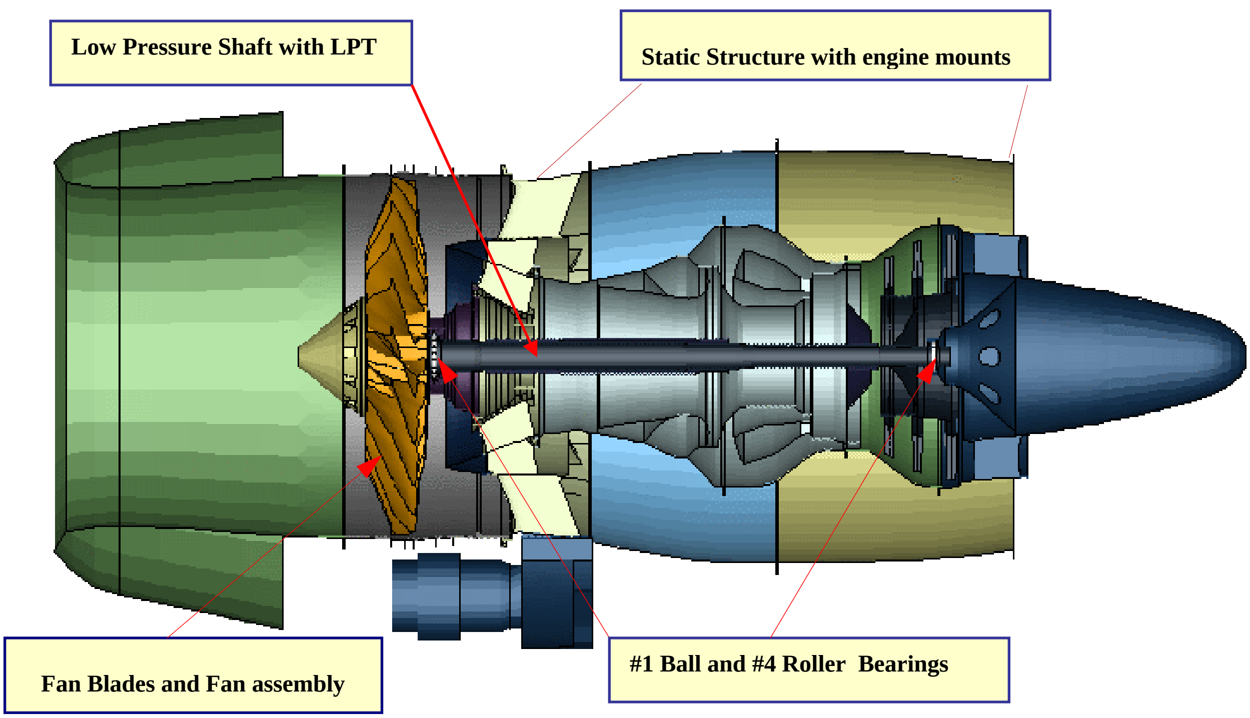


***Figure 1**: Typical PWC full engine FE model for explicit transient dynamic analysis.*

2.1 Understanding Contact – Hierarchy of Importance

The major systems are not physically connected. They can only interact with each other through contacts. The importance of different contacts is described by a system of hierarchy.

Level "A0" – Active Force Contact. Fan Blade Interaction or Fan Blade FOD interaction – (see fig. 2a). This is important for fan blade deformation and all contacts with a higher order level.

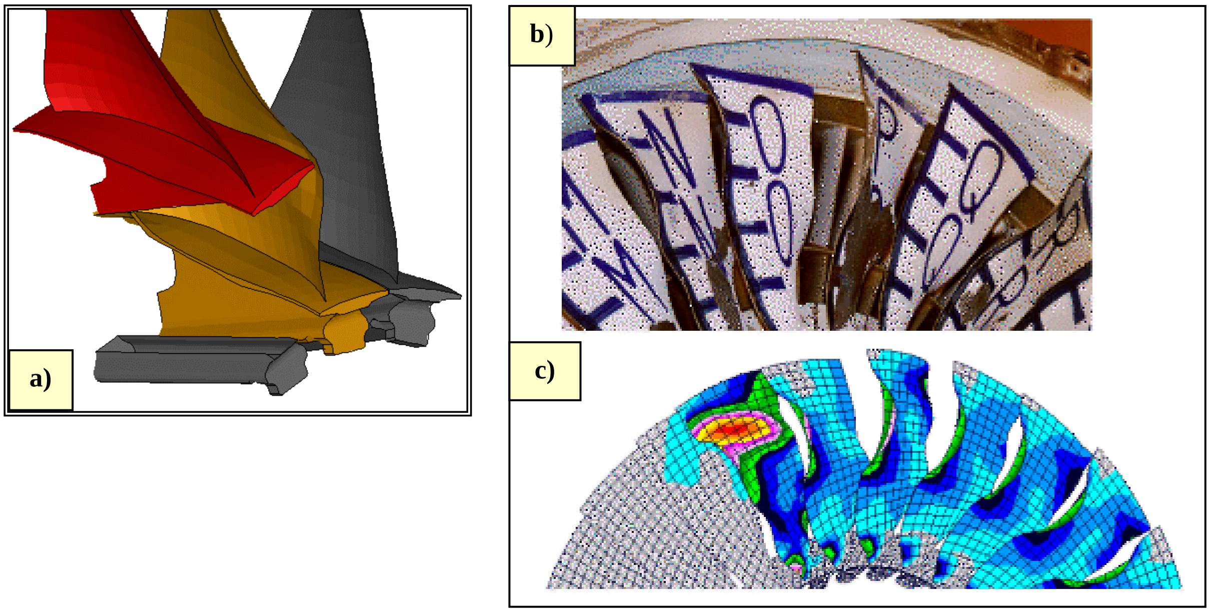
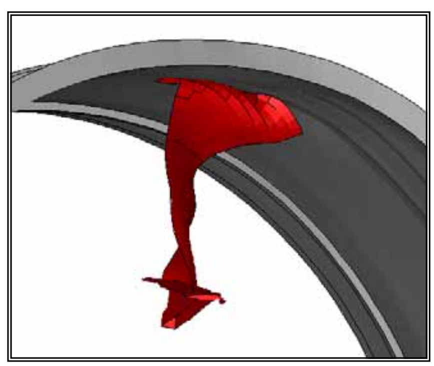


Figure 2: Contact level "A0" *– Active Forcing Contact. It is critically important for fan blade deformation. Also, an unbalance generated by fan deformation imposes the load on the whole engine.*

a) PWC - Release Blade - Following Blade Interaction – , b) Fan deformation – after Medium Bird Strike Rig test. C) *Medium Bird Strike Computer Simulation Airfoils Final deformation*

Level "A1" - Fan Blade Interaction or FOD interaction with the fan case – (see fig.3). Critically important for fan case deformation and all contacts with higher order level. Also level A1 has significant impact on Level A0 contact.

Figure 3: - Contact level "A1" *– Active Forcing Contact. It is critically important for fan case plastic strain. On the left is PWC Fan Blade off Computer simulation – Release Fan Blade Impact on Fan Case.*



Level "AB" - Fan assembly including fan blades, fan hub, nose cone and fan blade retaining ring. The FE mesh must be modelled with a great accuracy to simulate proper sliding interaction between fan blades and fan hub (see fig.4) - Critically important for following blade and fan blade retaining ring analysis and all contacts with higher order level.

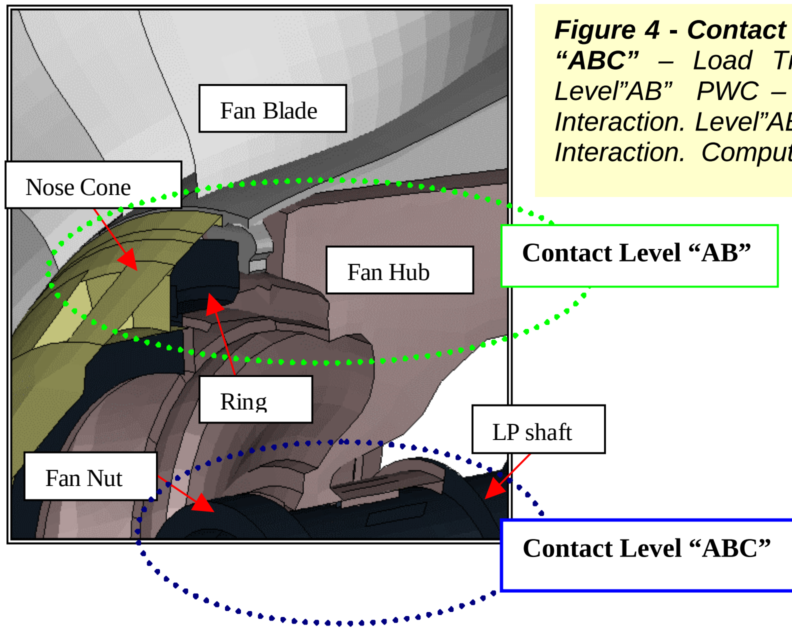
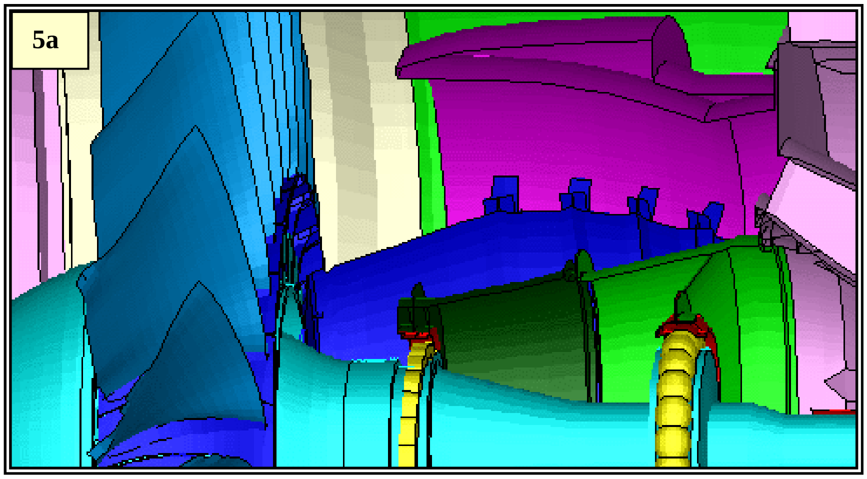


***Figure 4 - Contact level "AB" and level "ABC"** – Load Transporting Contacts. Level"AB" PWC – Fan Blades/Fan Hub Interaction. Level"ABC" Fan Hub/Fan Nut Interaction. Computer simulation.*

Level "ABC" - The fan assembly interacts with the low-pressure shaft through a spline, front and rear spigot and the fan assembly nut (see fig.4)– Critical for fan assembly nut and all contacts with higher order level.

Level "ABCD" - Fan rotor interacts with the bearing housing through the contact between inner races, ball and roller and outer races. This level also includes interaction between LP and HP rotors – (see fig.5). Critical for bearing housings and all contacts with higher order level.



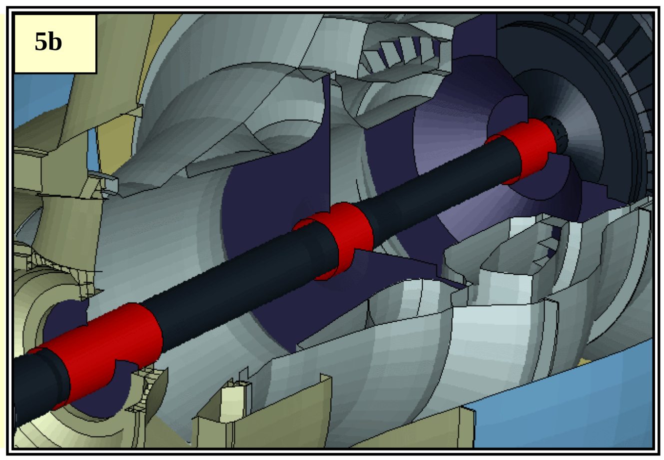
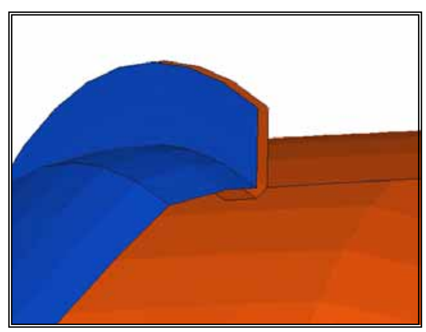


Figure 5 Contact Level "ABCD": *Interaction through contact between rotating components and static structures. At figure 5a, interaction between the bearing elements and the races in the bearing housing sand LP shaft. At figure 5b, interaction between the LP shaft and the HP rotor. The HP rotor is modelled by a representative static structure, with expected contact regions (shown in* red).

Level "ABCDE" – Casing interactions at all flanged connections (face-to-face, spigot-to-spigot contacts) with spring connections at the bolt locations (see fig.6)– Critical for bolts and casings.

Figure 6 – Contact Level "ABCDE": *Casing interaction at flange connections. Contact between flange faces and spigots transmit load through the structure*



Contacts level "A0" and level "A1" are the **active load forcing contacts**. They affect the accuracy of the analysis and must be modelled as realistically as possible. Contact levels "AB" and higher are **load transportation contacts**. To avoid load "leakage", it is necessary to check the contact forces. In case of inadequate load transportation through the contact, the contact must be refined.

2.2 Stiffness, Mass and Inertia

The stiffness, mass, and inertia of the engine components affect the accuracy of all contacts. Components that are on the main load path need to be modelled based on their geometry, materials and static-dynamic functionality.

2.3 Pres-Stress Analysis

The low-pressure rotor needs to be pre-stressed (typically for between three to six milliseconds) in order to simulate an imposed steady rotational velocity. The pre-stress is done inside MSC.Dytran using a centrifugal body load option (RFORCE) and SPC2 option. The whole engine model, especially the fan blade, is deflected into quasi-static shape prior to the transient events.

2.4 FE Model Validation

Prior to the transient run (Blade off, FOD) the generated FE model must be validated.

2.4.1 Validation of the Fan Blade

A fan blade stress and deflection validation run is performed at the maximum rotational speed (N1) on a single fan blade. The stress at the fan blade root should be steady (see fig.7a).

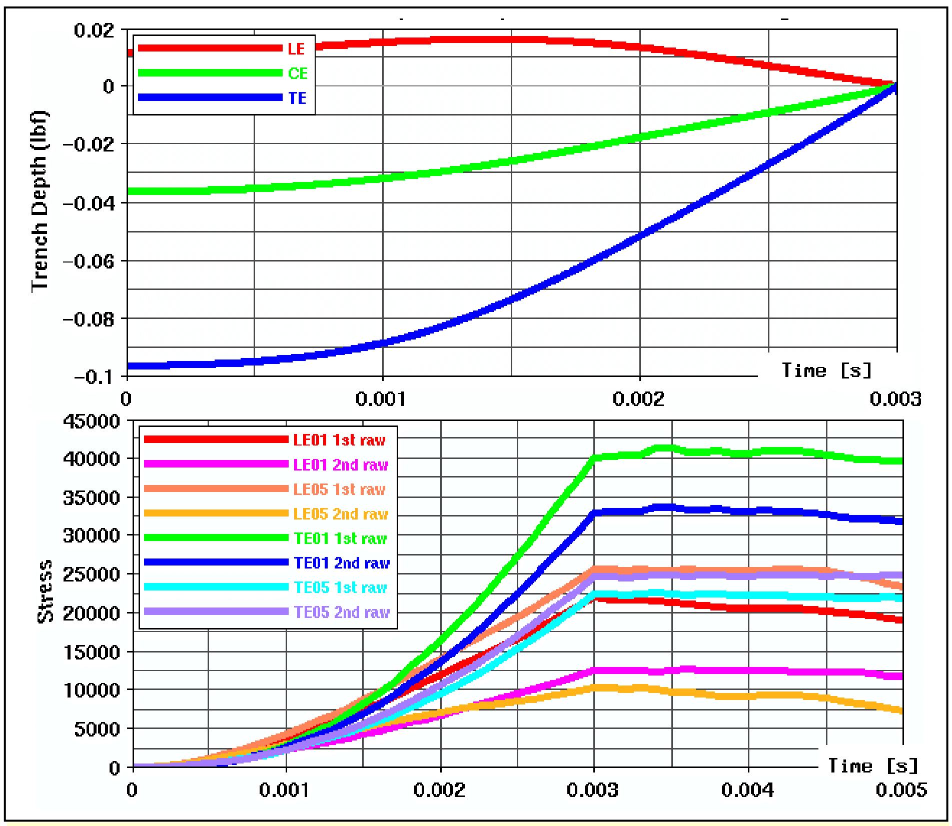


Figure 7a - Fan Blade Pre-stress: *After 3.0 ms the stress at the fan blade root becomes steady.*

2.4.2 Full FE Engine Model Validation – RPM Run

Full FE Engine Model Validation includes analysis of the full FE model of the engine under maximum rotational velocity loads (N1).

Under steady rotational load (RPM run), there is no unbalance in the fan plane, therefore bearing housings and engine mount loads should be zero (aerodynamic loads are neglected). (see fig. 7b)

A successful RPM validation run is absolutely necessary before any transient run—high vibration levels must be eliminated through refining contact sets or adjusting contact parameters.

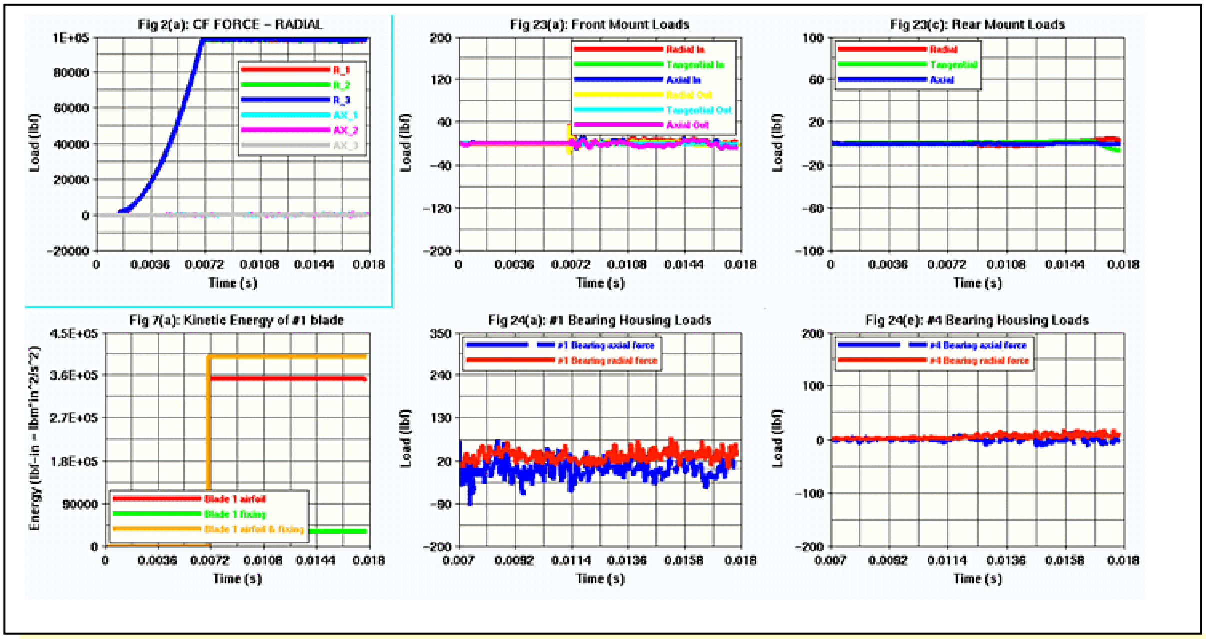


Figure 7b *– Validation of the FEM of the full engine. "RPM" run – Steady state response of the contact and section loads.*

2.5 Bird model, using adaptive multiple Euler domains

The general coupling algorithm in MSC.Dytran, that allows fluid structure interaction, is used for this simulation. The latest enhancements in dytran allow fluid to flow from one euler domain to the other. Since the model includes air and water (bird) the multi material eulerian solver is used.

The fan blade finite element model is shown in Fig. 8a. A coupling surface is created for each pair of blades. To create a closed volume, dummy shells are used as shown in Fig 8b. The entire fan blades and dummy shells that form the 15 coupling surfaces are shown in Fig 8c.

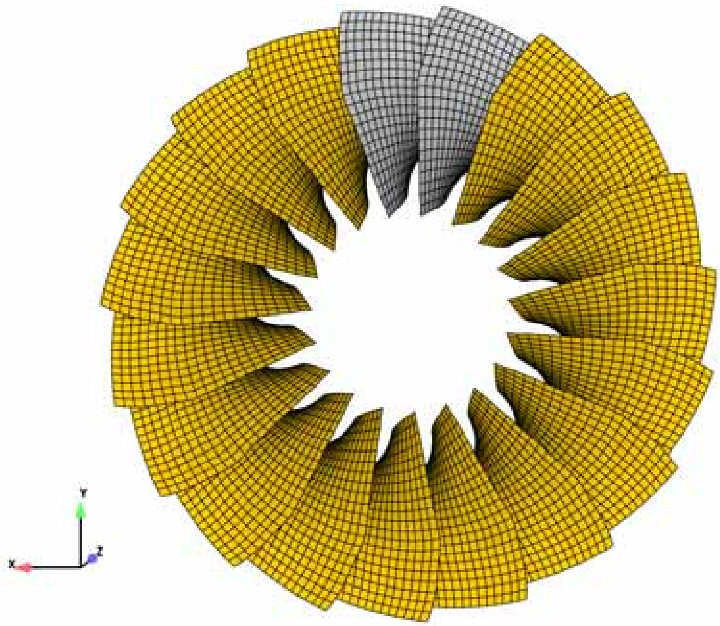


***Figure 8a** – Fan blade finite element model.*

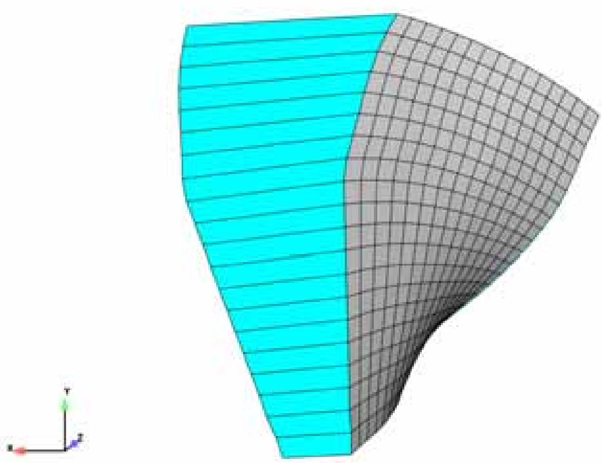


***Figure 8b** – Dummy shells created between 2 fan blades to create closed volume for the coupling surface*

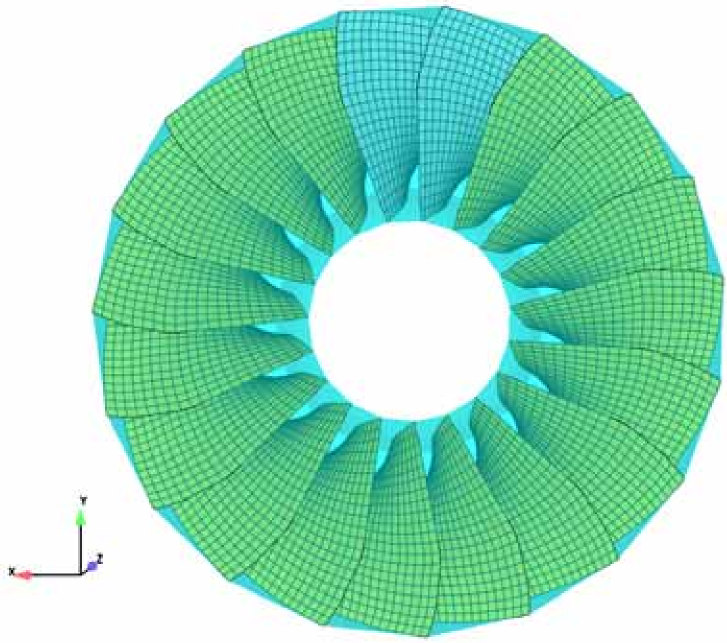


Figure 8c *– Entire fan blades and dummy shells that form 15 coupling surfaces*

These coupling surfaces are initialized with air inside. The euler elements outside these coupling surfaces should not be processed and therefore the COVER is set to OUTSIDE in the COUPLE card. Fig 8d shows the inner coupling surfaces and its respective adaptive euler domains. The euler domains are created automatically by MSC.Dytran, using the MESH=ADAPT entry. When the blades (which are part of the coupling surface) rotate the euler domain follows its coupling surface path.

To model the environment outside the blades, a final coupling surface with all the dummy shells is created. Figure 8e shows this coupling surface and the euler domain associated with it. This euler mesh is created using MESH=BOX entry. This coupling surface is used for simulating fluid (air and bird) outside the coupling surface. So euler elements inside the coupling surface should not be processed and the COVER is set to INSIDE in the couple card. The euler domain is initialized with air and a cylindrical bird with water property. The bird has a initial velocity of 2496 inches/sec in the +ve Z-dir. The inner and outer euler domains have meshes that do not coincide.

The dummy shells are part of both outer coupling and the inner coupling surfaces, which in turn are associated with outer and inner euler domains respectively. The dummy shells at the front and rear faces of the fan blades have been made porous. This allows bird from the outer euler domain to enter and exit the inner euler domains. The COUPOR entry defines porosity of a coupling surface and is referred from the COUPLE card. The PORFLCPL entry defines flow between two coupling surfaces and is referred from a COUPOR entry.

Porosity is not defined for the dummy shells created between the root and the tip of the fan blades. This defines the boundaries of the static components, the fan hub and fan case respectively, where the bird is bound to get reflected in to the fan blades domain.

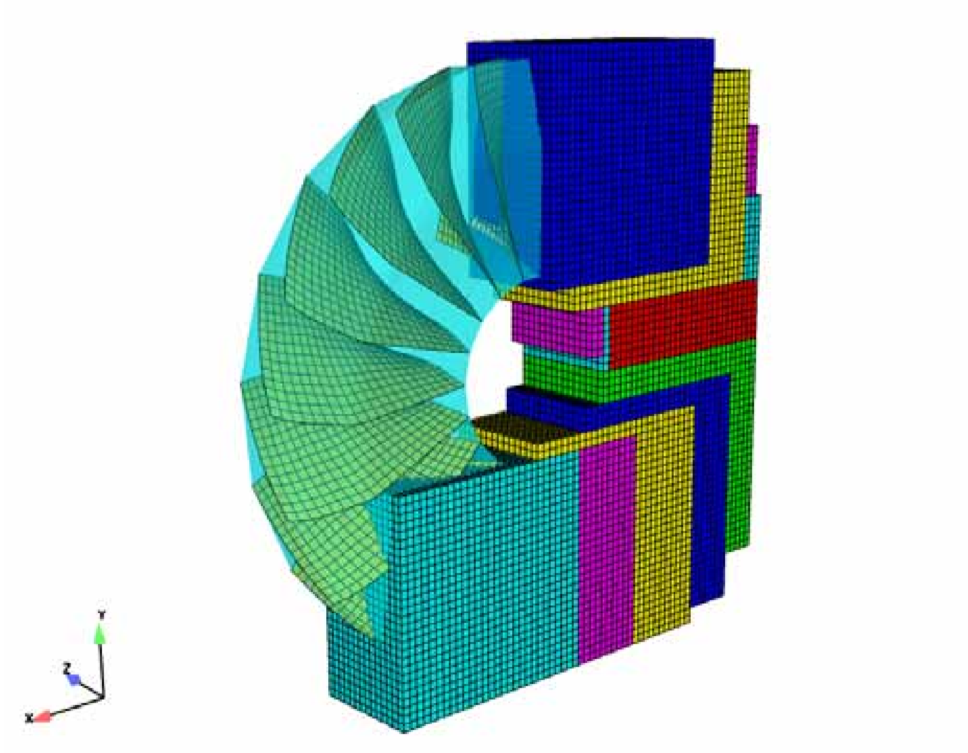


***Figure 8d** – Inner coupling surfaces associated with its respective adaptive euler domain*

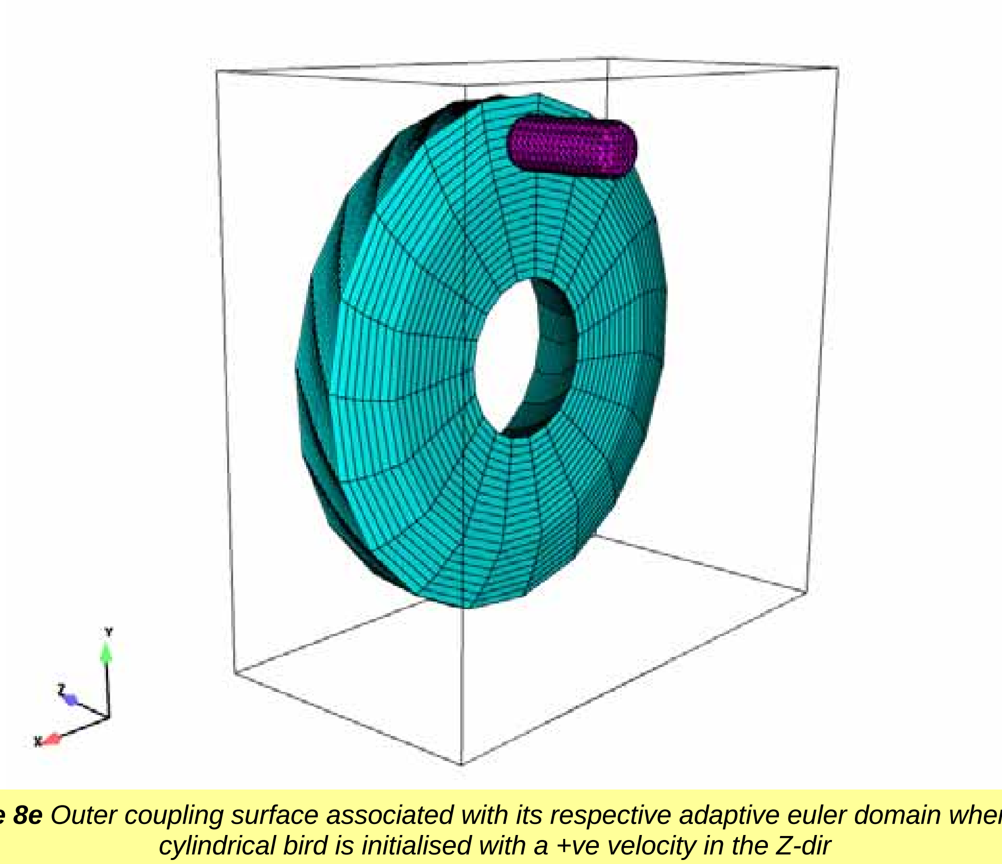


***Figure 8e** Outer coupling surface associated with its respective adaptive euler domain where the cylindrical bird is initialised with a +ve velocity in the Z-dir*

The simulation is carried out in 2 phases. The first phase is the pre-stress run where the stresses due to centrifugal forces (using RFORCE entry) are computed and a solution file is written out. Fig 8f shows the stress results at the end of pre-stress run.

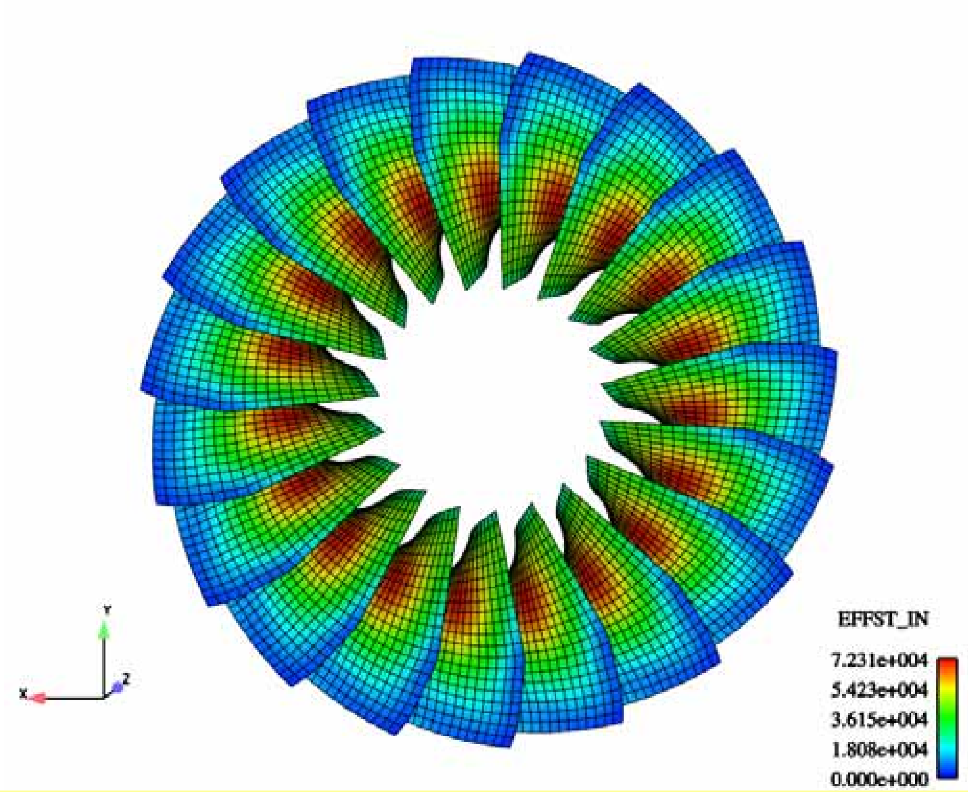


Figure 8f *Effective stress results from the pre-stress run*

The second phase is the transient run where the solution file from the pre-stress run is first read before the transient bird strike event. The translation velocity of the bird and the rotational velocity of the fan blades are initialised in this phase. The results of the transient simulation are shown in Fig 9. This procedure of reading the solution file from the pre-stress run allows the analyst to use the same solution file for different transient events comprising different bird shapes and velocities.

All figures shown in this section of the document are created using CEI.Ensight.

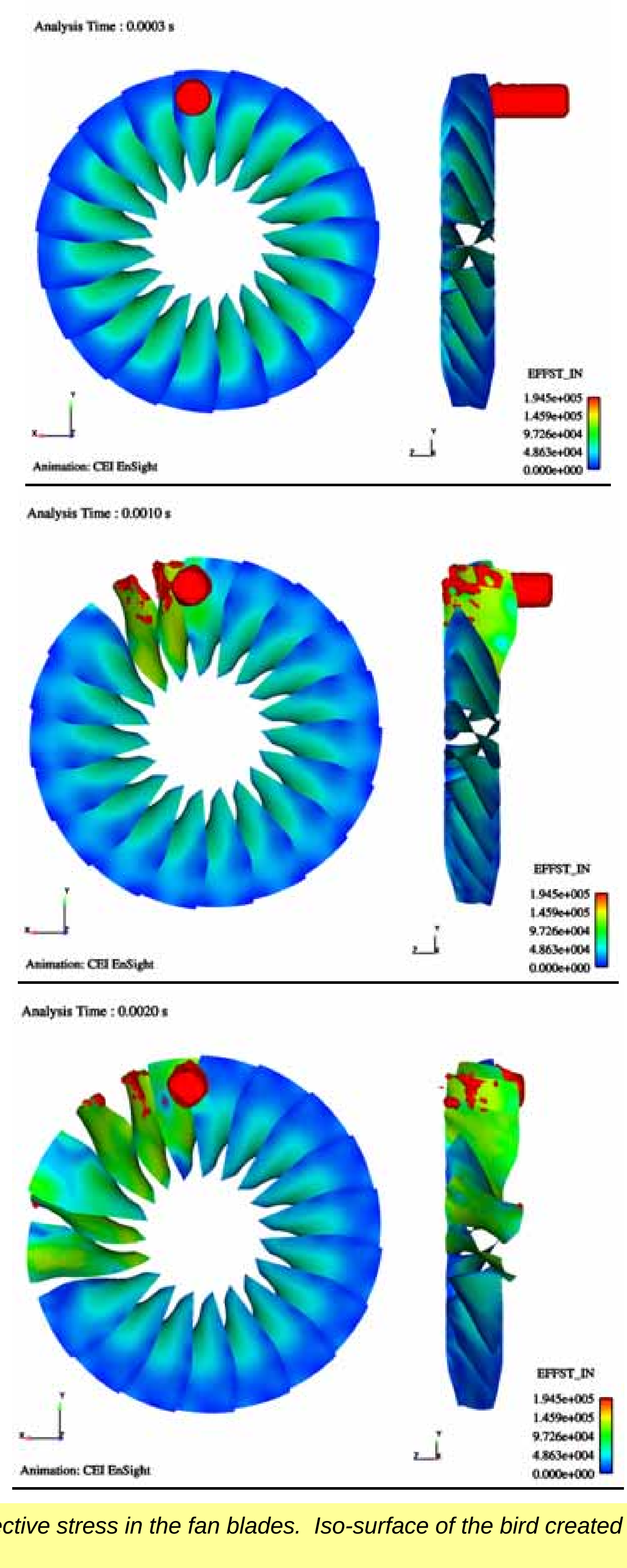


Figure 9 *Effective stress in the fan blades. Iso-surface of the bird created using FMAT variable.*

4.0 Medium Bird Strike Calibration

Three simulation results are compared to experimental data:

Fan Deformation
#1 Bearing Housing Loads
Fan Case Trenching

4.1 Fan Deformation

Multiple blade damage for turbo-fan engines with a small engines diameter are more likely to occur than for engines with a larger fan diameter (higher rpm with the same axial speed of bird). Six out of 19 blades are subjected to direct bird impact (see fig 10).

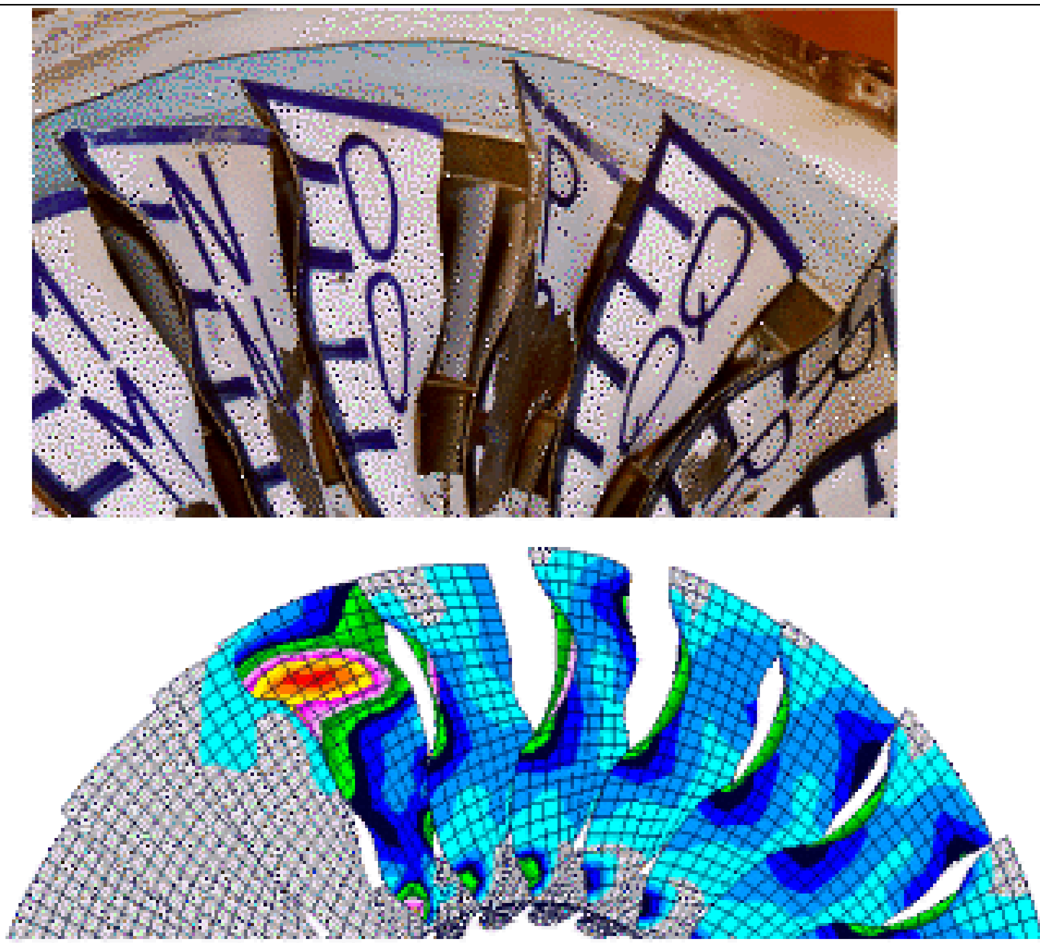


Fig.10. a) – PWC Fan – Deflection of the fan blade after Medium Bird Strike –Test
b) PWC Fan – Deflection of the fan blade after Medium Bird Strike - Simulation .

4.2 #1 Bearing Housing Loads

The response of the No.1 bearing housing depends on:

- fan unbalance caused by bird interaction – "forcing load" ,
- geometrical proportion of low pressure shaft supports (fan overhang, bearing spans),
- overall radial and tangential stiffness (must also meet Rotor Dynamic Requirements),
- local bearing housing geometry (absorption energy capability – number of the plastic hinges),
- material property (yield level, modulus of plastic hardening, maximum elongation).

The predicted stress at No.1 bearing housing due to a medium bird strike on the PW545 engine is 65.4 ksi, which is within 10% of the measured stress (60.9 ksi) - see figure 12.

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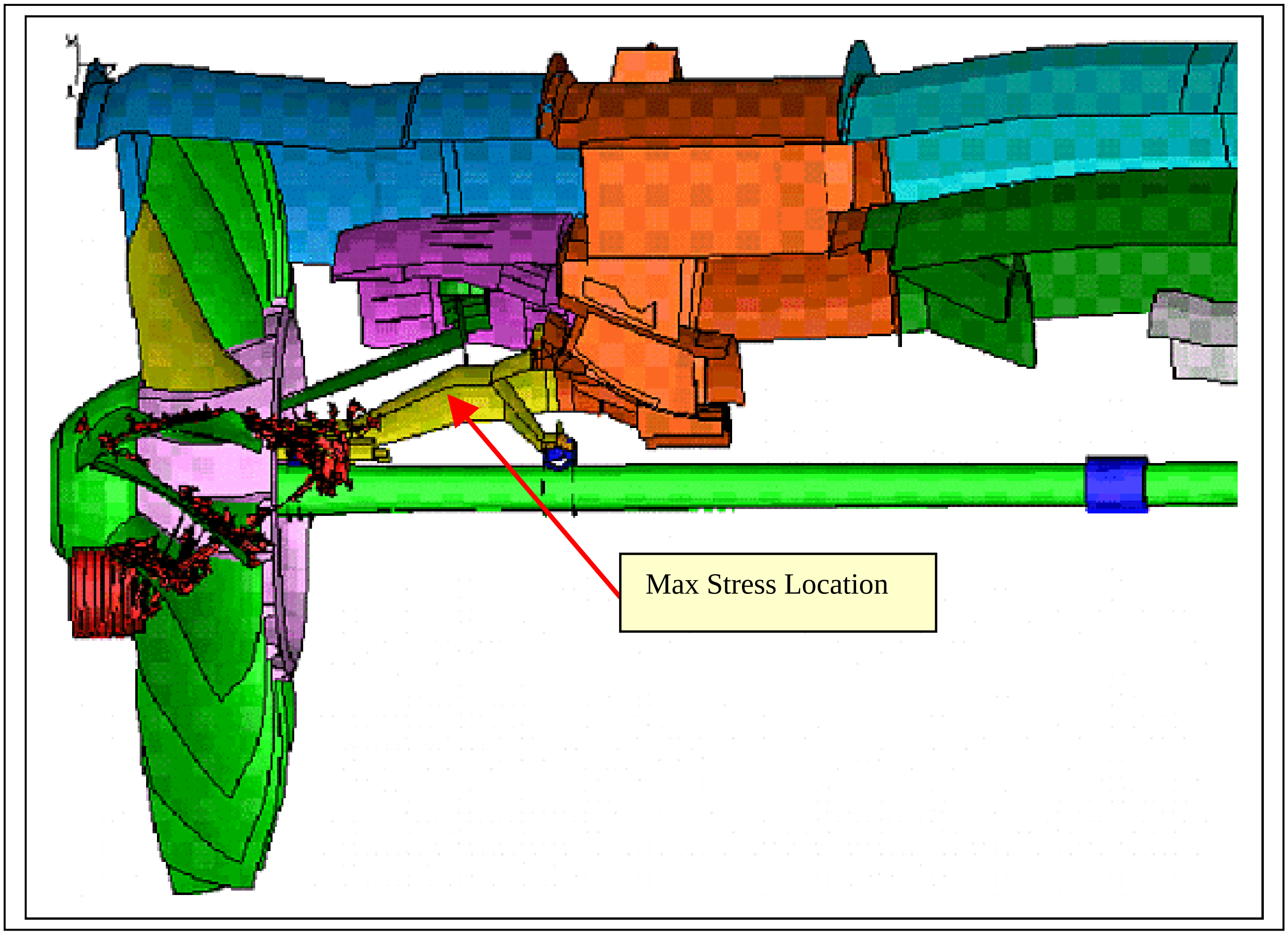
The radial loads on #1 Bearing Housing is shown in figure 11. The analytical prediction is very close to the measured test data.

Figure 11 – Stress on #1 Bearing Housing (Predicted and measured(*Maximum calculated Stress – 65.4 ksi Maximum measured Stress: – 60.9 ksi*)



4.3 Fan Case Trenching

The Summary of the prediction of the fan tip clearance by MSC.Dytran analysis compared with actual measurements is presented in fig.12. There is predict numbers is ~ 10%conservative.
Fan tip trenching is caused by opening of the fan blades during blade/bird interaction, and fan rotor deflection due to fan unbalance.
MSC.Dytran full engine model is able to realistically capture the deformation of the fan - contact level "A0". The unbalance is transported through contacts level "AB", level "ABC", level "ABCD" and level "ABCDE". Finally, the supporting structure response is based on the 3D geometry and non-linear material and geometry behaviour (continuously changing depends on the load) (see fig. 12 for 2D visualisation of the Fan Tip Clearance as a function of time).

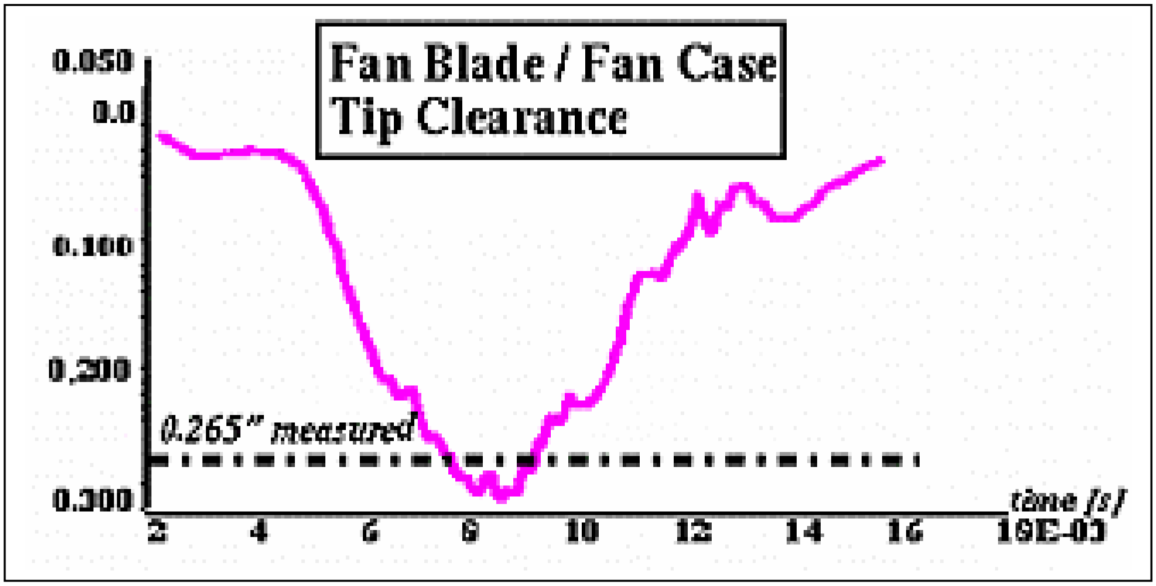


Figure 12: Fan Case Trenching (Predicted and measured)

5.0 Conclusion

The adaptive multiple Euler domain technology of MSC.Dytran has been successfully used to predict a medium bird strike event on a small engine.

This paper demonstrated:

- Fan blade deformation due to bird strike is a forcing contact. It generates an unbalance loads, #1 BR housing and engine mount loads. It is the major factor for residual thrust prediction. The accurate prediction of the fan deformation is the most important task. The adaptive multiple Euler domain technique, available in MSC.Dytran allows this accurate prediction.
- FEM of the full engine model must have steady state response under standard max RPM load before modelling any transient dynamic event (fig 7a,7b).
- Under medium bird strike, multiple blade damage for turbo-fan engines with a small engines diameter are more likely to occur than for engines with a larger fan diameter (higher rpm with the same axial speed of bird - (fig 10).
- The interaction of the chopped bird pieces with fan blade is automatically captured by developed Eulerian bird model.