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# PREDICTION OF ENGINE LOADS AND DAMAGES DUE TO FAN BLADE OFF EVENT

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## **ABSTRACT**

The requirements of the civil engine authorities certification include the demonstration of a successful fan blade off test performed on a whole engine mounted on a rig. In order to comply with these severe criteria, manufacturers carry out expensive containment spin tests during the development phase of a new engine. However, the numerical Finite Element analyses is an appropriate means to understand the fan blade off event and to prevent the financial and time delay risks caused by any failure occurring in the validation process.

In the present paper, the simulation of a fan blade off on the front part of an engine is investigated. The prediction of the engine behavior thanks to a non-linear fast dynamic code is compared to experimental data gathered during one of these containment tests conducted by Snecma Moteurs. The good agreement between the calculated and measured results confirms the reliability of the applied method to assist in the design and optimization of the engine components.

## **1. INTRODUCTION**

The unlikely loss of a fan blade is one of the most critical failure that can occur in a commercial civil engine during in-flight service. The out-of-balanced force, induced by the blade release, and the impacts of the high-energy blade fragments generate extreme loads in the structures that can jeopardize the integrity of the aircraft and the safety of passengers. In order to ensure that the fan blade off (FBO) event will not lead to further engine and aircraft damages, the airworthiness authorities (FAA and JAA) impose on turbomachine manufacturers severe criteria

concerning the blade containment and the shutdown of the engine. These criteria must be validated through a FBO certification test where a fan blade is deliberately released on a whole engine mounted on a test rig. The reliable design of the engine must then consider the FBO requirements and needs to perform numerous destructive tests during the development process. Nevertheless, the experimental validation of the technological choices satisfying the engine characteristics and the FBO criteria remains very expensive. Moreover, they can only be carried out at the end of the design phase and any failure would significantly delay the design process and increase the global cost of the project.

The Finite Element (FE) analyses of the structural dynamics problems involving fast transient loading and high-velocity impacts can provide insight of the engine behavior following the FBO event. Therefore, the numerical simulation is useful to assist in the confident design of the engine components subjected to FBO loading conditions and then to reduce the number of development tests. Furthermore, predictive FE computations could be useful to validate towards the authorities minor modifications on an already certified engine without carrying new certification tests.

This paper addresses the problem of simulating a FBO on the front part of a development engine during the first round after the blade release. The main objective of this work is to prove the reliability and quality of the adopted FE strategy to predict the engine behavior. For this purpose, the calculated results are compared to the experimental data. Afterwards, the technique can be profitably integrated in the industrial mechanical design iterations.

## **2. DESCRIPTION OF THE FBO EVENT**

First, a good numerical simulation of FBO relies on the understanding of the event to be predicted. That is why the preliminary stage of the study consists in describing, identifying the major experimental phenomena and verifying that none of them is omitted in the simulation. The following list proposes the chronological sequence of events and characteristic engine behaviors happening in a typical fan containment test:

- ejection of a fan blade. In a test, the blade is purposely released at root with an explosive charge to reproduce the accidental failure during in-flight service.
- orbit of the rotor: as soon as the blade is ejected, the rotor becomes considerably unbalanced and tends then to orbit so as to rotate around its new center of gravity.
- impact of the released blade on the fan casing and fragmentation process: the released blade moves out in radius and hits the casing. After this first impact, the blade rolls up along the casing and starts to break into several fragments.
- casing deformations and damages: the fan casing has two main roles, which consist in guiding the incoming airflow into the fan compressor and ensuring the fragment containment. It must indeed withstand the high loads, applied to very small areas over short time spans, to maintain structural integrity without any hazard for the aircraft.
- impact on the adjacent blade: as the rotor keeps on rotating, the root of the released blade hits the pressure side of the trailing blade. This blade must not break entirely and avoid a dramatic sequence of blade ruptures.
- behavior of the following blades: due to the large orbiting of the rotor and the casing deformations, the remaining blades may rub against the stator, what can yield to rotor/stator interaction, and finally they can break as well.
- transmission of dynamic load in the whole structure: the energy transmitted from the rotor to the stator (through the impacts, the bearings...) generate high loads, which spread inside the rest of the engine. It can provoke the opening of the bolted flanges and the failure of the fuse if such a protective system is used.

## **3. DESCRIPTION OF A FAN CONTAINMENT TEST**

Manufacturers carry out several intermediate tests to validate the design of all the structural engine

components. The development engines are then subjected to specific loads resulting from normal conditions and extreme events such as bird strike or FBO. In the present study, the test consists in a fan containment on the front part of a development engine composed of:

- several wide chord fan blades assembled on the disc, and one truncated blade, preceding the released blade. The blades are separated by platforms whose role is to ensure the shape of the entering airflow at the blade root. The other blades are replaced by simple masses to keep the rotor balanced,
- the fan disc, the low pressure shaft and two fan bearings,
- the fan containment casing and a simplified intermediate structural casing, that usually makes one of the two links between the engine and the aircraft wing,
- a fuse system to reduce the loading in the structural casing, in case of FBO. The objective is to avoid the failure of very important structural components and to preserve the integrity of the aircraft.
- a simplified booster and its casing to reproduce the rotor/stator contact in the booster and the load transmission to the stator,
- other pieces belonging to the test stand and to the engine-to-stand attachment.

The FBO is performed under vacuum. Thanks to a driving shaft, electrically power driven, the rotor is speeded up to its redline speed, which corresponds to the highest possible energy conditions for FBO. The loss of a fan blade is initiated with an explosive charge located at the blade root. The engine response at strategic positions is measured with numerous strain gauges and accelerometers and the results which do not lend to direct measurements are observed by high speed cameras placed in the test rig. The correlation between the calculated prediction results and experimental data enables to improve the quality and the time of the design.

## **4. FE MODEL FEATURES**

The seek of both more efficient and lightweight systems renders more difficult the design and optimization of the engine components. The role of FE simulation is consequently to predict the blade loss event with the ultimate aim to reduce the number of intermediate validation tests. Thereby, when the FBO phenomenon has been accurately described and when the geometry of the engine has been decided on the preliminary design, a suitable computation strategy can be established. It includes the choice of

the temporal integration scheme, the definition of the FE model and the hypothesis.

#### 4.1. Choice of the integration scheme

The behavior of a whole engine is usually simulated with implicit computations with a simplified model. They provide good estimates of the global quantities such as load levels. But the linear materials laws generally used can not give the precise information for the areas subjected to very local and transient non-linearities, inherent to the problems involving impacts. In the current work, the phenomena which have to be modeled fall into the class of problems comprising fast, transient and highly non-linear responses of the structures. Thus the computation should preferably be carried out with an explicit integration FE code<sup>1, 2</sup>. The non-linear fast dynamic code chosen by Snecma Moteurs to perform the present FBO simulation is PLEXUS<sup>3</sup>, developed at the French Nuclear Research Agency (“Commissariat à l’Energie Atomique”). The explicit temporal method for the dynamic equation resolution is based on the classical Newmark<sup>4</sup> central difference algorithm. The equations of the discrete nodal positions and velocities are:

$$\begin{cases} x^{n+1} = x^n + \Delta t \dot{x}^n + \frac{(\Delta t)^2}{2} \ddot{x}^n \\ \dot{x}^{n+1} = \dot{x}^n + \frac{\Delta t}{2} (\ddot{x}^n + \ddot{x}^{n+1}) \end{cases} \quad (1)$$

where  $x^i$ ,  $\dot{x}^i$  and  $\ddot{x}^i$  are respectively the nodal displacement, velocity and acceleration vectors,  $\Delta t$  is the time step size,  $n$  and  $n+1$  are the time step indexes. The equation of motion is then written at the time step  $n+1$ :

$$M\ddot{x}^{n+1} = F_{\text{ext}}^{n+1} - F_{\text{int}}^{n+1} \quad (2)$$

where  $M$ ,  $F_{\text{ext}}$  and  $F_{\text{int}}$  are the diagonal mass matrix, external nodal force and internal nodal force vectors.

#### 4.2. FE model

The description of the experimental event highlights the very local mechanical behaviors of the structure and the contribution of the interactions between the different components in the engine response: blades with blades, blades with casings, shaft with bearings, and more generally rotor with stator. In addition, the considerable progress in computational structural dynamics and in hardware processing technologies allow increasing the FE model size to very large dimensions. As a result, it has been decided to model each component with a maximum of detail in order to reproduce precisely the test.

Nevertheless, in such a computation including already thousand hundreds of DOF, some compromises have

been decided to simplify the physical system and to achieve the resolution in a reasonable time.

This model is meshed with 3D elements (shell, shell brick and brick elements) and is composed of about 500,000 degrees of freedom. The geometry of the FE model is presented in figure 1.

#### 4.3. Model simplifications

The major assumptions consist essentially in simplifying the complex geometry and the non-linear dynamic behavior of some components, trying not to degrade dangerously the solution and keep realistic results.

- blade model: the meshes of the released and adjacent blades are sufficiently fine to reproduce the local behavior whereas the grids of the other blades are much coarser to limit the computation time. Moreover the attachment system between the blades and the disk is simplified.
- bearing model: the roller and ball bearing models used in this simulation are linear. Zero bearing to housing clearance is assumed and the ball inertia effects are neglected. The stiffness of the bearing has been calculated by static measurements under unidirectional loading.
- bolted flange model: numerous components of an engine are linked thanks to bolted flanges. Those attachment systems must be efficient enough to endure the dynamic load. But a complex flange model including the meshing of all the bolts is too expensive in such a calculation. Here, the bolts are not meshed, the material and contact non-linearities are not taken into consideration.
- engine-to-stand attachment system and boundary conditions: the test rig and the development engine are connected with an elastomer ring joint for the stator and a driving shaft for the rotor. In the present application, the analysis duration is short enough to consider that the material law is elastic linear, thus to ignore the non-linear phenomena. Besides the joint circumference is supposed to be perfectly embedded and the axial displacements of the shaft end are blocked.

## 5. PLEXUS CALCULATION SPECIFICITIES

#### 5.1. Material laws

The constitutive materials of the whole structure are described with linear elastic laws, excepted for the blades and the fan casing. For these components, the material behaviors are described with elastic-plastic laws, with a dependence of the strain-stress relation

on the strain rate speed. They have been experimentally identified with Hopkinson tests in a wide range of deformation speed.

### 5.2. Contact definition

Numerous contacts are considered between the different components:

- between the released blade and the fan casing,
- between the released blade and the following blades
- between the shaft and the booster casing.

The contact detection consists in a slave nodes-master surfaces technique. At this stage, various solutions exist to compute the nodal contact forces. The first one is the penalty method<sup>5</sup>. A second one uses the Lagrange multiplier<sup>6</sup>. This method enables to couple the calculation of all the links and ensures the continuity of contact conditions between the structures, without using a shock stiffness coefficient provided by the user. Besides, it gives better results than the penalty method. It is also possible to uncouple the different links in order to make considerable savings in calculation times. The last technique, which is most appropriate for the large-sized application, has been chosen. Moreover, on the sliding surface, friction can be introduced according to the Coulomb law.

## **6. COMPUTATION PROCEDURE**

The blade is released while the engine runs at its redline speed. Thus, two successive steps are needed to perform the complete FBO simulation:

- the stable rotation induces centrifugal forces that pre-stress the rotor and modify its original shape and dynamic behavior. The pre-stresses are calculated in the relative frame and the computational method consists in applying a force proportional to the radial position and rotation speed on each node of the rotor. The response is numerically damped and the final results are obtained after stabilization.
- the FBO simulation is then performed on the complete model in a fixed frame. The calculated pre-stresses are injected as initial state and the initial velocity field is imposed at each node of the rotor, including the ejected blade. The released blade is disconnected to the disk model at the first time step of the calculation.

## **7. COMPARISON OF TEST AND CALCULATION RESULTS**

With the described FE model, boundary and initial conditions, the non-linear FBO analysis are performed using PLEXUS.

### 7.1. Pre-stresses

The result of the pre-stresses field in the rotor is shown in figure 2. The stress field repartition is consistent with the state of stress expected and its relatively good symmetry around the disk confirms that the rotor is well balanced.

### 7.2. FBO simulation

The calculated results of the FBO event are compared to the experimental measurements identified in the previous test description.

#### 7.2.1 Fragmentation process of the released blade

The kinematic of the blade depends on the way the released blade will break into fragments. The following events, such as the impacts on the casing and on the trailing blade, and the dynamic loads that will be transmitted, depend on the fragmentation sequence. That is why, it must be well represented to reproduce properly the whole FBO event. A criterion depending on the plastic deformation rate is used to determine the positions of the blade fragments.

The comparison of the reconstitution of the released fan blade after the test and the position of the calculated fragments shows that the first fragment is well predicted (figure 3). On the other hand, discrepancies appear in the prediction of the other fragments. In fact, the experimental dispersion inherent to this kind of FBO tests makes a perfect correlation difficult to reach. However, the simulation seems to predict with enough accuracy the fragment weight proportions. In consequence, the minor discrepancies between test and calculation will have few effect on the subsequent phenomena involving the global behavior of the engine.

#### 7.2.2 Impacts on the fan casing

The FBO requirements impose that the fan casing must fully contain all the fragments which could be dangerously ejected toward the aircraft. The containment function of the casing and thus its design features directly hinge on the impact positions and on the impact energies that depend on the weight and speed of the fragments. These two effects must then be adequately reproduced.

The impact energies of the first three blade contacts on the casing are displayed in figure 4. Their respective value augments, what theoretically leads to increasing deterioration of the fan casing. The

differences in the damage level appear indeed on the corresponding impact prints observed after the test inspection. Besides, the released blade impact positions on the casing after the test and the simulation results are well correlated (figure 5): the angular positions of the impacts along the casing circumference as well as their orientation related to the engine rotation axis match perfectly the experimental ones. These results confirm that the prediction of the released blade fragmentation is accurate.

#### 7.2.3 Impact of the released blade on the adjacent blade

The relative impact position between the two blades is essential to predict the adjacent blade resistance and must be precisely simulated. The experimental data can only be provided by the observations of the FBO film analyses and of the impact prints on the released and following blades. Consequently the comparison with the computation results is not trivial. However, the calculated position of the impact along the chord and the height of the blade, as shown in figure 6, is in a good agreement with the experimental one.

Furthermore, as the first contact between the two blades occurs after the apparition of several fragments from the released blade, and thus hinges on the fragmentation process, the good correlation suggests once again that this process is relatively well approximated.

#### 7.2.4 Fuse load and failure

The prediction of the fuse behavior under critical loads is a primary concern for the sizing of this specific component. By recombining the signals of some gauges located at strategic positions, the load transmitted to the fuse can be calculated. Figure 7 shows the temporal evolution of the fuse load, measured experimentally and predicted by the FE simulation. It shows a good correlation considering the maximum value and the instant when it is reached. At this stage, the fuse is supposed to have completely split. The sudden fall of the load level, corresponding to the fuse failure, is in good agreement with measurements.

#### 7.2.5 Orbit of the rotor

The unbalanced force induced by the ejection of the fan blade makes the rotor orbiting. High loads are transmitted to the stator through the bearings and through the blades: the following fan blades rub against the deformed fan casing as well as the low pressure compressor blades against the booster casing.

The only experimental data employed for the comparison are the largest off-centering radius of the

rotor and the time when it is reached. Figure 8 illustrates the evolution of the calculated orbit and the position of the corresponding test result. It shows that the maximum displacement is reached at the end of the first round after the blade loss. The only difference occurs on amplitude, the calculated orbit radius being 10% lower than the real one.

#### 7.2.6 Compared sequence of phenomena

The FBO event is composed of numerous main phenomena, each one being described and compared previously. But a good representation of each phenomenon independently is not enough to guarantee the exact simulation of the whole engine. In fact, they do not occur successively and distinctly but their respective effects influence each other. Hence it is also essential to reproduce properly the complete chronological sequence and the time delays between the events to assert that the modelization is accurate.

The comparison of the experimental sequence of events, observed and analyzed on video and gauge signals with the calculation results, shows good agreement. This point is illustrated with:

- the positions of the different impacts of the released blade on the fan casing, following the blade fragmentation process,
- the time interval between the first impact of the released blade on the casing and the impact of the released blade root on the following blade,
- the time when the main events occur or reach their maximum: maximum orbit of the rotor, evolutions of the fuse load...

## **8. CONCLUSIONS**

This paper has described a part of the methodology employed for this Fan blade Off analysis. The study has mainly focused on the comparison between the calculated results and the experimental data observed during a fan containment test and performed at Snecma Moteurs. The combination of dynamic material characterization and relevant hypothesis in the model constitution has been shown to be effective in predicting the engine behavior after a FBO event.

Nevertheless, the CPU times remain an important problem for this kind of computation. A real hard work has then been necessary on the modelization in order to find original but cost-efficient solutions. The similarity of the sequence of events and the good agreement between test measurements and analysis concerning the global quantities confirm that the mass and stiffness of the test rig is well reproduced even if locally the model is not always very accurate. Consequently, it demonstrates the reliability of the numerical simulation using the Finite Element method

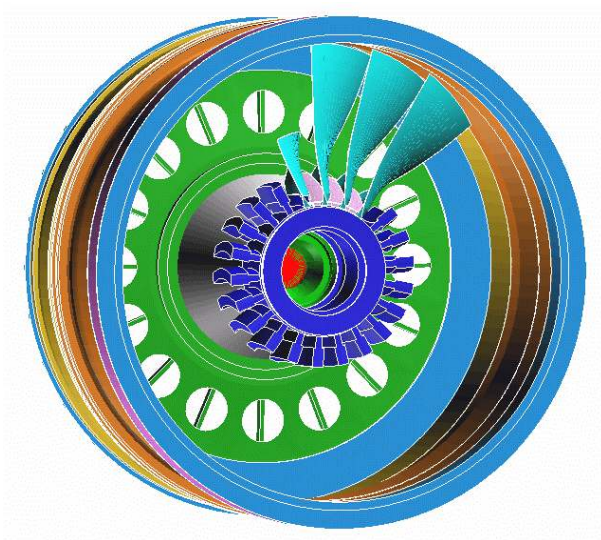
to predict the transient engine loads, damages and behavior in the first round after the release of the blade.

## **ACKNOWLEDGEMENTS**

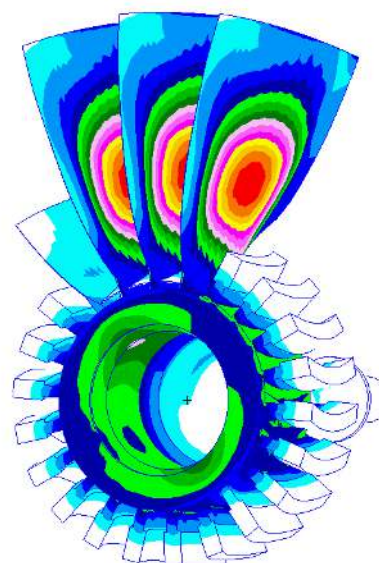
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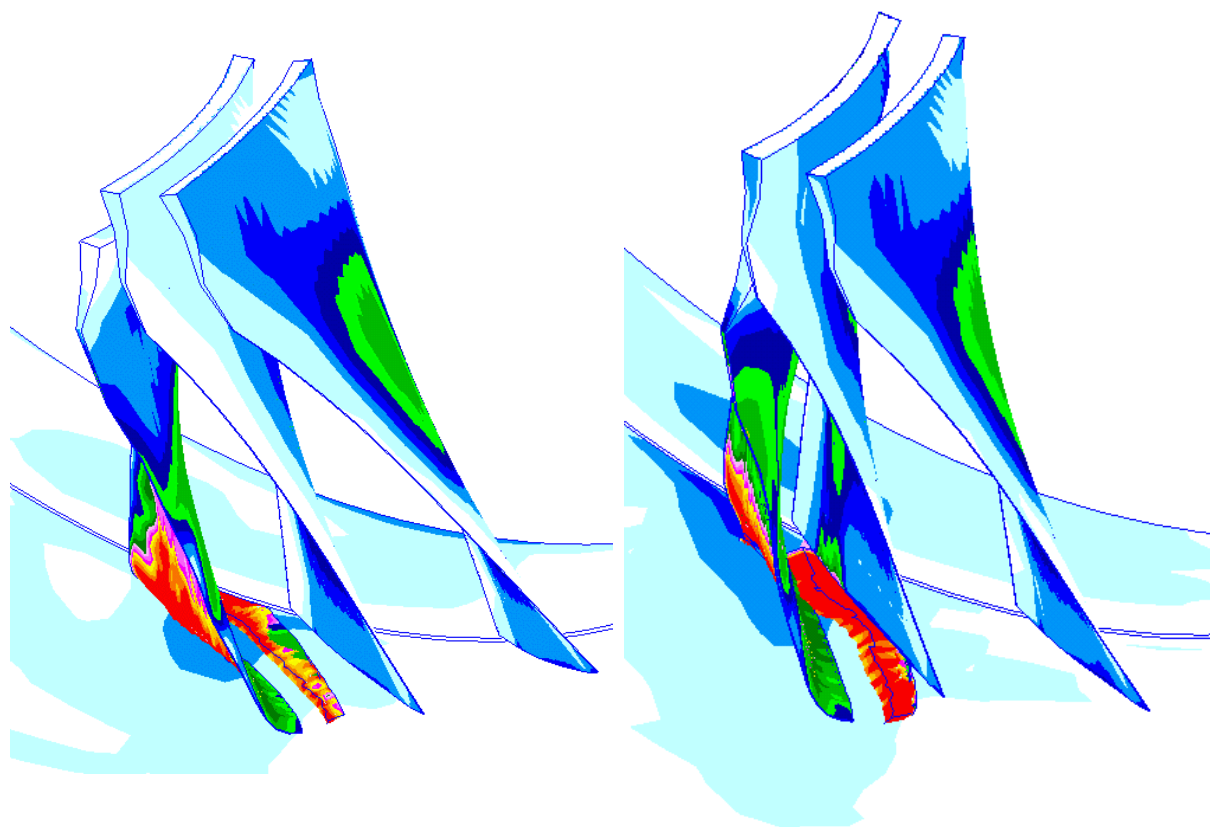
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**figure 1** *FE model geometry of the test engine.*



**figure 2** *Pre-stresses field in the rotor.*

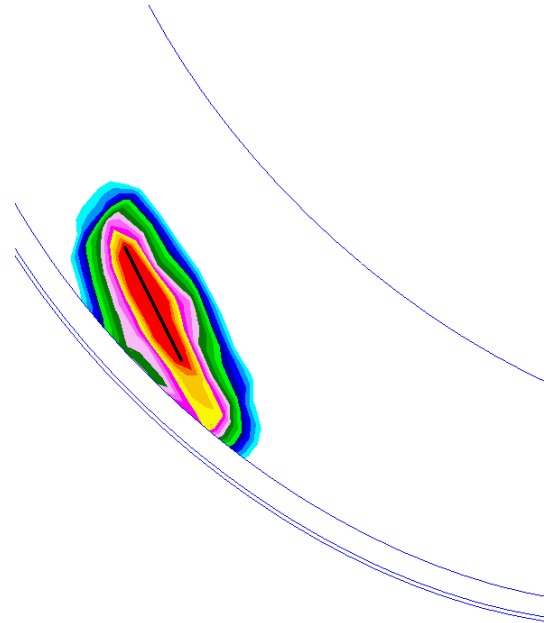
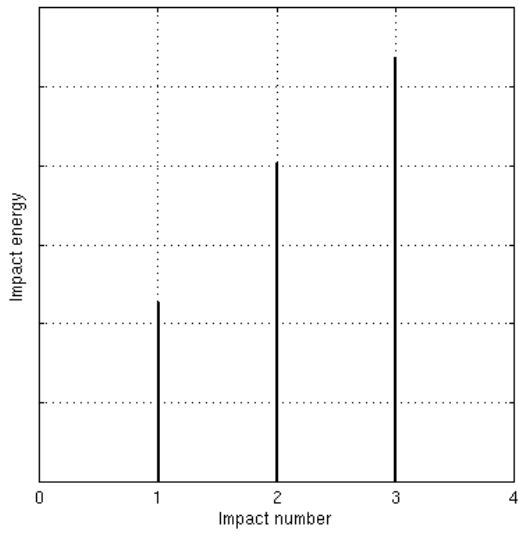


(a) First fragment

(b) Second fragment

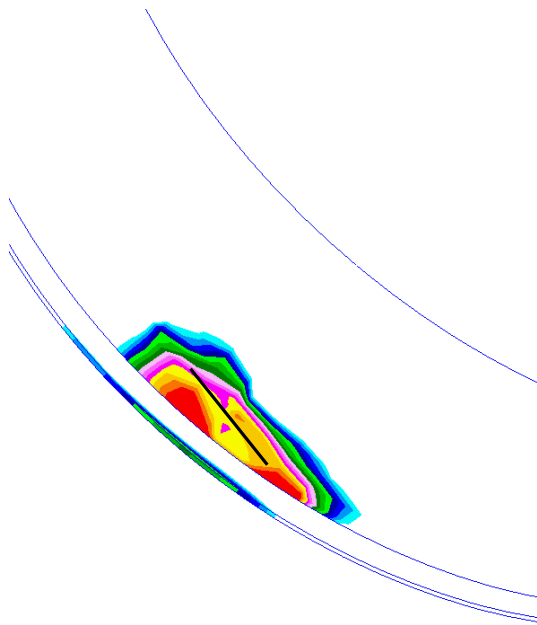
**figure 3** *Fragmentation process of the released blade.*



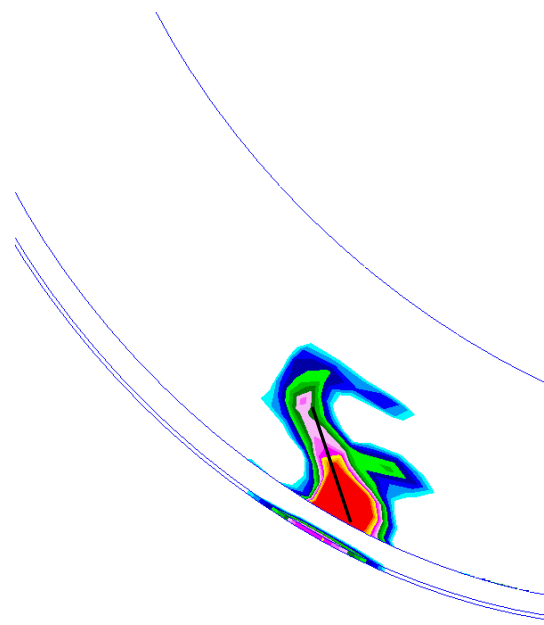


(a) First impact on the casing

**figure 4** *Impact energy of the fan blade fragments.*

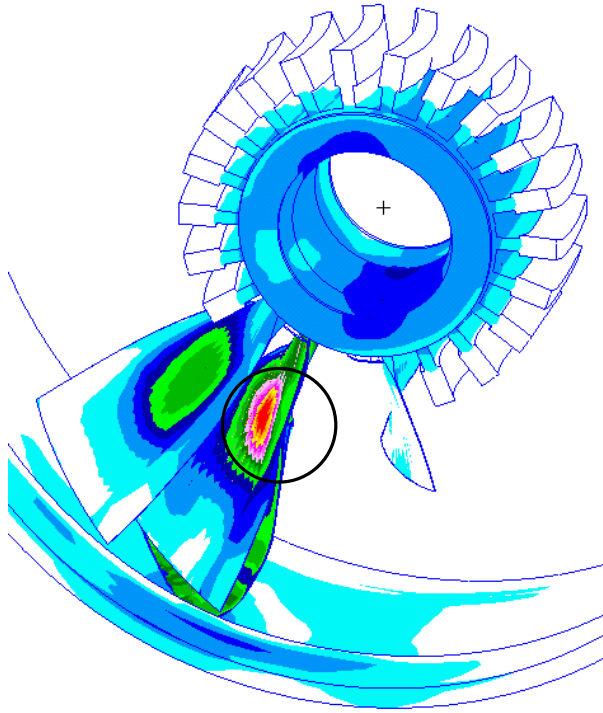


(b) Second impact on the casing

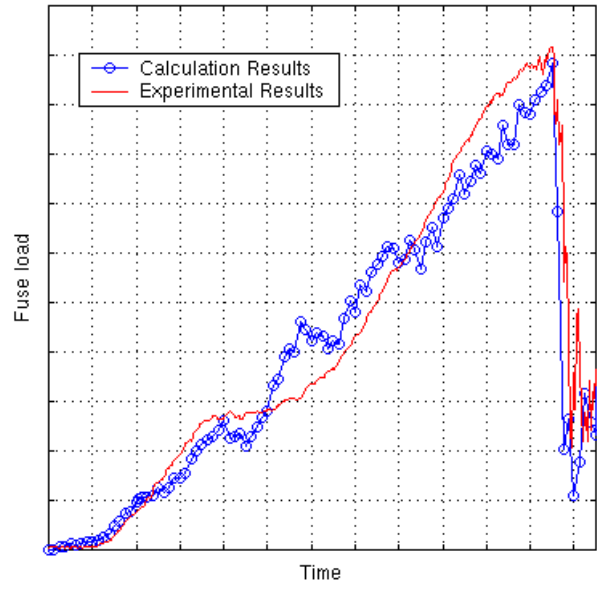


(c) Third impact on the casing

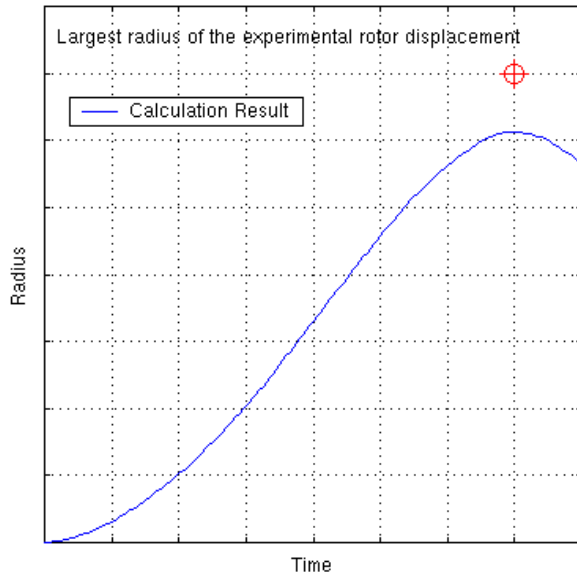
**figure 5** *Calculated impact areas of the released blade fragments on the fan casing.*



**figure 6** *Impact of the released blade on the following blade.*



**figure 7** *Fuse load versus time.*



**figure 8** *Orbit radius of the rotor.*