Aircraft Engine Blade-Out Dynamics

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ABSTRACT

A primary problem in the design of aircraft gas turbine engine internal and support structures is the accurate simulation of the fan blade-out event and the subsequent windmilling of the engine. Reliable simulations of the blade-out event are required to ensure structural integrity during flight as well as to guarantee successful blade-out certification testing. A model and procedure has been developed which successfully predicts the key physical behavior of a generic engine structural dynamics. The key procedures and modeling techniques for this application are given.

Keywords:
Containment, fan case, impact, rotodynamics, rub, unbalance

INTRODUCTION

The current environment for designing aircraft engine and engine-airframe structural systems requires extensive levels of effort to prepare and integrate models, generate analysis results and post-process data. Additionally, the accuracy of the simulations is less than desired, leading to less than optimal designs, costly testing and re-designs and most important, uncertainties in factors of safety. One of the primary concerns of aircraft structure designers is the accurate simulation of the blade-out event. Typically, the most severe blade-out occurs when a first stage fan blade in a high bypass gas turbine engine is unintentionally released. Structural loading results from both the impact of the blade onto the containment ring and the subsequent instantaneous unbalance of the rotating components. Reliable simulations of the blade-out event are required to ensure structural integrity during flight as well as to guarantee successful blade-out certification testing. The loads generated by these analyses are critical to the design teams for several components of the airplane structures including engine, nacelle, strut, and wing, as well as the aircraft fuselage.

The process currently used to generate the required information for the aircraft blade loss loads analysis is a collection of test, flight and analytical data. The principal loads analysis for the engine-airframe system is performed using implicit analysis in a general purpose finite element tool, with forcing functions that have been derived from test data (Lawrence, 2001). Figure 1 depicts a generic engine finite element model for use in a general purpose code. The forcing functions represent a variety of physical effects and are carefully tuned to reproduce the desired blade loading. As a result, a particular set of forcing functions is only good for a particular engine, or class of engines. Most often, the data from a blade-out test for a particular engine does not become available until that engine's design is nearly complete. Therefore, a higher degree of uncertainty than what is optimal exists while the design is being generated. This uncertainty is not eliminated until the design has been solidified, when it is too late to easily make modifications in the design. If a tool could be used to increase the accuracy of the implicit analysis at an early stage, by including in the forcing functions results from the physics of the blade loss problem, then a more optimal design may be achievable.

The high fidelity simulation tool, LS-DYNA, is being evaluated to assess if it can capture the structural loads resulting from the blade loss event. If successful, these loads may be used as input into an overall system model, using a general purpose, implicit finite element code, which includes complete structural models of both the engines and the airframe. The physics that the detailed simulation seeks to include are the time dependent trajectory of the lost blade and its impact on the containment structure, the unbalanced rotational dynamics of the remaining fan-rotor system, and the rub and impact of the remaining first stage fan blades on the containment ring, due to the unbalance.

Blade Out

The loss of a first stage fan blade in a high bypass turbine engine can be initiated by material failure due to fatigue, a bird strike (Vasco, 2000), or some other foreign object damage. The fan blades are initially rotating at a very high rate, on the order of 5000 rpm. The released blade will follow a tangential trajectory that is highly determined by its initial conditions. That trajectory will cause the blade to impact the containment case at a relatively consistent angle. Containment analysis of blades has been performed using LS-DYNA for quite some time. Most of this analysis has focused on the design of the containment structure itself, while the present work is concerned with predicting loads on a system that has already been adequately designed for containment. For example, while previous LS-DYNA simulations have been used to determine adequacy of containment structures to resist blade penetration the present work is interested in predicting fan blade/case interactions such as rubbing.

The rotational speed of the turbomachinery does not remain constant during the duration of the event. Instead, there is a rapid deceleration, where the rotor speed drops suddenly from the normal flight operating rotational speed down to the windmilling speed. (The windmilling speed is the speed at which, when the engine is shut down and not producing thrust, the engine rotates due to the air flowing through it because of the forward motion of the aircraft.) In severe cases, the rotor or bearings may be damaged such that the rotor speed drops even lower or more rapidly.

The blade-out event causes a large enough mass unbalance to significantly alter the inertia properties of the rotor. The resulting inertia properties after a blade loss will not be symmetric since the blade loss is localized at a particular rotor disk segment. The large instantaneous unbalance in the fan rotor causes it to spin off center. With each rotation the displacement of the centerline increases until the tips of the remaining blades begin to contact the case, first quickly wearing away the rub strip, then contacting the containment structure. The nature of the contact is in part a rubbing, with friction, wear and blade damage; and in part an impact between blades and case, due to the large off-center displacement and the system geometry. The contact between the blades and the case becomes part of the load path between the rotating and non-rotating sections of the engine, reducing the extremely large unbalance load that would otherwise be taken through the bearings. The unbalance loading continues until the blade tips are worn down to the point where they may no longer contact the case, or there is only intermittent rub. By this time, the rotation speed has dropped, somewhat reducing the unbalance load, which is in part a function of the rotational speed. While the initial impact takes places very quickly (with resulting very high strain rates), the total time of the complete event is almost one half of a second.

MODELING APPROACH

Structure and Mesh

In a containment model, the only components required are the case and three fan blades, whose rotation and position are specified. In order to include the effects of the unbalance load in the blade-out analysis, the rotor and bearings must be included to allow the centerline of the rotor to displace. In addition, a complete set of fan blades is required to include their mass properties, and the effect of their contact with the fan case. Other engine structural components are believed to be secondary in their effects on blade-out dynamic response. Additional components that may need to be modeled for accurate blade-out analysis are discussed in the results section.

A finite element model of a fan case, a first stage compressor blade assembly, and a rotor on bearings was assembled in LS-DYNA. Figure 2 depicts this detailed blade-fan case interaction model. A LS-DYNA finite element model of all engine and airframe components was deemed impractical due to the resulting matrix size. It was believed that the modeled components might accurately reflect blade-out dynamics. The components of the model were derived from several other models, in addition to information obtained from several diverse sources. Pratt and Whitney provided the generic engine model depicted in Figure 1, which provided the system level structural properties. A blade model was taken from preliminary models of the proposed, but never built, High Speed Civil Transport. There are 26 blades in the blade hub assembly. This model does not represent an actual engine, but it is instead, a tool used for technique development.

The geometry of the fan blades is defined by several complex three-dimensional curves. Along its edges, each blade is modeled by a single layer of shell elements. In the center portion of the blade, there is hollow section. This section is modeled by facing shells connected by edge-on shell elements. All of the shells elements use the S/R co-rotational Hughes-Liu formulation. There is also a very stiff root section. The stiff root section of the blade is attached to a rotor. The rotor is supported by three bearings, which are modeled as stiff translation springs. The forward and the rear bearings support lateral motion, and the middle bearing supports lateral and axial motions. The rotor is free to rotate about its axial direction. At the end of rotor, opposite the first stage fan blades, are masses that represent the turbine section that drives the first stage compressor.

Materials

The fan blades and the fan case utilized Titanium 6-4. The Titanium was modeled using material law 24, piecewise linear plasticity. Strain rate effects were included by defining a series of stress-strain curves. The data used was taken from a Wright Patterson report (Nicholas, 1980), which was based on Hopkinson bar test data. Ballistic tests of subsystems at GRC have suggested that very high strain rates can occur at the applicable velocities. In correlating analysis to this testing, definition of material behavior at strain rates higher than what was included in available data was required. Therefore, the data was extrapolated to the required higher strain rates of up to 20000 sec^{-1}. The increase in strength due to strain rate effects was assumed to follow a logarithmic pattern, as it does at lower strain. Additional data aiding in the definition of Titanium 6-4's strain behavior was provided in a FAA report (Lesuer, 2000).

The rotor used 304L Stainless Steel as its material. This steel was also modeled using material law 24, piecewise linear plasticity. For this material, a yield stress and a tangent modulus were defined. The strain rate effects were included by scaling the bi-linear elastic plastic curve. The data that was used to produce this model was also obtained from the Wright Patterson report (Nicholas, 1980).

Analysis

Before a blade-out occurs the rotor would normally be rotating at a constant velocity, and due to centrifugal effects, the blades would be deflected into a quasi-static shape. This preloaded geometry is calculated in a LS-DYNA implicit static analysis. The free rotation of the rotor is fixed and the rotational load is applied as a body force.

Deformed node and element data is written into a dynain file by an INTERFACE_SPRINGBACK card. The updated node and element cards and initial stress cards are used to initiate the explicit analysis. The blade is released soon after the beginning of the analysis by using spotweld constraints with a time of failure.

Several characteristics of this analysis lead to particular analytical difficulties. First, the velocity of the blade is very high, and sometimes the initial contact is difficult to capture correctly, leading to penetration errors. This is despite the mesh densities of the segments in contact being similar and the materials contacting each other being identical. The use of pinball-segment based contact, soft constraint formulation option 2, greatly improved contact algorithm performance. Eroding single surface was the contact algorithm used.

The second challenge was that, due to the relatively long duration of the unbalance response, the simulation must be allowed to continue for a long time. The simulation times are long enough that eventually even minor hourglassing will likely blossom into an unacceptable range. The primary location of the hourglassing is in the highly stressed regions of the fan blade. Since there are 26 blades, to contain the hourglassing by increasing blade-element density would lead to analysis times that, already extremely long, would become untenable. Therefore, the only method that was successful in controlling hourglassing was to prevent it from happening in the first place. After trying a number of combinations of element formulations and hourglass control, the S/R co-rotational Hughes-Liu formulation elements with the standard LS-DYNA hourglass control were successfully used with no hourglassing developing. Depending on the particulars of future analysis, other hourglassing controls may have to be used.

Aerodynamic loads are an additional physical force that will slow the rotor of the shutdown engine, but they have not been included in this model as an aerodynamic force. A global damping factor of 2. has been defined, which somewhat simulates the effects of the aerodynamics in addition to other non-identified non-conservative forces.

RESULTS

Several key parameters control the response of the dynamic system response. They include the stiffness of the rotor shaft, the inertia properties of the blade hub assembly, the rotational velocity of the shaft, and the interaction between the blade and the case. Several of these properties are fairly well defined, or can be conventionally analyzed, such as the rotation velocity, the inertia properties, and the stiffness. As a result, it is not surprising that the character of the LS-DYNA results match the general behavior of the blade-out event (HEIDARI, 2000). The results show the released blade making contact with the containment case and trailing blade. The released blade is broken into a number of pieces that fly in various directions. The rotating blade and rotor system then begins to wobble due to the unbalance in the system, as shown in Figure 3. Figure 4 shows the same data in an orbit plot. Because the centerline displacement begins from rest, the wobble is not initially in-phase with the rotor rotation. The remaining blades begin to contact the containment case with a combination of impact and rub. The blade tips deform and the tip area is bent back as shown in Figure 5. Some elements on the blade tips are removed due to plastic strain failure. The rotor slows down due to the contact between the blades and the case (Figure 6) and eventually the blades no longer contact the case. Figure 7 shows the deformed blade-fan case interaction model after blade loss and several unbalanced rotations, with the color contours depicting plastic strain.

An alternate model is displayed in Figure 8. In this model, the fan case has been extended out to where it would meet the nacelle. The hub has also been greatly simplified. These changes were made to reduce computation time. An additional alteration to the blade-fan case interaction model, which is being considered, is the addition of support springs that would represent the portions of the engine/airframe system not otherwise included. These springs would be in series with springs that currently represent the bearings. In an approximate way, this addition would include the effects of the complete system in the detailed analysis. Another addition to the model that may be required is modeling other compressor and turbine stages that might be contacting after the blade-out.

Test Verification

In order to increase the accuracy of the material models, in particular failure and mesh size sensitivity, and contact and friction modeling, a new test rig is being developed. This rub rig will bridge the gap between Hopkinson Bar tests and full up system tests. The rig will be used in conjunction with the NASA GRC Ballistic Impact Lab. A projectile traveling at a high velocity will impact a target on a pendulum arm. Figure 9 shows a plot of the pendulum and the rig before impact. A blade tip sample is attached to the arm. The arm swings around and the blade tip sample will impact and rub a containment case sample section. Figure 10 pictures the arm as it begins its trajectory. Analytical predictions will be compared and correlated to data from this test rig.

SUMMARY

Aircraft gas turbine engine blade-out occurs when a first stage fan compressor blade is released and a series of events is triggered that severely load the engine and airframe structure. A model has been successfully developed which successfully predicts the global behavior of the blade-out event in aircraft gas turbine engines. In order to develop this simulation, high strain rate material models, a method to preload the compressor blades and other analytical techniques have been used, in addition to the creation of the actual finite element model. This generic engine model has been used to guide further research, test, and development efforts. Work is continuing to both connect this simulation with test data and with a general purpose finite element code, thereby yielding reliable analytical predictions of the blade-out event.

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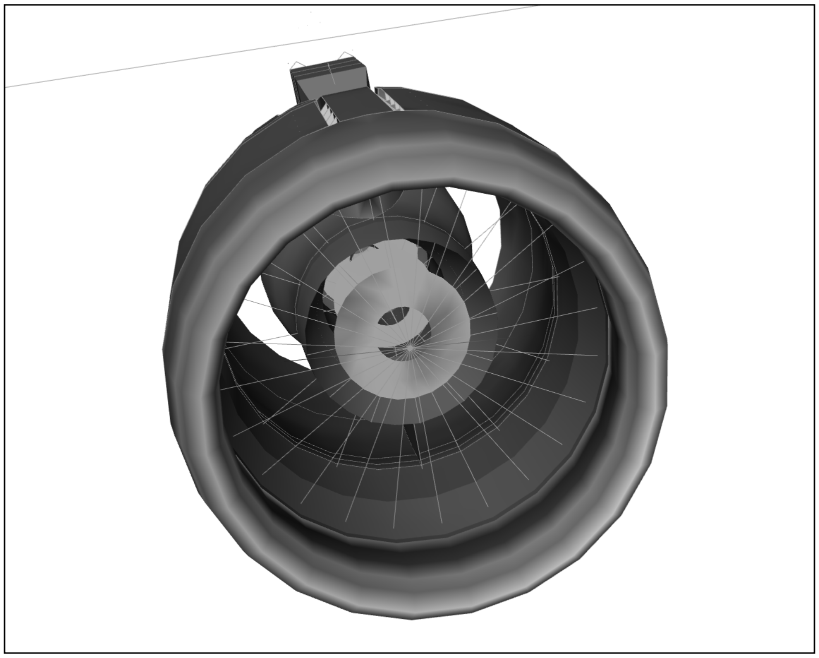

Figure 1. Generic Engine System Model

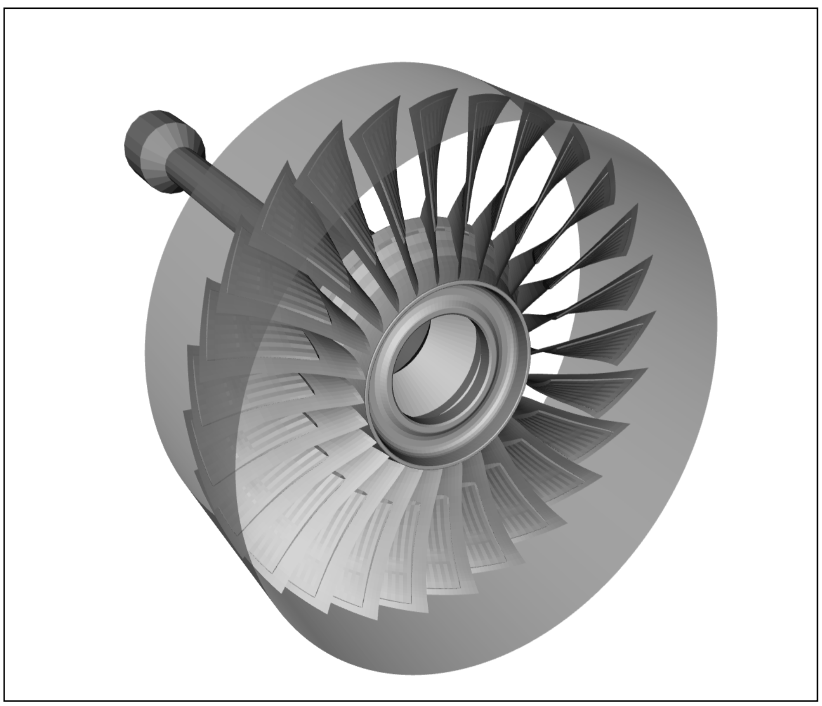

Figure 2. Detailed Blade-Fan Case Interaction Model

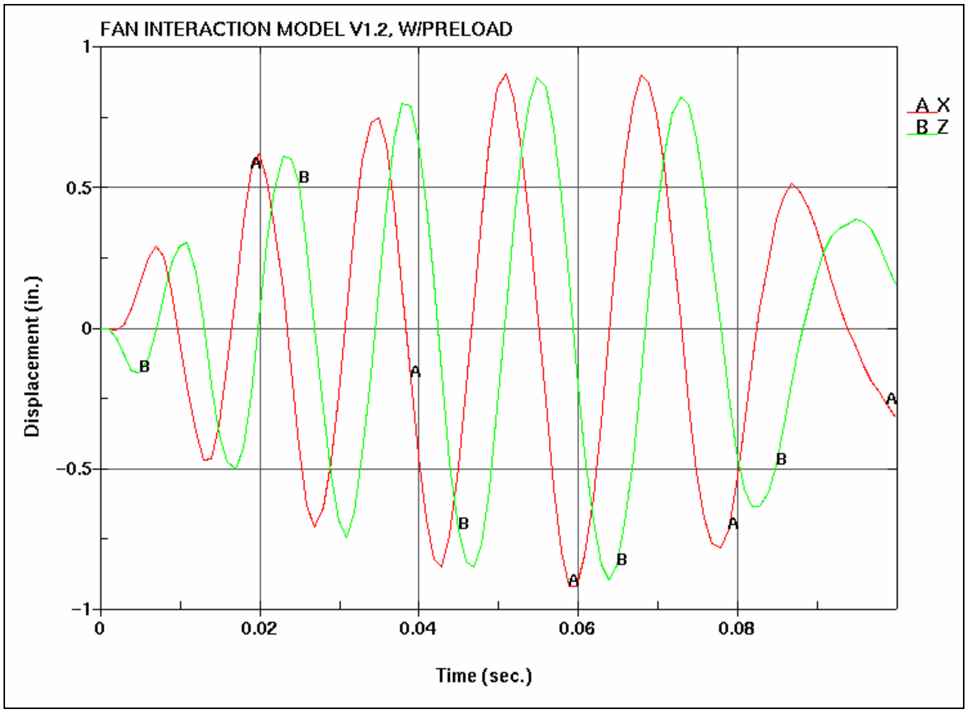

Figure 3. Centerline Displacement of the Rotor at the Forward Bearing

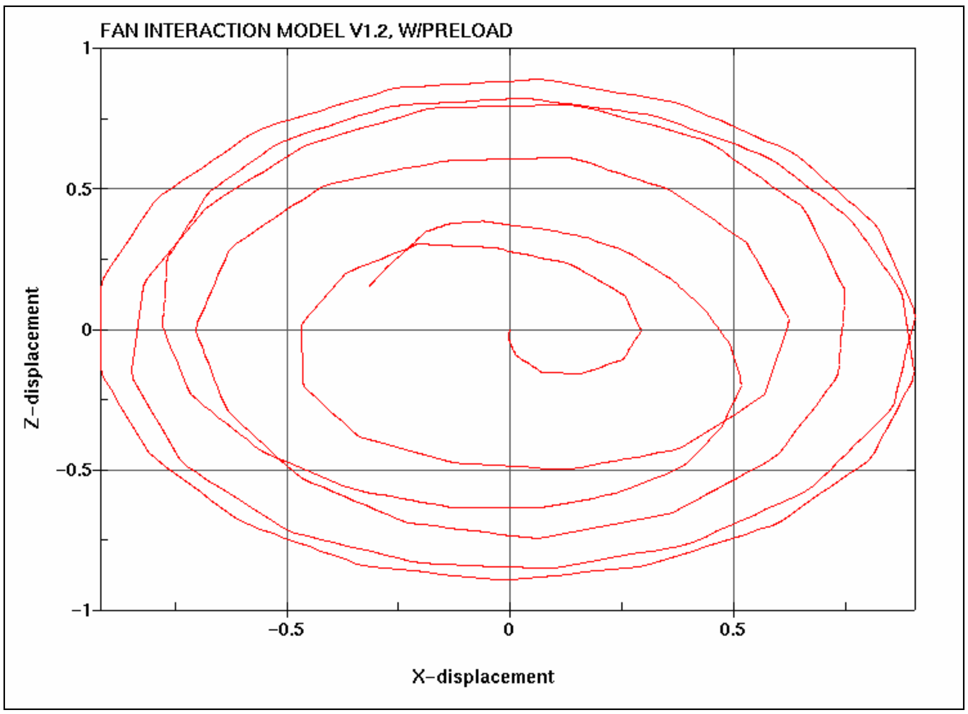

Figure 4. Centerline Displacement of the Rotor at the Forward Bearing

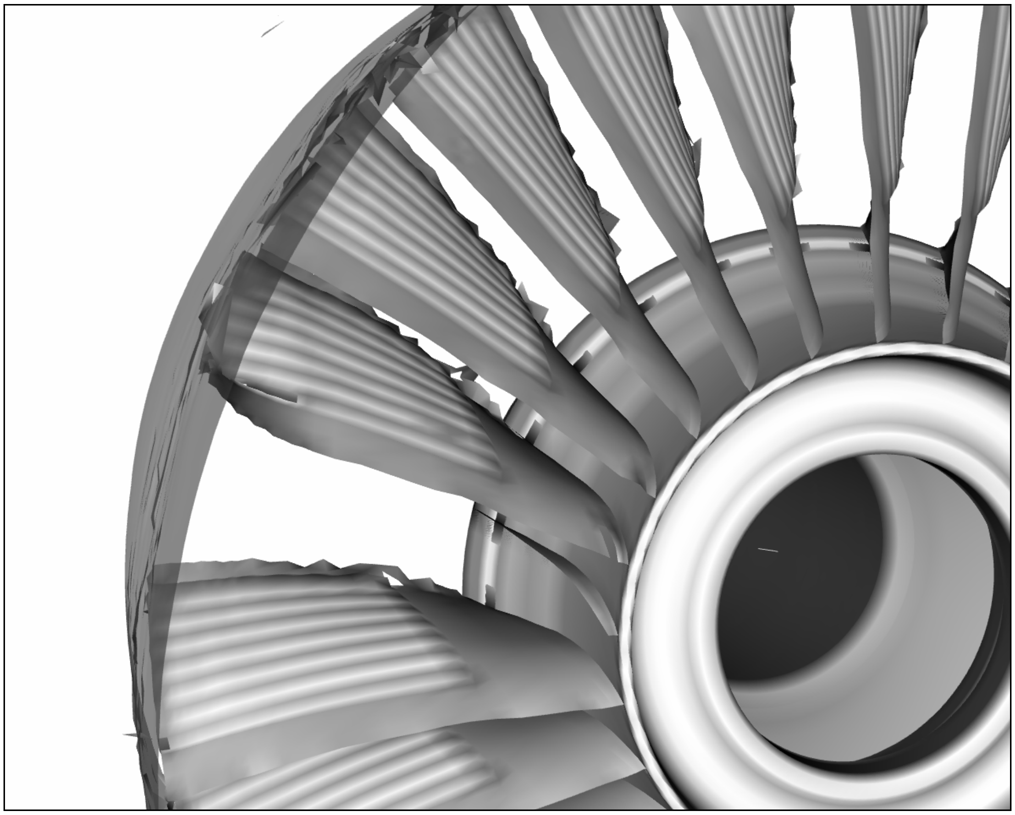

Figure 5. Close-up of Model after Blade-out

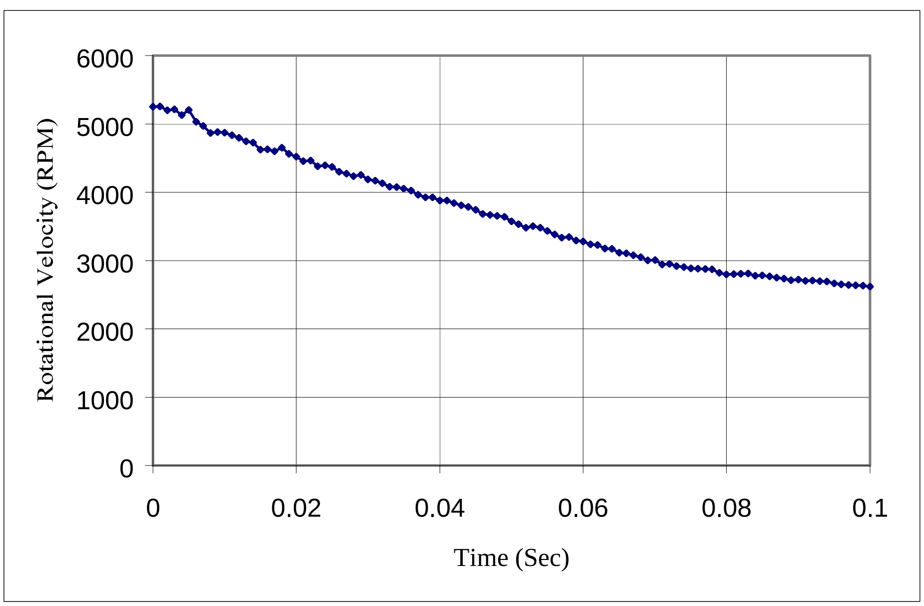

Figure 6. Engine Rotational Velocity after Thrust Cutoff

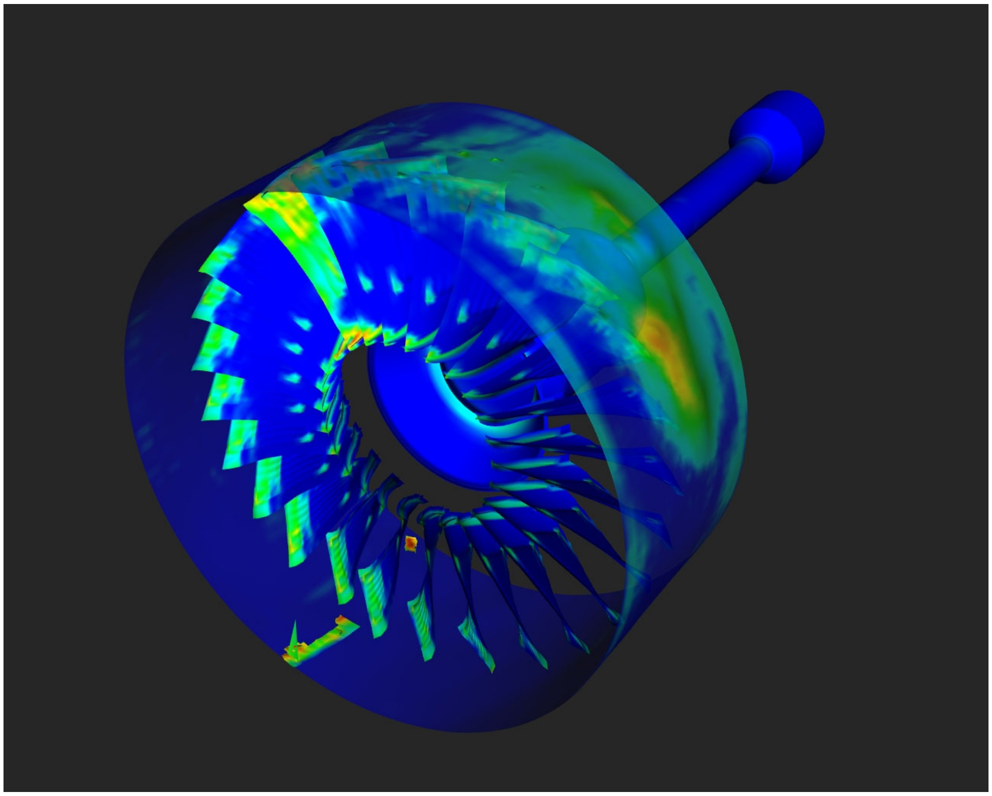

Figure 7. The Plastic Strains of the Deformed Blade-Fan Case Interaction Model after Impact and Unbalanced Rotation

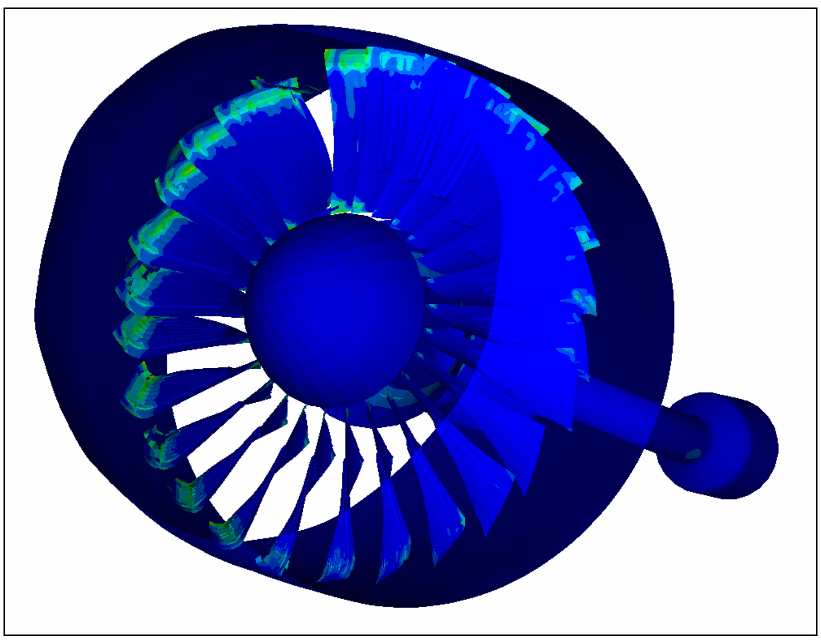

Figure 8. The Plastic Strains of the Alternate Model after Impact and Unbalanced Rotation

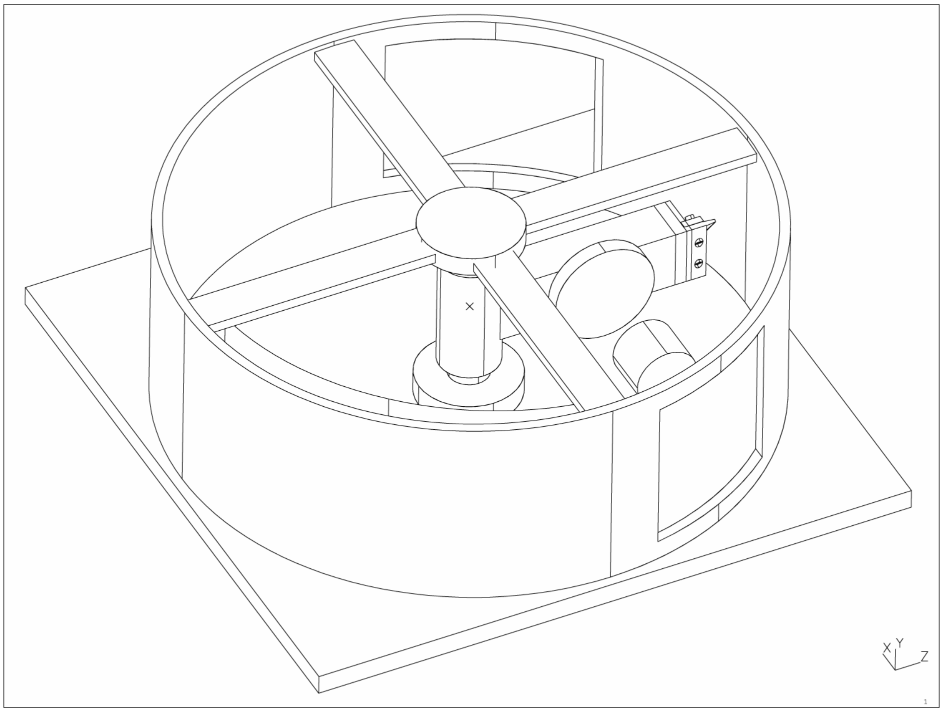

Figure 9. Preliminary GRC Rub Rig Design

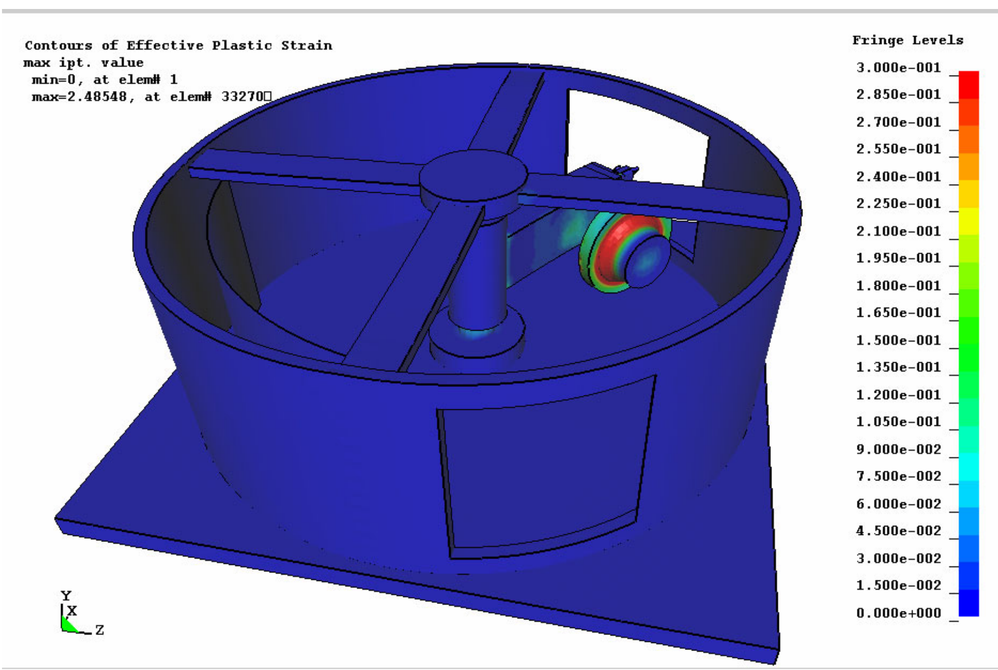

Figure 10. Rub Rig during Rotation after Initial Impact