



Jet Engine Bird Ingestion Simulations: Comparison of Rotating to Non-Rotating Fan Blades

Samuel A. Howard
Glenn Research Center, Cleveland, Ohio

Jeremiah T. Hammer
The Ohio State University, Columbus, Ohio

Kelly S. Carney and J. Michael Pereira
Glenn Research Center, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Fax your question to the NASA STI Information Desk at 443-757-5803
- Phone the NASA STI Information Desk at 443-757-5802
- Write to:
STI Information Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320



Jet Engine Bird Ingestion Simulations: Comparison of Rotating to Non-Rotating Fan Blades

Samuel A. Howard
Glenn Research Center, Cleveland, Ohio

Jeremiah T. Hammer
The Ohio State University, Columbus, Ohio

Kelly S. Carney and J. Michael Pereira
Glenn Research Center, Cleveland, Ohio

Prepared for the
Turbo Expo 2013
sponsored by American Society of Mechanical Engineers (ASME)
San Antonio, Texas, June 3–7, 2013

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

Acknowledgments

The authors acknowledge the support of NASA's Fundamental Aeronautics Program—Subsonic Fixed Wing Project and Aviation Safety Program for supporting this work.

This report contains preliminary findings,
subject to revision as analysis proceeds.

This work was sponsored by the Fundamental Aeronautics Program
at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

Jet Engine Bird Ingestion Simulations: Comparison of Rotating to Non-Rotating Fan Blades

Samuel A. Howard
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Jeremiah T. Hammer
The Ohio State University
Columbus, Ohio 43210

Kelly S. Carney and J. Michael Pereira
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Bird strike events in commercial airliners are a fairly common occurrence. According to data collected by the US Department of Agriculture, over 80,000 bird strikes were reported in the period 1990 to 2007 in the US alone (Ref. 1). As a result, bird ingestion is an important factor in aero engine design and FAA certification. When it comes to bird impacts on engine fan blades, the FAA requires full-scale bird ingestion tests on an engine running at full speed to pass certification requirements. These rotating tests are complex and very expensive. To reduce development costs associated with new materials for fan blades, it is desirable to develop more cost effective testing procedures than full-scale rotating engine tests for material evaluation. An impact test on a non-rotating single blade that captures most of the salient physics of the rotating test would go a long way towards enabling large numbers of evaluative material screening tests.

NASA Glenn Research Center has been working to identify a static blade test procedure that would be effective at reproducing similar results as seen in rotating tests. The current effort compares analytical simulations of a bird strike on various non-rotating blades to a bird strike simulation on a rotating blade as a baseline case. Several different concepts for simulating the rotating loads on a non-rotating blade were analyzed with little success in duplicating the deformation results seen in the rotating case. The rotating blade behaves as if it were stiffer than the non-rotating blade resulting in less plastic deformation from a given bird impact. The key factor limiting the success of the non-rotating blade simulations is thought to be the effect of gyroscopics. Prior to this effort, it was anticipated the difficulty would be in matching the pre-stress in the blade due to centrifugal forces. Additional work is needed to verify this assertion, and to determine if a static test procedure can simulate the gyroscopic effects in a suitable manner. This paper describes the various non-rotating concepts analyzed, and demonstrates the effect believed to be gyroscopic in nature on the results.

Introduction

Due to the large frequency of bird strike events in commercial airliners, the FAA has established standards for bird ingestion for certification of aero engines (Ref. 2). Rotating bird strike tests such as those required by the FAA require large-scale and expensive test facilities and procedures. The cost associated with these tests, make it difficult to assess new materials for fan designs. It is not the goal of this work to replace the bird strike certification tests, which consider aspects of a bird strike other than the direct impact damage (such as the ability to continue operating at a reduced power level) and are necessary to ensure compliance with certification requirements. Rather, the goal is to determine if simpler, less costly testing could be used for fundamental material development testing and still retain most of the physics of the rotating test. Stated another way, can a single non-rotating blade be impacted with a bird or simulated bird in such a way as to duplicate the damage that same blade would experience in a rotating bird ingestion test? If the answer to that question is yes, such a test could be used as a cost-effective screening test for new materials and fan designs that could then go further in the development cycle and eventually be tested in a rotating test. If the answer is no, then it provides a scientific rationale for conducting the expensive rotating tests.

The Impact Dynamics Group at NASA Glenn Research Center has been working to answer the above question and design a non-rotating test to simulate the damage a blade would sustain in a full-scale, rotating, bird-ingestion test. To assess whether a static test can simulate a rotating test, 3-D finite element simulations were performed using a gelatin bird model and a generic fan design. Hereafter, the term “bird” is used to refer to a simulated bird projectile. Numerical simulations were carried out with a rotating fan blade as the baseline case and results were compared to non-rotating blade numerical simulations with various concepts to apply rotating-like loads to the blade. It is important to note that the baseline

case has not been vetted against experimental results for accuracy. However, the techniques and analysis tool used are consistent with prior work that has been shown to correlate well to experimental results in similar analyses (Refs. 3 to 7). Additionally, the intent is to compare the rotating and non-rotating cases rather than focus on the accuracy of the predicted impact results. Furthermore, additional work is planned to corroborate the results obtained so far, including experimental validation, after which the conclusions drawn here can be re-evaluated.

There has been extensive work over the past several decades intent on modeling bird strike events on aero structures, including fan blades and other engine components. Together, Nizampatnam (Ref. 8) and Mao, et al. (Ref. 9) provide a good review of the representative literature. A large majority of the work has been focused on the development of an appropriate artificial bird model, including the bird shape, bird material, and modeling technique (Lagrangian, Euler, Arbitrary Lagrangian-Eulerian, etc.). Considering the remainder of published work, few have concentrated on the rotational effect on blade deformation. The reports that did consider rotational effects either did not compare deformation between rotating and non-rotating blades, or concluded that the centrifugal forces acted to reduce the global deformation of the rotating blades (Refs. 3, 4, 10 to 12). Because of that finding, and independent anecdotal evidence from aero engine designers, it was anticipated that any non-rotating test techniques would need to include pre-stressing the blade to have a chance of successfully simulating a rotating test condition.

Due to the above observations, early simulations were focused on duplicating the pre-stress field near the impact zone. Later simulations focused on different methods for constraining the blade, to help determine if the method of applying pre-stress in addition to the magnitude is important. Results were disappointing, with none of the attempts accurately duplicating the plastic deformation of the rotating blade. The deformation of the rotating blade was found to be less than all of the non-rotating blade simulations, no matter what pre-stress condition was present, including identically matching the centrifugal pre-stress condition to the rotating case. Therefore, there is clearly some other factor influencing the deformation as well. The gyroscopic effect, or the effect of changing the rotational inertia of the rotating fan blade, is not included in the non-rotating analysis and could lead to the over-prediction of deformation of a non-rotating blade.

This paper gives a summary of the results of the many simulations conducted along with a discussion of the rotating effects. Future plans to continue the search for a non-rotating material screening test are also presented.

Nomenclature

F	Force
I	Mass Moment of Inertia
M	Moment (Vector Quantity)
m	Mass
p	Spin Velocity (Vector Quantity)
r	Radius
t	Time
θ	Angle of Rotation About Spin Axis, p
Ψ	Precession Angle
Ω	Precession Velocity (Vector Quantity)

Methodology

LS DYNA, a general-purpose finite element program, was used in all the simulations reported herein (Ref. 13). The fan blade model used was developed at NASA Glenn Research Center for aero-elasticity studies and was originally for a large engine approximately 144 in. (3.65 m) in diameter. Since the fan size of interest in this study is about half that size, the fan blade was scaled down to about 72 in. (1.82 m) in diameter with a blade length of approximately 24 in. (0.6 m). Figure 1 shows a single blade mesh used in these studies. The material model for the blade was *MAT_PIECEWISE_LINEAR_

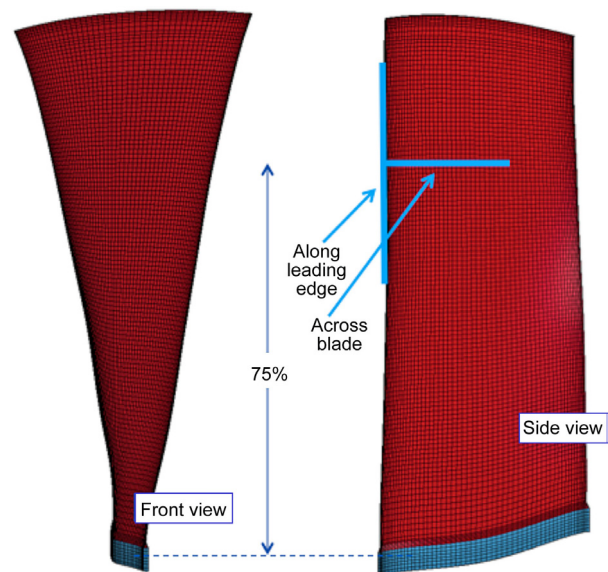


Figure 1.—Blade mesh showing location of bird impact and paths for result plots.

PLASTICITY with the strain-rate dependent properties of Titanium 6Al-4V given in Figure 2 (Ref. 14). The blade was modeled using LS DYNA solid element formulation 2 (8-node fully-integrated selective reduction).

Prior work has shown that birds can successfully be modeled as fluids using straight-ended cylinder, hemispherical-ended cylinder, and ellipsoid shapes (Refs. 4, 5, and 15). Likewise, artificial gelatin bird models with these shapes are commonly used in experimental studies to simulate real birds (Refs. 16 and 17). The bird model used in these numerical simulations was a cylindrical gelatin slug with a hemispherical leading edge as seen in Figure 3. This shape was chosen

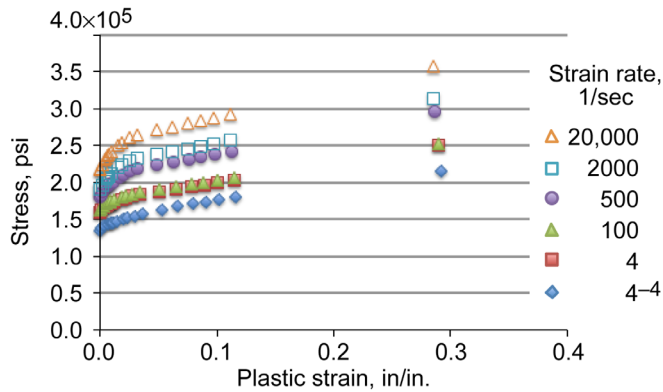


Figure 2.—Strain rate dependant stress strain curves for titanium 6V4AL.

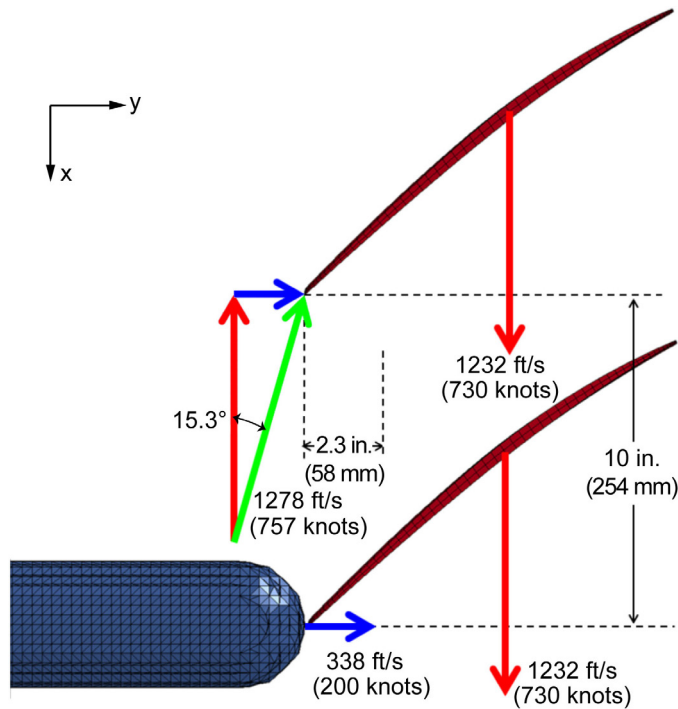


Figure 3.—Illustration of gelatin bird model entering fan blade row for determination of the extent of penetration and velocity vectors.

to match the shape that is typically used for in-house testing at NASA Glenn, and has been shown to correlate well with analyses (Ref. 17). The formulation used for the bird was Arbitrary Lagrangian-Eulerian (ALE). While there are other common formulations, such as Lagrangian, Eulerian, and Spherical Particle Hydrodynamics, the ALE formulation has been used successfully by the authors, and the focus of this work was to explore potential non-rotating test configurations compared to rotating tests rather than finding the best bird formulation. The material properties for the bird were based on previous work with gelatin as a bird substitute (Ref. 17), and were somewhat similar to water.

The bird was positioned to impact the blade at 75 percent of the distance up from the root to the tip, as seen in Figure 1. The rotational velocity of the fan blade was set to match the approximate maximum speed of a fan of this size based on sonic velocity at the blade tips, which corresponds to 500 rad/sec (4775 rpm). The air speed of interest in bird strike events is the velocity of a given airplane shortly after take-off when the plane is at an altitude most likely to encounter birds. For an airplane size consistent with a 72 in. (1.8 m) diameter fan that air speed is approximately 200 knots (103 m/sec). Because the blade in a bird strike test does not translate in the global sense, the bird is given a velocity of 200 knots in the direction toward the fan blade (y-direction) as shown in Figure 3. An assumption is made that the impact would be the same whether a bird travels toward a fan or a fan travels toward a bird, as long as the relative velocity is the same. Following this same assumption, in the non-rotating blade simulations, the bird moves with a velocity of 200 knots in the direction along the axis of the fan (y-direction), and with a velocity equal to the blade leading edge velocity at the point of impact (730 knots, 376 m/s) in the direction toward the fan blade, (negative x-direction) as shown in Figure 3.

Figure 3 also illustrates the determination of the maximum distance the bird can penetrate into the fan before hitting the first blade. The blade spacing is based on the number of fan blades in the entire fan, which in this case is 18. Given the spacing of the blades at the impact zone, and the relative velocities of the blade and bird, one can determine that a maximum of 2.3 in. (58 mm) of the bird can penetrate the fan before being hit by the first blade if it just misses the previous blade. This geometry was used for all the simulations as the worst-case scenario.

The criterion used to compare two different simulations is the plastic strain near the impact point. Hereafter, plastic strain and effective plastic strain are used interchangeably. Figure 1 shows a path along the leading edge and across the blade where plastic strain was evaluated when comparing non-rotating simulations to the rotating baseline case. Plotting plastic strain in the elements along these two paths gives a good indication of how similar two different simulations are in terms of permanent damage to the blade.

Rotating Simulation Results and Discussion

The first numerical simulation carried out was that of a rotating fan blade with a gelatin bird fired in the axial direction at the maximum take-off velocity. The approach used to develop the stress field and elastic deformation in the blade prior to the impact follows that used by others in modeling bird ingestion and also follows Test Case 5 available from the LS DYNA Aerospace Working Group (Refs. 3 and 16). The method involves two separate analyses, wherein the first run calculates the stresses and strains using implicit analysis. Then, the results of that run are fed into an explicit run as initial conditions for a secondary calculation of the transient impact event.

For the rotating case, the implicit pre-stress calculation was done with a fan blade rotational velocity of 500 rad/sec. The 500 rad/sec velocity was maintained throughout the impact in the explicit analysis such that the fan blade did not decelerate during the simulation.

The results of the pre-stress calculations are given in Figure 4. The top row shows the radial (z -direction) stress, and the bottom row shows the radial displacement, both at several different speeds from zero to the maximum rotation speed of 500 rad/sec (4775 rpm). At full speed, the stress generally increases from zero at the blade tip to a maximum in the middle of the blade at the base.

The results of this pre-stress calculation at maximum speed (500 rad/sec) were then used as initial conditions for the transient impact analysis that followed. In the transient

analysis, the bird model was analytically shot at the rotating blade at a velocity of 200 knots (103 m/sec) such that the blade would impact the bird at a distance 2.3 in. (58.4 mm) behind the leading edge of the bird as shown in Figure 3.

The results of the bird impacting the rotating blade are presented in Figure 5. One can see plastic strain as it develops from time zero, just before the impact, to time 350 μ sec in the top row of figures. The bottom rows show the top, side, and front views of the maximum principle stress as it develops in time. As mentioned earlier, the main parameter of interest is the plastic strain at the impact zone. Figure 6 gives the plastic strain along the leading edge of the blade and across the face according to the geometry shown in Figure 1. Also in the figure is a contour plot of plastic strain for reference.

The damage, measured in terms of plastic strain, is mostly localized near the impact zone. In Figure 6, one can see that the maximum plastic strain of about 0.21 occurs just above the impact point, and decreases to nearly zero 4 in. or less away from the impact point in all directions. The impact point is defined as location of first contact between the bird and the blade. In reality, the gelatin bird model has a diameter of 3.33 in. (84.6 mm), so the impact occurs over an area roughly that diameter. There is some plastic strain at the base of the blade near the leading and trailing edges, and some small areas at the blade tip leading and trailing edges as well. The plastic strain resulting from this rotating case is the baseline against which non-rotating bird-strike results will be compared.

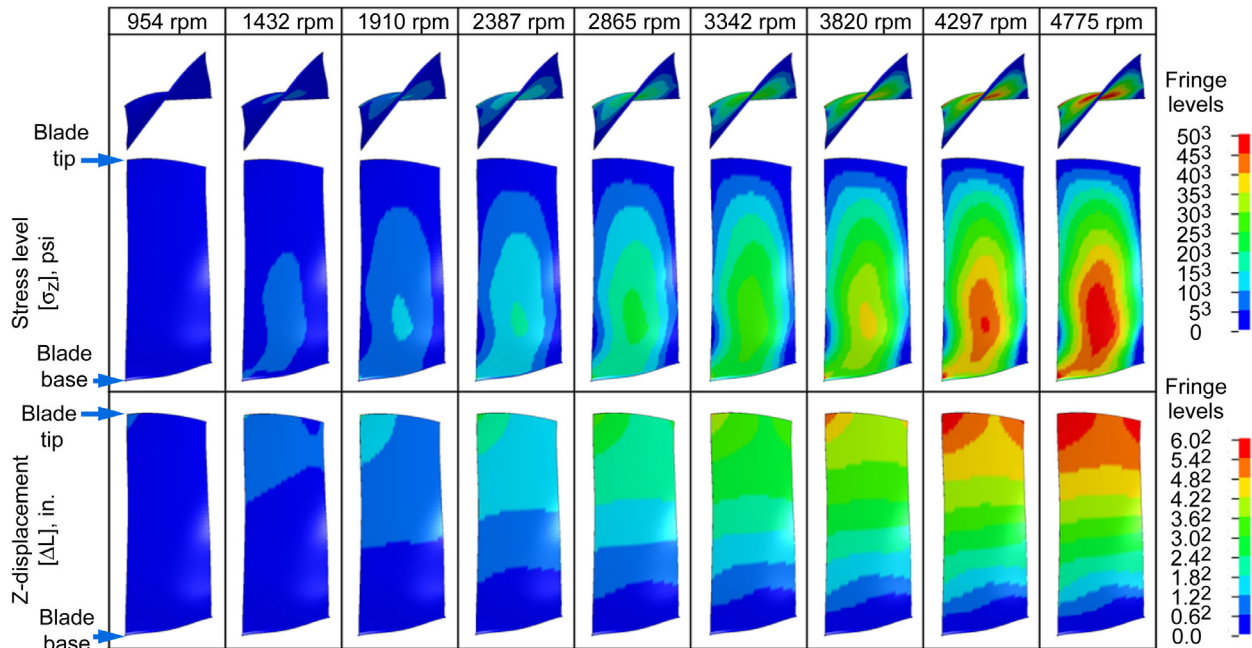


Figure 4.—Progression of stress and displacement with increasing speed from 0 to 4775 rpm (500 rad/sec). Results of pre-stress calculations before the bird impact analysis.

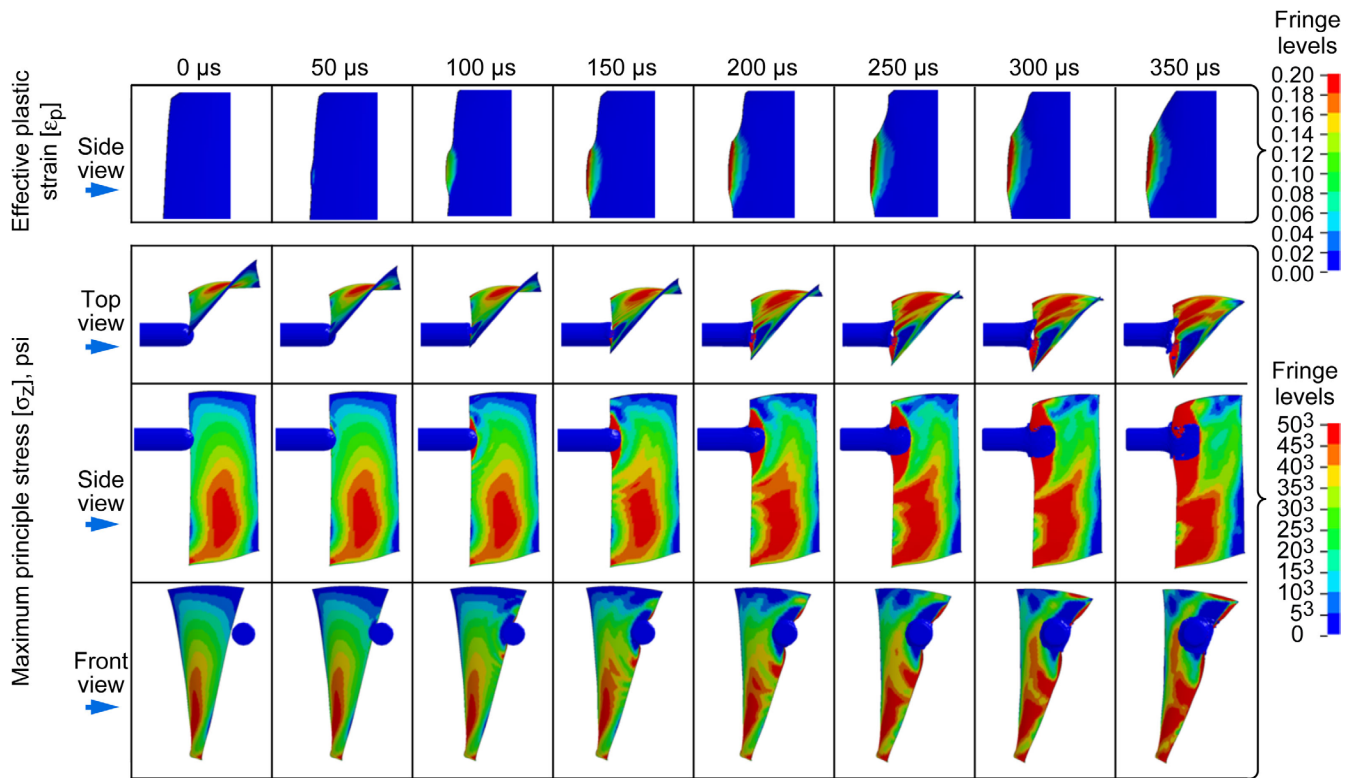


Figure 5.—Progression of plastic strain and maximum principle stress with increasing time after the impact from 0 to 350 μ sec.

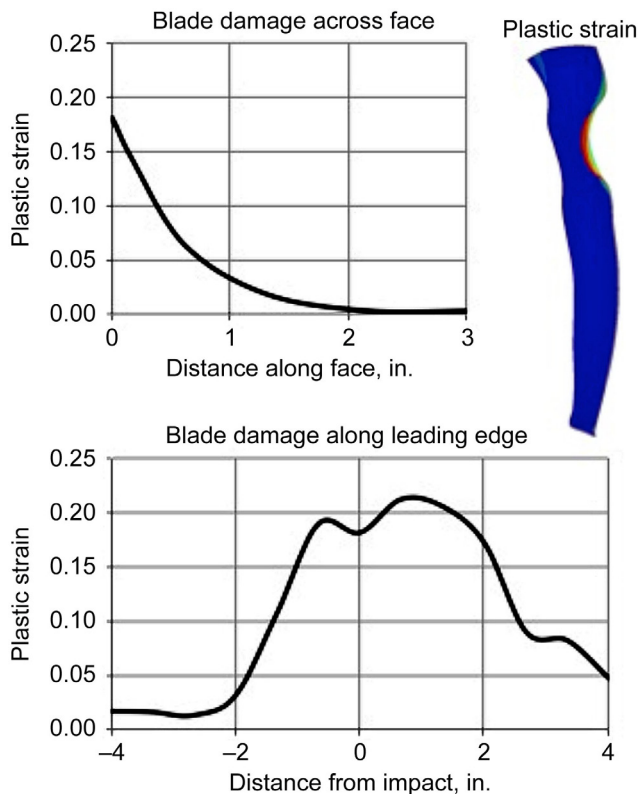


Figure 6.—Plastic strain as a function of distance from the impact point.

Non-Rotating Simulation Results and Discussion

A series of non-rotating blade simulations were done to determine the possibility of approximating the rotating blade damage with a non-rotating blade test. Because the damage was localized to the impact area in the rotating test, it was originally thought that good results might be possible if the pre-stress in the blade in the impact zone was similar to the rotating pre-stress. Several different methods for applying a load to the non-rotating blade were analyzed.

The first method of applying a force was to pull on the blade with a series of cables attached at the tip of the blade. Figure 7 shows the analytical model of the blade with cables attached to the tip. By changing the diameter and length of the cables, and the displacement at the upper end (cable stretch), the force applied to the blade can be changed. The cables are shown as being short in the figure to conserve space, but in reality, the cable length is long compared to the length of the blade to reduce the tangential constraint of the blade tip. The cable stretch is set such that the pre-stress in the blade matches the pre-stress in the rotating case at the impact zone. In order to generate a pre-stress condition with the cables that matched the rotating case at the impact zone, many different attempts were made using different cable lengths and cable stretch.

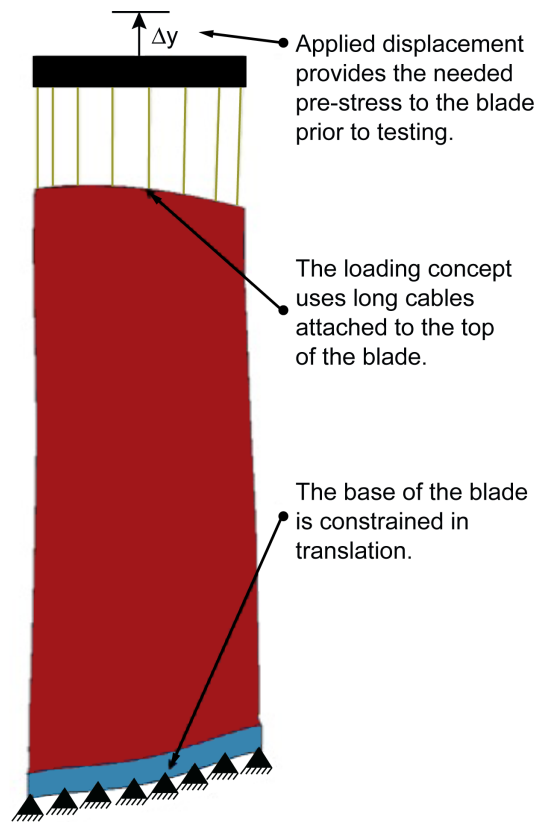


Figure 7.—Schematic of the non-rotating blade test concept using cables at the blade tips to apply a radial force.

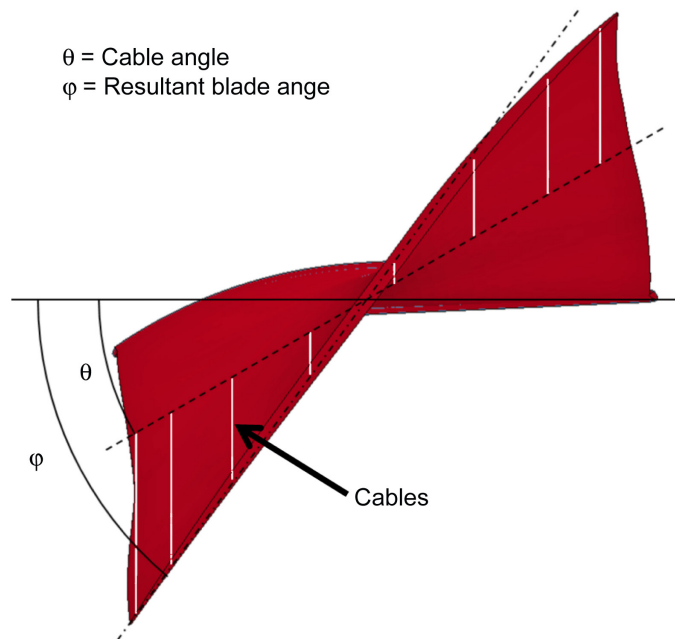


Figure 8.—Top view of the blade showing the cable angle and resultant blade angle relative to the base of the blade.

It was discovered at this stage that the angle between the line connecting the tops of the cables and the base of the blade (called the cable angle) had a significant effect on the angle of attack of the blade. In other words, the blade untwisted from the applied radial force, which it also did in the rotating case, but by different amounts depending on the conditions. In order to simultaneously match the stress at the impact zone and the angle of attack, the cable angle became another important parameter. The sketch in Figure 8 defines the cable angle and the resultant blade angle (at the blade tip) relative to the base of the blade.

In the end, 25 different conditions were analyzed to find a combination of cable stretch, cable length, and cable angle that resulted in a pre-stress condition that closely matched that of the rotating blade at the impact zone. Figure 9 shows a few selected examples of z-direction pre-stress conditions that were attempted, along with the rotating case z-direction pre-stress condition. Condition 23 resulted in the best combination of pre-stress and angle of attack when compared to the rotating baseline case, and was used for the first non-rotating analysis. Additional cases were studied focusing on the other components of stress, but the results were essentially independent of those components as the z-direction was the dominant stress component due to centrifugal forces.

The bird is given an axial velocity equal to the axial velocity in the rotating case combined with a tangential velocity equal to the velocity of the blade in the rotating case as shown in the velocity triangle in Figure 3. The resultant velocity of the bird was 1278 ft/sec at an angle 15.3° from the tangential direction.

The non-rotating blade using condition 23 is impacted with the bird using the above velocity vector. The damage to the non-rotating blade is shown along with the baseline rotating blade damage in Figure 10. As one can see from the figure, the damage, in terms of plastic strain, in the rotating blade is significantly less than the damage in the non-rotating blade, even though the pre-stress condition at the impact zone was similar and the impact velocity was matched. This case is called non-rotating concept 1. As indicated before, it was hoped that matching the pre-stress at the impact zone, the angle of attack, and the bird velocity vector at impact would result in similar damage whether the blade was rotating or not rotating. After studying non-rotating concept 1, it was thought that perhaps the boundary condition used to apply the load to the blade might have an influence on the resulting plastic deformation of the blade. Therefore, several different methods of applying a load to the blade were devised and simulated to determine if any methods might provide similar results to the rotating baseline case. For brevity, the details of each concept are not discussed; rather each will be described briefly, with a summary of all the results compiled into one plot at the end.

The second concept applies a constraint at the tip of the fan blade that prevents large transverse displacements at the tip, but does not apply a radial force. Two cables were attached at an angle to each other to each of the previous attachment points as shown in Figure 11 as concept 2.

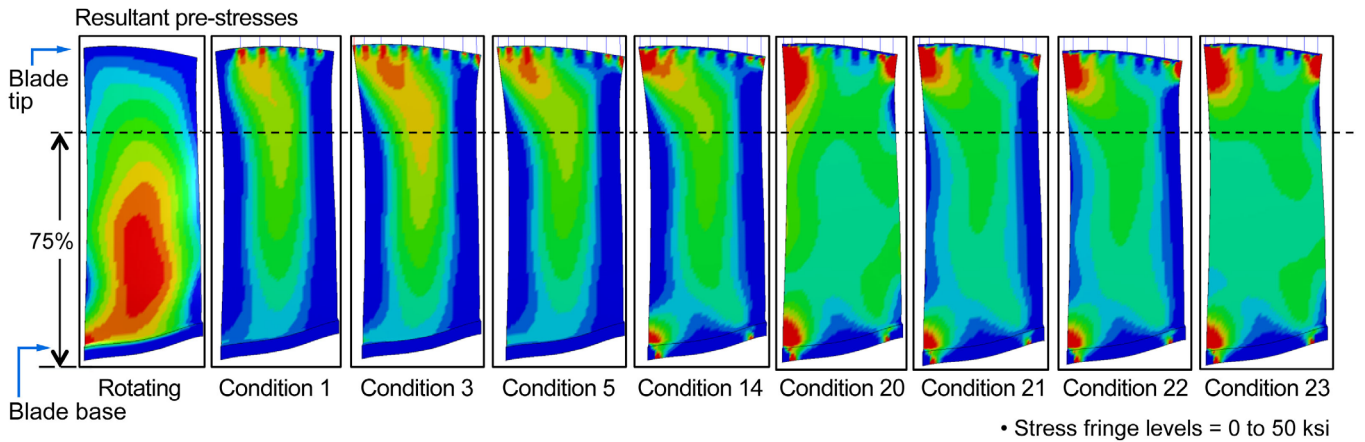


Figure 9.—Examples of various conditions analyzed in attempting to match z-direction pre-stress and angle of attack to the rotating baseline case. Dashed line at 75 percent of the height indicates impact zone. Condition 23 represents the best match of pre-stress level and angle of attack.

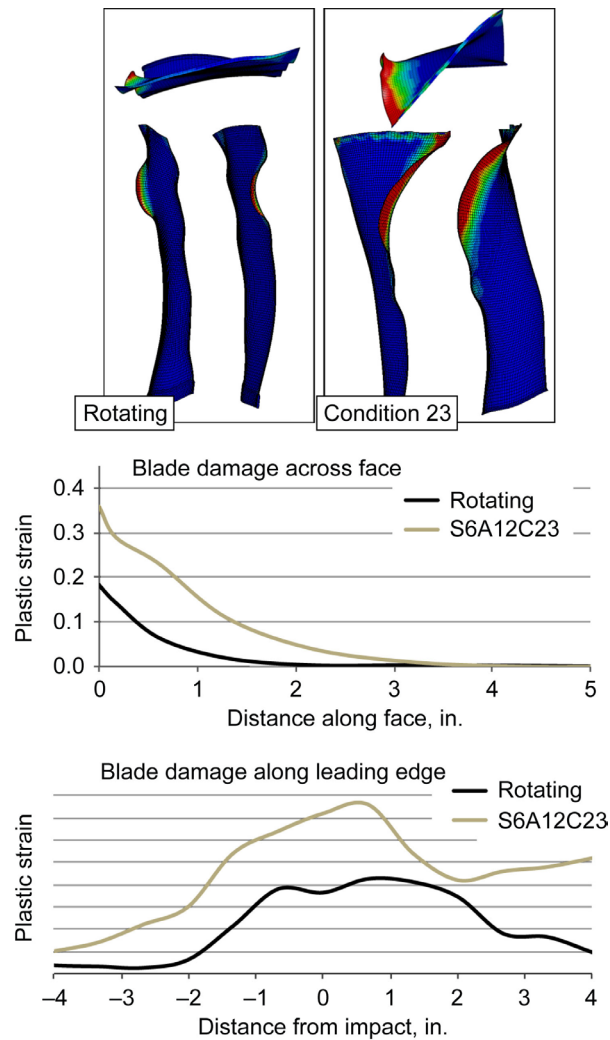


Figure 10.—Comparison of damage between rotating and non-rotating concept 1.

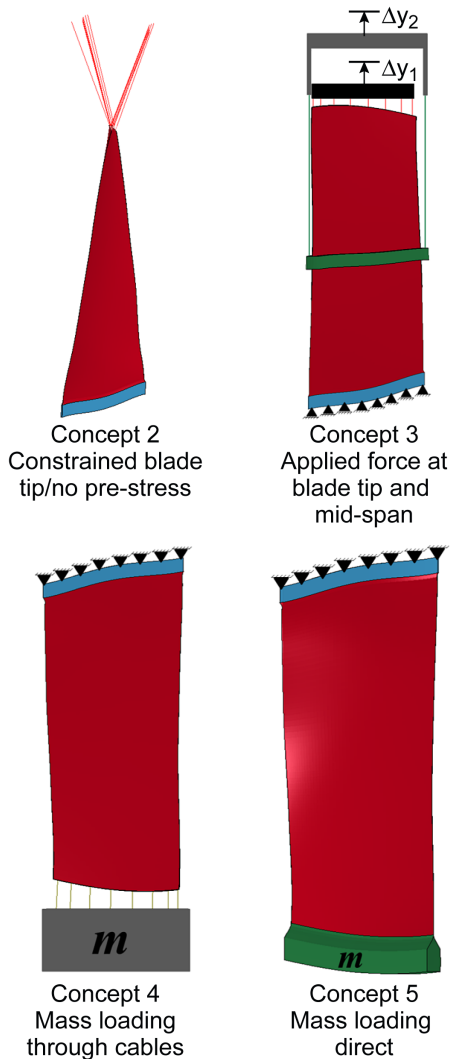


Figure 11.—Schematic of loading concepts 2 to 5.

The next simulation, concept 3, was to apply a radial force at two distinct radial locations. One location was at the blade tip as in concept 1. The second was below the impact zone, where a fixture was attached to the blade, and a second set of cables pulled on the fixture. Since a rotating blade has a radially variable pre-stress, it was thought matching the pre-stress at just one location may not have been sufficient. With two load application points, the stress could be matched at the impact zone, and near the base of the blade. A sketch of this concept is shown in Figure 11 as concept 3.

Concept 4 was similar to concept 1 with the exception that instead of a prescribed stretch applied to the cables, the free end of the cables was attached to a large mass, and a body force (i.e., gravity) was applied to provide the radial force, see Figure 11. The difference between these two methods is that the force in concept 4 is constant and the direction of application of the force can change slightly since the mass is not fixed in space. In concept 1, the free end of the cables are

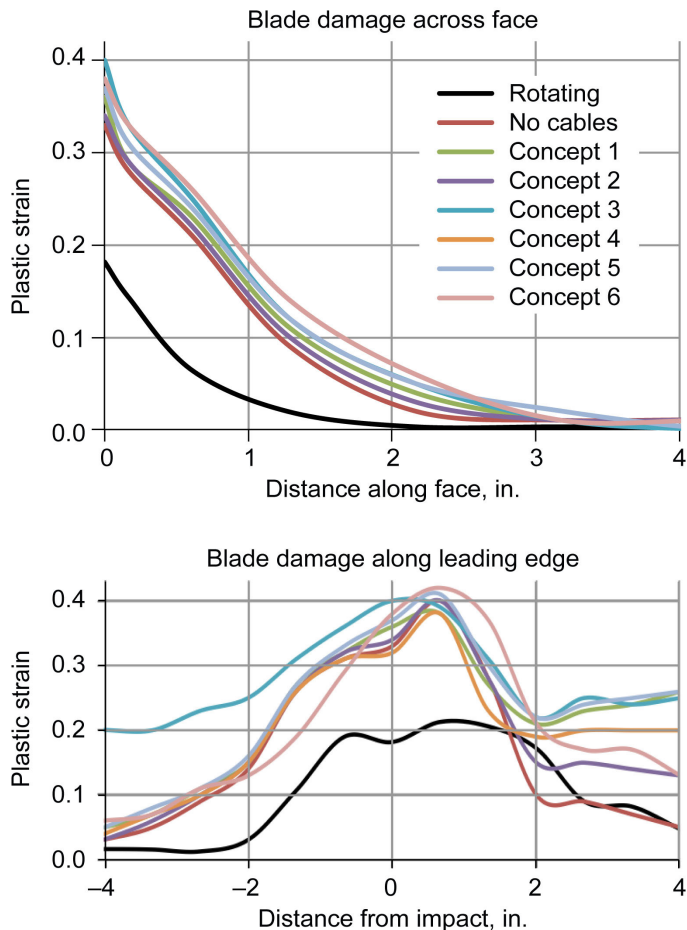


Figure 12.—Plastic strain in the fan blade across the face and along the leading edge for the rotating and various non-rotating test concepts.

fixed after applying the pre-stress, such that as the blade tip moves, the force applied changes as the cables elongate or shrink.

Concept 5 is similar to concept 4 but with the mass fixed directly to the blade tip rather than through cables. The body force due to gravity in this case is still constant, but the large inertia of the mass is tied directly to the blade tip as shown in Figure 11.

Lastly, concept 6 will be discussed shortly, but had very similar damage results to the other non-rotating cases.

The results of all the non-rotating experimental concepts are summarized in Figure 12. The rotating case is included to show the “correct” result (the goal). Additionally, a non-rotating case with no cables (i.e., no pre-stress) is included in the results for comparison. The results clearly show that none of the non-rotating cases result in blade damage that matches the rotating case sufficiently well. The other interesting result is that all of the non-rotating cases resulted in similar damage in terms of maximum plastic strain and all had very similar shapes, with only concept 3 having any significant deviation from the rest. In summary, the blade damage in the non-rotating cases near the impact is not highly dependent on the

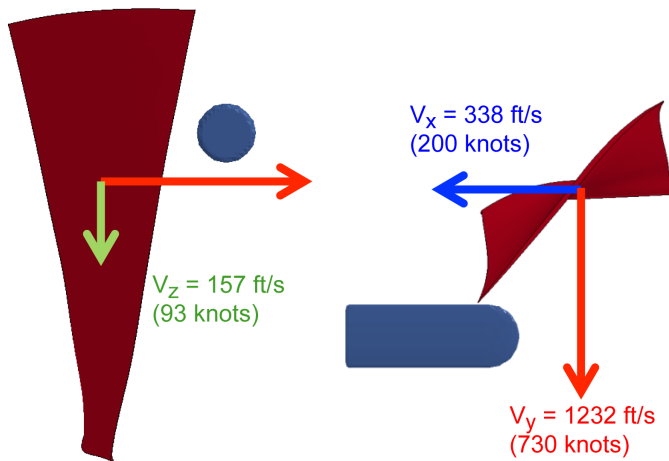


Figure 13.—Velocity vectors for blade shooting at a stationary bird.

pre-stress boundary condition, but does differ significantly from the rotating blade case.

We propose two hypotheses to explain why the rotating blade deforms less than the non-rotating blade: either the impact dynamics are different, meaning the force profile is not the same, or there's a dynamic phenomenon in the rotating case that is not included in the non-rotating case. In regards to the impact dynamics being different, one can consider the simple case of two rigid bodies colliding together. The impact force between the two bodies does not depend on the individual velocities of the bodies, rather it depends on the relative velocity of the two bodies. Extending that concept to this problem, it was assumed the impact forces in the non-rotating case would be the same as the rotating case as long as the relative velocity between the bird and blade were the same. After observing the result shown in Figure 12, it was thought perhaps that assumption was incorrect, and maybe it does matter if the blade is moving as well. Concept 6 was analyzed in order to determine if the damage to the blade would be different if the blade was moving and the bird was stationary. Figure 13 shows the velocity vectors applied to the blade, which are equal in magnitude, but opposite in direction to the vectors applied to the bird earlier. In this manner, concepts 6 and concept 1 are the same except that 6 has the blade impacting a stationary bird, and concept 1 has the bird impacting a stationary blade. In fact, the results are not identical as can be seen in Figure 12, but they are very similar. The peak plastic strains differ by less than 10 percent. Therefore, it seems likely that matching the relative velocity, but shooting a bird at a stationary blade can come close to simulating the impact event in terms of the contact mechanics.

This leaves the second point above that there may be something in the overall system dynamics that is not modeled, or is not included in the non-rotating cases by virtue of the fact that the blade is not rotating. One such dynamic effect that is not included in the non-rotating models is gyroscopics (Ref. 18). When a rigid body rotates, a moment is required to counteract the gyroscopic effects generated whenever there is

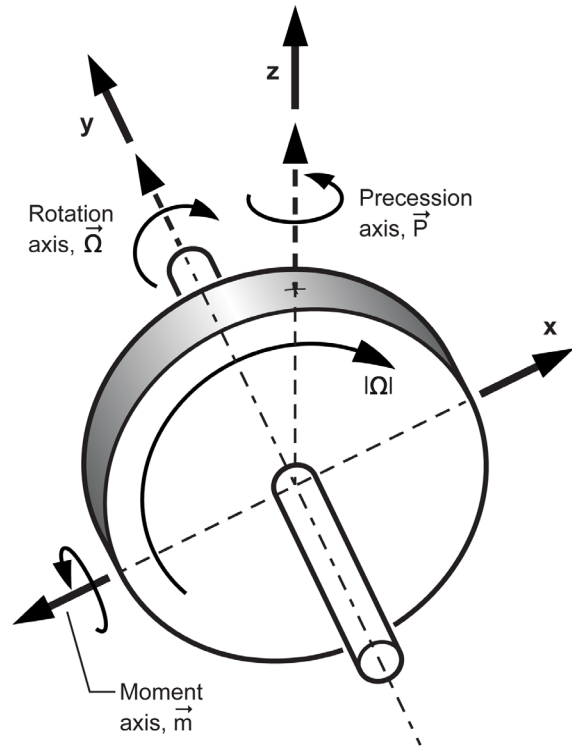


Figure 14.—Illustration of gyroscopic effect in a spinning disk.

a precession of the rotating rigid body about any axis other than its principal rotation axis. For example, consider a spinning car tire and wheel. If the car is moving forward, the tire's rotation vector points to the left. In order to turn the car to the right, the tire must precess, or turn, clockwise looking down from the top. When this happens, there is a moment required to keep the tire vertical with respect to the ground that is orthogonal to the precession direction. Figure 14 illustrates this concept, and the moment can be calculated according to Equation (1).

$$\vec{M} = \vec{p} \times I\vec{\Omega} \quad (1)$$

Where \vec{M} is the moment vector, I is the mass moment of inertia of the spinning body about its rotation axis, $\vec{\Omega}$ is the spin vector, and \vec{p} is the precession vector (Ref. 18).

Now, consider the spinning fan blade depicted in Figure 15. The blade spins about the y, y' -axis at the geometric center of the fan assembly, shown by the vector p . At time zero, the blade is located on the coordinate axis: x, y, z . At time δt , after an impact with a bird, it has rotated an angle θ to the position labeled with coordinates x', y', z' . Sometime between $t = 0$ and $t = \delta t$, a bird, travelling in the negative x -direction, struck the leading edge of the fan blade, and applied a force given here by F . Looking at a differential element of mass, δm , the force applied by the bird created a moment about the z -axis of the blade.

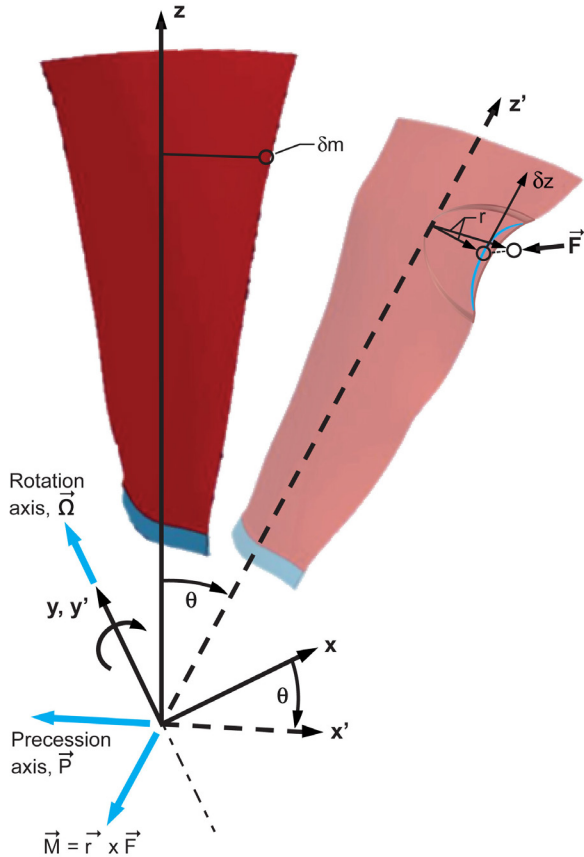


Figure 15.—Illustration of the gyroscopic effect as it applies to the bird impact problem.

If that differential mass element were not part of a blade, but were simply a point mass, it would have precessed about the local x -axis according to the gyroscopic effect described previously. That precession would have resulted in a differential displacement in the positive z -direction, δz . However, since the differential mass is connected to the adjacent differential mass, and so on, it is partially constrained in the z -direction. Therefore, the blade would behave as if it were stiffer than it really is. The authors believe this may be an explanation for the reduced deformation observed in the rotating case when compared to all of the non-rotating cases, but more work is needed to verify this.

To illustrate this effect in the present problem, a case was run with the pre-stress and strain calculated for a rotating blade as the initial condition for a non-rotating blade impact. Therefore, at $t = 0$, the pre-stress and pre-strain in the blade are identical to the rotating case, but the dynamics when the bird impacts are identical to the non-rotating case. To simulate rotation loads in the non-rotating case after $t = 0$, a body force is applied to the blade equal to the acceleration in the rotating case. In other words, the pre-stress and strain and the body forces in the non-rotating case are identical to the rotating case, but the blade is not rotating, so gyroscopic effects are not included. Figure 16 shows a progression in time of z -direction stress in the rotating and non-rotating blade as the bird

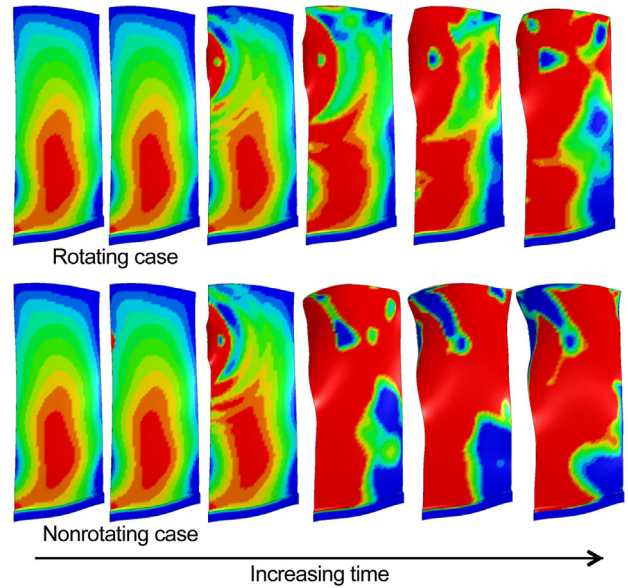


Figure 16.—Z-stress in the rotating blade and the non-rotating blade with body force during the impact event.

impacts. Clearly, the stress before the impact is the same in both cases, but as the impact event occurs, the stress field develops somewhat differently. Additionally, Figure 17 presents the plastic strain in the two cases after the impact. One can see that the resulting damage to the blade is quite different.

The above case demonstrates that matching the pre-stress condition between the rotating and non-rotating cases is not sufficient to simulate the impact event in a non-rotating test. The final case to be discussed was analyzed to determine if the effects of the rotating blade could be simulated without spinning an entire fan assembly. In this case, the blade rotates about its center of gravity at the same rotational velocity as in the rotating case, 500 rad/sec. Since the radius from the center of rotation to the point of impact is less than in the initial rotating case, the bird's transverse velocity is adjusted to maintain the same impact velocity. Figure 18 gives a schematic of the geometry. Figure 19 shows the results of this final concept. Qualitatively, the damage looks very similar between the two cases as seen in the plastic strain contour plots at the top of the figure. Quantitatively, they agree very well also, with the maximum plastic strain within 7 percent, and the shape of the strain profiles along both the leading edge and across the face matching well.

Keeping in mind the goal of this work is to identify an experimental technique that can be used to simplify testing of a single blade while simulating the results of a full rotational test, this method may not be viable. It would be less difficult to rotate a single blade about its center of gravity than to rotate a full fan, but the timing of shooting a bird to hit the blade at just the right time and place would be more difficult.

Therefore, it may or may not be a realistic test method, but the results are interesting, and further support the notion that the rotating effects are more important than the pre-stress in the blade.

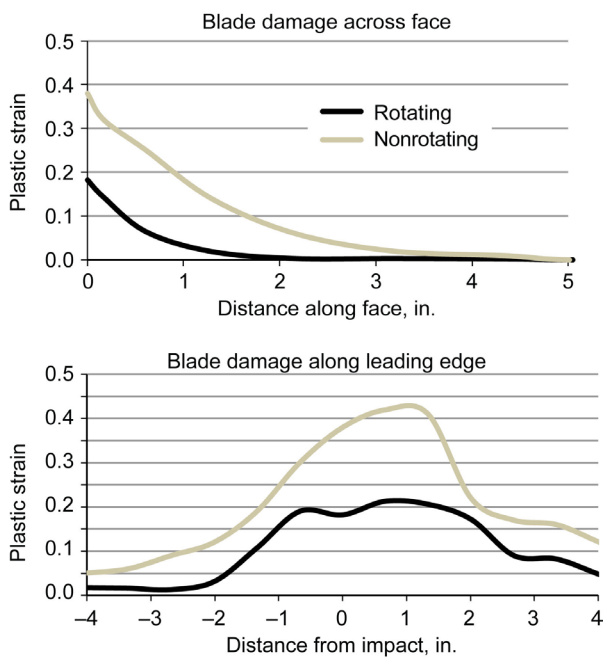
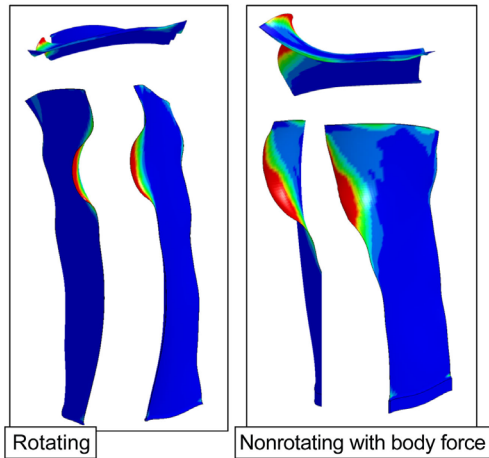


Figure 17.—Damage comparison for rotating blade and non-rotating blade with body force.

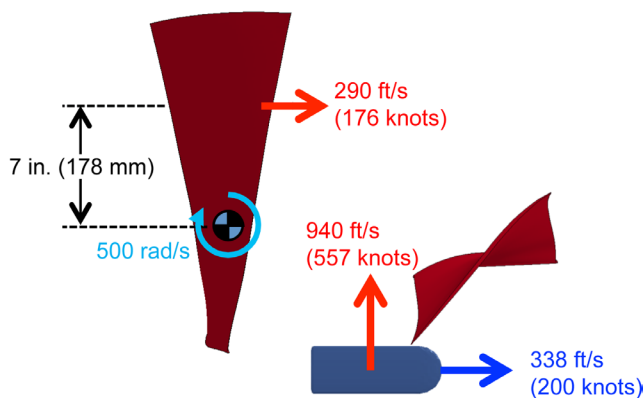


Figure 18.—Schematic of blade rotating about its own CG.

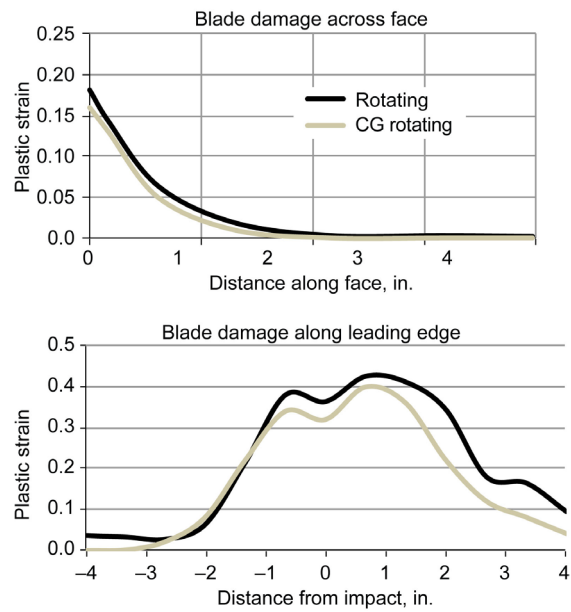
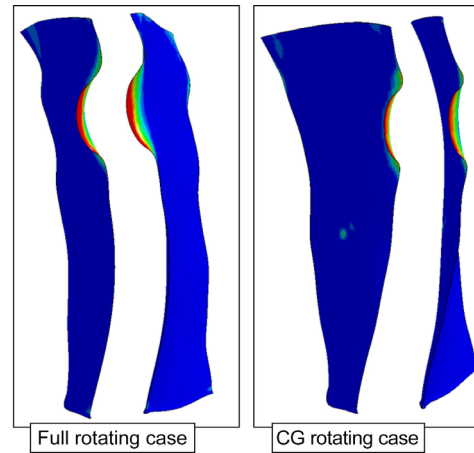


Figure 19.—Damage comparison for rotating blade and blade rotating about its CG.

Summary

Due to the high cost and complexity of impacting a rotating aero engine fan assembly with a bird, or simulated bird, in a controlled test environment, there is interest in developing a test method for impacting a non-rotating, single fan blade that reproduces similar damage results to a rotating test. The motivation for this type of simple test for fan blades is for research and development in materials for fan blades. Because current test methods involving rotating a fan or several blades of a fan are very expensive, material developers cannot create many samples of new materials and test them for screening purposes. The desire is to develop a simple, cost-effective test that can closely resemble to rotating test for screening purposes such that many different candidate materials can be tested and the promising materials can go on for further testing using more accurate and traditional methods.

Using LS DYNA to analytically simulate impact events, several non-rotating and rotating bird impact events were analyzed to determine the possibility of firing a simulated bird at a non-rotating blade to get similar results to a rotating impact with the same bird model. At the outset, it was anticipated that the difficulty in obtaining good agreement between rotating and non-rotating blade damage would be in matching the pre-stress condition of the blade. The stress field in a rotating blade varies radially, and no method for duplicating a radial variation equivalent to the rotating case could be conceived. There was hope, however, that matching the stress condition in the blade at the impact zone may be sufficient because the damage was observed to be mostly local near the impact. For that reason, the early effort was focused on techniques to load the blade in a manner that would match the stress conditions in the rotating blade at the point of impact.

The techniques to generate a pre-stress in the blade were variations of two basic ideas: applying a force through cables attached to the blade tip and applying force through mass attached in some way to the blade tip. Various degrees of success were attained in matching the pre-stress conditions at the impact point. However, it was found that no matter how the pre-stress was generated, the blade damage was similar, and was always more than the rotating case.

With that un-anticipated result, suspicions arose that some aspect of the blade rotation was acting to stiffen the blade in the rotating case, resulting in less damage. At that point, two additional analyses were conducted. The first was a non-rotating blade that had the same pre-stress and body forces as the rotating blade without rotation. This condition is possible to simulate numerically, but would be difficult or impossible to recreate experimentally. However, the results verified that, in fact, matching the pre-stress is not sufficient to guarantee similar damage. The second additional case had a rotating blade spinning about its center of gravity impacted by a bird model shot with the same relative velocity as the full rotating case. The results of this analysis indicated that rotating effects are significant, and likely overshadow the pre-stress effects in stiffening the blade.

Future work includes more analysis to verify these findings, as well as some experimentation to validate the models and compare findings.

References

- Blackwell, B.F., Devault, T.L., and Fernandez-Juricic, E., 2009, "Wildlife Collisions with Aircraft: A Missing Component of Land-use Planning for Airports," *Landscape and Urban Planning*, 93, pp. 1-9.
- "Bird Ingestion." 14 FAR 33.E.33.76, 2007.
- Vasko, T.J., 2000, "Fan Blade Bird-Strike Analysis and Design," 6th International LS-DYNA User's Conference, Dearborn, MI, 2000.
- Castelletti, L.L., Anghileri, M., 2008, "Birdstrike onto Structures in Rotational Motion," ICAS 2008-9.4.4, *Proc. 26th Congress of the International Council of the Aeronautical Sciences*, Anchorage, AK, pp. 1-11.
- McCallum, S.C., and Constantinou, C., 2005, "The Influence of Bird-Shape in Bird-Strike Analysis," Paper Number 2C-77, *Proc. 5th European LS_DYNA Conference*, Birmingham, England.
- Huerta-Ortecho, C.A., 2006, "Robust Bird-Strike Modeling Using LS_DYNA," UMI# 1435268, Master Thesis, University of Puerto Rico, Mayaguez.
- Tho, C., and Smith, M.R., 2008, "Accurate Bird Strike Simulation Methodology for BA609 Tiltrotor," *Proc. 64th American Helicopter Society International Annual Forum 2008*, Curran Associates, Inc., Alexandria, VA, 3, pp. 2156-2167.
- Nizampatnam, L.S., 2007, "Models and Methods for Bird Strike Load Predictions," Ph.D. Dissertation, Wichita State University, Wichita, KS.
- Mao, R.H., Meguid, S.A., and Ng, T.Y., 2007, "Finite Element Modeling of a Bird Striking an Engine Fan Blade," *Journal of Aircraft*, 44(2), pp. 583-596.
- Miyachi, T., Okumura, H., and Ohtake, K., 1991, "An Analysis of the Effect of Centrifugal Force on the Impact Resistance of Composite Fan Blades for Turbo-Fan Engines," *Proc. Society of Automotive Engineers*, 246, pp. 619-626.
- Schutte, W., 1990, "Blade Behavior During Birdstrike," *Proc. 5th International Conference on Science and Engineering on Supercomputers*, pp. 145-157.
- Shioya, T., and Stronge, W.J., 1985, "Impact Bending of a Rotating, Rigid-Plastic Fan Blade," *Journal of Propulsion and Power*, 1(5), pp. 375-380.
- LS DYNA KeyWord User's Manual Version 971, Livermore Software Technology Corporation, Livermore, CA, 2006.
- Carney, K.S., Pereira, J.M., Revilock, D.M., and Matheny, P., 2009, "Jet Engine Fan Blade Containment Using an Alternate Gempetry," *International Journal of Impact Engineering*, 36, pp. 720-728.
- Meguid, S.A., Mao, R.H., and Ng, T.Y., 2008, "FE Analysis of Geometry Effects of an Artificial Bird Striking an Aeroengine Fan Blade," *International Journal of Impact Engineering*, 35, pp. 487-498.
- Olivares, G., Tufano, M., Dohle, N., Pereira, J., and Revilock, D.M., 2012, "Development and Validation of a Gelatin Bird Substitute," *Proceedings of the Aerospace Structural Impact Dynamics International Conference 2012*, Wichita, KS, Nov. 6-9, 2012.
- LS DYNA Aerospace Working Group, "Test Case 5: Bird Strike on Rigid Plate," awg.lstc.com.
- Meriam, J.L., and Kraige, L.G., 1992, *Engineering Mechanics*, John Wiley & Sons, New York, NY, Chap. 7, pp. 570-573.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-08-2013		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Jet Engine Bird Ingestion Simulations: Comparison of Rotating to Non-Rotating Fan Blades			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Howard, Samuel, A.; Hammer, Jeremiah, T.; Carney, Kelly, S.; Pereira, J., Michael			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 473452.05.06.02.02		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-18629-1		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2013-217904		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 37 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Bird strike events in commercial airliners are a fairly common occurrence. According to data collected by the US Department of Agriculture, over 80,000 bird strikes were reported in the period 1990 to 2007 in the US alone. As a result, bird ingestion is an important factor in aero engine design and FAA certification. When it comes to bird impacts on engine fan blades, the FAA requires full-scale bird ingestion tests on an engine running at full speed to pass certification requirements. These rotating tests are complex and very expensive. To reduce development costs associated with new materials for fan blades, it is desirable to develop more cost effective testing procedures than full-scale rotating engine tests for material evaluation. An impact test on a non-rotating single blade that captures most of the salient physics of the rotating test would go a long way towards enabling large numbers of evaluative material screening tests. NASA Glenn Research Center has been working to identify a static blade test procedure that would be effective at reproducing similar results as seen in rotating tests. The current effort compares analytical simulations of a bird strike on various non-rotating blades to a bird strike simulation on a rotating blade as a baseline case. Several different concepts for simulating the rotating loads on a non-rotating blade were analyzed with little success in duplicating the deformation results seen in the rotating case. The rotating blade behaves as if it were stiffer than the non-rotating blade resulting in less plastic deformation from a given bird impact. The key factor limiting the success of the non-rotating blade simulations is thought to be the effect of gyroscopics. Prior to this effort, it was anticipated the difficulty would be in matching the pre-stress in the blade due to centrifugal forces. Additional work is needed to verify this assertion, and to determine if a static test procedure can simulate the gyroscopic effects in a suitable manner. This paper describes the various non-rotating concepts analyzed, and demonstrates the effect believed to be gyroscopic in nature on the results.					
15. SUBJECT TERMS Bird strike; Impact; Fan blades					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	20	19b. TELEPHONE NUMBER (include area code) 443-757-5802

