Large Air Transport Jet Engine Design Considerations for Large and for Flocking Bird Encounters

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Introduction

The history, efforts, and accomplishments of everyone involved in understanding and mitigating the threat of birds to aircraft came under intense public scrutiny when US Airway's Flight 1549 splashed down in the Hudson River on January 15, 2009.

Largely absent from the recent public discussion about bird threats is the time, labor, and resources that industry invests in continuously learning, developing, and incorporating features into aircraft designs to mitigate the consequences of bird strikes. Pratt & Whitney, as a designer and manufacturer of jet engines for a variety of aircraft, including large commercial transport aircraft, is an integral part of many of these efforts.

This paper will present a synopsis of recent bird regulatory improvements which govern all jet engine designs presented for certification within the United States. This is followed by a high level description of some of the processes employed by Pratt & Whitney to balance bird strike damage tolerance with other critical engine design criteria, and the importance of bird strike reports in assisting with design improvements.

Regulatory Background

The hazard that birds can present to aircraft is not constrained by geopolitical borders, and is a recognized issue around the world. Significant improvements to the bird ingestion certification standards have been made by regulatory agencies from the European Union, Australia, United States and Canada, among others. The modern bird ingestion regulation standards reflect extensive research, analysis and collaborative effort on an international scale, with the intended benefit of harmonious regulation between agencies.

Within the United States, formalized industry efforts to mitigate the effect of birds on aircraft engines date back to 1965. In response to an Eastern Airlines Electra accident in 1960 at Logan International Airport due to bird ingestion, the Federal Aviation Administration issued Advisory Circular 33-1 “Turbine Engine Foreign Object Ingestion and Rotor Blade Containment Type Certification Procedures”. This initial effort provided guidance for complying with Federal Aviation Regulation §33.13 and §33.19. These regulations stipulated that the engine design and construction must minimize the development of an unsafe condition. At the time, AC 33-1 addressed the potential unsafe conditions caused by the ingestion of foreign objects by the engine, and birds fell into this broad category of foreign objects. As the understanding of the issues specific to birds improved, AC 33-1 went through two revisions that updated the bird size and quantity to better match the certification requirements with service experience.

In 1974, the certification requirement for Foreign Object Ingestion (which includes birds) was added to Federal Aviation Regulation (FAR) §33.77 with updates to the bird criteria previously defined in the Advisor Circular.

Then in 1975, a DC10 encountered a flock of sea gulls during take-off roll at JFK International Airport and suffered a power loss and fire to one engine after ingesting birds.[1] The aborted takeoff and subsequent fire resulted in the loss of the aircraft. The existing engine certification requirements did not specifically address the threat that these size birds, or their growing population, presented to airplane operational safety.

Subsequent to this event, the FAA conducted three separate studies with the assistance of Pratt & Whitney and other manufacturers. The results from these lengthy studies was utilized to develop FAR §33.76, which was published in 2000. This new rule was based on ingestion events recorded over the prior several decades, making the regulations more consistent with the numbers and sizes of birds experienced in service. The result was two requirements; 1) to demonstrate continued operation after ingestion of medium flocking birds (2.5 lbs.), such as Herring gulls, and 2) elevated the bird weight standard for safe shutdown after ingestion of a large bird (i.e., Canada goose) from 4 lbs. maximum for all size engines to 4 - 8 lbs., depending on engine size.

Large flocking birds (>2.5 lbs.) were further studied subsequent to the adoption of FAR §33.76 in response to increasing populations of Canada and Snow geese. This resulted in an update to FAR §33.76 in 2007, which now includes a requirement for continued engine operation after ingestion of a large flocking bird (4 to 5.5 lbs., depending on engine size). This update to the FAA large flocking bird requirements was developed in an international cooperative effort that established harmonized regulations with the European (Joint Aviation Authority / European Aviation Safety Agency) authorities.

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[1] NTSB Report DCA76AZ010

These federal regulations are uniformly applied to every manufacturer of aircraft jet engines certified in the United States, and must be met or exceeded to receive FAA Type Certification for a specific engine design. The regulations are also crafted to address passenger and crew safety during bird encounters. This is done by demonstrating a safe engine shutdown from the expected ingestion of the largest birds. In addition, it must be shown that after the ingestion of medium and large flocking birds the engine will continue providing sufficient power to perform a flight diversion or air turnback and safe landing.[2]

Pratt & Whitney's Efforts to Mitigate the Consequences of Bird Strikes

Industry Involvement:

From the beginning of an engine design, the regulatory requirements, including both the FAA and the European standards, are carefully reviewed to determine how specific bird ingestion criteria apply to the engine being proposed. The required bird sizes and quantities are fundamentally driven by the engine size, essentially the diameter of the inlet to the engine.

Pratt & Whitney not only designs and manufactures aircraft engines, but also closely follows the performance of our engines throughout their service life, including their reaction to bird ingestions. As such, Pratt & Whitney has gathered data on thousands of bird strike events. This field service information is critical to Pratt & Whitney, and is shared with industry and regulatory agencies, primarily through industry committees, to assure that the overall safety objectives related to bird ingestion continue to be met. The field service information is also a vital tool in Pratt & Whitney's engine design process.

Engine Development:

The ability to withstand bird strikes is considered in concert with a multitude of other critical factors during the design of the engine. In addition to meeting regulatory considerations, the engine must be economically viable for initial purchase and recurring maintenance, and must also meet aggressive weight and efficiency targets to support the intended aircraft mission.

Within Pratt & Whitney, as an engine designer, the process that leads to demonstrating an engine's ability to tolerate bird strikes is an extensive, closed loop process (Figure 1) that includes assessing service events of bird strikes reported to our Flight Safety Office. The database of bird strike events is a critical element in the engine design process, providing for data based analysis of engine response to various bird sizes, flight regime, strike locations, and many other variables. These strike reports are also the basis for our contribution to the regulatory process.

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[2] US Department of Transportation Docket No. FAA-1998-4815

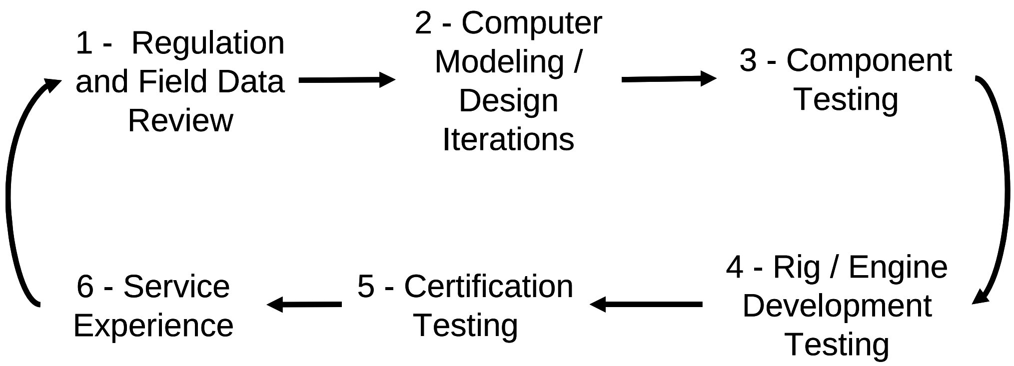

Figure 1 Closed Loop Design Process for Bird Strike Mitigation

The bird strike field reports are continuously evaluated as part of the design process. The lessons learned from this review are combined with the legacy information built into our engineering standard workscope and used to highlight potential improvements to an engine's bird strike tolerance.

For very large birds (up to 8 lbs.), the design consideration is to protect the ability to safely shut down the engine. For flocking birds (up to 5.5 lbs.), the engine must continue to make thrust for continued flight and for executing a diversion and safe landing.

Birds and Fan Blades

When considering ingestion of birds, the forward most stage of the engine, the fan, presents unique design challenges. The location of the fan blades in the forward stages of a modern commercial high by-pass turbofan engine is shown in Figure 2. Meeting these design challenges can have significant downstream effects on both the engine and the aircraft.

In a modern commercial jet engine, up to 80% of the engine's thrust is produced by the fan stage, and damaged fan blades can affect the ability of the fan to produce thrust. Thus, in the event of bird ingestion, the engine's ability to continue producing thrust depends on the number of affected fan blades and the amount of permanent damage to the fan after processing a bird, in addition to continued engine core function.

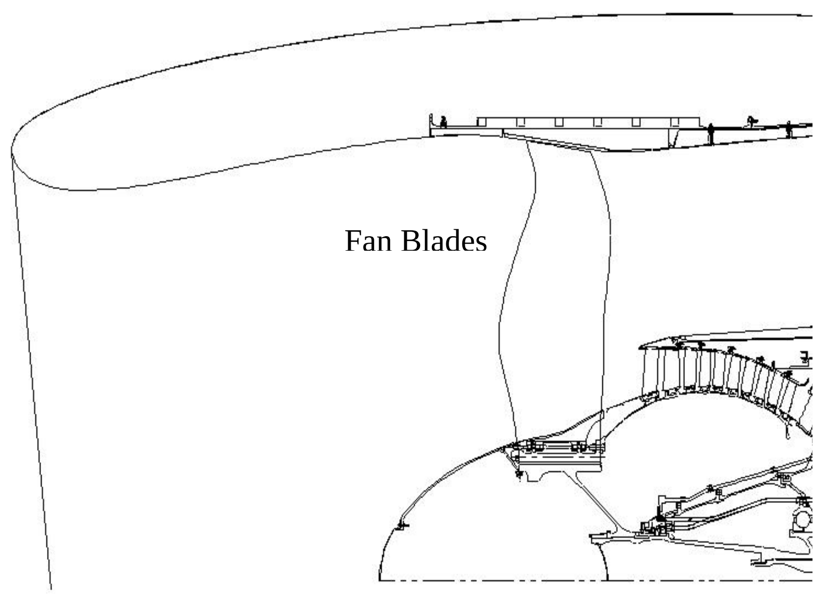

Figure 2 Modern Commercial Turbofan Jet Engine Inlet and Fan Stage

Damage to one or more fan blades can also cause the engine to vibrate due to either aerodynamic or mechanical forces. Aerodynamic imbalance can result from non-uniform air flow characteristics induced by damaged fan blades. Vibration could also be created if a significant amount blade material were to break off, causing a mechanical (weight) imbalance. This concern extends to potential malfunctions of unrelated engine and aircraft systems due to excessive vibration.

In addition to their intended function of pumping air, fan blades are equally adept at pumping soft materials such as avian bodies. When encountering a bird, the fan blades slice into it and accelerate the body slice up to the fan rotational speed, which can be in excess of 1,400 feet per second at the blade tip during the takeoff or climb portion of a flight. The combined speed of the blade and the airplane can result in an impact velocity upwards of 850 knots. This imposes a significant impact load on the fan blade, an impact force which is roughly equivalent to dropping a men's bowling ball onto the fan blade from about 10 feet. Impacts of this magnitude from a bird strike generally result in what is referred to as "soft body" damage (Figure 3), characterized as a smooth cusp in the leading edge of the fan blade. The fan rotor speed is by far the largest contributor to the impact energy the blades must absorb during a bird strike. This is reflected in the bird strike data, which shows that most damage is incurred from strikes during takeoff and climb when the engine is at high power (i.e. high rotor speed) compared to approach and landing when rotor speeds are lower[3].

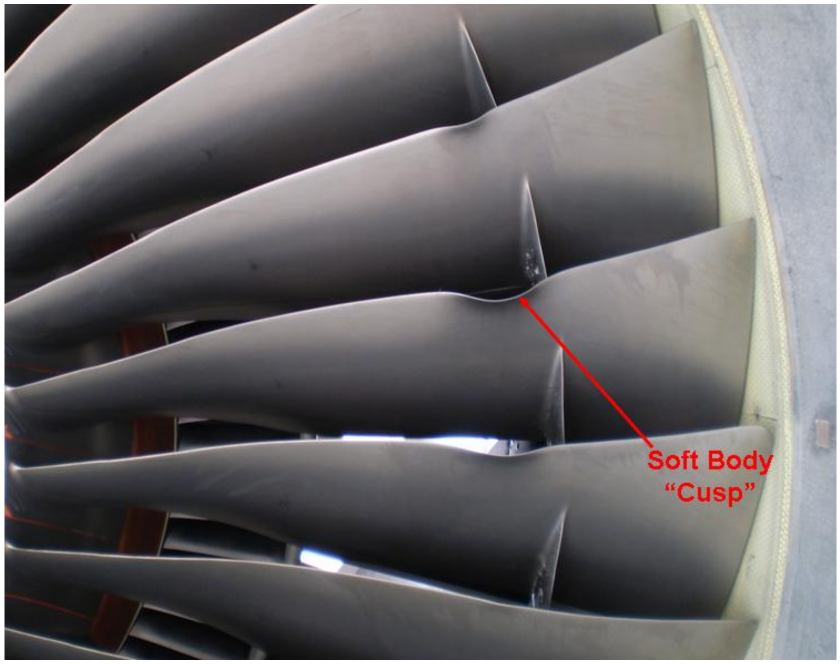

Figure 3 Typical fan blade "soft body" cusps due to bird strike

With small birds (i.e. European starlings), the fan blade damage is usually limited, affecting one or two blades. As the bird size increases, there is more soft material being "pumped" by the fan blade, increasing the load and often resulting in more deformation, or damage. At large levels of deformation, cracks may form, and some of these cracks may result in the loss of pieces of the blade.

The orientation of a smaller bird upon impact with a blade can also influence the amount of damage it causes. The bird can impact its full mass upon a single blade or it can spread out over two or more blades. For larger birds, there is a physical limit to the size of the "bite" taken by an individual fan blade; therefore, soft body damage can appear on more than one blade. This effect can mask the true size of the bird when based purely on damage assessments, making field data on the bird identification from bird feather / tissue recovery important to correlating the fan blade damage findings.

The seemingly straightforward answer to dealing with the issue of fan blade deformation is to add thickness to the blade to make it more robust. However, it will be seen that this solution is not without its drawbacks.

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[3] Dolbeer, R.A., paper "Bird damage to turbofan and turbojet engines in relation to phase of flight – why speed matters", Bird Strike Committee-USA/Canada, Kingston, Ontario Canada, 10-13 Sept 2007

Other Considerations

Fan blades are an integral part of modern turbofan engines. Beyond providing the lion's share of engine thrust, the design of the fan blade can also have an affect on the aircraft. These affects, some of which are discussed below, must be carefully considered during the fan blade design.

Bird strikes are one of the many challenges to the engine fan stage that must be addressed in an engine design, carefully balanced with efficiency, weight, aerodynamic instabilities, hard body ingestion, ice accretion, erosion (both sand and, oddly enough, rain), vibration, and fatigue. This design balance may not be obvious outside of the engine manufacturing world. Looking at fan weight, for example, any increase in the thickness of the fan blade results in a heavier airfoil; however, this results in heavier containment cases. Additional material must also be applied to the fan disk to be able to hold onto these heavier fan blades while they rotate. This then requires stronger bearings and support structures, thicker shafts, and finally larger engine mounts to manage all this extra weight. This additional weight may significantly affect the performance of the aircraft by reducing fuel burn efficiency (increasing jet fuel usage) while simultaneously reducing the payload, and ultimately contributing to increased environmental emissions.

A Pratt & Whitney internal study showed that adding a tiny amount of material to the fan blade, equivalent to the thickness of two sheets of copy paper, could result in over 100 lbs of extra engine weight due to required structural compensation. Furthermore, the airframer might need to bolster the engine pylon structure to handle hard landings, which then could impose a significant extra load on the pylon. After this comes reinforcement of the wing structure to support the heavier engine and pylon load. The increased aircraft weight then requires more fuel to meet its intended mission. In an interesting twist, the aircraft then needs to carry extra fuel to be able carry the weight of the extra fuel needed for the extra aircraft weight, to the detriment of the aircraft's ability to meet its intended mission.

Once the certification criteria are established, Pratt & Whitney starts the process of designing the fan blade, beginning with the aforementioned analysis of collected bird strike data from the field and historical in-house testing. This information is translated into a structural model where the critical bird attributes (size, velocity, and fan rotation speed) are modeled. With these models, various fan blade design concepts can be studied in virtual space using computational tools. Again, it needs to be pointed out that the fan blade is being designed to simultaneously meet many other important criteria (vibration tuning, efficiency, weight, durability, cost, etc.) needed to meet a host of engine requirements.

Pratt & Whitney's next step is to perform component testing in a laboratory using jelly balls fired by air cannons. Jelly balls are oblong shaped bird substitutes which can be readily molded, have less variation in mass properties than real birds, and are good simulations of soft body impacts. Preliminary design blades are fabricated and subjected to jelly ball impacts during lab component tests. During these component tests, the test blades are instrumented and high speed cameras are employed to capture data that will be used to calibrate the structural models for the specific design attributes. This testing and model calibration provides for further optimization of the design. It also provides confidence about the blade's performance following a bird strike in follow-on full-scale rig and engine testing.

If all goes well during the component testing and the blade performs as intended, the blade design is completed and then subjected to extensive full scale rig testing. Rig testing provides an economical way of testing expensive hardware in an environment where only the hardware being tested is put at risk, not a full engine. At this stage the engine design intent hardware is tested against the different bird ingestion criteria, using euthanized birds to ensure the blade performs as designed. Here, we examine the effects of the blade spacing, impact location, and rotor speed during a bird strike event.

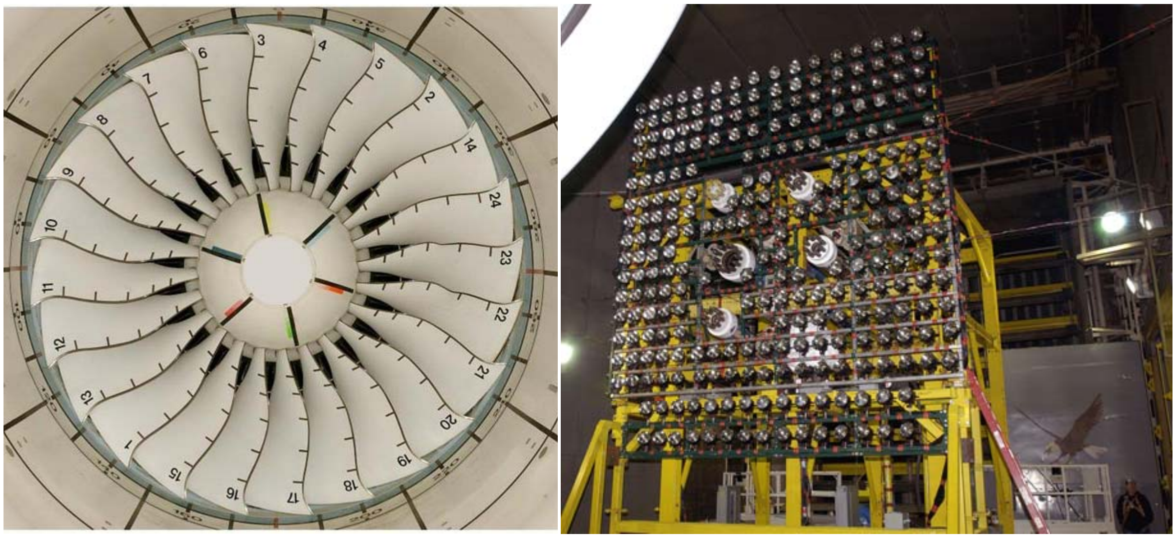
An advanced look at engine vibration and thrust response to a bird damaged fan rotor is often accomplished before the design is finalized. This information is gained by running bird damaged fan blades from the rig tests in an engine test by assembling the rig damaged hardware into a full engine. If no issues are found, preparations begin for the time consuming and costly engine bird ingestion tests.

As an example of the required full-scale engine tests, a recently certified engine now in service on a wide body transport category aircraft is presented. This particular engine has an inlet diameter of over 9 feet, which per FAA regulations requires a demonstration of the capability of ingesting four medium flocking birds (2.5 lbs.), including one into the engine core. After the ingestion, the engine continued running and met the FAA run-on requirements, including successfully maintaining over 75% takeoff thrust during the first two minutes of the 20 minute demonstration.

This engine was also required to demonstrate the ability to ingest a large flocking bird (5.5 lbs.) at 200 kts. After the strike, the engine completed the FAA mandated 20-minute run-on test, which included extensive operation at over 50% takeoff thrust. This test demonstrated the engine's ability, after a large flocking bird strike, to propel an aircraft to return to the airport and execute a safe landing.

In addition to the flocking bird engine ingestion tests, a large bird impact test was conducted per the regulations using a bird weight as defined in Table 1 of FAR §33.76. In this test, the hardware demonstrated that a strike from an 8 lbs. goose at a speed of 200 knots into an engine operating at take-off conditions did not result in any hazardous consequences that could have impacted the aircraft's ability to continue safe flight.

The full scale bird ingestion tests were run in indoor test stands using large air cannons, which were calibrated before the test using euthanized birds of the correct weight, to accelerate the birds up to the target speed. Engine components were instrumented to allow for extensive post-test engineering analysis. The engine hardware of interest (generally the fan and inlet) was painted white to reflect as much light as possible to accommodate several high speed cameras, which were operated at frame rates of up to 8,000-10,000 frames per second. Such high framing rates require extremely high light levels, which are achieved using enormous banks of lights (over 200) rated at 1000W each to illuminate the fan during the actual test. A typical full scale engine bird ingestion test arrangement is shown in Figure 4.



Engine Inlet Ready for Bird Ingestion Testing

Test Stand Inlet Light Racks and Air Cannons (looking forward from the engine inlet)

Figure 4

The knowledge and insights gained during these extensive development and certification efforts, when combined with field data, pay dividends in the form of continuous improvement in engine bird strike damage tolerance over time, contributing substantially to overall aircraft and passenger safety. Specific improvements made over the years that have improved bird ingestion tolerance include the following: increased spacing between the fan and the core of the engine to minimize the amount of bird material that can be ingested into the core of the engine, use of wide chord fan blades with greater flexibility and mass per blade, new vane retention methods to hold the airfoils in place under bird strike loading, fan blade leading edge geometry, fan spinner construction enhancements, engine bleed architecture, and Foreign Object Damage (FOD) engine control logic, to name a few such improvements.

After certification and entry into service, we look forward to the real world feedback that is provided by the field reports of bird strikes. We rely on the help of airport and airline operations personnel, wildlife biologists, and aircraft and engine maintenance staff to collect the bird debris following a strike event and to provide reports on the aircraft operation at the time of the strike event. With this information, we can further evaluate the effectiveness of the design, calibrate our tools, and build on new lessons learned for continued product improvements on existing and future designs.

Summary

As noted earlier, the collaborative efforts of the FAA, industry, wildlife biologists, and wildlife strike data collectors resulted in significant improvements to the bird ingestion regulations over the past 45 years. The current regulations better match engine bird ingestion capability requirements with field experience, and address a much broader range of bird sizes.

As an engine manufacturer, Pratt & Whitney has actively participated in various government and industry working groups addressing bird strike concerns. A collective assessment of bird strike events by these teams has contributed to the valuable improvements to the bird ingestion regulations. Pratt & Whitney will continue our active involvement in industry teams and regulatory efforts to further improve the ability of aircraft to withstand bird strikes.

Pratt & Whitney engines have also benefited from the steadily increasing capability and development of advanced computational tools for bird strike modeling. With models calibrated to field experience and knowledge gained from advanced rig and engine tests, improvements to fan blade durability and engine run-on performance in new engine designs have been realized. These same tools have led to advancements with other engine components; improvements to spinners, compressors, and engine control logic have all been made possible.

Engine design improvements and successful test outcomes are the result of many years of analysis, development, testing and continuous improvement. These successes are strongly driven by what we learn from bird strike reports from our aviation partners; wildlife managers, airport operations, airlines, government entities, fellow manufacturers, and engine shops. The support of these groups has been critical in the past, and we are highly thankful for it. Going forward, we urge everyone involved in wildlife hazard management to help us continue to advance aviation safety by diligently reporting bird strikes through the FAA Wildlife Strike Reporting system and through our engine company field representatives whenever possible.

Pratt & Whitney shares the government and industry objective of advancing aviation safety by continuing to build upon past gains in bird strike capabilities. To this end, we will continue active participation in regulatory discussions, sharing our knowledge with aviation industry working groups. We will also continue to actively contribute to the growth of the wildlife strike database through our investigation activities. We look forward to the benefit all these activities will provide in bird ingestion capability for our future engine designs.

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