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Radar to detect foreign object ingestion
by a jet engine

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ABSTRACT

Each year commercial, private and military aircraft jet engines are damaged by the ingestion of foreign objects. Annual engine repair costs for ingestion damage is in the tens of millions of dollars. Bird strikes represent the major foreign object threat to aircraft engines, although large hail and objects found on the ramp can also damage an engine. A radar based foreign object ingestion detection system (FOIDS) concept, the subject of this paper, is capable of determining when an object as small as 4 millimeters has entered a fan jet engine. Additionally, such a system is capable of determining the relative size of the object and the approximate point within the engine where the object impacts the engine. These data can be displayed in real time to the pilot. In addition, the information recorded in the data base can be used by the mechanics between major engine inspections to determine if a detailed inspection of the turbine blade roots or other hard to access engine parts is required. Long term statistical data developed by the system can also be used as a measure of the foreign object and bird ingestion problem at various airports and improve the reporting of ingestion and bird strike events above the currently estimated 20 percent reporting rate.

Keywords: radar, foreign object, jet engine, bird strike, aircraft safety, pilot aid

Introduction

Each year commercial, private and military aircraft jet engines are damaged by the ingestion of foreign objects. Annual engine repair costs for ingestion damage is in the tens of millions of dollars. Bird strikes represent the major foreign object threat to aircraft engines, although pieces of ice, large hail and objects found on the ramp can also damage an engine. Several serious crashes occurred recently because of engine damage by birds, many times during critical flight operations such as at take-off or during the final approach for landing. When a high bypass turbo-fan or turbo-jet engine ingests a large bird, the engine may be damaged to the point where it must be shut down, even though it meets Federal Aviation Administration (FAA) foreign object survival certification. Most major foreign object ingestion events involving large birds are known to the flight crew as they occur due to the detectable effects of the damage that occurs at the time of impact. Existing cockpit instrumentation such as the exhaust gas temperature, compressor shaft RPM, and shaft vibration monitoring systems all deviate from their normal operating range when an engine is damaged by a large foreign object. In addition, the pilot may, during daylight operations, see the offending bird(s) seconds before ingestion. Pilots have reported hearing the impact of the bird with the aircraft in the case of large bird strike or ingestion. The detection of ingestion events that involve small objects cannot be detected by existing engine instrumentation, but can be detected by the FOIDS.

The foreign object ingestion detection system (FOIDS) that is the subject of this paper can detect all foreign objects, even those as small as 4 millimeters, when they enter a turbo-fan or turbo-jet engine. The relative size of the object and the approximate point within the engine where the object impacts the engine can also be determined by FOIDS. These data are displayed in real time to the pilot. In addition, the information recorded in an associated resident data base can be used by the engine inspection team at any time to determine if an inspection of the turbine blade roots or other hard to access engine parts is required prior to regularly scheduled maintenance.

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FOIDS Design

The FOIDS concept is the subject of a United States Provisional Patent. Elements of the system have been tested. The system is comprised of 4 solid state Doppler radar sensors mounted on the engine nacelle at the 0, 90, 180 and 270 degree points around the engine, as shown in Figure 1. Radar mounting techniques may vary slightly to accommodate the de-icing equipment sometimes located inside the nacelle lip. The four radars are under a protective radome. Foreign objects entering the engine are detected before entry and tracked by the signal processor into the engine. It is estimated that the cost to equip an aircraft with the FOIDS would be approximately \$20,000 per engine for the sensor package and \$10,000 for the pilots display and data recording system, assuming that there are not excessive costs for system certification.

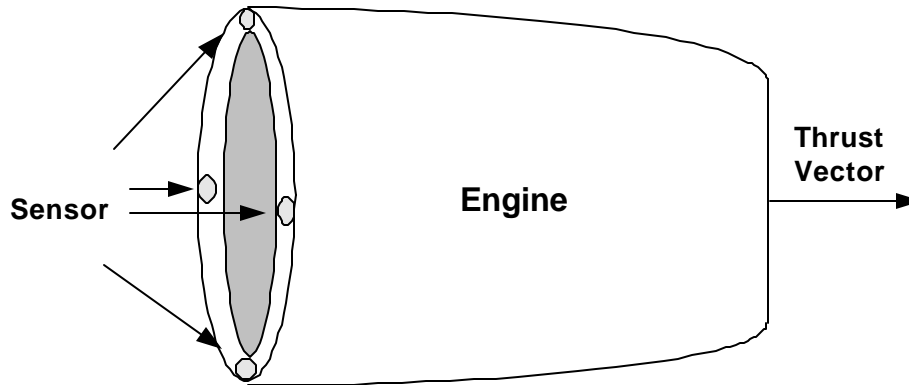


Figure 1. FOIDS sensor mounting positions on fan-jet engine.

Figure 2 shows the system diagram. The outputs from the four Doppler radars are fed into the signal processor. The velocity of the foreign object and its track are used to compute the probable point of impact within the engine. The relative size of the object is also computed. The processed data are converted into a message stream that is sent to the pilot's display. An alarm is sounded when ingestion is detected. The identification of the affected engine is provided on the pilot's display, as is the relative size of the impacting object.

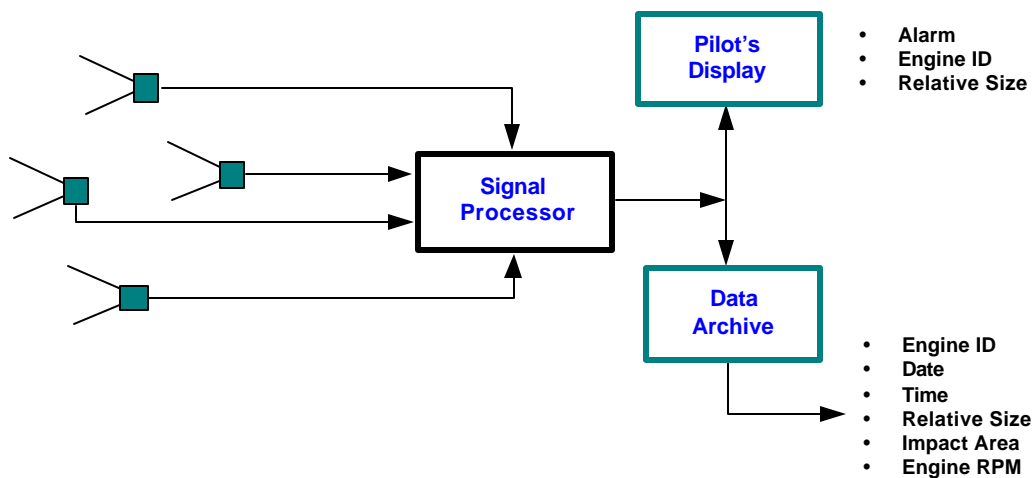


Figure 2. FOIDS top-level system diagram.

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The ingestion related data are also sent to the FOIDS data archive unit. The date and time of ingestion, the relative size of the object, and data relating to the point within the engine where the object impacted are also stored for later recall. Other data on the aircraft's primary data bus can also be captured and stored with the alarm serving as the trigger for the data collection process. These data could include the engine power settings, RPMs at impact, the location of the aircraft at the time of impact, and any other useful parameters that are normally available on the aircraft's data bus. The recorded data are stored until recalled. The data would be downloaded using a laptop computer communicating through an RS-232 interface by an engine inspector at major inspection times or between major inspections.

Justification for FOIDS

The airframe manufacturer, jet engine supplier, the airlines, the aircraft regulatory agencies, and the airport operators would each benefit from the installation of a FOIDS on every turbo-fan and turbo-jet operating both within the United States and internationally. The FOIDS also has military application even with low electromagnetic profile aircraft.

Airframe Manufacturer

The airframe manufacturers are primarily responsible for aircraft design and the incorporation of safety features capable of preventing accidents. During take-off roll when the aircraft is still below take-off velocity, the pilot can elect to abort take-off. The aircraft's speed at the point the decision is made will determine if the take-off can be aborted without damage to the aircraft. Even when a safe abort is performed, the service life of tires and brakes may be shortened. An inspection may be required before the aircraft is allowed to continue service. The FOIDS is thought to be capable of providing information to the pilot to assist in making the abort decision sooner than currently possible and the FOIDS would report an ingestion when the event was not sensed by other engine instrumentation or sensed visually, in the case of night time operations. The FOIDS confirms that an ingestion event has occurred and provides the pilot with an estimate of the relative size of the object(s), the point of impact within the engine and the number of objects that were ingested.

Statistics show that the ingestion events that cause the most damage are bird strikes and that these events are more frequent than the flying public would like to believe. The Federal Aviation Administration's Airport Safety and Operations group released a report¹ entitled *Wildlife Strikes to Civil Aircraft in The United States 1991-1997* that presents statistics on the number of bird strikes to aircraft in the United States, Puerto Rico and the U.S. Virgin Islands during the period that is covered by the report. The problem is very serious. A total of 16,477 bird strikes were reported for the eight year period. Of the total number of bird strikes that were reported, 62% occurred during the daytime hours, 24% at night and the rest at either dusk or dawn. The majority (34% of strikes) occurred when the aircraft was on approach to the airport, 19% during take-off, 16% during climb, and 15% during landing roll. The rest were either not specified or were below 5%. Of the total of 16,477 strikes, 39% occurred while the aircraft wheels were in contact with the ground, 16% between 1 and 99 feet above ground level (AGL) 7% between 100 and 199 feet AGL, 5% between 200 and 299 feet AGL, 5% between 1,000 to 1,499 feet AGL and the rest up to altitudes of 39,000 feet AGL. One surprising statistic showed that 106 of the bird strikes occurred between 10,000 to 14,999 feet AGL.

Of the 16,477 total bird strikes that were reported, 2,246 were strikes to the engine area. These engine area strikes did not indicate a breakdown of engine type (turbo fan/jet versus reciprocating), but damage was reported in 921 cases. The windshield area was the only area on the aircraft with a higher strike frequency with a total of 2,773 strikes but with only 226 cases of damage being reported due to rigid windshield standards and operational procedures.

The Safety Branch of Transport Canada prepared a report² *Bird Strikes to Canadian Aircraft: A Seven Year Summary 1991-1997* that confirms the trends cited in the FAA report. This report provides both Canadian and international trends. The statistics on international bird strikes that follow were developed and presented in the Canadian report from data held by the Bird Strike Information System of the International Civil Aviation Organization. The statistics presented for international trends are only for the years 1989 through 1992, and are based on 16,488 bird strike reports for the 4 year period. These international findings show that:

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- 71% of the reported strikes occurred during daylight hours, 21% occurred during night, and the remainder occurred at dawn or dusk.
- 75% of the reported strikes involved a turbo fan (over 27,000 kg) aircraft classification
- 36% of the reported strikes occurred during approach, and 23% occurred during the take-off run.
- 58% of the strikes occur below 100 feet AGL

In 86% of the reported strikes, the pilots were not warned of bird activity.

The statistics relating to points on the aircraft struck by the bird(s) show that there were 1,897 strikes to the radome, 2,157 to the windshield, 2,247 to the nose area, 2,688 strikes to at least one engine, 135 to two engines, 10 to three engines, and 2 to all four engines. There is no breakdown showing how many of the engines were turbo fan or other type of jet engine and how many were propeller driven engines.

The statistics support the thesis that aircraft bird strikes are a serious threat to the aviation industry, aircraft crews and the flying public. Most bird strikes to aircraft worldwide occur in the day time when birds should be able to see and avoid the aircraft but do not. It also appears that the larger the aircraft, the more strikes that occur, but this statistic may be the result of the larger aircraft presenting a larger area to be struck. A high percentage of the strikes occur to the engines. If a FOIDS were installed, every ingestion events would be detected with high probability. The statistics also show that the majority of the bird strikes occur close to the ground during a critical phase of flight, a situation where the pilot requires quick information quickly to make an abort decision or take other time sensitive actions.

Engine Manufacturer

There has been a temptation for the engine manufacturer to dismiss the usefulness of the FOIDS because their engine has been "hardened" to meet FAA certification requirements found in FAR 33 – Airworthiness Standards, Section 33.77, with Amendments.³ FAR 33 also establishes standards for a turbofan high-bypass engine's tolerance to hail, breakaway ice formed on the fuselage, and bird strikes. While birds are primarily responsible for most engine damage, hail, baggage tags, tools and any other foreign objects common to the aircraft operational environment all pose a threat to turbofan engines.

Engine survivability of a bird strike is tested by the manufacturer mounting the engine on a test stand and running the engine at operational RPMs. During certification testing a compressed air cannon fires freshly killed birds and, in some cases, frozen birds into the test engine undergoing certification at velocities close to those that will be encountered during flight below 10,000 feet AGL, typically 200 to 250 knots. These tests are photographed at high speed so that a frame to frame evaluation can be made of the bird's impact with the compressor/turbine assembly and any resulting damage from the bird's ingestion. Using this test configuration, according to section 33.77, ingestion of a 4 pound bird may not cause the engine to:

- Catch fire
- Burst (release fragments through the engine case)
- Generate loads greater than those ultimate loads specified
- Lose the capability of being shut down

There is no requirement that the engine ingesting a 4 pound or larger (8 pound) bird continue to run and develop thrust. In practice, a strike from 4 or 8 pound birds usually damages the compressor assembly, causing tip drag against the engine casing, and may cause turbine blade failure and distortion requiring engine shutdown.

The ingestion of 3 ounce birds or 1.5 pound birds must not:

- Cause a sustained 25% power or thrust loss
- Require the engine to be shut down within 5 minutes of ingestion

Part 33.78 also addresses an engine's survival of ice and hail stone ingestion and how testing for ice ingestion is to be conducted using the cannon to fire ice into the engine. An engine's survival from heavy rain without flame-out or other types of thrust reducing behavior is also specified. There is a Notice of Proposed Rulemaking (NPRM)⁴, Docket No. FAA-1998-4815; Notice No. 98-19 that, if adopted, would make certification tests even more stringent based on historical experience. This proposed rulemaking, if adopted

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in its present form, would “amend 14 CFR 33.77 to increase the maximum number of birds in the various size categories required to be ingested into turbine engines with large inlets.” Safety Recommendation A-76-64 also states, “these increased numbers and sizes should be consistent with the birds ingested during the service experience of these engines.” The “experience” factor was developed as the result of an industry wide study of the types, sizes and quantities of birds that have been ingested into aircraft turbine engines of all sizes, and the resulting affects on engine performance.

It might be argued that when the first stage of the engine is damaged by a large object, there is already existing instrumentation that the pilot can use to confirm that damage. When turbine blades are damaged, the compressor assembly will become unbalanced and the imbalance condition will be displayed to the pilot by the engine vibration monitor. Engine damage may be indicated by a rapid rise in the exhaust gas temperature. The compressor shaft RPM monitor will also indicate a change when a large bird is ingested and impacts with the compressor assembly. A higher power setting may also be required to maintain a given value of thrust when there is engine damage.

Even if new engine certification requirements are adopted to further “harden” and engine, the FOIDS would serve as a secondary collaborative verification system that a foreign object had been ingested into the engine and that the problem was not from internal parts failure.

There is another type of more subtle jet engine failure that occurs that FOIDS may be the only current method of detection and monitoring. This type of event, called delayed failure, may be caused by the normal wearing and fatigue of engine parts. However, the delayed failure damage is usually caused by the ingestion of an undetected foreign object impacting an engine component at high velocity. The delayed failure of an engine part is usually detected during a major detailed engine inspection. There is also the chance that the damaged part will fail before an inspection can be conducted. Occasionally, turbine blade separation from the compressor hub causes an uncontained failure resulting in the blade or other engine parts penetrating the engine housing. Recently, an airline passenger was killed during an uncontained engine failure event after high velocity engine parts penetrated the fuselage.

The previously cited Canadian report² documents that DC-8 struck a bird during take-off from Rome, Italy. The pilot witnessed the bird strike in the engine area and landed as a precautionary measure. Visual inspection of the engine did not reveal a problem and the flight resumed. The engine failed (delayed failure) hours later in flight. A later major inspection of the engine showed that a turbine blade had failed due to the earlier bird strike.

The report also contains an account of a DC-8 striking a large flock of Sandpiper Sparrows as it lifted off the runway in Canada. Cockpit instruments gave no indication of a problem. Fortunately, the pilot witnessed the strike, reported it to the tower, and an inspection of the runway revealed a number of dead birds. The flight returned to the airport where an inspection of the engine revealed damage to eight fan blades total in two engines. It was predicted that engine failure would have occurred half way across the Pacific Ocean had the ingestion event not been visually detected and the aircraft landed for an inspection.

While speculative, it might be argued that if these two situations had occurred at night the pilot would most likely not have witnessed the bird strike event and the outcome in the two example cases may have resulted in a serious situation. If FOIDS had been installed it could have provided additional verification of the bird strike for the daytime case and would have been the sole warning system if either event occurred at night. It is suspected that many undetected ingestion events occur annually causing delayed damage that is not detected until the engine fails at a later (inopportune) time. It is further suspected that delayed damage from ingestion events is discovered during routine maintenance but not correlated to the ingestion event that caused the damage.

Airline Utilization of FOIDS

Foreign object and wildlife ingestion costs the airlines tens of millions of dollars annually. For example, American Airlines alone suffered 177 bird ingestion's events during one recent year of operation at a cost of \$500,000 for repairs. These bird strike incidents caused either delays or cancellations. These are the reported costs to just one airline. Most engine damage occurs either at the airport or near the airport. The

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airport operating authority is responsible for keeping the wildlife under control, in the airspace over the airport also for keeping foreign objects off of the ramp. Recently, Air France recovered damages in a legal action against the Port Authority of New York and New Jersey regarding the damage to two Concorde engines caused by a bird strike. Airline collection from the airport authority for foreign object damage may be a trend of the future. The FOIDS would supply accurate data that could be used for wildlife ingestion documentation. Accurate ingestion documentation would ensure that airport operators were not blamed for ingestion events occurring outside of their responsibility area. FOIDS data would also identify airports with a history of foreign object ingestion problems.

Aviation Week reported⁵ that Scandinavian Airlines System in Denmark, operating a fleet of 150 aircraft, (MD-80s, B767s, B737s and MD-90s), began a program in 1995 to track the last five landing sites of aircraft suffering unwitnessed foreign object damage. They are seeking to establish common threads to help identify and correct foreign object damage prone locations or practices. The carrier's transports average about five flights a day and most foreign object damage is discovered during nightly checks. While no information is available concerning the type of foreign object that is of concern, an installed FOIDS would identify the aircraft's location each time a foreign object was ingested, further documenting the exact location of the aircraft. Only engines experiencing a documented ingestion event would require more than a cursory inspection, assuming that FOIDS data were available on every engine.

Regulatory Agency use of FOIDS Data

It has been estimated by John J. Goglia,⁶ of the National Transportation Safety Board (NTSB) that only 15% of the bird strikes are actually reported, even when known. Goglia said he planned to call for studies aimed at determining what type of data collection is necessary to help the airline industry pinpoint maintenance problems that could lead to accidents. The proposed study has not yet been funded by the FAA. Goglia reports, in personal communications with the author, that a recent bird strike incident that flamed out two engines while the aircraft was within 1,000 feet of the ground may place renewed emphasis on the need for the study.

The (NPRM), Docket No. FAA-1998-4815 cited previously proposes raising the standards for engine certification against bird strikes on the basis of real world experience with bird strikes and the damage actually assessed to have occurred. If a FOIDS were installed on most aircraft in the United States, the bird strike problem could be very well documented with a very detailed database. The resulting database would be much more complete and definitive than any developed to date using a form that is voluntarily submitted as it is considered that bird strikes are under reported.

Summary

The FOIDS can serve the needs of the aviation industry and improve safety, if the system were to be installed on most commercial aircraft in airline service, as a minimum. The military should find the system very useful to determine when bird ingestions occur during low altitude training flights, also during normal flight operations. The worry of putting another emitter on a stealth platform is not a major problem. The FOIDS system can be designed to provide a very low probability of intercept radio frequency (RF) signature to keep the electromagnetic signature of the system undetectable from the ground.

The engine manufacturers would find the data developed by the system invaluable to use in statistical evaluations of ingestion frequency and ingested object size studies. The regulatory agencies that set the engine foreign object survival standards would also find the data from the system very useful to ensure that the threat is characterized properly so that standards do not exceed practical requirements. The data would also allow a change in threat level to be detected early in the changing trend's cycle.

The airline industry should find both the real time and historical information developed by the FOIDS extremely useful. The FOIDS would provide pilots real time data on which to make decisions when operation near the ground (where there is the highest threat of ingestion and bird strike). The data base

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would allow inspectors to determine which engines should receive inspections in advance of normal inspection cycles to ensure that delayed failure of engine parts do not occur while in flight.

Air France has already been reimbursed by airport operators for two damaged engines on the Concord. The FOIDS will provide irrefutable evidence regarding the time and place of an ingestion event. The use of FOIDS will ensure that airlines have proof for their damage claims against the airport operators and that an airport operator is not falsely accused of negligence when the ingestion event did not occur at their airport. The FOIDS historical data will also allow airports to be rated on their performance for foreign object control efforts. Operators of corporate jet aircraft would find the real time and historical data developed by the FOIDS extremely useful, given that many of these flights start and terminate at smaller airports that are without a full time wildlife officer and in some cases an aggressive program to discourage birds from nesting near the airport.

References

1. Cleary, E. C., Wright, S. E., Dolbeer, R. A., *Wildlife Strikes to Civil Aircraft in the United States 1991-1997*, Report of the Associated Administrator of Airports, Office of Airport Safety and Standards, Airport Safety and Operations, Washington, D.C., September 1998.
 2. MacKinnon, Bruce, *Bird Strikes to Canadian Aircraft: A Seven Year Summary, 1991-1997*, Report of the Aerodrome Safety Branch, Transport Canada, 1998.
 3. Federal Aviation Administration, *Airworthiness Standards: Aircraft Engines including Amendment 33-19*, Federal Register, March 26, 1998.
 4. Federal Aviation Administration, *Notice of Proposed Rule Making (NOPRM)*, Docket No. FAA-1998-4815, Notice No. 98-19 to 14 CFR Parts 23 and 33.
 5. Industry Outlook, "FOD Tracking," *Aviation Week & Space Technology*, December 4, 1995.
 6. Air Transport, "Bird Strike Threat Draws New Warning," *Aviation Week & Space Technology*, February 5, 1996.
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