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BIRD INGESTION AND THE ROLLS-ROYCE WIDE CHORD FAN

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ABSTRACT

This paper introduces the Rolls-Royce wide chord fan blade and explains its advantages over high aspect ratio, snubbered fan blades. The latest generation superplastically formed fan blade is compared with other styles of fan, showing the principles of its construction and the duty it has to perform.

One of the many requirements for the fan is that it must be able to withstand the impact of birds and still produce adequate thrust. The design work and tests which lead up to engine certification for bird ingestion are described.

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1. Introduction - why do engines have large wide chord fans?

At the risk of stating the obvious, a jet engine works by taking in air at the front and pushing it out at the rear with a much increased velocity. The increase in the momentum of the air is what provides the thrust of the engine. For a given thrust, this process is more efficient if a large mass of air is passed out at low velocity than if a small amount of air is passed out at high velocity. This propulsive efficiency as it is called, is the driving force for the development of the turbojet into the turbofan, where the thrust not only comes from the hot gas stream from the core engine, but also from part of the airflow from the fan which is diverted down a bypass duct, missing the core engine entirely. The two gas streams are then usually mixed at the rear giving a higher mass flow at lower velocity than would be the case in a turbojet. The ratio of the mass flows down the bypass duct and the core engine is called the bypass ratio. The quest for ever greater propulsive efficiency drives the bypass ratio up and this has resulted in the typical modern turbofan lay out where a very large large fan is driven by a relatively small core engine.

The large diameter of modern fans (over 3m) has a great effect on engine weight. It is a general rule that the fan weight can be minimised by having a large number of relatively long, narrow chord (the distance between the leading edge and trailing edge of the aerofoil) blades in the fan.

These high aspect ratio blades, however, are flexible and have natural vibrational frequencies which can allow resonances to occur at normal engine operating speeds. This would soon cause fatigue failures if a design feature called a snubber, or mid span shroud, was not included (fig 1). The snubber is a projection which extends out from each side of the aerofoil. As the fan rotates snubbers on adjacent blades lock together to form a stiffening ring round the fan assembly, so raising the natural frequencies of the blades out of the troublesome range.

Unfortunately, the snubbers also reduce the efficiency of the fan - about 4% reduction - and they also cause ingestion problems. It is a common misconception that the snubber is there to help in impact, in fact the aerofoil usually has to be thickened round the snubber to avoid cracking under bird impact loads, further increasing the efficiency penalty.

It can be readily appreciated that a fan design which dispenses with snubbers would have a significant performance advantage. One way is to make the blades much stiffer by reducing the number of blades and increasing the blade chord (fig 2). Each blade then is inherently stiffer and the aerodynamic efficiency is improved. However, such a fan would also be impossibly heavy. The Rolls-Royce solution is to make the blades hollow.

Hollow wide chord fan blades are stiff, efficient and, with the right manufacturing techniques, are also very light for their size. The first generation Rolls-Royce hollow fans were fabricated from titanium outerskins stabilised by a titanium honeycomb core. These blades have been in service since 1984 and can be found in the RB211-535E4, the IAE V2500 and the RB211-524G.

The second generation wide chord blades have diffusion bonded superplastically formed (DBSPF) titanium internal structures which are more suited to robotic manufacture and which allow more efficient use of the blade core in carrying centrifugal loads, resulting in a 15% weight saving and a 30% cost saving relative to honeycomb blades.

The DBSPF wide chord fan is a feature of the Trent 700 series of engines going into service on the A330 and the Trent 800 which will power the Boeing 777.

So, to summarise, the modern jet engine fan blade has an arduous job to do. In a Rolls-Royce engine such as the Trent 700, it is approximately one metre long, on take off its tip is travelling at nearly 1.4 times the speed of sound, the aerofoil is exerting a load of over 90 tonnes force on the disc, each blade is producing well over 2 times the thrust of Frank Whittle's first jet engine : then it hits a flock of birds - and it must keep running.

2. <u>Designing for bird impact</u>

Bird ingestion is not a rare event, on average it happens once in 5000 flights. The great majority of ingestions cause no engine damage at all, but occasionally, when heavy birds are involved for instance, the consequences can be more serious. Figure 3 shows an RB211-534E4 which ingested 3 or 4 Canada Geese on take off from Chicago. In this case the engine continued to run and was only shut down by the crew when a safe altitude had been reached.

This is an extreme example : the certification regulations of the FAA and JAA are aimed at more commonly encountered situations, ensuring the engines can continue to deliver thrust after ingesting the types of birds likely to be encountered in flocks (medium birds - currently $1\frac{1}{2}$ lbs, soon to be increased to $2\frac{1}{2}$ lb for larger engines) and that engines can be safely shut down if they ingest single, heavy birds (large birds - currently 4 lbs, soon to be increased to 6 or 8 lbs for larger engines).

The ingestion performance of engines in service can be judged against the severity of the regulations to which they were certificated by examining the results of surveys such as these conducted by the FAA in 1981 to 83 and 1989 to 91. These surveys are invaluable sources of data, supplementing Rolls-Royce's own ingestion records on the RB211, which have been collected for over 20 years, and making possible statistical modelling of in-service birdstrike experience.

Using statistical modelling it is possible to assess quantitatively how strong engine components, such as the fan, have to be in order to meet a desired target of in-service reliability. Using this approach Rolls-Royce came to the conclusion that new large engines should be designed to withstand an encounter with a flock of $2\frac{1}{2}$ lb birds, and it is this standard which has been applied to the new Trent engines even though the Trent 700 is only required to pass a $1\frac{1}{2}$ lb certification test.

Rolls-Royce is continuing to develop the statistical analysis of birdstrike and is currently, in collaboration with the UK's CAA, funding Dr John Allan of the UK Ministry of Agriculture to carry out bird flock density measurements using a novel stereo video technique.

Having established some ground rules about the size operating conditions and required strength for a new fan blade, design work can begin.

The outside form of the fan blade is dictated by aerodynamic requirements. However, because the fan is hollow, there is great freedom, within wide manufacturing constraints, to adjust the panel thicknesses and core structure and it is found that bird impact requirements dominate the design of the tip of the blade. As weight at the blade tip has to be carried by more metal lower down on the blade, into the disc, shaft and containment system (1 kg at the tips puts $2\frac{1}{2}$ kg onto the engine) it is very important to be sure that no excess metal is added.

Figure 4 shows the basic impact mechanism which is the cause of fan blade damage. As the unfortunate bird enters the fan it is sliced by each blade in turn. The mass of each slice is accelerated very quickly by the blades and passes out at the rear of the fan with greatly increased velocity. The acceleration imparted to the bird mass produces high pressure loadings on the fan blade surface, typically 15 MPa (1 tsi), producing a dent or cup in the leading edge.

If the fan is not strong enough, the leading edge can be overstretched and crack, the crack may propagate under the centrifugal stresses and the complete blade tip may be released. As the wide chord blade is also hollow, the blade panels may crack if their thicknesses are too low or if the panels have the wrong distribution of thickness. The strength of the core structure also affects the reaction of the blade to impact loads. Even if the fan does not suffer these failures, the depth of the leading edge dent may also have to be restricted as the dents disturb the airflow through the fan and can cause vibration and thrust loss which, as defined by air worthiness regulations, must not exceed 25% of take-off thrust after the ingestion of a number of medium birds.

The ingestion of a large bird is permitted to cause metal loss from the aerofoil as long as the out of balance force generated does not exceed the capability of the engine to absorb it, usually demonstrated by a blade-off test, and as long as the engine can be shut down safely.

All this must be achieved at minimum weight.

The structure of the DBSPF fan blade tip has evolved gradually, incorporating the results of ingestion research work, honeycomb blade experience and finite element stress modelling. Today we can very quickly produce an initial design by calculating relatively simple impact parameters and this approach is used to set the basic layout of the blade, but increasing use is being made of complex dynamic stress modelling to further refine the design.

The analysis tool that Rolls-Royce prefers to use is Dyna3D. This is a finite element code which can handle geometrical and material non-linearity and which was written specifically to deal with impact problems. Figure 5 shows a typical model, illustrating how the blade deforms under the bird impact load.

Following the design phase, the blade then has to go through a rigorous testing programme, leading up to the final engine certification test.

3. Bird Ingestion Testing

As a first step, Rolls-Royce uses a simplified bird impact testing technique in which a single rotating blade is impacted by a gelatine dummy bird which is dropped into the fan (fig 6). The timing of the dummy bird and the rotation of the fan is closely controlled so that the blade slices off the correct mass at the correct incidence angle, thereby reproducing exactly the pressure loadings and damage which would be experienced by the blade in the engine. The blade shown in figure 7 has just sliced through a simulated 8 lb dummy bird.

As this test method shows an obvious cost saving over the alternative of using a fully bladed fan, it is subject to continuous improvement, not least in the definition of the dummy bird.

It is important to have the correct shape, dimensions and material for the dummy bird in order to avoid under or over testing. Rolls-Royce is interested in entering into collaborative research on this subject not only to improve existing test techniques, but also with a possible long term goal of replacing real birds entirely by suitable synthetic birds, even for certification tests.

At this point in the development programme, a fully bladed rotor may be tested if required. During development of the Trent 700, an early standard of Trent fan was rig tested as a fully bladed rotor using real birds in order to confirm the capability of the production Trent 700 fan to ingest successfully medium weight birds. Figure 8 shows the results of a tip strike with a $2\frac{1}{2}$ lb bird at maximum take off power. The typical leading edge damage can be seen, but the blade has remained intact and the deformation of the fan would not hazard the 75% thrust recovery criterion.

At this point all is now ready for the certification test on a running engine. A special multi-barrel air gun (Fig 9) has been constructed which is capable of firing up to eight birds, electronically timed and individually aimed at selected, critical areas of the engine as agreed by the certification authority.

High speed cine and video is widely used to record the test, being used to check the speed of the birds and the accuracy of the strike positions. Ducks are used for this test and are humanely killed before being loaded into fibre glass sabots made to fit the gun barrel. On firing, the sabot is removed by a sabot catcher mounted on the end of the barrel and the bird then continues into the engine.

After the ingestion the engine has to perform a running-on period (currently 20 minutes) and demonstrate satisfactory handling characteristics, simulating a circuit round an airport and subsequent landing.

The Trent 700 engine has recently completed such a certification test. Eight $1\frac{1}{2}$ lb birds were fired at 170 knots into an engine running at maximum take-off power. The resulting damage to the fan is shown on figure 10. The engine lost only 2% of thrust and demonstrated that the new second generation wide chord fan will continue to uphold the reputation for ruggedness established by Rolls-Royce turbofan engines over many years of exposure to bird ingestion.

4. Acknowledgements

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FIG 1 SNUBBERED FAN BLADE

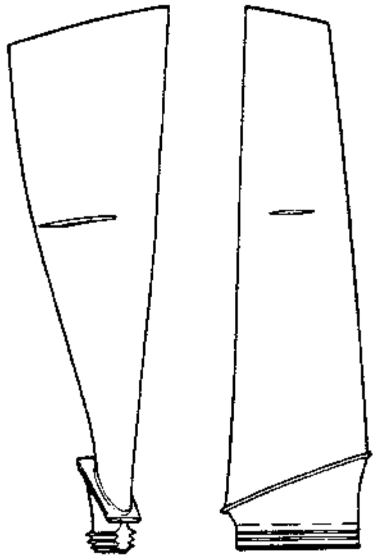


FIG 2 WIDE CHORD FAN BLADE

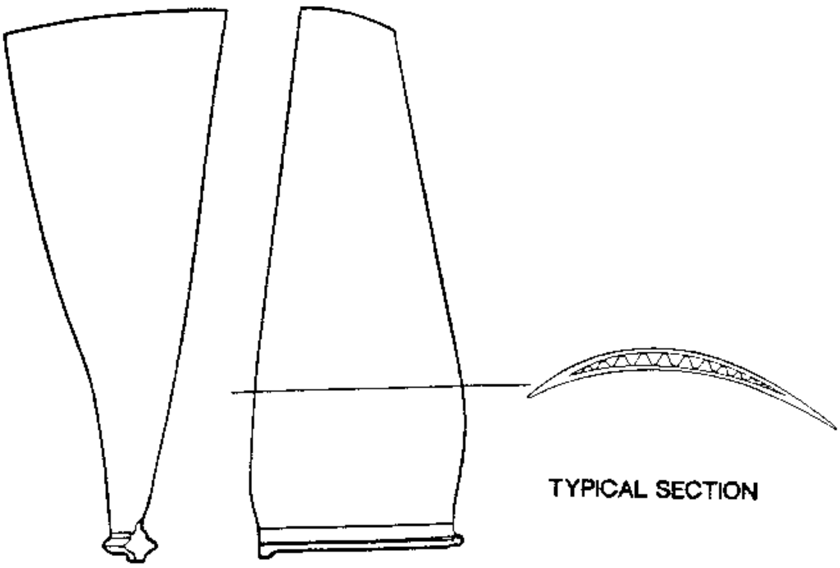


FIG 9 INGESTION TEST BED

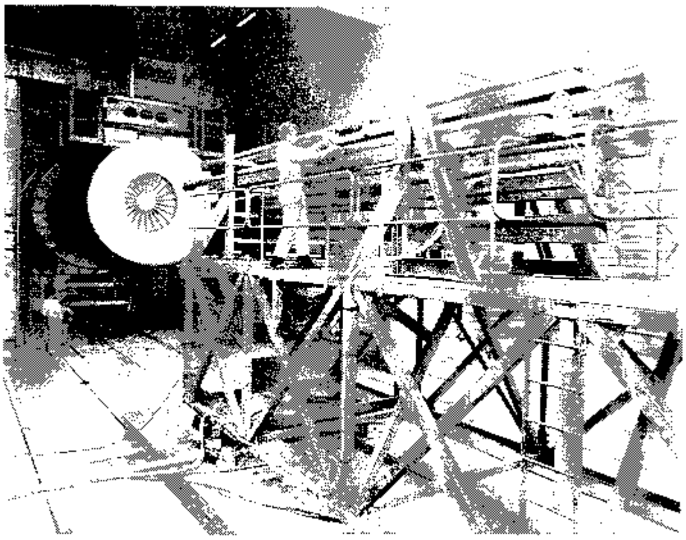


FIG 10 TRENT 700 MEDIUM BIRD CERTIFICATION TEST

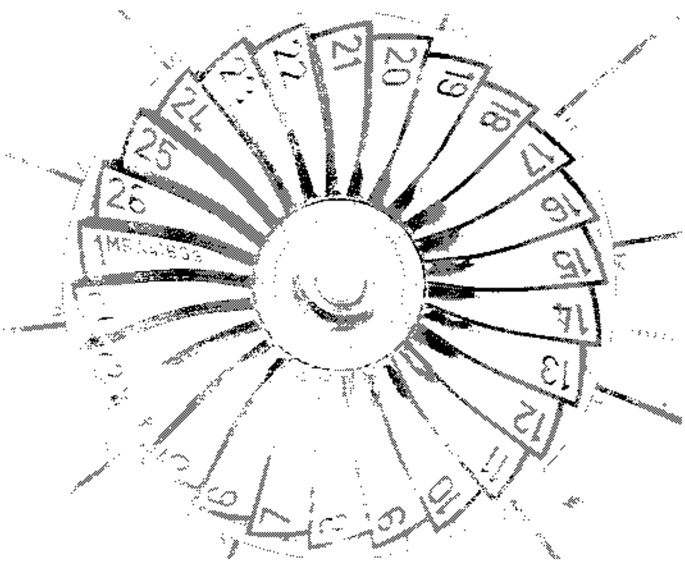


FIG 7 TRENT FAN BLADE IMPACTING
8LB DUMMY BIRD

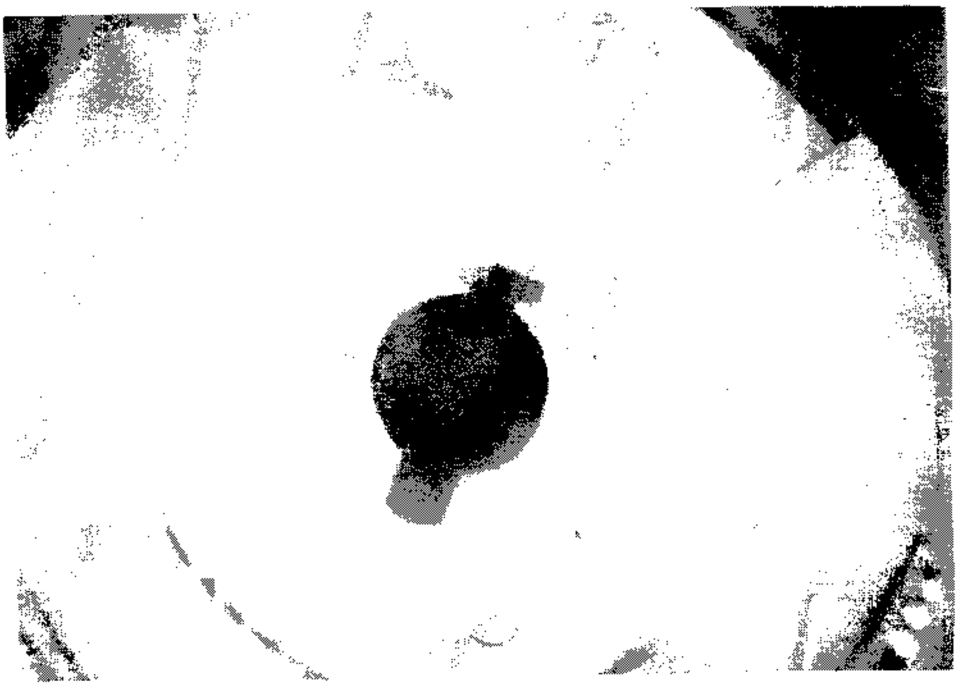


FIG 8 TRENT FAN AFTER INGESTING
2.5LB REAL BIRD

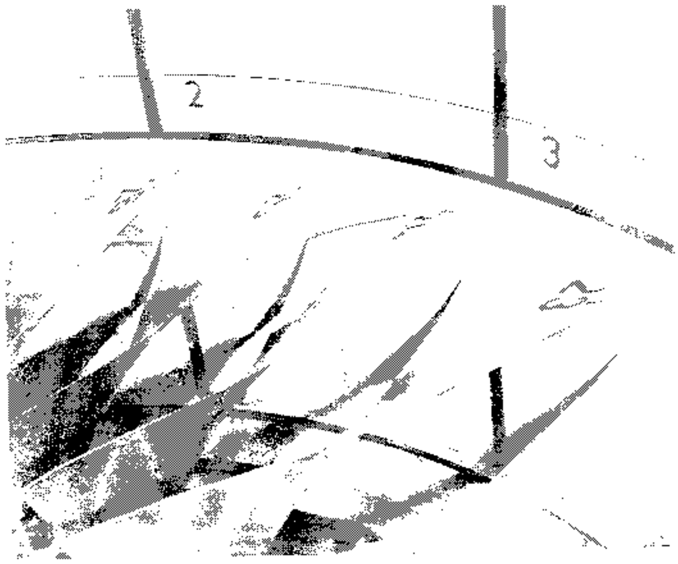


FIG 5 DYNA3D MODEL OF BIRD IMPACT

FIG 6 SINGLE BLADE RIG ASSEMBLY

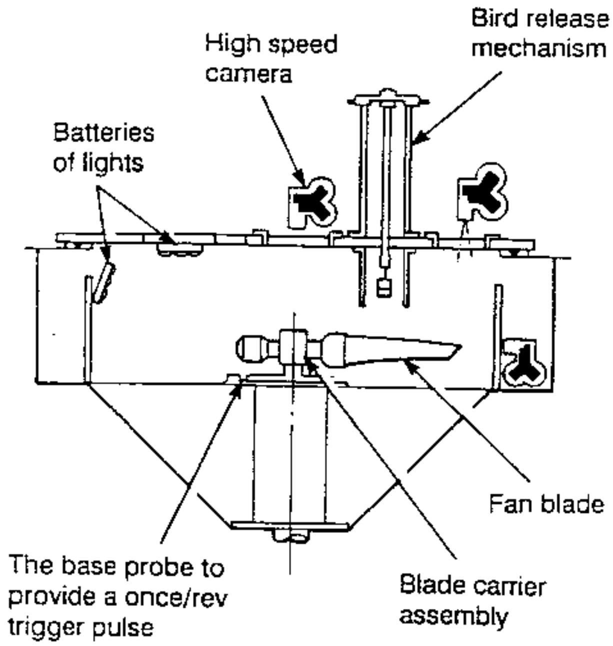


FIG 3 RB211-535E4 AFTER INGESTION

OF 3 OR 4 CANADA GEESE

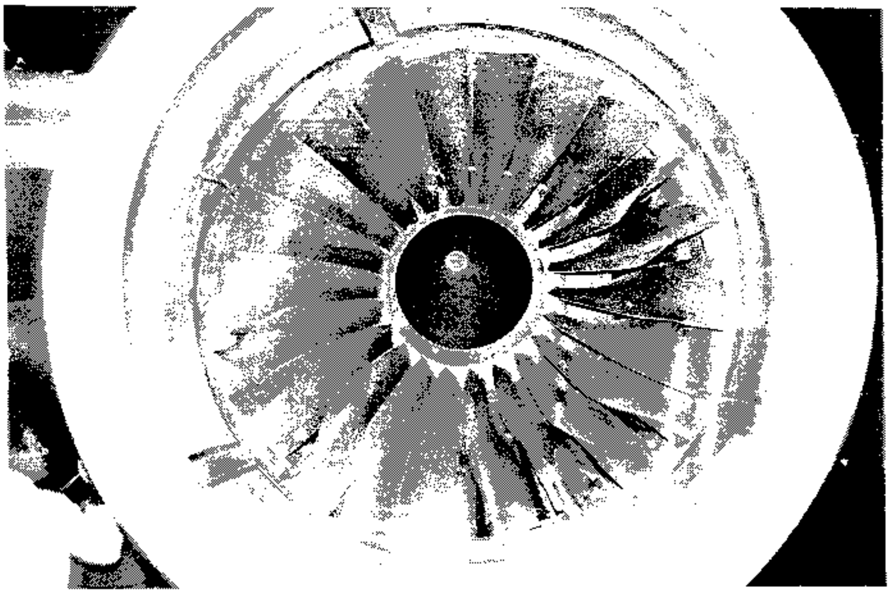
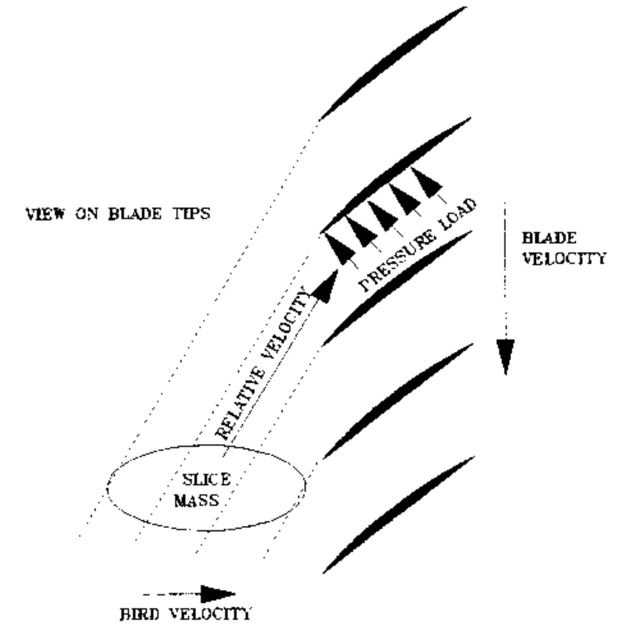


FIG 4 BIRD SLICING MECHANISM



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