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INTAKE ENGINE INTERACTIONS OF A MODERN LARGE TURBOFAN ENGINE

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ABSTRACT

An engine experiment has been carried out to investigate Fan Stability and response to ambient wind conditions during static high power running of a modern large turbofan engine. This paper describes the experiment and the conclusions.

Intermittently the inlet would separate and drive the fan into stall from which it did not recover when the inlet cleared up: on high working lines one inlet separation could stall the fan; on lower working lines the inlet separation / fan flow / bypass duct pressure would develop a divergent 10Hz oscillation which could eventually stall the fan. The interaction of the stalled fan with the turbine and mixed nozzle would then raise the fan running line above the stall dropout level thus locking the fan into stall even when the inlet cleared up. A one dimensional dynamic model of the engine was created that would exhibit similar behaviour to the engine when a delay was introduced between the inlet loss and fan face loss. The engine never showed steady operation with the inlet separated.

INTRODUCTION

Modern large turbofan engines running statically at high power can be susceptible to the fan stalling, particularly in a crosswind condition. The design of the intake and fan, as well as the ground clearance have a significant influence on these phenomena. To improve the understanding of these phenomena it was decided to run an engine with a flight inlet outdoors on a normal test bed with a 5 meter engine centre line: an artificial ground was installed under the inlet to replicate the aircraft engine ground clearance. The fan operating line could be adjusted since the engine was fitted with a final nozzle which could be closed off with blockage plates. The general arrangement of the engine on the stand is shown in Fig. 1. The pipes on the ground plane are smoke ducts from theatrical smoke generators.

To reduce the damage if an event happened the engine was fitted with a slave control system that could detect an event and then cut the fuel supply and simultaneously control the data acquisition system so only interesting data was acquired. The control system was provided with the normal engine parameters to control the engine, in addition it could characterise a fan stall and trigger the damage limitation and event recording action.

The engine was fitted with Kulites on the inlet lips, total pressure rakes just in front of the fan connected to Druck pressure sensors, Kulites along the bypass ducts and total pressure heads on the Fan OGVs also connected to Druck transducers - Fig. 2. Fan strain gauges, speeds and local wind speeds were measured. All the data was read, up to 80 channels, and digitised continuously into a buffer: when triggered the system saved data for a fixed time before and after the trigger. The system could also be triggered manually if an interesting event occurred, a subset of the data was recorded continuously on tape as a backup. The engine was then run at high power to see if the fan would stall.

The engine ran and the fan did stall after running at steady power for several tens of minutes.

FAN STALL EVENTS

The first event was accompanied by a heavy rumble, an increase in fan speed, but no damage except for a rub on the fan track. Data from the first stall at 90% speed is shown in Fig. 3 - this shows a fan inlet Kulite, 3 taps of a fan inlet total pressure rake and a bypass duct inlet static pressure. There are 5 regions (annotated 1-5 in fig 3):

1) Steady except for the near wall tapping on the side inlet rake
2) A rapid drop of inlet total pressure on all tappings almost down to the fan inlet static
3) A fall in bypass duct pressure, chaotic spikes on the inlet static pressure

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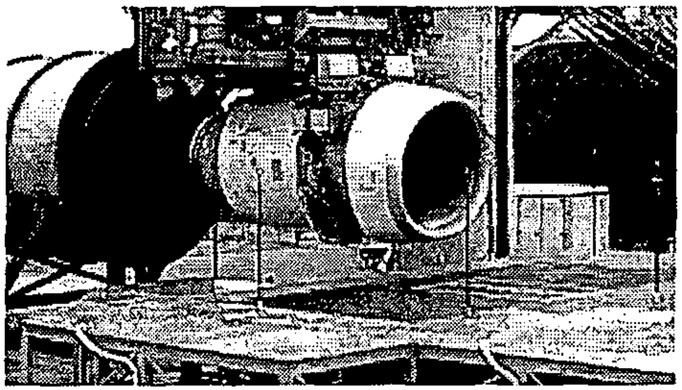

Fig 1 - Engine Test Setup showing Artificial Ground Plane

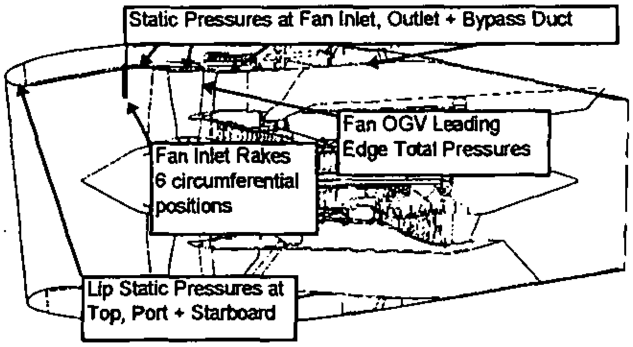

Fig 2 - Location of Dynamic Pressure Measurements

4) A rise in inlet total pressure and bypass duct pressure and an ordering of the fan inlet Kulites into a 2 cell stall
5) Recovery of the inlet total pressure and a regular one cell rotating stall seen on the fan inlet static and total.

Shown in Fig. 4 is that the inlet separation typically only covered ~1/4 of the inlet circumference. The unsteady pressure prior to separation is a combination of mains 50Hz and LP order 53Hz.

The process can be described as an inlet separation due to ambient wind at high engine mass flows: this separation transiently raises the fan operating line as well as providing fan inlet distortion. If the working line shift / distortion is severe enough the fan drops into rotating stall, the flow falls, the inlet recovers but the fan remains locked in stall, showing hysteresis, with an accompanying rise in working line. The core operated normally throughout. Several more stalls were experienced on the same working line. One was different in that instead of the inlet separating once before the stall it separated twice at ~0.1 second intervals: the second more violent one caused the fan to stall. The most intense separation was seen on rakes on the upwind side in the quarter between the horizontal centre line and the top. The activity was sufficiently intense that the horizontal centre line rake became loose and was removed for the rest of the testing: this made the testing less comprehensive.

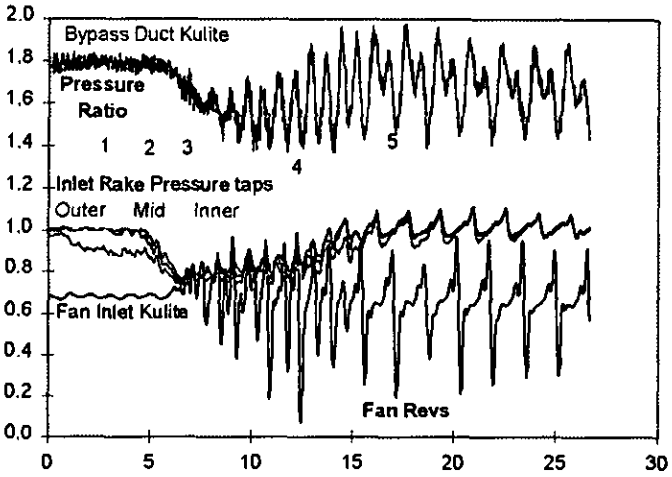

Fig 3 - Dynamic Pressure Data from First Stall Event

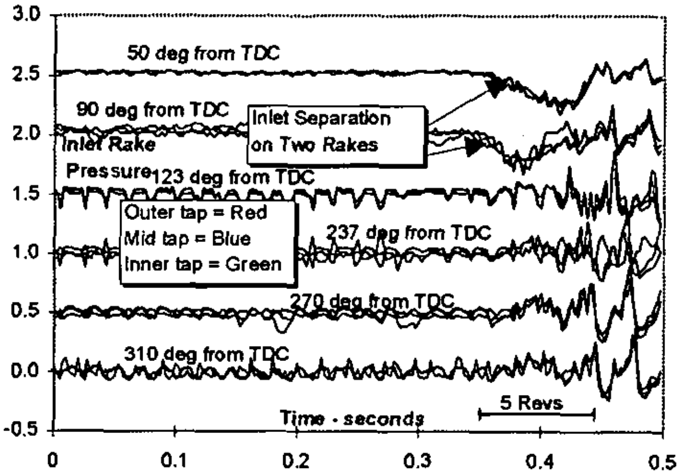

Fig 4 - Inlet Rake Pressure Data from Stall Event

The fan working line was lowered by removing blockage plates. The fan would still stall but the pattern was different in that invariably the inlet separated several times each more violent than the one before until the fan stalled, the inlet recovered but the fan remained locked into stall. The data from one such stall is shown in Fig. 5: shown are the lip Mach numbers (calculated from lip Kulite statics), fan inlet rake pressures, and fan inlet static pressures. The figure shows the lip Mach numbers intermittently rising and falling from around 1.5 to 1 at the top and both sides. The port or upwind side has a larger amplitude but all are more or less in phase. The inlet Mach number variation increases with time. Shocks are forming in the supersonic patch around the inlet highlight: these shocks cause the inlet pressure to rise and fall on the upwind side but not on the downwind side. The fan face static pressure drops on the up wind side but oscillates on the down wind side. The downwind side response indicates a pulsation in the whole flow which is also visible on video recordings. When the amplitude reaches some value the fan drops into stall and the inlet recovers; the fan remains locked into stall.

A similar event is shown in Fig. 6, this figure shows the data presented as the area average fan map. It shows as the inlet separates

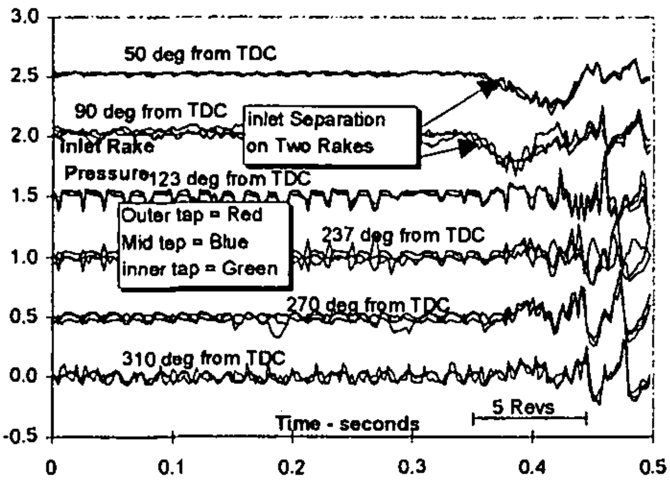

Fig 5 - Relative Pressures and Lip Mach Numbers

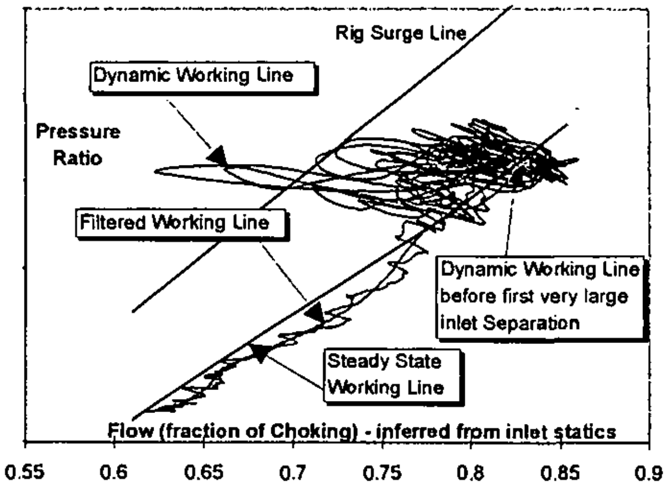

Fig 6 - Area Average Fan Map

the working line rises almost to the surge line on a 1D basis: a similar calculation of the worst sector shows the working line overshooting the rig surge line; the inlet recovers to a level below the steady operating point; the inlet separates again and the operating point then goes even higher before recovery to below the steady state point. Eventually the fan stalls and the inlet recovers. The slave control system spots the stall and drops the fuel flow. The working line then drops and the fan slows down out of stall: as the fan drops out of stall there is a characteristic step in working line level.

When the steady working line was dropped even further the fan did not develop locked in stall and so the control system did not automatically trigger the data acquisition system and manual intervention was employed. This showed that the fan would develop transitory stall but no regular single cells. However when the taped data was examined the event shown in Fig. 7 was seen - the AVM (Aircraft Vibration Meter) is seen to have a 10Hz divergent oscillation that was stopped when the throttle was closed due to excessive noise.

The pattern was therefore:

- One separation leads to fan stall on a high working line;
- As the working line is lowered more of the 10Hz divergent oscillations are needed to stall the fan;
- When the working line was low enough the fan did not develop locked in stall but would stall and recover as the inlet separation came and went.

The test engine had an Ultrasonic Anemometer fitted in front of the inlet, the anemometer measured x/y/z velocities and the speed of sound i.e. air temperature. The wind speed and direction would vary substantially in a second.

Examination of the ambient wind using the Ultrasonic Anemometer showed no significant 10 Hz content in the ambient wind: the wind speed variation was all below 5 Hz and mostly below 1 Hz; however it did show that there were sizeable gusts lasting 0.5 seconds and less so it was possible for a gust to trip the inlet, and a second later the wind speed would be too low to trip the inlet into separation. Without being locked in stall the system could have recovered. The fan however was locked in stall.

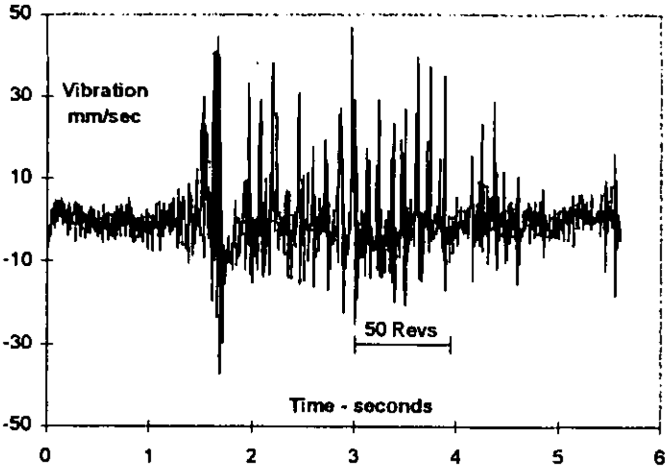

Fig 7 - Vibration Response Showing '10Hz' Phenomenon

DESCRIPTION OF EVENTS

The engine had demonstrated behaviour contrary to that expected. Greitzer (1976) had shown that, with undistorted inlet flow, compressor instability starts out as rotating stall but develops into 1D surge or deep rotating stall depending on the environment. The events began by an asymmetric non-rotating disturbance that led to rotating stall. Previous studies by Motycka (1984) had shown that the presence of a fan would attenuate the steady distortion generated by the inlet: here the fan could either attenuate or amplify the steady state distortion depending where in the cycle one looked. There was no steady state solution. The assumption often made in inlet / fan compatibility assessments that the 1D working line was the same as the undistorted working line was not valid and so the assumption that the only effect of the inlet was steady distortion of the fan was not valid. Hodder (1981) showed also that a fan attenuated inlet distortion but that there was also some 'random' structured unsteady behaviour of the fan and inlet even when

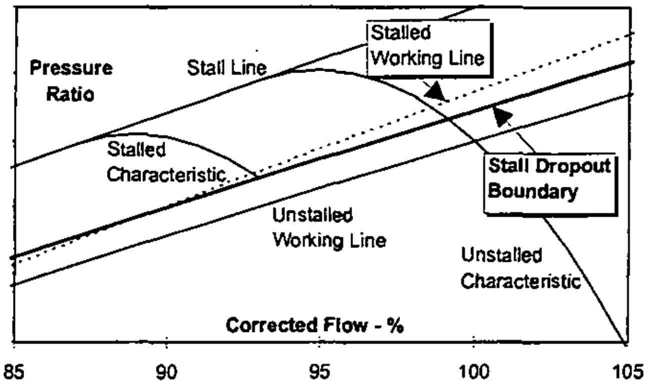

Fig 8 - Sketch Showing Working Line Hysteresis Effect

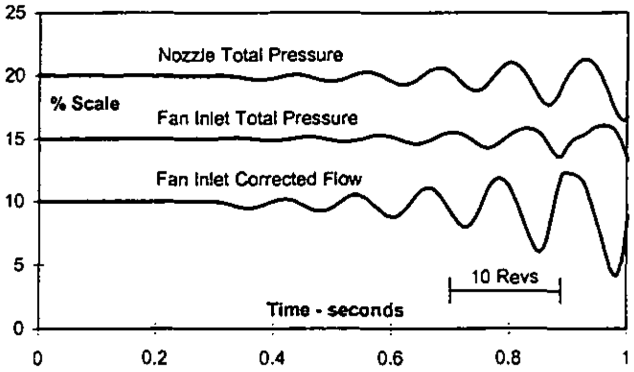

Fig 9 - Model of Helmholz Response of Engine

operating in a wind tunnel with a full sized engine. Greitzer (1981) showed that the stability of a compressor can be increased or decreased due to interactions with other components. This is clearly a case where the stability of the fan depends on the active interaction of the fan, inlet, and exhaust duct. Aircraft inlets with crosswind at high flows have loss increasing with flow, they are 'Choked' when tested in a wind tunnel or full scale with a suction facility.

Many studies of inlet engine compatibility (Ref. 1, 2, 6, 8, 9) appear to take the inlet distortion upstream of the fan as being defined by the inlet alone and that the inlet / fan compatibility problem is that of how the fan would respond to the 'given' inlet distortion.

The other behaviour of the engine was that whether the engine was stalled after a wind gust had separated the inlet was dependent not on the stall drop in boundary but on the stall drop out boundary i.e. the hysteresis in the stall line and working line. This effect is discussed by Steenken (1986) in the context of modelling post stall transients. The effect of Hysteresis on stall drop out is also discussed by Day et al. (1978)..

LOCKED IN STALL

A compressor is said to be locked in stall if after the event that drove it to stall has passed the compressor remains in stall when apparently restored to the conditions where it was previously unstalled. This behaviour has two elements: hysteresis in the stalling of the compressor and hysteresis in the working line. Day (1978) shows examples of hysteresis in the stalling and unstalling of compressors. The working line has to be lower to unstall than to stall: the Stall Drop Out Boundary is below the Stall Drop In Boundary. With no other change the compressor will be locked in if the Stall Drop Out Boundary is below the normal working line. .

The engine working line also suffers from hysteresis. In stall the efficiency is lower so even with a simple nozzle the working line will be higher in stall than out. The criterion for recovery is that the stall dropout line must be below the 'clean' working line plus the working line shift due to being stalled. On a mixed engine the working line rise due to being in stall is greater. This arises because the core exhaust runs at the same flow (the fan stall is as expected confined to the tip and has little effect on the core section) but a lower total pressure: it ends up using a larger fraction of the total nozzle area as a result, and consequently throttles the bypass flow.

The overall situation is shown in the sketch of Fig. 8, which illustrates a case where the working line hysteresis just keeps the fan stalled after the initial disturbance which triggered the stall has disappeared.

'10HZ' AND UNSTEADY FLOW MODELLING RESULTS

The engine has exhibited a 1-D unsteady mode at about 10Hz when exposed to natural winds as discussed above. This is often a precursor to fan stall, with the amplitude increasing until stall occurs. If the engine is operating on a low enough working line, so that it is not prone to locked stall, then the 10Hz can exist in it's own right for several seconds.

During the instability, the inlet separates and then reattaches in a periodic manner. The fan *may* stall briefly, the inlet flow falls, the inlet reattaches again, the fan unstalls (if it was stalled), the inlet flow rises and the cycle repeats. It would *appear* that the frequency is related to natural delays in the system, rather than being coupled to a system mode.

A 1-D compressible unsteady flow model of the engine was constructed to investigate this instability, following the work of Steenken (1986). The model contained a representation of the intake, fan and the bypass duct and nozzle. The intake loss could be varied with flow and time. The core flow was not modelled in detail, due to the high bypass ratio and the observed steady nature of this flow in the engine. The model used 14 approximately equal length elements from forward of the intake highlight through to the final nozzle exit plane. The equations of conservation of mass, momentum, and energy were applied in each element. It was run with a 6mS timestep which was shown to be suitably small by examining the model behaviour with larger timesteps.

There *is a system mode* at just under 10Hz, a distorted Helmholz mode - Fig. 9. In this case no allowance was made for a change of fan characteristic due to stalling in the model, as only the *unstalled* behaviour was being modelled. This behaviour was obtained in the

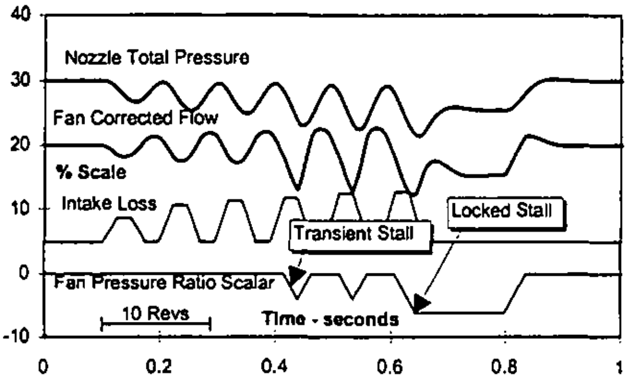

Fig 10 - Model of Engine '10Hz' Instability

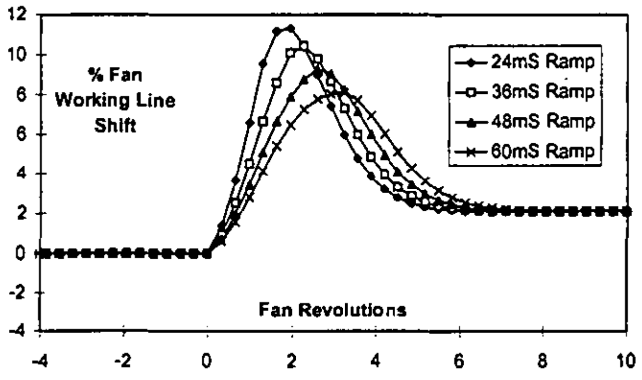

Fig 11 - Dynamic Working Line Shift Following Separation

model by 'bending' the fan characteristics - making them more positively sloping - the normal way of establishing this natural instability of the system: the instability shown in fig 9 arises purely because the pressure rise - flow relationship of the fan is too positively sloping. The typical phase relationship between inlet flow and downstream 'plenum' pressure - here the final nozzle entry pressure -is clear as the amplitude increases, with the maximum rate of increase of flow corresponding to the lowest nozzle pressure. If this mode is being excited in the engine, it may be necessary to have a marginally stable fan as part of the system.

This mode can be initiated by sudden inlet separations. It needs there to be a suitable *delay* between separation and reattachment which may be provided by the convection time of the separated flow. It may also be related to stalling / unstalling of the fan. There is a mechanism for increasing amplitude, as the separation intensity increases with increasing flow, and the flow 'overshoots' it's starting value on the first cycle. This will be exacerbated by transient stall / unstall and increasing RPM. Figure 10 shows a possible sequence, where the transient stalls modelled on the 4th and 5th cycles increase the size of the fluctuations. The intake loss and Fan Pressure Ratio Scalar were inputs to the model. In this case the change in fan performance due to stall was allowed for in the model, together with a time period for stalling and unstalling of about 2 revs. The engine response was dominated by the inlet behaviour and it's time delays: this would only excite the 'Helmholz' response if the fan was close to stall.

The dynamics of the inlet separation have also been investigated, since the engine always stalls immediately following a large separation event. The model is limited, as it is a 1-D model, nevertheless it shows that the dynamics of separation are extremely important for the operating point trajectory of the fan. Figure 11 shows the working line movement, based on the change in outlet corrected flow of the fan, as a function of time for different rates of application of intake loss. The dynamic operating point moves typically five times as far towards stall as the steady state solution with the same level of loss. The time scale is shown in terms of fan revs, and it can be seen that the dynamics persist for long enough to be a serious problem (ie more than 2 fan revs).

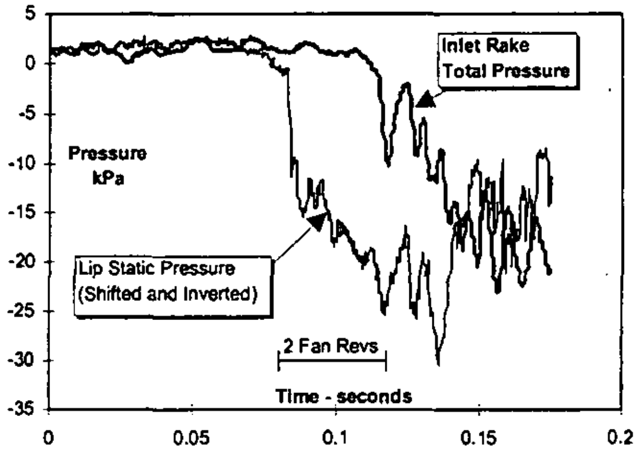

Fig 12 - Delay between Lip and Inlet Pressures

TIME DELAYS

The separation of the inlet is first seen as a rapid drop in Mach number at the inlet highlight: it drops from ~1.5 to ~1.0 typically. The spacing of the lip Kulites precluded a more precise definition of the Mach number change. Shortly afterwards the fan inlet rakes showed a large drop in total pressure comparable with the pre separation axial dynamic head.

The time lag between the fan face flow and the loss is made up of at least 3 elements, fan face flow to inlet highlight flow, inlet highlight flow to shock formation time and the convection time back to the fan face. The Inlet has a length of about 1.6 meters and runs at a mean Mach Number of ~0.55-0.60 hence the inlet flow will lag the fan face flow by around 11 milliseconds, the convection time for none shock flow is about 7 milliseconds, the convection time for low total pressure flow is correspondingly longer. Inlets operating at high flow are limited by the formation of shocks on the lip and consequent flow separation which convects down the duct. Figure 12 shows the static pressure on the lip and the mean fan inlet pressure for a single separation event. It shows that the rake pressure lags the lip pressure: the lip pressure rises sharply i.e. there is a shock; later, the rake pressure falls as the loss reaches the rake. A formal cross spectrum transfer function shows a mean lag of 40 milliseconds.

Simple calculations using the attached static pressure distribution and a lower post highlight shock total show that to account for the observed lags - around 40 milliseconds - the flow must be near separation for a sizeable distance along the inlet. The time for information to return to the inlet highlight from the fan is therefore 52 milliseconds if the fan responds instantaneously, it was observed that the downwind lip static rose about 50 milliseconds after the first increase on the upwind lip. The engine appeared to have a delay between fan face flow and loss of about 50 milliseconds. The simple calculation showed itself to be very sensitive to the loss so it is intended to apply 3D unsteady CFD to see if the delay can be predicted.

CONCLUSIONS

1) The engine / inlet combination produced an unstable oscillation of the flow apparently driven by the delay between the fan flow and the inlet response that coupled into the basic Helmholz like frequency of the engine.

2) The effect of the delay in the inlet was such as to make the combined characteristic of the inlet and fan unstable. This then drove the duct oscillation.

3) The inlet separated initially due to transient wind gusts that lasted longer than the basic 100 millisecond time period of the engine response.

4) When the Fan was pushed into stall the inlet would recover as the flow falls but the fan remains locked into stall because of the mixed nozzle characteristic and the fan stall hysteresis.

5) The model of the engine produced 10 Hz oscillations when supplied with the measured delay.

6) The delay time the engine produced was 4 times the freestream transit time from highlight to fan face.

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