THE EFFECT OF INTAKE FLOW DISTURBANCES ON APU COMPRESSOR BLADE HIGH CYCLE FATIGUE IN THE AIRBUS A300

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K. W. Lotter and J. Jörg
Messerschmitt-Bölkow-Blohm GmbH
Aircraft Division
Postfach 801160, 8000 München 80
Federal Republic of Germany

ABSTRACT

Premature compressor failures of the APU in the Airbus A300, related to high cycle fatigue, led to a detailed investigation of the relevant intake/engine parameters. Relatively high total pressure distortion and excessive flow angularity have been determined to be the cause of high alternating blade loads and, in combination with the chosen material of the compressor disk and blades, surface fretting. In systematic test steps intake modifications were developed to improve the intake flow quality. It is shown that only relatively minor intake modifications were required to achieve a substantial improvement in total pressure distortion and swirl. In addition, a suitable modification at the compressor blade dovetails was initiated to increase the blades' fatigue strength.

1. INTRODUCTION

Intake total pressure distortion and flow angularity do not only affect compressor stall margin and performance but also the generation of blade vibrations. These can significantly impair the structural integrity of the blades and vanes. Whether blade vibration is excited and to what extent is dependent on the magnitude and pattern of total pressure distortion and flow angularity and additional parameters like rotor speed, blade/disk resonance frequencies, damping characteristics, etc.

Although all these aspects are generally taken into consideration during the intake design phase, compressor high cycle fatigue failures due to blade vibration are sometimes experienced whilst the engine is in service.

Failures of this kind have occasionally occurred in the low pressure compressor of the APU in the Airbus A300. In order to fully understand and diagnose the problem, both the intake flow pattern and the possible engine related contribution were reconsidered during a joint investigation carried out by the intake and engine manufacturer.

This paper deals with the measurements and related analyses made to identify and improve the intake flow condition and describes modifications incorporated in the intake and engine compressor to eliminate the high cycle fatigue problem.

2. AIRBUS A300 APU INSTALLATION

2.1 Aircraft Requirements

The auxiliary power unit (APU), which in commerical aircraft is usually used on the ground for the power supply of the various aircraft systems and for starting the main engines, must be operable in the A300 aircraft also during flight. This feature enables the APU to supply the environmental control system (ECS) and the wing deicing system up to 15.000 ft and for shaft power output (generator) up to 30.000 ft. For the latter application the APU has been certified as an "essential unit" in order to allow a regular aircraft take-off even if one main engine generator has failed. If a single failure occurs during flight (failure of second main engine generator) the APU is then able to provide the required energy. It is possible to start the APU in flight up to 25.000 ft, thus not requiring continuous APU stand-by operation in case there is a pre-flight failure of one main engine generator.

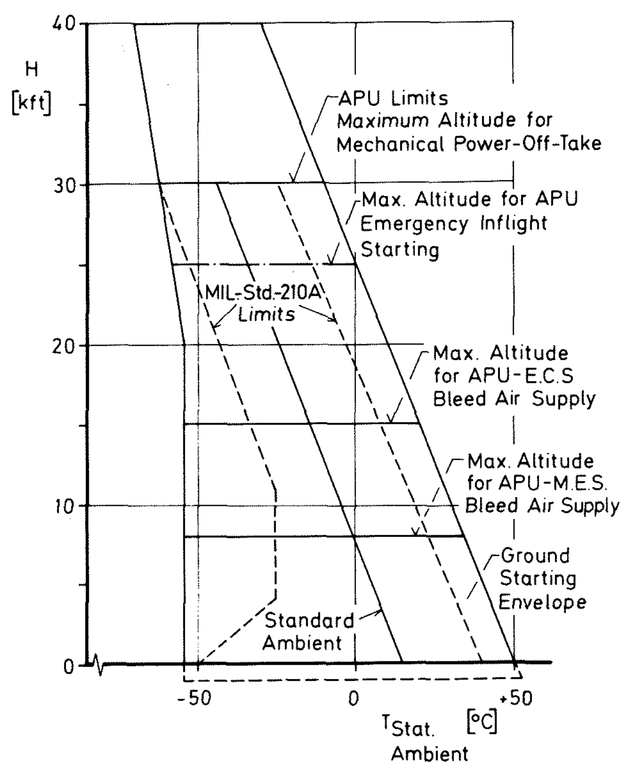

Figure 1. APU Altitude/Temperature Operating Envelope

The temperature/altitude envelope of the APU is shown in Figure 1 together with the altitude limitations for the different operating conditions.

In order to assure safe in-flight starting, an installation pressure ratio of IPR ≧ 1 (IPR = ratio of inlet total pressure divided by exhaust static pressure) is required. Furthermore, the wind milling speed of the low pressure rotor should not exceed 10 %.

2.2 APU TSCP 700-5

The APU TSCP 700-5 (Figure 2) contains a three-stage axial flow low-pressure compressor, followed by a single-stage high-pressure centrifugal compressor, a combustion section comprising a reverse flow annular burner, counter-rotating high-pressure (HP) and low-pressure (LP) spools on coaxial shafts, an accessory gear train that drives the fuel pump, oil pump, cooling fan and an output shaft to drive the generator. The high pressure compressor and single-stage axial turbine are mounted on the outer spool which drives the gear train, output shafts and accessories at a constant speed. The low-pressure compressor and the two-stage axial turbine are mounted on the inner spool. This variable-speed spool provides bleed air for the aircraft's use. The LP spool speed varies automatically, compensating for changes in the pneumatic load.

The control system automatically reduces the bleed-air load to give priority to the shaft load when the load limit is reached. A surge control valve is incorporated in the bleed-air output system to prevent surging of the APU during certain operating conditions, and to provide compressor stability during any no-load or shaft-load only operation and during the starting cycle.

2.3 Installation

The APU is installed in the tail cone of the fuselage (see Figure 3). This position was favoured after consideration of the essential installation requirements for fire protection, compatibility with the rear fuselage structure, accessibility, maintainability and icing. Aerodynamic requirements were: high ram recovery, low distortion, installation pressure ratio greater than 1.0 and low intake drag in flight. A major design constraint was the requirement for the APU system not to pass beyond frame 92 (Figure 3) with the APU or the intake system. This excluded some of the potential intake positions shown in Figure 4, i.e. No. 1 to 4. Of the remaining two positions, the one close to fuselage bottom centre line (No. 5) was finally chosen as it provided higher total pressure recovery and lower distortion for APU ground operation than position No. 6.

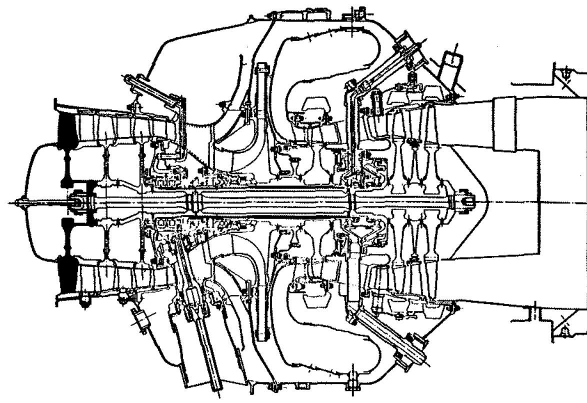

Figure 2. APU Longitudinal Section

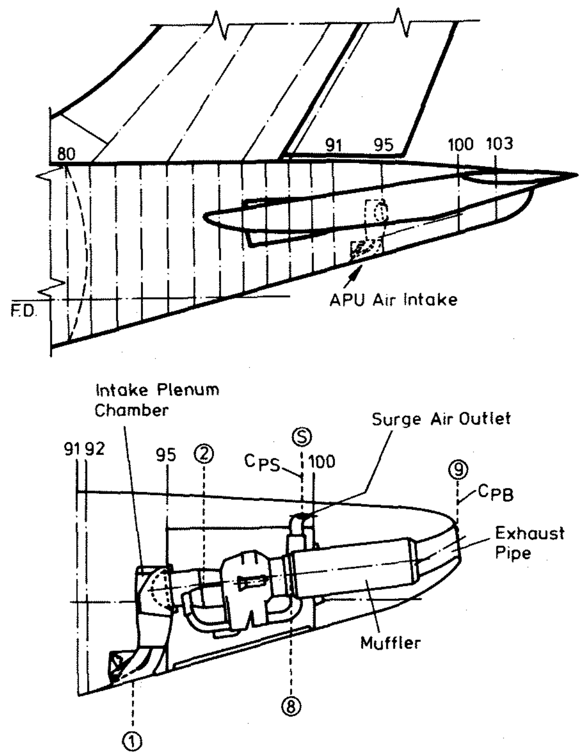

Figure 3. APU Installation in the Tail Cone

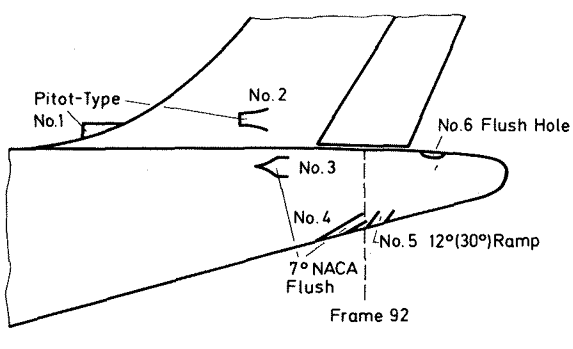

Figure 4. Investigated Intake Positions

3. REVIEW OF THE AIR INTAKE DEVELOPMENT

3.1 Intake Concept and Design Restrictions

The initial intake design which dates back to 1969, is shown in Figure 5. A flush ramp intake was chosen in order to meet the requirement for a low drag installation during aircraft cruise when the APU is inoperative. Downstream of a short rectangular intake duct there is a plenum chamber from which the air is sucked through a bellmouth and a cylindrical duct and fed to the APU. A screen has been installed in front of the bellmouth to prevent the ingestion of foreign objects. A ring splitter in the cylindrical duct was initially considered to suppress APU noise radiation. The restriction not to pass beyond section 92 of the rear fuselage structure (Figures 3 and 4) with the air intake system, together with the limited space in the rear cone for the APU and the plenum chamber, did not allow the incorporation of a low ramp angle. A 26° ramp angle relative to the lower fuselage surface was chosen to provide a sufficiently high throat area for ground operation. This, of course, necessitated relevant tests to demonstrate the in-flight operation using this geometry.

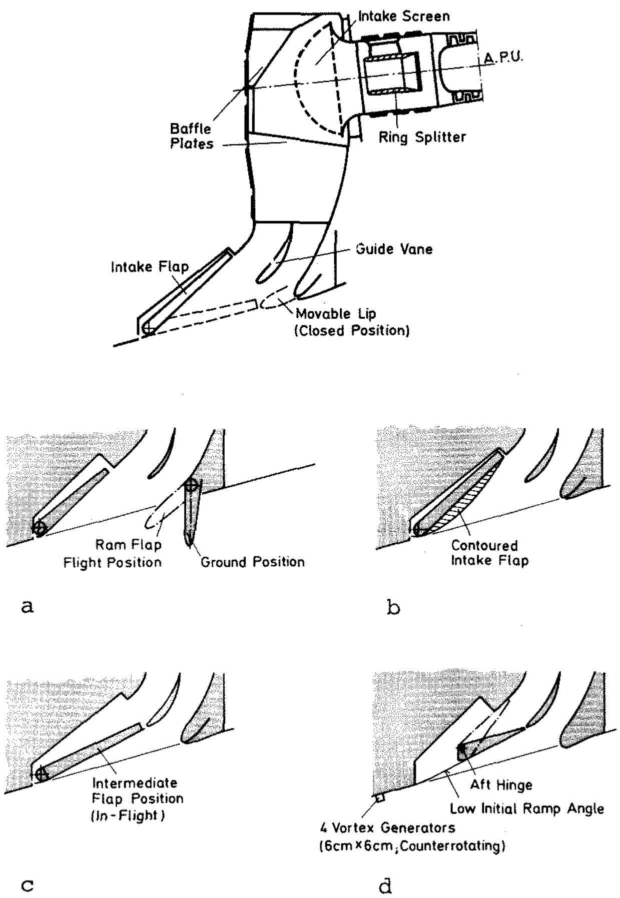

Figure 5. Initial Intake Design

3.2 Development of the Air Intake

During the intake development, experimental investigations were carried out comprising full scale static tests, different wind tunnel model tests and flight tests. An analysis of the test data indicated that the original intake design did not provide sufficient ram pressure for in-flight starting of the APU. At the time, a ram flap (rotatable inlet lip) with two operating positions was considered to be a possible solution (Figure 5a). In-flight flow separation at the ramp in the fully open ramp position caused afterbody vibrations and made additional modifications necessary. The essential geometric variations during the flight test phase covered:

- rotatable cowl (ram flap), Figure 5a
- contoured intake flap to reduce the initial ramp angle, Figure 5b
- intermediate flap position during in-flight operation, Figure 5c, to avoid in-flight flow separation
- aft position of the flap hinge with a low initial ramp angle, Figure 5d
- four vortex generators immediately upstream of the intake leading edge, Figure 5d.

The intake configuration eventually selected is shown in Figure 6. It provided good internal performance on the ground and in flight, low drag and a sufficiently high installation pressure ratio (IPR $\geqq$ 1.0) for in-flight starting. The ring splitter in the cylindrical duct (Figure 5) was not installed in any of the flight tests as acoustic tests had shown that the specified noise level could be achieved without this device. The initially planned in-flight swirl measurements were not performed after all due to the successful intake/engine operation using the selected intake configuration.

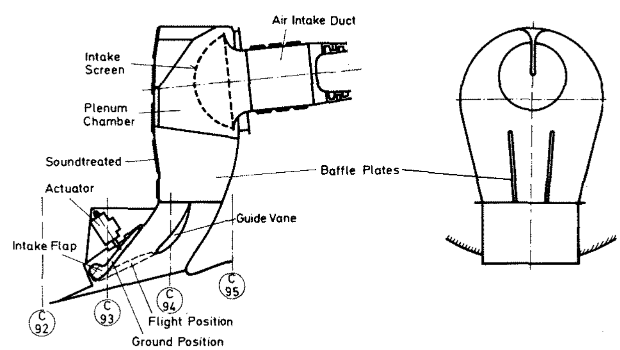

Figure 6. Air Intake Configuration

4. COMPRESSOR BLADE HIGH CYCLE FATIGUE FAILURES

4.1 Blade Dovetail and Disk Platform Separations

To the same extent as the number of aircraft in service and the accumulated flight hours per aircraft increased, a growing number of cracks (Figure 7) or blade separations was experienced in the low pressure compressor, especially in the first stage. Surface micrograph analysis identified high cycle fatigue (HCF) as the reason for these failures. In a number of failures, blade dovetail and/or disk single platform separations occurred (Figure 8), which is typical of high cycle fatigue. The inspection of the blade dovetails revealed that the cracks had been induced by fretting (see Figure 8).

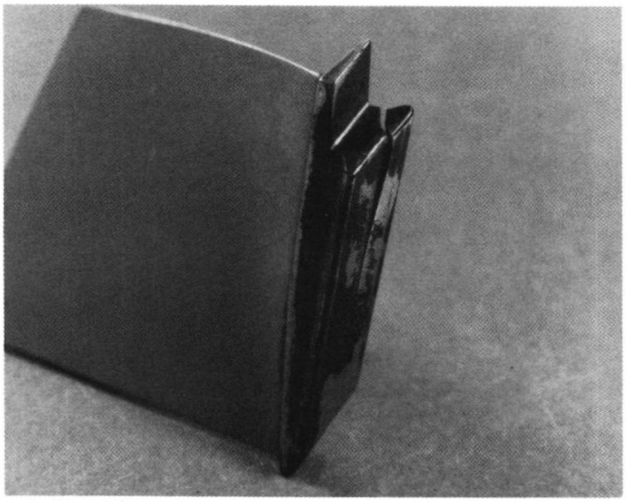

Figure 7. Crack in Blade/Dovetail of 1st Stage LP Compressor

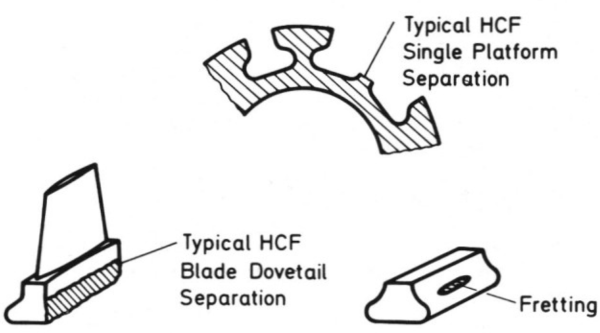

Figure 8. Blade Dovetail Fretting and Typical HCF Failure

4.2 Field Incident Summary

The average number of operating hours accumulated at the time of failure was about 2000 to 3000 with a large scatter beyond these numbers. The main findings were:

- Some aircraft experienced more HCF incidents than others
- Some APU's experienced more HCF incidents
- The majority of incidents occurred at 100 % N_L (a speed limitation below 100 % was incorporated in some of the APU's in service)
- No correlation was established between ground and in-flight operation
- Surface fretting on the blade dovetails was found in 80 % of the blade failures
- The majority of failures occurred in the first stage of the LP compressor.

4.3 Possible Causes of HCF Failures

Right from the beginning, the investigation of the causes of the HCF failures was directed towards both the intake flow non-uniformity and the possible APU-related factors.

Intake Flow Non-Uniformity. Any steady state intake flow which, however, is circumferentially non-uniform, is always associated with substantial relative flow-incidence and/or velocity-variations for the rotating blade, obviously initiating dynamic blade loading.

In Figure 9 some typical intake non-uniformities are shown together with their effect on the velocity diagram. The varying incidence and/or magnitude of the relative velocity create the cyclic dynamic blade loading. A quantitative correlation of non-uniformities of intake flow and dynamic blade forces has been presented in (1).

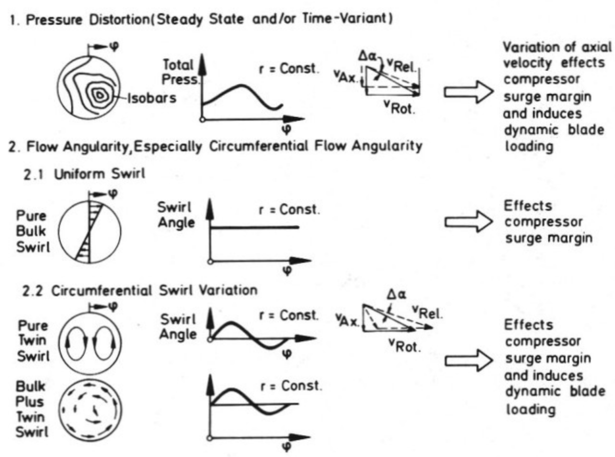

Figure 9. Possible Contribution of Intake Flow Disturbances to Compressor Blade High Cycle Fatigue

Engine Related Contribution. The Campbell diagram (Figure 10) for the first stage compressor indicates a blade-disk resonance vibration for the 3rd engine order within the ECS operating range of the APU. A further resonance case for the 2nd engine order occurs at 100 % rotor speed, i.e. when starting the main engine. That means that an intake flow distortion with a three per revolution excitation component would create blade/disk resonance excitation during ECS operation and with a two per revolution excitation component during MES operation. The latter resonance case may explain the reduced failure rate which was experienced in service, when the speed limitation in the control system was set below 100 %. This was incorporated in a part of the fleet.

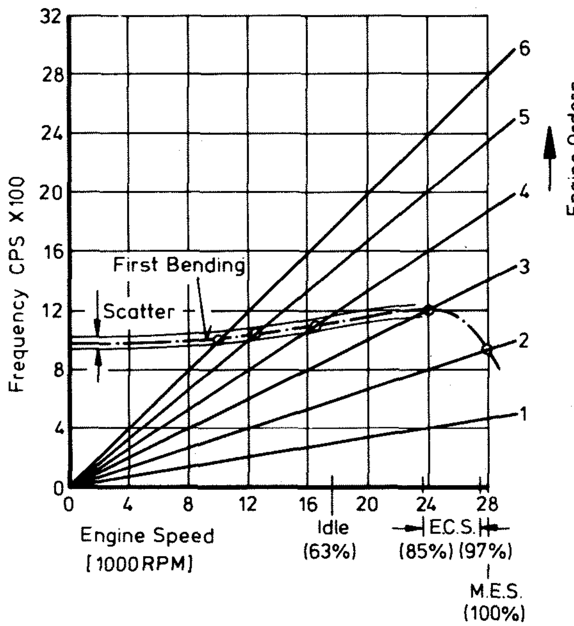

Figure 10. Campbell Diagram with Coupled Blade-Disk Frequency

The observed blade dovetail surface fretting was suspected to be at least partly attributable to the material combination which was chosen for the blade and the disk. Both the blades and the disk are made of the same material, i.e. Ti-6Al-4V. It is a well-known fact that this is a potential source of surface fretting which, however, can be eliminated by surface coating.(2)

Combined Effect. It has been hypothesized that the observed HCF failures might have been caused by a combination of intake flow non-uniformity, blade/disk material selection and blade/disk resonance excitation:

In Figure 11 the fatigue curve is shown for both the ideal surface blade and the fretted surface blade. It is a well-known fact that Titanium is extremely sensitive to surface fretting (2) resulting in a considerable reduction of permissible alternating stress, down to 30 % of that for the unfretted surface.(3) Together with an excessive alternating stress due to intake flow disturbances and resonance excitation, a fatigue failure is possible at $n>>10^7$ cycles, which is well beyond the 10^5 to 10^7 cycles where usually no fatigue damage is expected. In order to investigate the possible contribution of the intake flow to the HCF problem, a program was initiated aimed at identifying the intake total pressure distortion and swirl.

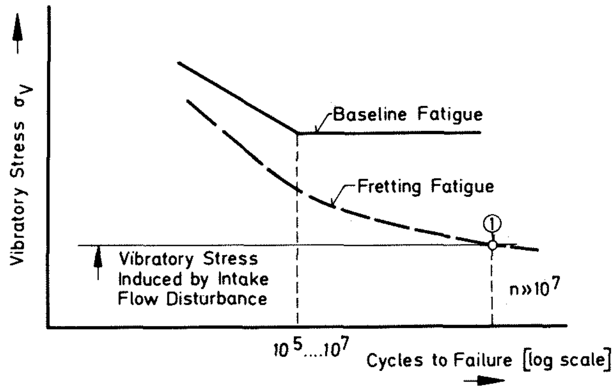

Figure 11. Fatigue Curve for Ideal and Fretted Surface

5. INTAKE FLOW INVESTIGATIONS

As mentioned above the APU intake of the Airbus A300 comprises a flush ramp inlet on the rear fuselage underside which is followed by a plenum chamber. From there the air is ducted through a cylindrical pipe to the APU. Detailed flow investigations were performed mainly in that pipe, but some additional data were obtained from the plenum chamber and the APU annulus duct wall.

5.1 Testing Techniques

The majority of the flow data was obtained from a five-hole probe rake in a measuring plane located 128 mm upstream of the 1st stage compressor blade leading edge (see Figure 12a). The rake incorporated 13 five hole probes and was rotatable in 30° or 45° increments thus giving flow information at 37 or 25 measuring plane locations (Figure 13). This rake was used to measure the total pressure recovery, the total pressure distortion and, most important of all, the flow angularity.

To obtain a quick impression of the overall flow pattern a smoke probe was used and smoke photographs were made.

However, this method required transparent areas of the plenum chamber and duct wall and thus could only be used during static and wind tunnel testing.

Therefore, coloured oil was used to make the duct wall flow visible and this test method was applied mainly in APU ground and flight tests with the A300 development aircraft of Airbus Industrie.

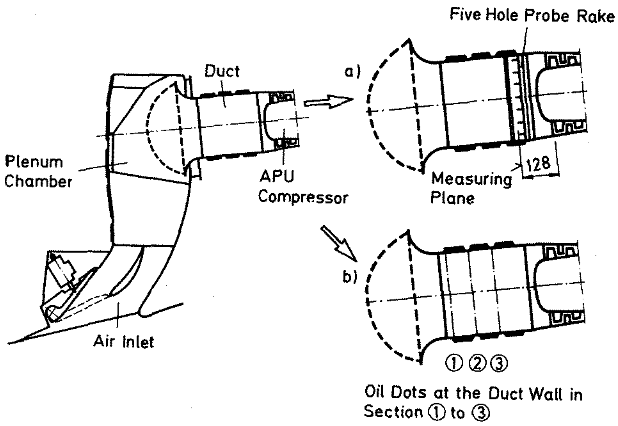

Figure 12. Testing Techniques

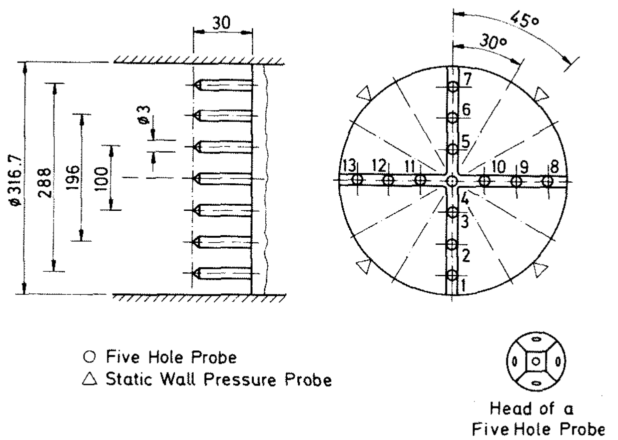

Figure 13. Five-Hole Probe Rake

In order to obtain such flow pictures small drops of oil were put in three or four sections of the duct wall (Figure 12b). The APU was started and then kept at a constant speed for about five minutes. After APU shut-down the duct was removed and a copy of the oil traces was obtained by pressing a suitable sheet of paper to the wall of the cylindrical duct. Figure 14 shows a copy of a duct flow picture. This method was not only used in APU ground runs but also in APU in-flight operation. In this case, the drops of oil were positioned immediately prior to the aircraft take-off without using the APU for MES or ECS purposes. At a specific flight altitude and flight Mach number the APU was started and operated for several minutes. After shut-down it was not used again during that flight or after landing. In this way it was possible to obtain a copy of the wall flow picture belonging to the specific flight conditions. It was found that there was no detrimental influence on the flow pictures from the windmilling air flow which occured in flight before or after the APU test run. It was even possible to copy the oil traces up to 24 hours later without there being any changes in the results.

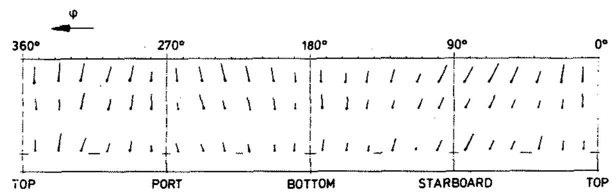

Figure 14. Copy of an Intake Duct Wall Flow Picture

5.2 Test Steps

The test activities included a full-scale static test, a full-scale low-speed wind tunnel test and flight tests both with the unmodified APU air intake and several modified ones.

The test set-up of the static test is illustrated in Figure 15. APU ground operation was simulated by mass flow suction. During this test phase the unmodified APU intake configuration was tested first, followed by a number of modified configurations which were intended to reduce flow angularity and distortion. Flow data were obtained from the five-hole probe rake and from flow visualization by using smoke and oil flow pictures.(4)

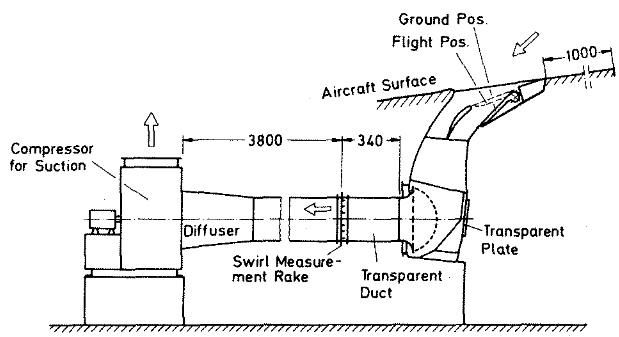

Figure 15. Test Set-Up of the Full Scale Static Test

Ten different intake modifications were tested during a low-speed wind tunnel test phase (Figure 16). The aircraft surface was simulated by a profiled shell and suction was provided by a compressor. Static and wind-on tests were carried out to simulate APU ground and in-flight operation conditions. As in the previous static test, flow data were obtained here from the rake as well as from flow visualization by using smoke and oil flow pictures. (5)

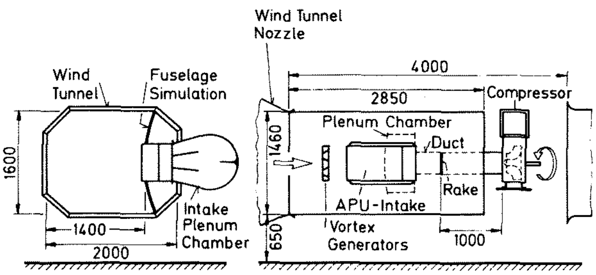

Figure 16. Model Installation in a Low-Speed Wind Tunnel

Flight tests were carried out both with the unmodified APU intake (production aircraft configuration) and with various modified intake configurations which were found to be favourable during the different previous tests. (6, 7) Flow data were obtained from the five-hole probe rake and from flow visualization by using the oil drop technique mentioned above. This method yielded additional information especially about cases where high swirl angles occurred which exceeded the usable measurement range of the five-hole probes (i.e. exceeding 20° to 25°).

6. TEST RESULTS

As can be seen from Figure 9 the intake duct total pressure distortion and the circumferential flow angularity upstream of the compressor both cause dynamic blade loading. Therefore, in the following account, emphasis is laid on the comparison of these two factors in the unmodified series intake and the improved intake configuration.

6.1 Unmodified Intake Flow Pattern

Initial testing was aimed at identifying the flow pattern in the cylindrical duct upstream of the APU for the series intake configuration and at understanding the overall intake flow pattern. Figure 17 gives an outline of the APU intake flow including the plenum chamber. With the intake flap in the fully open position (corresponding to APU ground operation) flow separation and back flow areas occur at the front and side walls of the plenum chamber and at the intake vane. This flow pattern causes an intake duct flow with a high circumferential swirl variation.

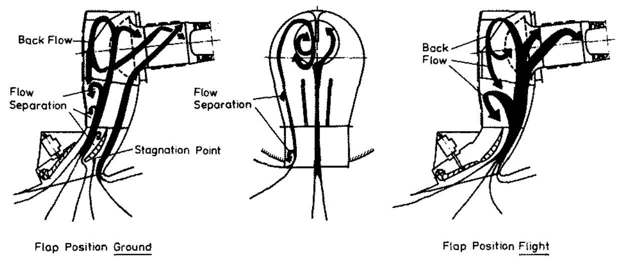

Figure 17. Unmodified Intake Flow Pattern (from Smoke Flow Visualization)

With the intake flap in the half-open position (corresponding to APU flight operation) the sudden expansion at the intake vane trailing edge gives rise to a strong back flow in the plenum chamber and leads to a duct flow pattern with higher swirl angles than in the case of the fully open flap. It has to be noted that this result has been obtained from static testing and, therefore, the external flow which occurs in flight has not been taken into account. However, it was shown that the main contribution to the intake flow pattern comes from the internal intake geometry and to a lesser extent from the outside flow conditions. Thus the intake flow pattern is represented here quite well.

In addition, the variation of APU mass flow within the normal operation range had only a small effect on the flow pattern and the magnitude of swirl angles both during ground operation and in flight. The flight Mach number was found to have a minor influence on the flow pattern and the intake duct swirl angles.

6.2 Intake Modification

Two ways of reducing the swirl angles in the intake duct were considered:

- flow improvement by a flow straightener attached to the intake duct,
- flow improvement by avoiding strong separation areas in the plenum chamber.

In addition to various flow straighteners many plenum chamber modifications were tested, such as changing the baffle plates' position or the intake vane shape and position, adding fairings or rounding the intake/fuselage skin corners. This led to a solution which is given in Figure 18 consisting of

- a modified position of the baffle plates (parallel to each other),
- a fairing between the two baffle plates attached to the rear plenum chamber wall.

The position of the two baffle plates was found to have a major effect on the plenum chamber and the intake duct flow pattern. With the new position and the fairing a considerable duct flow improvement has been obtained and a relatively simple modification has been found which resulted in low modification cost.

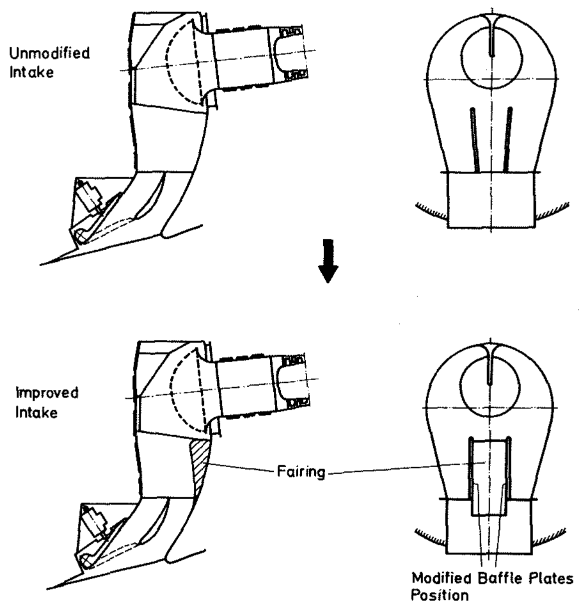

Figure 18. Intake Modification

6.3 Flow Improvement

Figure 19 shows a comparison of the unmodified intake flow angularity in the intake duct measuring plane including rake and wall flow visualization data with the corresponding result of the selected intake modification. Due to a rake failure during flight testing, rake data are not available from the APU ground run using the intake which has eventually been selected. However, the wall flow angles proved that an effective flow straighening was achieved. As the flow angles can be expected to be smaller at some distance from the wall, a good flow improvement throughout the whole cross section can be expected. The maximum swirl angles at the duct wall have been reduced from 40° to 20°, i.e. by 50 %. This can be seen from Figure 20 where the wall flow angles are plotted versus the circumference.

In flight, the maximum swirl angles at the duct wall have been reduced from a level of near 50° to 26°, and within the duct cross section the improvement has been from a level outside of the five-hole probes' usable measurement range down to 18° (Figures 21, 22). At one isolated position a swirl angle of about 26° was measured, however, the corresponding probe has been suspect.

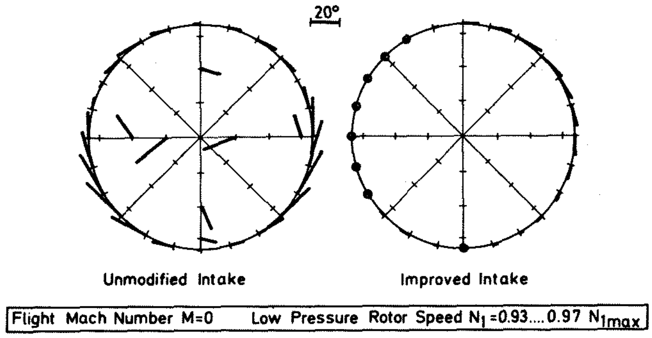

Figure 19. Intake Duct Flow Angularity (APU Ground Operation)

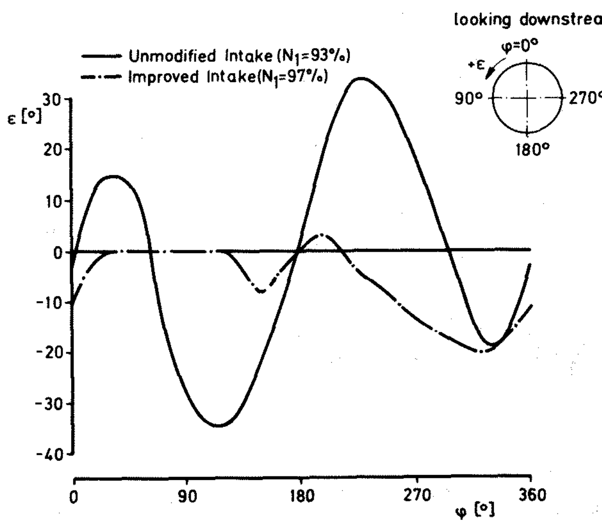

Figure 20. Intake Duct Wall Flow Visualization Results (APU Ground Operation)

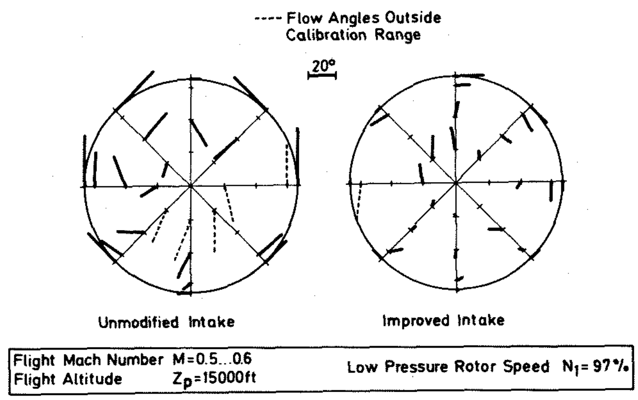

Figure 21. Intake Duct Flow Angularity (APU Flight Operation)

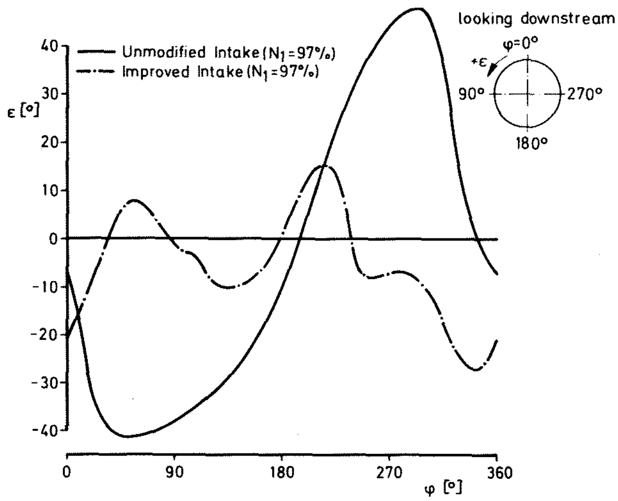

Figure 22. Intake Duct Wall Visualization Results (APU Flight Operation)

Like the swirl angles the in-flight total pressure distortion is reduced roughly by half (Figure 23). This improvement can be assumed to be correct although the absolute distortion levels may be too high due to the fact that all the total pressure data were obtained from the centre holes of the five-hole probes: Under high swirl conditions the centre hole of such a probe indicates a lower total pressure than a typical pitot probe would do, i.e. with a pitot probe rake lower distortion levels would have been measured.

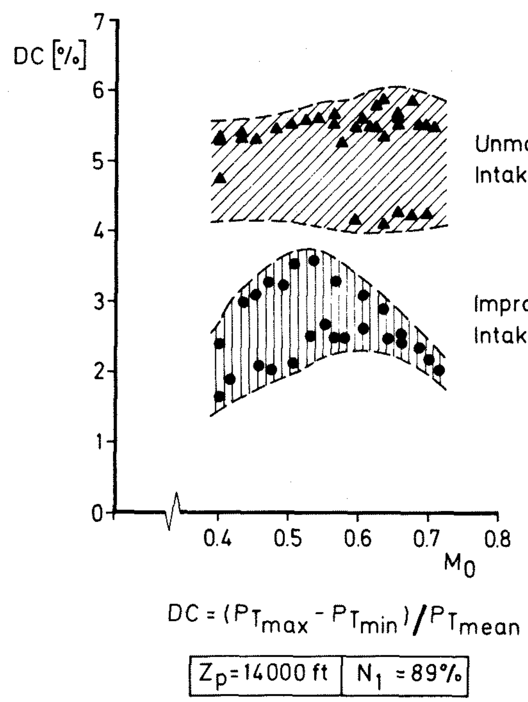

Figure 23. In-Flight Total Pressure Distortion

In order to find out what effect the flow improvement measured in the intake duct has on the first stage blades of the APU compressor, the flow visualization technique was applied to the APU annulus duct directly upstream of the first stage of the low pressure compressor. In this region the duct cross sectional area is reduced by a factor of nearly 2 which increases the maximum duct flow Mach number from $M_{D1} \approx 0.25$ to $M_{D2} \approx 0.50$. According to Figure 24, the maximum swirl angles at the APU annulus wall are obviously smaller than the corresponding ones at the intake duct wall for both the unmodified intake and for the improved intake. This can be explained by assuming a constant circumferential velocity component in relation to the increasing axial component. The swirl reduction factor at the APU annulus wall is nearly the same as in the intake duct.

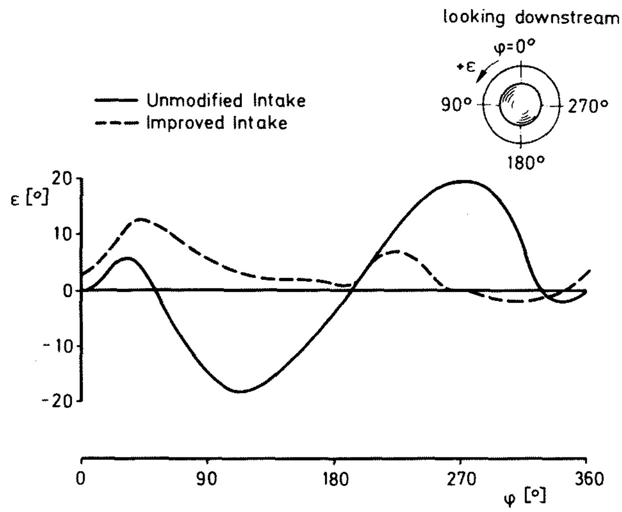

Figure 24. APU Annulus Duct Wall Flow Visualization Results (APU Ground Operation)

It can, therefore, be concluded that the flow improvement which has been realized with the aid of the above-mentioned intake modification will reduce the first stage compressor blade oscillations in an effective manner and thus greatly eliminate the aerodynamic cause of the high cycle fatigue problem.

7. APU MODIFICATION

As mentioned in para. 4.3, the use of the same material for blades and disk was considered to contribute to surface fretting. A generally applied solution to suppress or avoid fretting is shot peening and surface coating (2). As both the disk and the blade dovetails had already been shot-peened it was proposed to apply a copper/nickel coating to the blade dovetail to eliminate a possible APU-related cause of the HCF failure. Field experience with a limited number of coated LP compressor blade sets proved to be successful with respect to fretting resistance. The modification proposal for coated LP compressor blades was made on this basis.

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