INTAKE SWIRL - A MAJOR DISTURBANCE PARAMETER IN ENGINE / INTAKE COMPATIBILITY

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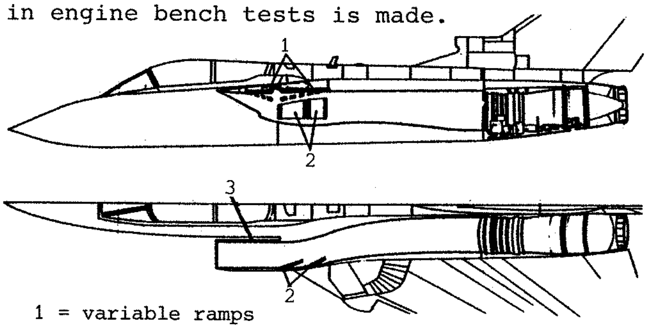
Abstract

Based on theoretical considerations and primarily on experiment it is shown that all supersonic intakes of present combat aircraft produce essentially two types of swirl components of varying magnitude i.e. bulk and twin swirl. Depending on the sensitivity of the engine towards such disturbances serious engine/intake compatibility problems may arise, as for example engine surge and fan vibration.

The remedial measures to overcome this problem are described and the solution of fenced intakes selected for Tornado is discussed. It is expected that this intake modification may also be of advantage for other high performance combat aircraft having similar intake configurations.

Finally the relevance of dynamic total pressure distortion as prime compatibility parameter is questioned and a proposal for an improved intake disturbance simulation in engine bench tests is made.



1 = variable ramps
2 = auxiliary air intake doors (AAID)
3 = boundary layer diverter

Figure 1. Tornado Inlet Geometry

1. Introduction

To avoid malfunction of the engine, e.g. surge and fan vibration, the intake flow must be of sufficient quality, especially of sufficient uniformity for the engine to tolerate. In past fighter projects, this engine tolerance to intake flow distortions was almost exclusively based on total pressure distortion parameters defined at the engine face. These distortion parameters have been defined for steady state and for time variant conditions and differ in definition from engine manufacturer to engine manufacturer. Statistical methods had to be used in some cases to quote "success rates" when trying to correlate an engine surge with a preceding triggering peak in the instantaneous pressure distortion.

The acquisition and analysis of instantaneous distortion coefficients represents a considerable effort, especially if this is also done in flight testing, as was the case e.g. with the F111 and the F15. During the flight testing of the Tornado aircraft it soon became apparent that pressure distortion by itself, be it steady state or instantaneous DC60, is probably not the decisive compatibility parameter. At least of equal importance for the Turbo Union RB199 engine the intake cross-flow is considered, as will be shown in the following.

2. "Handed" Problem

To assess inlet/engine compatibility only steady state and instantaneous pressure distortions near the compressor entry plane were measured during early Tornado inlet model testing. As expected, these patterns were symmetric relative to the aircraft symmetry plane. The magnitude of the distortion coefficients were within specified limits, although relatively high both at subsonic flight/high incidence and at high supersonic Mach numbers/low incidence conditions. To minimize the risk of intake/engine incompatibility the combination of the full scale intake and the engine was also investigated: For subsonic flight a right hand intake was installed under the fuselage of a Vulcan bomber serving as a Flying Test Bed (FTB, Fig. 2) while for supersonic flight speeds a left hand intake was tested in Cell 4 of the National Gas Turbine Establishment (NGTE) in Pyestock, United Kingdom (UK). Apart from occasional "rough running" of the engine under adverse conditions, which

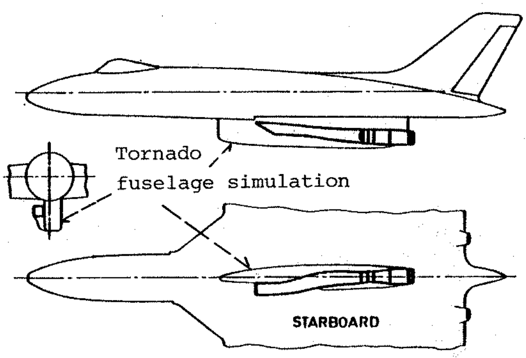


Figure 2. Flying Test Bed

was attributed to the early engine standard, no serious compatibility problems could be clearly predicted. Therefore, it was only after prototype flight testing had started that engine surges were consistently found for the left hand engine at $M < 1$ / $\alpha \gg 0^\circ$ and for the right hand engine at $M > 1{,}8$ / $\alpha \approx 0^\circ$. Besides surge, also an increasing difference in fan RPM of the left hand and the right hand engines was observed with increasing incidence at subsonic flight speeds, Fig. 3. In summary, there seemed to be a clear indication that the early intake/engine incompatibility of Tornado was a handed problem, which could not have been readily detected by pressure distortion measurements.

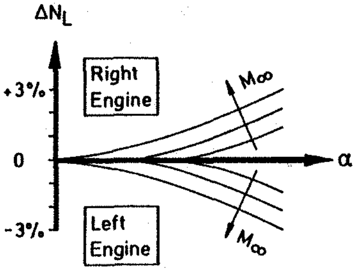


Figure 3. Effect of Incidence on Fan-RPM

It should be noted that even if the right and left hand intakes had been exchanged in the engine tests, the incompatibility would have either not emerged at all or at least appeared in a much milder form. This is because in the FTB the fuselage of the Vulcan provided sufficient shielding of the Tornado intake thus reducing the effective incidence, while in the Cell 4 tests the total pressure rake installed ahead of the compressor face improved the flow quality. This flow straightening effect was confirmed in later model tests and prototype flying with a rake installed.

3. Cross-Flow in Curved Pipes

After the handed compatibility problem had been encountered in (subsonic) prototype flying, theoretical and especially experimental investigations on this topic were initiated at the airframe and engine manufacturers as well as at the UK research groups NGTE and RAE. Some of the main results are presented in this paper.

3.1 Twin Swirl

The existence of twin swirl in flows through curved pipes has been well known: centrifugal forces push the higher energy stream lines towards the outer radii of the bend while the low energy stream lines are in turn forced to move inwards, Fig. 4 and 5. For example, in a thesis by Detra in 1953 (1), this phenomenon was investigated as well experimentally as theoretically (inviscid) and its effect on turbo engines, as regards performance degradation, pointed out.

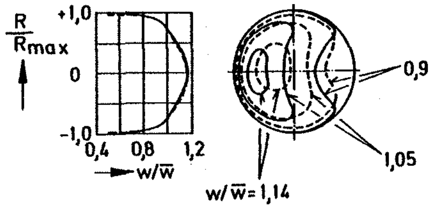


Figure 4. Comparison of Computed (Solid Lines) and Measured Twin Swirl (Dashed Lines) in a 21° Bent Pipe. Lines of Constant Axial Velocity Ratios;$\bar{w}$=41,6 m/s;Ref.1

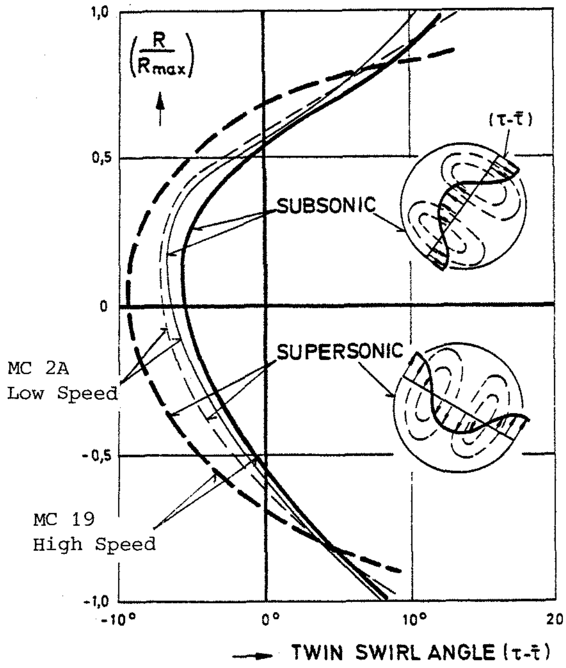


Figure 5. Similarity of Twin Swirl for Different Free Stream Conditions (Legend at End of Paper)

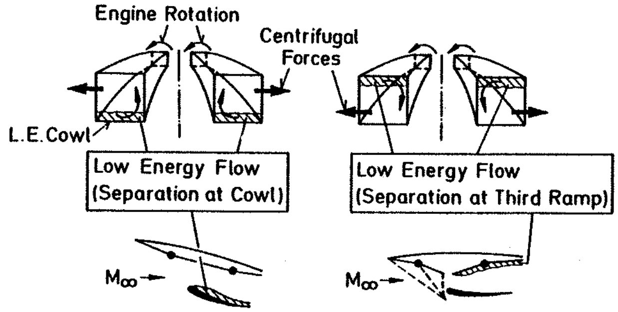
In the Tornado inlet models and in the full scale aircraft, which all had the identical S-shaped curvature of the intake duct, this twin swirl could be identified. It proved to be the most stable component of the total swirl pattern measured at the engine face. That is, it was little affected by external flow field (M_∞, α) or by internal intake modifications like flow straighteners (see below).

As an example, Fig. 5 shows the circumferential angle $(\tau-\bar{\tau})$ of the twin swirl component versus intake duct radius for a subsonic, high incidence condition and for a simulated, high supersonic inlet ramp geometry as measured in the low speed 1/7th scale BAe model MC2A of the unmodified inlet. For the supersonic simulation, which was carried out prior to the actual supersonic wind tunnel tests, the mass flow ratio A_O/A_C was approximately duplicated and, of course, no shocks were present. The twin swirls obtained from later tests in the transonic and supersonic wind tunnels with the 1/6,5th scale high speed MBB model MC19 are in qualitative agreement, as indicated in the same figure.

3.2 Bulk Swirl

Bulk swirl is defined here as the circumferential mean value of the circumferential flow angles for each radius R = const. For Tornado this swirl type was found to be similar to a solid body type rotation; its generation can be explained in the same way as above if only one half of the "twins" is considered:

A region of low kinetic energy (low total pressure) located asymmetrically at one portion of the duct perimeter, e.g. either at the intake cowl or at the third ramp, is pushed towards the inner radius of the bend while the high energy air is moved outwards by centrifugal forces as illustrated in Fig. 6.



a) Subsonic, High Incidence

b) High Supersonic, Low Incidence

Figure 6. Generation of Intake Swirl

Fig. 6 also explains why the bulk swirl is contra-rotational to the fan at $M_\infty < 1$, $\alpha >> 0^\circ$ in the left hand engine and at $M_\infty > 1{,}8$, $\alpha \approx 0^\circ$ in the right hand engine respectively. This is in agreement with the handed occurrence of surge in flight. Bench tests conducted by Turbo Union and intake modifications tested in flight by BAe also confirmed the surge triggering effect of intake swirl being contra-rotational to the engine fan.

In contrast to the twin swirl, bulk swirl is rather sensitive i.e. it changes considerably in magnitude and also in sign for varying external flow conditions. It can be reduced significantly by flow straightening devices.

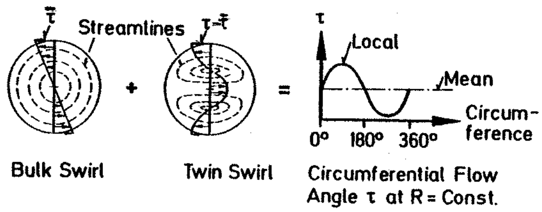


Figure 7. Superimposing of Bulk and Twin Swirls

3.3 Typical Fighter Intake Swirl

In the Tornado intake there is always a combination of twin swirl and some degree of bulk swirl present. Fig. 7 illustrates the superimposing of these two basic intake swirl components. In all other combat aircraft intakes studied by MBB in this respect, the situation is quite similar and should, therefore, also apply to the inlets of the F-111, F14, F15, MIG25, etc. As an example Fig. 8 shows a flow separation at the cowl and at the last (subsonic) ramp of the F15 intake, which resembles very much the flow separation in the Tornado intake. The isobars for the supersonic ramp position, when compared with fig.4 are rather symmetric and therefore indicate a strong twin swirl with only moderate bulk swirl.

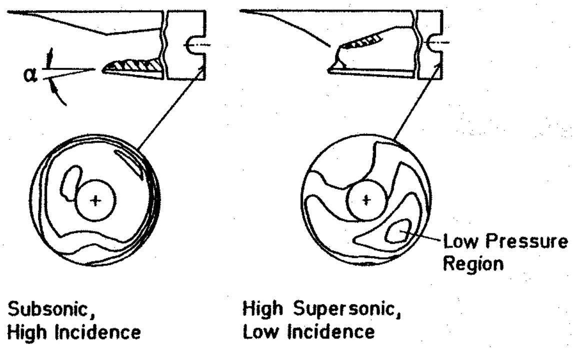


Figure 8. F15 Inlet Flow Separation(10)

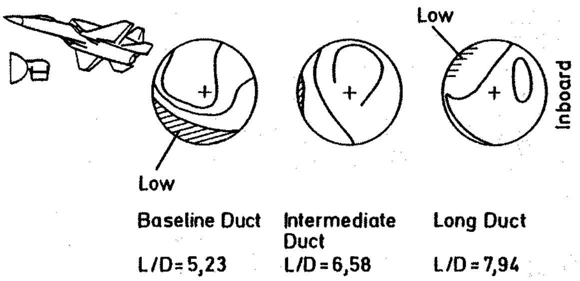


Figure 9. Rotation of Total Pressure Distribution with Duct Length

During the US intake/airframe integration project Tailor-Mate, among others, a side-mounted 2-D inlet configuration was investigated(4). The isobars measured at three different axial stations show a circumferential rotation of the low pressure region by about 100° for a downstream shift of 2,7 duct diameters, Fig. 9. This is indicative of a bulk swirl, as will be illustrated later in Fig. 19. Fig. 10 shows the engine face swirl pattern as measured by MBB in a low speed wind tunnel for a sidemounted inlet with (minimum) shielding by a canard. The components of bulk swirl and twin swirl have been obtained very clearly from the measured local values. Fig.11 demonstrates the superiortiy of the fuselage-shielded inlet when combined with negligible lateral inlet/engine offset (minimized separation located symmetrically).

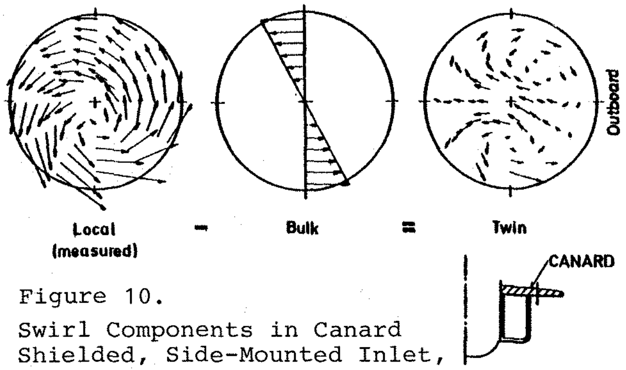


Figure 10.
Swirl Components in Canard Shielded, Side-Mounted Inlet, Incidence = 70°

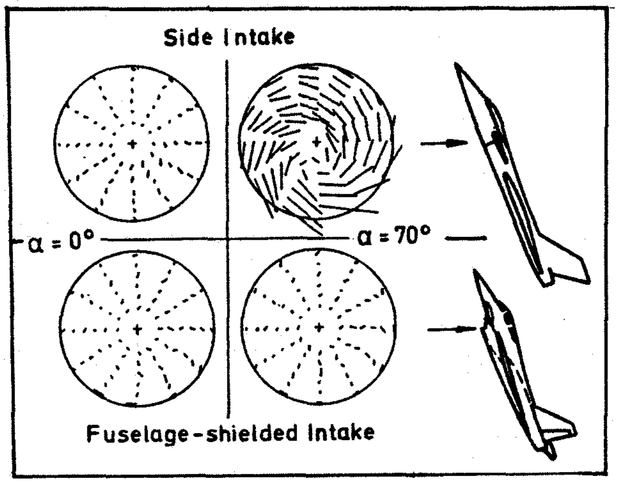


Figure 11. Effect of Incidence on Engine Face Swirl for Fuselage-Shielded and for Side-Mounted, Canard-Shielded Intakes

4. Tornado Results

Although the results presented in this paragraph were obtained for Tornado, they should, as has been explained above, also apply to similar intakes of other aircraft.

4.1 Swirl Data

At subsonic speeds both the bulk and twin swirl increase with incidence (Fig.12): The extremes in deviation from the mean value, the local maximum and minimum values at the outermost measuring station R = 0,87 R_{max}, are a measure of the strength of the twin swirl, which is more than doubled towards the high incidence end. In flight, engine surges occurred consistently in the left hand installation at high mass flows well before the maximum swirl angles were reached; the right hand engine was surge-free.

At supersonic speeds an analogous dependence of swirl versus second ramp angle δ_2 was found, Fig. 13. The swirl being now largely contra-rotational to the fan rotation of the right hand engine and obviously co-rotational to the left hand engine. As expected, the right hand engine surged regularly while the left hand engine was now surge-free.

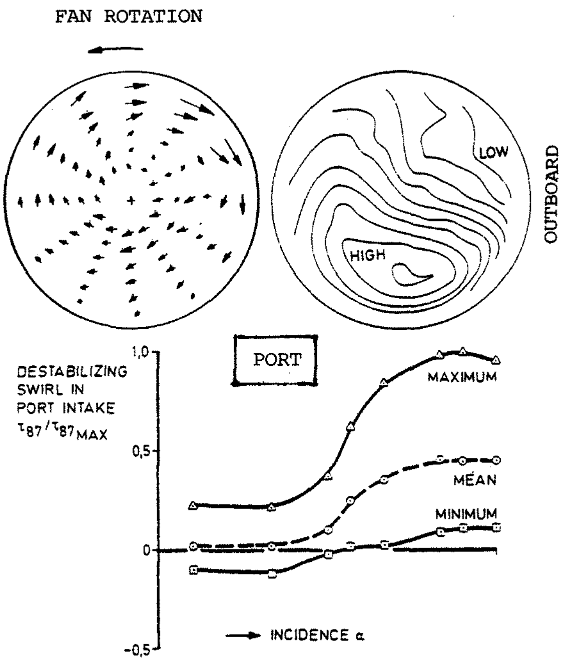


Figure 12. Swirl of Basic Tornado Inlet at High Incidences, M_∞ = 0,7, Max. Dry Engine Mass Flow (3)

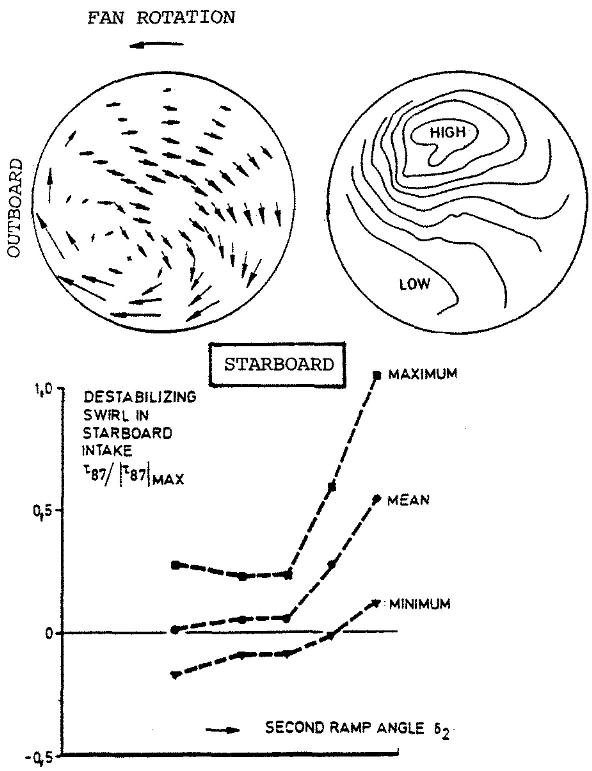


Figure 13. Swirl of Basic Tornado Inlet at High Ramp Angles, M_∞ = 1,8, α= 3° Combat Engine Mass Flow, AICS Controlled (3)

Reducing the engine mass flow at intermediate incidences produced swirl angles of similar magnitude, however, of opposite sign, Fig. 14.

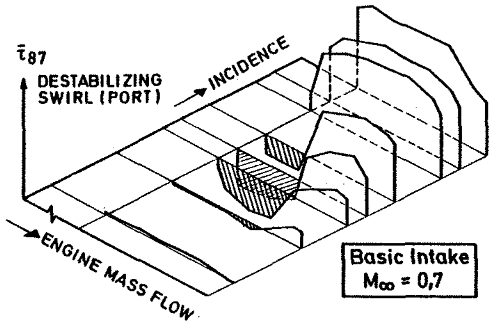


Figure 14. Effect of Incidence and Engine Mass Flow on Mean Swirl ($R = 0{,}87\ R_{max}$)

A comparison between model and full scale data was made under static conditions. As shown in Fig. 15, the flow angles at the duct wall of prototype P01 obtained by the oil flow technique agree quite well with the flow angles measured in the 1/6,5 scale model by a rotatable 8 arm rake having 24 five-hole probes. This is an important result, as it indicates that there are no significant Reynolds number effects present. Also, as known from boundary layer research, the cross-flow angles change only mildly near the wall, although the flow velocities decrease rapidly towards zero. Lastly, measurement of the wall flow angles alone may suffice in many cases for a quick evaluation of intake modifications and their effect on flow angularity in the complete cross-section.

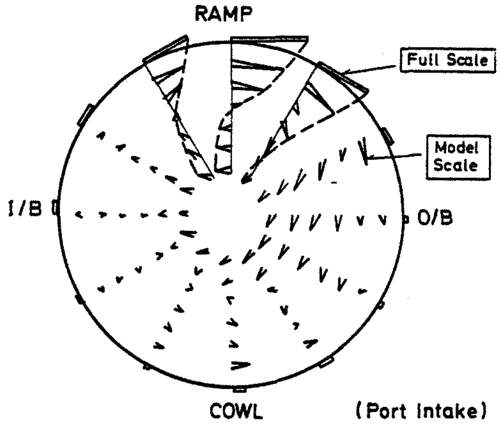


Figure 15. Model/Full Scale Comparison of Intake Swirl at $M_\infty = 0$

4.2 Flow Straighteners

To resolve the compatibility problem various geometric intake modifications ("fixes") were tested with the aim of either preventing cross-flow at source, i.e. at the place of separation (cowl) or further downstream near the engine face. Fig. 16 shows the geometry of these fixes

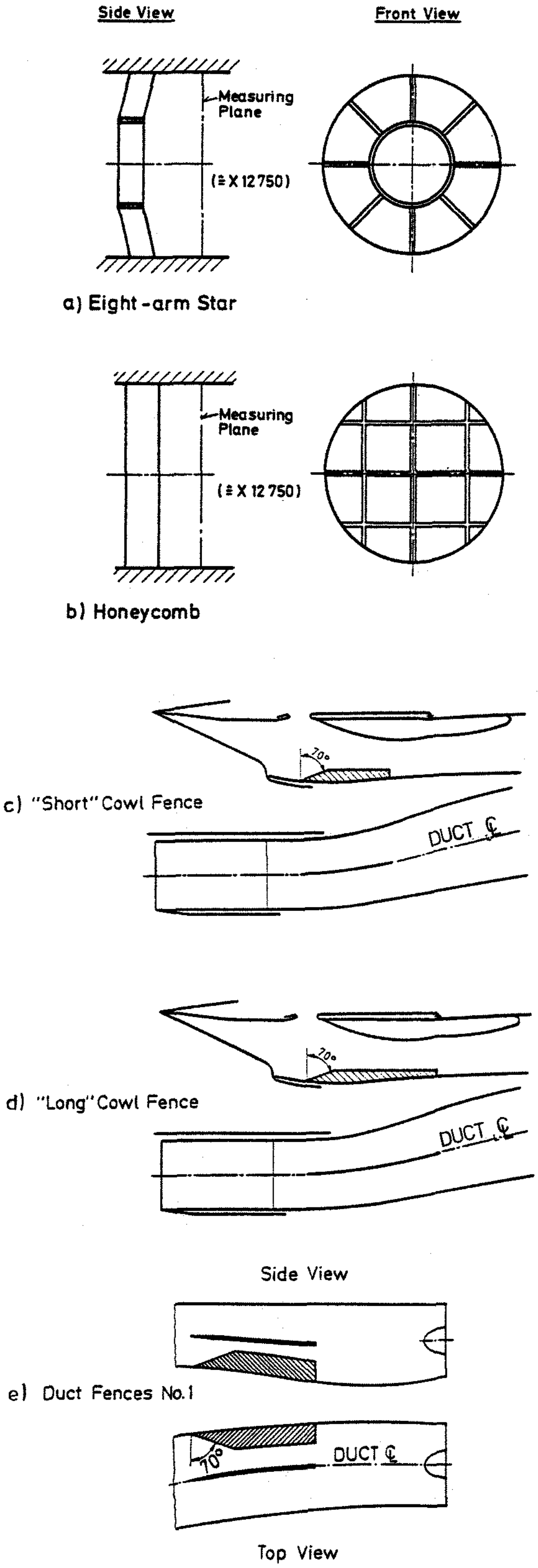
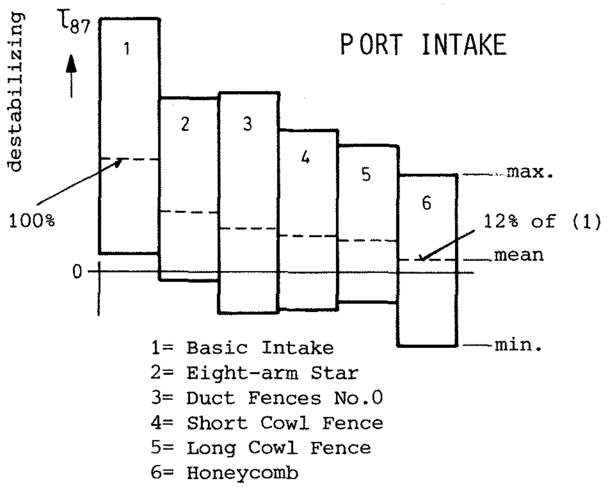


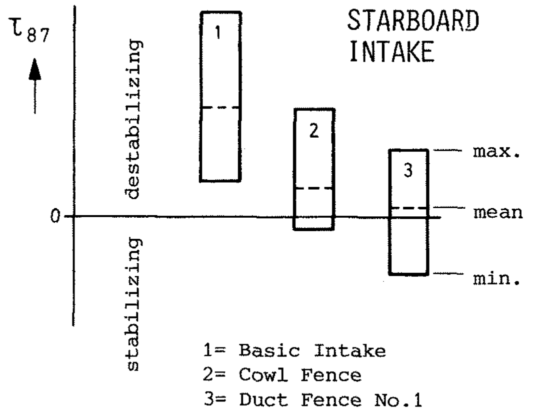
Figure 16. Geometry of Fixes

Sea Level, $M_\infty = 0{,}6$

Auxiliary Air Intake Doors (AAID) closed while Fig. 17 gives their effectiveness in reducing swirl. As mentioned earlier, bulk swirl can be reduced by a large amount (88 %) unlike the rather stable twin swirl (= maximum - minimum swirl) which in our example shows a maximum reduction of only 28 % at M_∞ = 0,6. For M_∞ = 2,0 similar statements hold. Note that the M_∞ = 0,6 data were obtained by prediction from low speed tests. However, the actual transonic measurements gave only slightly different results.



a) Subsonic: M_∞ = 0,6 (extrapolated from low speed)
Sea Level, AAID closed



b) Supersonic: M_∞ = 2,2
H= 11km, ISA
AICS controlled intake

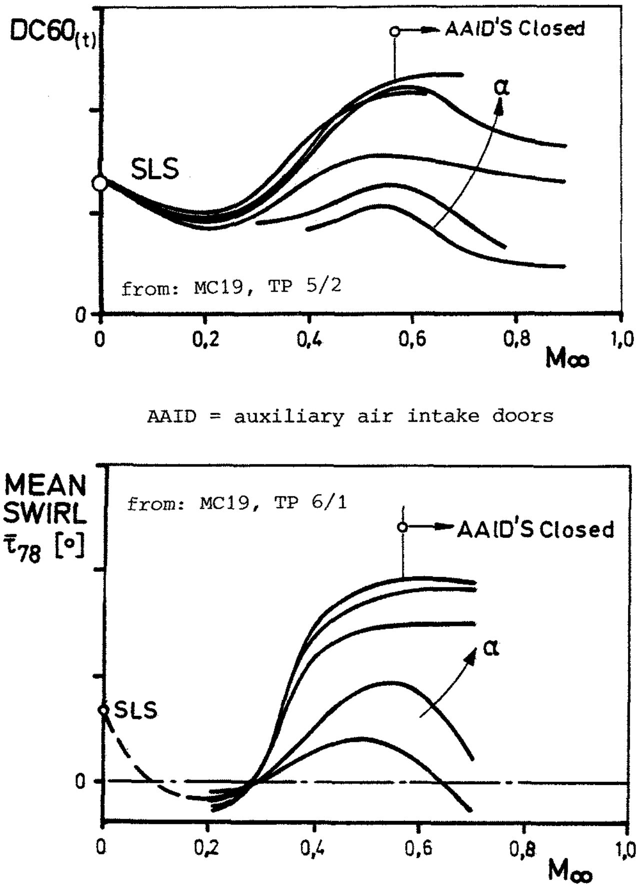
Figure 17. Effect of Fixes on Swirl

Prototype flight testing conducted by British Aerospace Warton with the easier-to retrofit fixes (cowl fence in the left hand intake and duct fences in the right hand intake) resulted in complete success, i.e. from engine/intake compatibility point of view the modified aircraft has no incidence limitations subsonically and there are no flight restrictions up to the maximum Mach number. The more complicated solutions like inlet guide vanes (IGV) and honeycomb flow straighteners were, therefore, abandoned. In the meanwhile, the left hand cowl fence has been introduced into series production.

As a by-product of the supersonic wind tunnel testing, the subsonic fix, the left hand cowl fence, was found to be effective in reducing swirl also in the right hand intake at supersonic Mach numbers, although only with about half the effectiveness of the duct fences (Fig. 17). However, subsequent flight tests up to the maximum Mach number proved the cowl fence to be sufficiently effective in preventing engine surge also in the right hand installation. Especially for retrofitting, the cowl fence represents a noteworthy cost saving as compared with the duct fences.

5. Similar Trend in Different Compatibility Parameters

Fig. 18 compares time variant pressure distortion with mean swirl as function of Mach number. The similar trend is apparent. For a given Mach number and



AAID = auxiliary air intake doors

Figure 18. Comparison of Instantaneous Total Pressure Distortion with Mean Swirl Angles. Basic Intake, Sea Level, R = 0.87 R_{max}

varying engine mass flow Fig. 19 shows that the rate of change in angular position of the DC60 sector and the total pressure maxima/minima corresponds to the rate of change of the mean swirl angle.

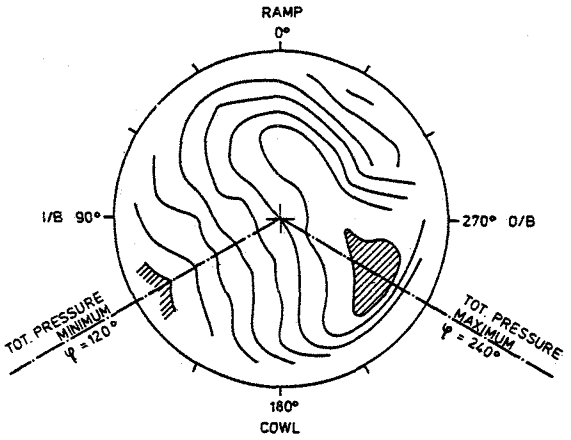


Figure 19a. Determination of Angular Position φ of Total Pressure Maximum and Minimum from Isobarplot

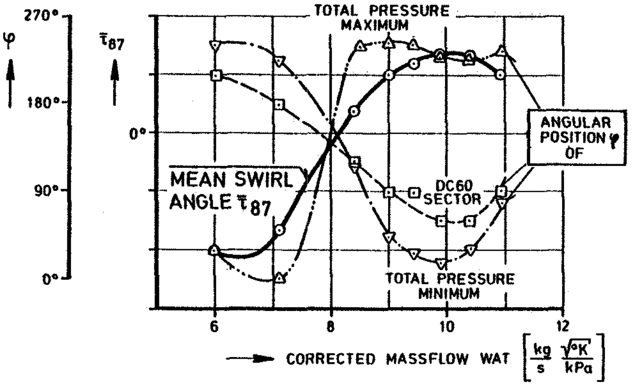


Figure 19b. Rotation of Total Pressure Maximum and Minimum Corresponds to Change of Circumferential Mean Swirl Angle $\bar{\tau}_{87}$, Basic Intake, $M_\infty = 0,5$, $\alpha = 15°$

These results suggest that the parameters shown are closely interrelated. In addition, considering the surge events in Tornado, one could argue that swirl is the decisive compatibility parameter rendering steady state and time variant pressure distortion to secondary importance. This is not to say that the flow in a different inlet with maximum total pressure distortion and "zero" swirl could not cause engine surge, since it is the change in velocity triangles at the compressor face which matters and this change can be caused not only by swirl but, to a much smaller degree, also by total pressure distortion (see next paragraph). In fact, such a flow type has been found in recent MBB investigations for an intake configuration in which the cowl separation was located symmetrically relative to the symmetry plane of the S-bend. That is, the total pressure deficit is only a prerequisite for swirl to be generated in a bend and may, but need not always trigger swirl. To put it in perspective, had all Tornado inlet compatibility testing been restricted to (steady state) swirl and had all dynamic pressure distortion measurements been left out, the same good compatibility result would have been achieved at an earlier stage of the programme perhaps, however, by different means, e.g. by the provision of engine inlet guide vanes (IGV). This, of course, implies that the engine manufacturer can specify what type and magnitude of swirl and pressure distortion harm his engine.

6. Oscillating Blade Loads

According to Lecht and Weyer (5) circumferential non-uniformities in total pressure as well as in pre-swirl flow " ... do not only affect the compressor stall margin but result in severe unsteady aerodynamic load of the rotor blades thus initiating or aggravating airfoil vibrations and flutter ... . Preswirl distortions tend to create more intense blade force fluctuations than even very strong total pressure distortions". The paper on the high cycle fatigue problem encountered in the APU of the Airbus A300 (6) is another example of the paramount importance of intake swirl.

In the Airbus APU inlet there is an almost pure twin swirl present, similar to that in the modified Tornado inlet, Fig.20.

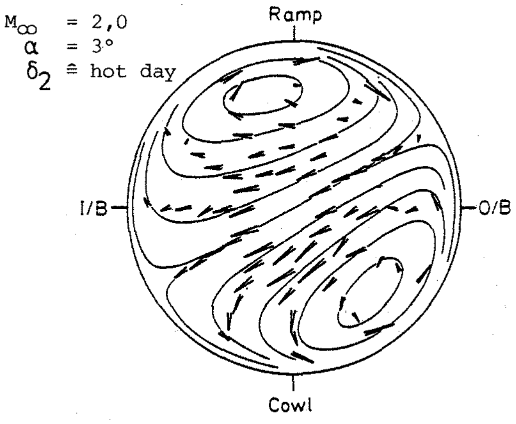


Figure 20. Typical Twin Swirl Pattern (Mean Swirl ≈ 0), Intake with Cowl Fence

However, for the unmodified Tornado, as has been shown above, there is in addition bulk swirl in both critical flight conditions ($\alpha >> 0°$ $M < 1$ and $\alpha \approx 0°$ $M > 1,8$). The resulting spanwise incidence distribution felt by one blade during one revolution is shown in Fig. 21 for two extreme circumferential positions: there is a change in sign not only per revolution but also in spanwise direction for a fixed angular position (alternating "twisting" and oscillating bending of the blade).

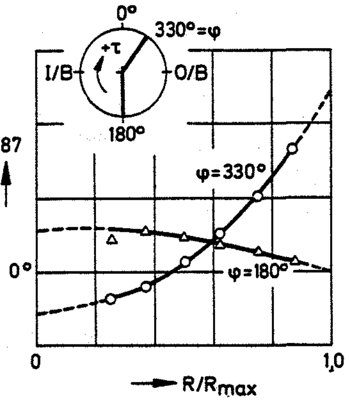


Figure 21. Alternating "Twisting" and oscillating Bending of Blade during one Revolution, Basic Intake

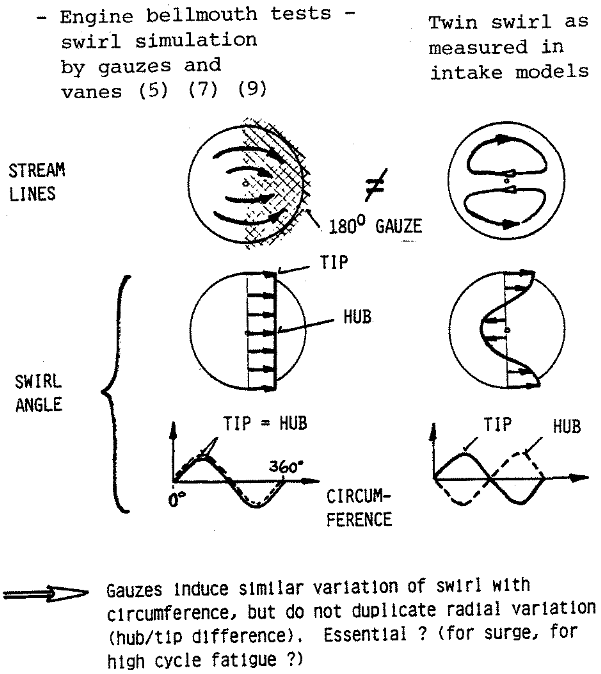
7. Swirl Simulation in Engine Bench Tests

In engine bench testing with bellmouth inlets the flow distortions of the real inlets are normally simulated by gauzes. AEDC uses computer controlled airjets blown upstream (8). DFVLR (5) and RR (9) used gauzes and swirl producing guide vanes. Whilst NASA (7) have shown that their 180° gauze produced a sinusoidal variation in swirl of about ±15° in the annulus ahead of the compressor face (Fig. 22) and DFVLR (5) produced similar circumferential variations of ±25° by guide vanes, neither of the above simulation methods reproduced the hub to tip differences required for twin swirl simulation. The work in (5) suggests furthermore that, even if gauze and preswirl generating vanes yield the same deviation in blade incidence, the effect on blade relative velocity is still vastly different in both simulation techniques.

In summary, there seem to be significant short-comings in the correct simulation of inlet flow disturbances in current engine bench tests. In particular, the interaction of the real engine with the flow pattern obtained from intake model tests without engines seemed difficult to account for.

Fig. 23, therefore, suggests a different experimental approach to this problem:

a) The swirl pattern, undisturbed by engine interaction is obtained from the wind tunnel intake model.



Gauzes induce similar variation of swirl with circumference, but do not duplicate radial variation (hub/tip difference). Essential ? (for surge, for high cycle fatigue ?)

Figure 22. Discrepancy Between Required and Achieved Swirl Simulation

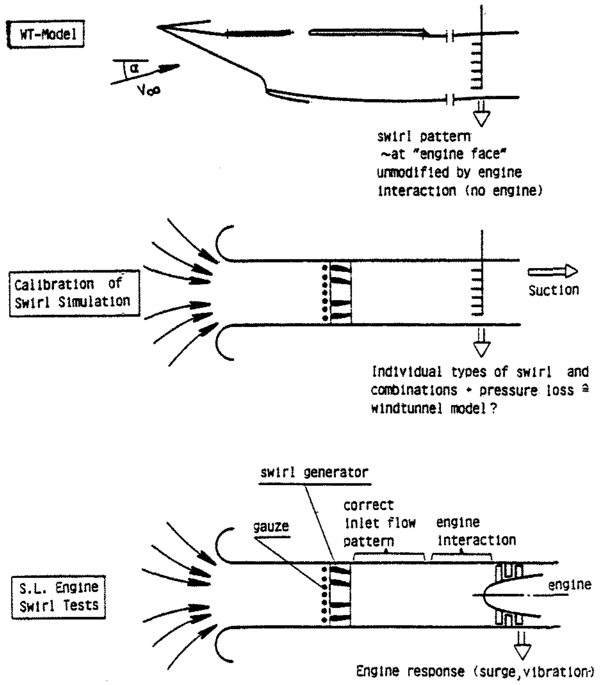


Figure 23. Suggested Experimental Approach

b) In the bellmouth bench tests the engine is either shifted downstream, to avoid interaction, or external suction is applied instead. In addition, the individual disturbance components (swirl, pressure distortion) and their combinations are simulated by gauzes and guide vanes. The correctness of the simulation is checked by flow survey. For cost reasons most of this development of the individual distortion simulators could be done using smaller scale models.

c) Having duplicated the inlet disturbance flow, the engine is installed and interacts with the simulated inlet flow.

The advantage of this method is that the interaction need not be known but may be checked, if so desired, by wall stream line measurement or other techniques.

8. Sensitivity of Engines to Swirl

In this paper it has been suggested that practically all supersonic combat aircraft with unshielded, variable geometry intakes produce similar flow angularities as the unmodified Tornado unless special measures to suppress separation and swirl respectively have been taken, as for example in the Saab Viggen (tangential blowing) or in the Russian MIG25 (variable cascade attached to the subsonic ramp). The question therefore arises, why aircraft like F-14, F-15, etc. seem to be less sensitive to swirl than the unmodified Tornado. Fig. 24 offers an explanation: all American modern military high performance engines - except the TF41, which is a derivative of the European Spey - and also the Russian Tumansky engine, have inlet guide vanes (IGV). The Tumansky engine even seems to have fixed, axisymmetric IGV, which have a purely flow straightening function. In Fig.17 it has been shown that as little as 8 vanes reduce bulk swirl noticeably and also twin swirl to a small degree. Should, therefore, all future engines of supersonic combat aircraft have IGV? The author feels that the answer is "no", since it appears to be better to tackle the problem at source, i.e. introduce a simple, lightweight fence, rather than to cure the problem where it becomes effective in hurting the engine (IGV). Furthermore, no penalties for the additional engine length and weight and for the deicing of the IGV need to be accepted. At least from compatibility view point, therefore, the (modified) Tornado engine/intake combination appears to be the better solution.

9. Concluding Remarks

9.1 Investigations on Tornado and other projects have shown that most conventional supersonic intakes of combat aircraft produce swirl (bulk and twin swirl). While bulk swirl can be reduced by relatively simple means e.g. by intake fences, twin swirl is rather stable and can only be moderately attenuated by simple devices.

9.2 From the above and from Tornado flight testing it has been found that engines without inlet guide vanes (IGV), like the RB199, react in a very sensitive manner to even small changes in magnitude of intake swirl if contra-rotational to the engine fan ("handed" problem). The resulting adverse effects are surge and forced blade vibration.

9.3 From compatibility view point it appears that the Tornado intake/engine combination, with fenced intakes and IGV-less engines, is superior to conventional intakes which are coupled with IGV-engines (less engine weight and length, no deicing requirement). The idea is to tackle the problem of swirl generation at source rather than trying to eliminate it by IGV. Copying of the Tornado intake fence is, therefore, recommended. It is speculated that even existing aircraft with IGV engines like the F111, F14, F15 might be improved by the installation of intake fences.

Engine Type	Engine Manufacturer	Installed in Aircraft	Inlet Guide Vanes	Remarks
RB 199	TU	Tornado	No	
M 53	SNECMA	Mirage 2000/4000	No	
	Tumansky	MIG 25	Yes	30 IGV,fixed,axisymmetric
TF 30 P 412	P+W	F 14	Yes	Fixed
F 100	P+W	F 15 / F 16	Yes	21 IGV,Variable
F 401	P+W	V/STOL	Yes	Variable
F 101	GE	B 1	Yes	Variable
F 404	GE	F 18	Yes	Variable
TF 41	Allison/RR	A 7	No	Spey-Derivative

Figure 24. Inlet Guide Vanes on Modern Military High Performance Engines

9.4 The validity of dynamic total pressure distortion as a decisive compatibility parameter is questioned at least for engines without IGV. In retrospect, had dynamic pressure distortion measurement been completely left out and swirl measurement been done instead, the same good engine/intake compatibility result would have been achieved at an earlier stage of the Tornado programme. Additional engine swirl tests to confirm the applicability of this result to other engine types are recommended.

9.5 Current engine bench testing techniques need improvement. The simulation of individual swirl components as well as combinations of them should be added to the duplication of (steady state) total pressure distortion.

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12. Legend of Figure 5

Model		
MC 19	━ ━ ━ ━	supersonic, $M_\infty=2$
MC 2A	- - - - - -	supersonic simulation ($\delta_2=16°$), $M_\infty\cong 0$
MC 2A	────	subsonic simulation, $M_\infty\cong 0$
MC 19	━━━━	subsonic, $M_\infty=0,6$