



AEROSPACE INFORMATION REPORT

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A Methodology for Assessing Inlet Swirl Distortion

RATIONALE

AIR5686 has been reaffirmed to comply with the SAE Five-Year Review policy.

A reaffirmed status is given to technical reports that have been reviewed by the technical committee and deemed to be current with no need for immediate revision. No changes have been made to this document as a result of this review.

FOREWORD

In some instances, inlet/engine compatibility may not be adequately described by consideration of total-pressure distortion, total-temperature distortion, or planar waves, either singularly or in combination. Many gas turbine installations can generate significant flow angularity ("swirl") as well as total-pressure distortion at the Aerodynamic Interface Plane (AIP). The SAE S-16 Turbine Engine Inlet Flow Distortion Committee has recognized the need for a methodology for assessing swirl distortion to be used in conjunction with SAE document ARP1420 which was written for inlet spatial total-pressure distortion.

This Aerospace Information Report brings together information and ideas which provide a framework for addressing swirl distortion. A common industry practice has yet to be established.

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1. SCOPE

This Aerospace Information Report (AIR) addresses the subject of aircraft inlet-swirl distortion. A structured methodology for characterizing steady-state swirl distortion in terms of swirl descriptors and for correlating the swirl descriptors with loss in stability pressure ratio is presented. The methodology is to be considered in conjunction with other SAE inlet distortion methodologies. In particular, the combined effects of swirl and total-pressure distortion on stability margin are considered. However, dynamic swirl, i.e., time-variant swirl, is not considered. The implementation of the swirl assessment methodology is shown through both computational and experimental examples. Different types of swirl distortion encountered in various engine installations and operations are described, and case studies which highlight the impact of swirl on engine stability are provided. Supplemental material is included in the appendices.

This AIR is issued to bring together information and ideas required to address the inlet-swirl problem for which common industry practice has yet to be established. This document should foster the tests and analyses necessary to mature the ideas proposed by the committee to a recommended practice. These tests and analyses must include information that justifies three main features of the proposed swirl methodology: (1) swirl descriptors for correlating inlet swirl and stability pressure ratio loss, (2) computational techniques for analyzing compression systems (inlets, fans, compressors), and (3) test protocols (instrumentation and test techniques). The committee anticipates serving the industry by using such information to establish the consensus necessary for issuance of an SAE recommended practice.

2. APPLICABLE DOCUMENTS

The references for this document encompass SAE publications, papers, and reports that support the material in the body of the report, as well as papers and reports which were reviewed and may be sources for added insight for the interested reader. The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org

ARP1420	Gas Turbine Engine Inlet Flow Distortion Guidelines.
AIR1419	Inlet Total-Pressure Distortion Considerations for Gas-Turbine Engines.
AIR5866	An Assessment of Planar Waves.
AIR5867	An Assessment of the Inlet/Engine Temperature Distortion Problem.
AIR5656	Statistical Stability Assessment.
AIR5826	Distortion Synthesis/Estimation Techniques.

2.2 Other Applicable Documents

1. Hercock, R.G., "Effects on Intake Flow Distortion on Engine Stability," Paper 20, AGARD-CP-324.
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2.3 Definitions

AEDC	Arnold Engineering Development Center
AICS	Air Intake Control System
AIP	Aerodynamic Interface Plane
AIR	SAE Aerospace Information Report
APU	Auxiliary Power Unit
ARP	SAE Aerospace Recommended Practice
ATM	Adaptive Throttle Management
A_1 and A_2	Duct area at inlet and at outlet, respectively
B	Total-pressure-swirl distortion interaction constant that can be positive or negative depending whether interactions are stabilizing or de-stabilizing
BLC	Boundary Layer Control
c	Vortex generator vane length
CFD	Computational Fluid Dynamics
C_i	Offset term used in calculation of stability margin loss due to total-pressure distortion
circ	Designation for circumferential flow injection scheme shown in Figure C37
D or d	Diameter
DC(60)	Distortion descriptor (face average total pressure - average total pressure in lowest 60 degree sector) divided by the average dynamic pressure
DPC/P	Total-pressure distortion parameter
D_1 or D_i	Duct inlet diameter
D_2	Duct outlet diameter
EGTC	Corrected Exhaust Gas Temperature
FSCIR	Designation for combined floor suction and circumferential injection scheme shown in Figure C39
h	Height of inlet above ground, also vortex generator height
h_1	Duct inlet opening height
HCF	High-Cycle Fatigue
i	Index designating a particular ring (radial location) on the AIP
IGV	Inlet Guide Vanes
IRP	Inlet Reference Plane
JSF	Joint Strike Fighter
k	Index designating a particular pair in a distortion pattern containing multiple pairs per rev
K_i	Offset term used in calculation of stability margin loss due to swirl distortion
KC_i	Circumferential total-pressure distortion sensitivity
KR_i	Radial total-pressure distortion sensitivity
KS_i^+	Sensitivity of ΔPRS_S to the positive sector swirl of ring i ($SS_{i,k}^+$)
KS_i^-	Sensitivity of ΔPRS_S to the negative sector swirl of ring i ($SS_{i,k}^-$)
KSD_i	Sensitivity of ΔPRS_S to swirl directivity on ring i (SD_i)
KSI_i	Sensitivity of ΔPRS_S to swirl intensity (SI_i)

KSP_i	Sensitivity of ΔPRS_S to swirl pairs for ring i (SP_i)
L	Length
l	Vortex generator lateral spacing
M_o or M_∞	Flight Mach number
M_{th}	Throat Mach number
N_1	Fan rotor speed
o	Vortex generator lateral offset
PR	Pressure Ratio
$PRDS$	Stability limit pressure ratio with distortion
PRO	Operating pressure ratio
$PR1$	Stability limit pressure ratio without distortion
P_T or P_t	Total pressure
P_{T0}	Free-stream total pressure
$P_{T2\text{ AVG}}$ or P_{T2}	Average total pressure at AIP
$P_{T2\text{ LOCAL}}$	Total pressure at a point on the AIP
$P_{T2\text{ MAX}}$	Maximum total pressure at AIP
$P_{T2\text{ MIN}}$	Minimum total pressure at AIP
$pyr1$	Designation for pyramid blowing scheme shown in Figure C38
R	Radius of curvature in a bend in a duct
r	Local radius
r_o	Radial location of edge of vortex core (Figure 26)
RPM	Revolutions Per Minute
s	S-duct meanline length, or duct axial coordinate
$SC(60)$	Swirl Coefficient (maximum average circumferential velocity in 60 degree sector at duct exit divided by mean duct velocity at throat section)
SD	Swirl Directivity, a value between plus and minus one defining, for a given ring, the equivalent bulk swirl rotational direction of a general swirl pattern
SD_i	Swirl Directivity for ring i (Eq. 7 for a one-per-rev pattern and Eq. B4 for a multiple-per-rev pattern)
SI	Swirl Intensity, the average of the absolute circumferential swirl angle in degrees for a ring at the AIP
SI_i	Swirl Intensity for ring i at the AIP (Eq. 6 for a one-per-rev pattern and Eq. B3 for a multiple-per-rev pattern)
$SM, SM_{\text{available}}$	Stability Margin
SP	Swirl Pairs, indicator of the effective number of pairs of positive and negative swirl direction changes that result from the swirl in a ring
SP_i	Swirl Pairs for ring i (Eq. 8 for a one-per-rev pattern or Eq. B5 for a multiple-per-rev pattern).
SP_1	Designation for lip suction combined with pyramid blowing as shown in Figure C40
SS	Sector Swirl, the average positive (co-rotating) swirl content, $SS_{i,k}^+$, or the average negative (counter-rotating) swirl content, $SS_{i,k}^-$
$SS_{i,k}^+$	Average swirl angle of the positive region of ring i (over the $\theta_{i,k}^+$ extent) for swirl pair k of a multiple-per-rev swirl pattern (Eqs. 4 and B1). For a one-per-rev swirl pattern the index k is left off (index is also left off in Figures 44-47 where a single ring is considered)

$SS_{i,k}^-$	Average swirl angle of the negative region of ring i (over the $\theta_{i,k}^-$ extent) for swirl pair k of a multiple-per-rev swirl pattern (Eqs. 5 and B2). For a one-per-rev swirl pattern the index k is left off (index i is also left off in Figures 44-47 where a single ring is considered)
STOVL	Short Takeoff and Vertical Landing
TDC	Top Dead Center
U	Absolute or total flow velocity (Figure 15)
U_C	Fan or compressor rotor velocity at a radial location, $U_C = \omega r$
U_i	Inlet flow velocity
U_R	Relative flow velocity
U_x	Axial velocity (Figure 15)
U_{XAVG}	Average value of U_x
U_θ	Circumferential velocity (Figure 15)
$U_{\theta MAX}$	Maximum value of U_θ
$U_{\theta MIN}$	Minimum value of U_θ
$U_{\theta 1}$ and $U_{\theta 2}$	Tangential flow velocity at rotor inlet and rotor outlet, respectively (Figure 39)
U_∞	Free-stream velocity
U_1 and U_2	Absolute flow velocity at rotor inlet and rotor outlet, respectively (Figure 39)
U_{1R} and U_{2R}	Relative flow velocity at rotor inlet and rotor outlet, respectively (Figure 39)
V/STOL	Vertical and Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing
w_{a_corr}	Corrected mass flow
w_C	Fan or compressor work
W_S/W_P	Fraction of duct flow removed by boundary layer suction
x, y	Cartesian coordinates
Z_P	Flight altitude
α	Swirl angle (Eq. 1), otherwise angle of attack
$\alpha(\theta)_{i,k}$	Swirl angle on ring i for pair k of a multiple-per-rev pattern as a function of circumferential location in a particular extent. In the case of a one-per-rev pattern, the index k is left off.
β	Angle of sideslip
δ	Boundary layer thickness
δ^*	Boundary layer displacement thickness
δ_2	Second ramp angle in supersonic inlet
$\Delta PC/P$	Circumferential pressure distortion intensity element
$\Delta PR/P$	Radial pressure distortion intensity element
ΔPRS	Overall stability pressure ratio loss (Eqs. 9 and 13)
ΔPRS_P	Stability pressure ratio loss due to total-pressure distortion alone (Eq. 14)
ΔPRS_{PS}	Stability pressure ratio loss due to the interactions between total-pressure distortion and swirl distortion when both are present
ΔPRS_S	Stability pressure ratio loss due to swirl distortion alone (Eqs. 15 and 16)
ΔP_T	Total-pressure difference

ΔSM	Loss in stability margin (Eq. 12)
$\Delta \theta$	Difference in θ
Γ	Circulation
λ	Wishbone vortex generator element width
ϕ	S-duct cross section polar coordinate (Figure C22)
θ	Circumferential position angle
θ_{AVG}	Average duct wall divergence angle (Figure 23)
$\theta_{i,k}^+$	Extent of the positive swirl region of pair k in a multiple-per-rev pattern along ring i. For a one-per-rev pattern, the index k is omitted.
$\theta_{i,k}^-$	Extent of the negative swirl region of pair k in a multiple-per-rev pattern along ring i. For a one-per-rev pattern, the index k is omitted.
θn_i	Location number n on ring i where the swirl changes sign
θ_{ref}	Reference extent angle
τ_{87}/τ_{87max}	Swirl at 87% span from hub/maximum swirl at 87% span in Figure A8
ω	Angular velocity

3. SUMMARY

Historically, many operability problems were avoided without explicitly accounting for swirl by coupling engines which were relatively insensitive to swirl (as a byproduct of employing Inlet Guide Vanes (IGVs)) with inlets unlikely to induce high levels of swirl (such as conventional fighter-aircraft inlets with relatively long and straight inlet-diffuser systems). Cases cited in this document show that this approach can fail if either a fan or compressor intolerant to swirl is used or if very high levels of swirl are produced by the inlet. Therefore, the problem of addressing swirl encompasses both the explicit characterization of the inlet system in terms of suitable swirl parameters and the fan/compressor response to swirl.

A structured methodology is presented in this document to account for the impact of inlet-swirl distortion on gas-turbine-engine operability. The swirl methodology is applicable to inlet/engine installations in which swirl distortion imposed at the Aerodynamic Interface Plane (AIP) is of sufficient intensity to impact engine operability. The determination of the swirl characteristics that are sufficient to impact operability is a key element of the structured methodology. The methodology is particularly warranted for engines that do not feature IGVs or other effective devices for reducing swirl. A stepwise methodology, similar to that for total-pressure distortion, has been outlined to address swirl distortion:

- a. Identify the AIP
- b. Characterize the Inlet Swirl
- c. Conduct a Sensitivity Assessment of Swirl on Engine Stability
- d. Assess the Overall Inlet-Engine Compatibility

This document categorizes the types of swirl that have been encountered in turbine-engine inlet systems and defines descriptors that quantify swirl using parameters that encompass the magnitude and shape of the swirl patterns. The descriptors can be used to quantify generalized steady-state, circumferential, swirl-distortion patterns in terms of swirl extent, intensity, directivity, and number of swirl pairs. The development and use of swirl descriptors are discussed as building blocks to be used in the overall engine/inlet compatibility assessment. The information in this report eventually will lead to correlating swirl descriptors with loss of stability pressure ratio as part of a methodology that applies the descriptors in a swirl test and evaluation process.

Detailed examples showing how test and computational techniques have or could be used throughout the methodology are presented. The characterization of the inlet swirl requires prediction or measurement of swirl. Cited case studies illustrate techniques which can be used to determine both the swirl and pressure distortion in an inlet. The actual measurement of swirl in the typical wind tunnel environment will require a significant increase in the number of individual measurements. Each local swirl measurement requires special probes which may, in turn, involve additional measurements. For example, pressure-based, flow-angularity probes require three or more individual pressure measurements. Thus, using such probes to map the swirl during an inlet test could easily result in a three-fold increase in pressure sensors. In addition to swirl measurement methods, example CFD simulations provided herein show predicted inlet analysis results which are consistent with test data.

Parallel compressor analyses provide a limited understanding of the response of a fan/compressor to swirl as well as to combined total-pressure and swirl distortions. The analyses illustrate the impact of swirl distortion on the engine stability boundary and provide a basis for correlating loss in stability pressure ratio with the swirl descriptors. The analyses also illustrate the complexity of the interactions between swirl and total-pressure distortion on degrading stability margin.

While application of the test and analysis techniques described in the following chapters enables the characterization of inlet swirl, there are still at least two important elements required for a robust methodology. The first is a method for generating specific swirl patterns, so that the impact of the swirl distortion on engine performance and operability can be determined systematically prior to full-scale system testing. The second is a database of generic test results that document the impact of various swirl distortion patterns on compressor and/or engine performance and operability. These test results are needed in order to establish sensitivity coefficients and limits for each of the swirl-distortion parameters defined in Section 6. Such results can then be used in conjunction with the inlet data to determine the acceptability of an inlet/engine system prior to full-scale testing or even prior to final design selection and hardware fabrication.

4. PROBLEM DESCRIPTION

Many gas turbine installations can lead to significant swirl in the engine induction system. Swirl is manifested in the appearance of a measurable parameter, the flow angularity in the inlet duct, which is defined as the deviation between the local velocity vector and a vector normal to the AIP. The total flow angle can be expressed as a combination of a radial component and a circumferential component. This circumferential component of the velocity vector can strongly affect the incidence angle on the downstream IGV or rotor, as well as the pressure rise and flow capacity of the fan or compressor. Therefore, in this document, swirl is defined as the circumferential component of the flow angularity.

The industry has lacked a structured approach to account for the loss of stability pressure ratio, the pressure ratio at which the stability limit is encountered, in gas turbine engines when subjected to swirl. Fortunately, the resulting risk has been reduced on many U.S. fighters and bombers because engine requirements dictated the use of IGVs to optimize compression system efficiency and operability. These IGV cascades took out the swirl component (with some increase in loss coefficient) prior to the flow entering the rotor. However, some combat aircraft and essentially all turbine-engine powered transport aircraft use engines that do not incorporate IGVs. Furthermore, some aircraft use inlet systems with features that can induce swirl, such as S-shaped diffuser ducts in the case of fighter aircraft or plenum chambers in the case of embedded auxiliary power unit (APU) installations. Embedded turbine engine installations for marine and industrial applications also use plenums that can induce swirl. Therefore, swirl can be expected to influence engine operability, performance, or structural integrity on such systems, as a number of documented case studies can attest. This document addresses the effect of swirl on operability.

The lack of a structured approach to address swirl during system development can lead to unexpected swirl-related problems with the associated costs and risks. For example, the inlet-engine compatibility evaluation practice failed to detect swirl-related problems until after two well-publicized weapon systems were fielded. First, in the twin-engine Tornado fighter-bomber, featuring horizontal S-ducts in the inlet system, swirl was found to be the primary contributor to an engine instability problem that was discovered during the flight test program. Second, in the Tomahawk cruise missile, swirl generated by the single vertical S-duct was a contributor to stability problems. Note that in both cases, the engines did not have IGVs. Summaries of these and other case studies appearing in Section 4.1 will be used to show that swirl can be a significant issue in any facet of aircraft operations from ground operations through supersonic flight and that a methodology for accounting for swirl throughout the vehicle development is needed to prevent costly problems.

4.1 Historical Case Studies of Swirl Effects

The need to consider swirl during operability assessments is evident in historical case studies that span the full spectrum of aircraft turbine engine applications, including transport aircraft, fighter aircraft, and cruise missiles. Some examples are presented in this section to illustrate installations and situations that can generate significant swirl distortion and to demonstrate the significant effect that swirl distortion can have on operability. The historical experiences discussed include examples from the following applications:

- a. Fighter-Aircraft Experience
- b. Cruise-Missile Experience
- c. Lift-Fan Experience
- d. Thrust-Reverser Experience
- e. Auxiliary Power Unit (APU) Experience

In these case studies it will be seen that swirl can be an issue in any region of aircraft operations. In the above list, there are examples of swirl issues in supersonic flight, subsonic maneuvering flight, subsonic cruise flight, low-speed subsonic flight with transitions to V/STOL operations, aircraft landing ground operations, and aircraft static ground operations.

4.1.1 Fighter-Aircraft Experience

The Tornado is a twin-engine fighter/bomber aircraft that features a pair of side-mounted inlets with “horizontal-turning” S-shaped diffuser ducts (see Figure 1). The Tornado is powered by the Turbo Union RB199 engine which does not use IGVs (see Figure 2). During early Tornado inlet-model testing, engine/inlet compatibility was estimated based on measurements of steady-state and instantaneous total-pressure distortion at the AIP near the fan/compressor entrance. Although the total-pressure distortion coefficients were relatively high for some flight conditions, they were within specified allowable limits for the engine. In addition, limited full-scale tests of the inlet/engine combination were performed. For subsonic flight, a starboard inlet (pilot’s right, facing forward) was flight tested under the fuselage of a Vulcan bomber. Additionally, a port-inlet configuration (pilot’s left, facing forward) was tested at supersonic flight speeds in Cell 4 of the National Gas Turbine Establishment in the United Kingdom. These full-scale tests did not show clear evidence of serious compatibility problems. However, when prototype flight testing of the aircraft began, engine surges were consistently found on the port engine at subsonic flight speeds while at high angle of attack and on the starboard engine at supersonic flight speeds near zero angle of attack. In subsonic flight, it was observed that there was a difference in fan speed between the port and starboard engines which increased with increasing angle of attack. The port engine speed decreased and starboard engine speed increased. In the case of this particular engine, such an increase or decrease in speed can be indicative of a corresponding increase or decrease in compressor loading. It is noted that although the non-symmetric or “handed” nature of the results suggested that bulk swirl combined with total-pressure distortion was playing a major role in the engine instabilities, swirl distortion went undetected by the initial testing. At this point, an extensive experimental investigation, complemented by analytical methods, was initiated to resolve the inlet/engine compatibility problem. The result was a successful and practical retrofit to the inlet, which corrected the stability problem by reducing bulk swirl.



FIGURE 1 - TORNADO AIRCRAFT IN FLIGHT

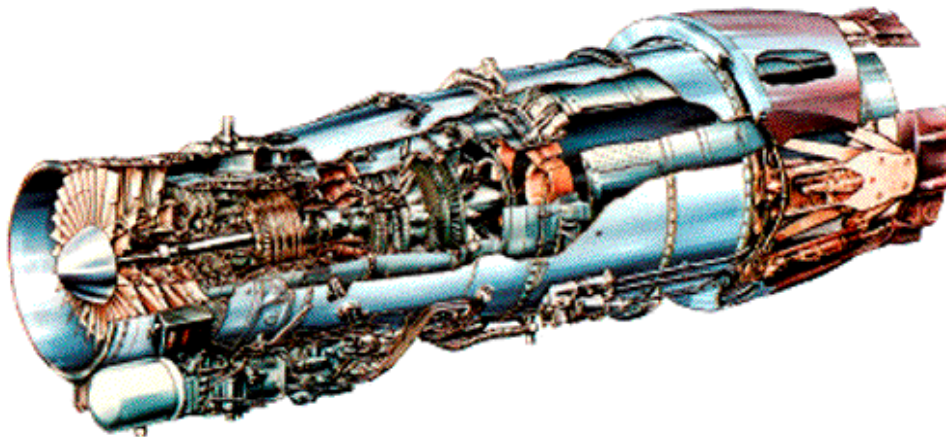


FIGURE 2 - TURBO UNION RB199 TURBOFAN ENGINE

The RB199 engine of the Tornado illustrates one other discovery with respect to swirl distortion. The presence of swirl distortion at the AIP can combine with total-pressure distortion to generate a more severe compressor stability problem than with either distortion acting on its own. If the swirl distortion is in a direction opposite that of compressor rotation (counter-rotating swirl), this can load the fan or compressor and cause engine instabilities, even though the total-pressure distortion is within allowable limits for total-pressure distortion alone. An example of this situation which occurred with the RB199 engine, taken from Reference 1, is shown in Figure 3. In the case of the RB199 turbofan engine, introducing co-rotating swirl, along with total-pressure distortion, decreased stability margin slightly compared to total-pressure distortion alone. However, counter-rotating swirl with total-pressure distortion greatly reduced stability margin. Additional details are presented in Appendix A.

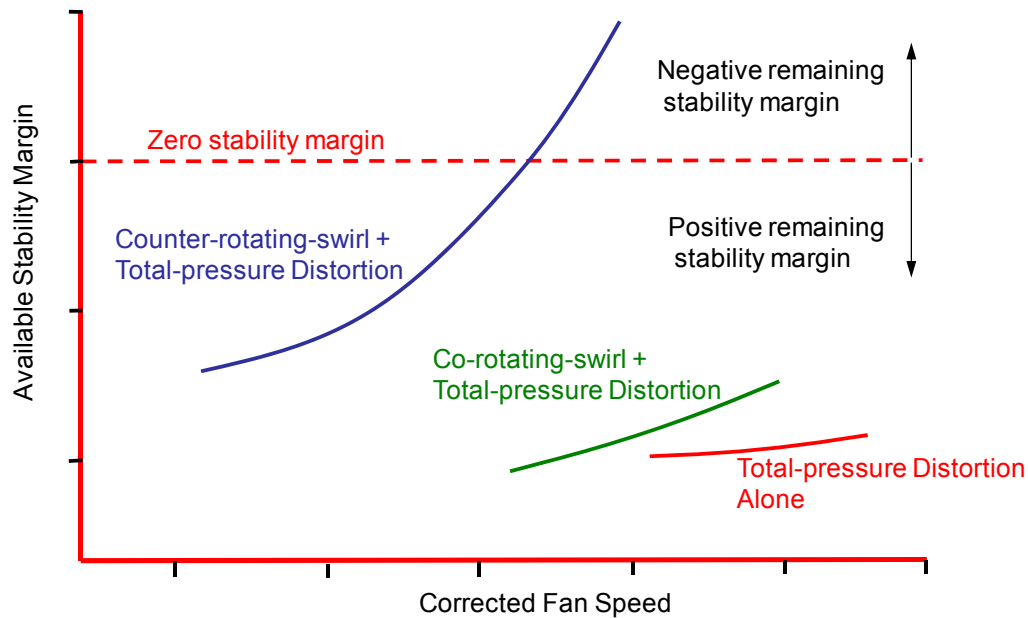


FIGURE 3 - EFFECT OF SWIRL AND TOTAL-PRESSURE DISTORTION ON ENGINE STABILITY

4.1.2 Cruise Missile Experience

The Tomahawk missile is powered by a low bypass-ratio turbofan engine (Williams International F107-WR-402 shown in Figure 4), which does not have inlet guide vanes.



FIGURE 4 - WILLIAMS INTERNATIONAL F107 TURBOFAN ENGINE

Air is supplied to the engine by a single bottom-mounted pitot inlet with an S-bend in the vertical plane. During the course of the free-jet tests at the Arnold Engineering Development Center (AEDC) and captive-carry tests, it was discovered that engine instability onset displayed an asymmetric or “handed” nature with angle of sideslip. Additionally, there were observed differences in engine performance with positive and negative angles of sideslip.

The asymmetric effect of sideslip on stability limit and engine performance is best illustrated by some results obtained during inlet-variability tests conducted in free-jet test cell J-1 at AEDC (See Reference 2). A photograph of this installation is shown in Figure 5. The test article was set for an angle of attack of zero degrees, with the angle of sideslip adjusted to either +2 degrees (corresponding to relative wind striking starboard side of aircraft), zero degrees, or -2 degrees (relative wind striking port side of aircraft).



FIGURE 5 - TOMAHAWK INLET/ENGINE MODEL IN AEDC TEST CELL J-1, REAR QUARTER VIEW

The effect of inlet-to-inlet manufacturing variations on fan stability limit was tested by determining airflow at the point of instability for eighteen production inlets. The same F107-WR-400 engine was used with all of the inlets. All eighteen inlets were tested for an angle of sideslip of +2 degrees. In addition, seven of the inlets were tested with a sideslip angle of -2 degrees (the latter tests were performed to identify effects of inlet-to-inlet asymmetry). The results of the tests at +2 degrees and -2 degrees sideslip indicated an asymmetric effect of angle of sideslip rather than random variations due to inlet asymmetry.

Further investigation of steady-state data taken at the start of each test indicated that the fan was more highly loaded at a sideslip angle of +2 degrees than it was at -2 degrees. During the inlet test a single engine was subjected to many surges and some engine deterioration was expected. A single data point was taken with free jet Mach number set to 0.65 at the beginning of each inlet test to monitor engine health. A rise in temperature due to deterioration was expected, but the step change found with sideslip angle was not expected. The change in temperature with sideslip angle indicates the fan loading was higher at +2 degrees than -2 degrees sideslip. Engine-speed match data supported the same conclusion. The results indicated swirl distortion was affecting engine operability characteristics.

The similarity of the asymmetric behavior of the Tomahawk inlet to that in the Tornado installation led to the conclusion in Reference 2 that the effect was caused by the presence of bulk swirl triggered by inlet-sidewall-lip separation at fairly low angles of sideslip. A brief study was performed to estimate the degree of swirl required to produce the observed speed match and turbine temperature changes. The study results indicated that a change in fan loading due to a mean swirl angle change of 1.5 to 2 degrees about zero was sufficient to cause the observed results. Consideration of the direction of swirl required to load the fan at +2 degrees sideslip angle suggested that the swirl was being generated by flow interactions near the second bend in the inlet. Based upon these test results, the Adaptive Throttle Management (ATM) algorithm was modified to prevent instabilities at worst case sideslip angles. More detailed Tomahawk case study information may be found in Appendix A.

4.1.3 Lift-Fan Experience

Fuselage-mounted or wing-mounted vertical lift fans installed in Vertical Takeoff and Landing (VTOL) aircraft can be subjected to cross-flow induced swirl distortion when the relative wind (resultant of environmental wind and aircraft motion) contains velocity components normal to the fan axis of rotation. An undesirable attribute of cross-flow distortion is non-axisymmetric fan disk loading. The effect is analogous to blade-load asymmetries experienced in advancing/retreating helicopter blades. The advancing blade (blade rotating into the relative wind) experiences counter-rotating swirl, thereby increasing its loading, while the retreating blade (blade rotating away from the relative wind) is presented with co-rotating swirl causing reduced aerodynamic loading. This produces a dual-fan characteristic, shown schematically in Figure 6, which is analogous to the effect which would be produced by a row of loss-free inlet guide vanes, each having a different pre-swirl angle.

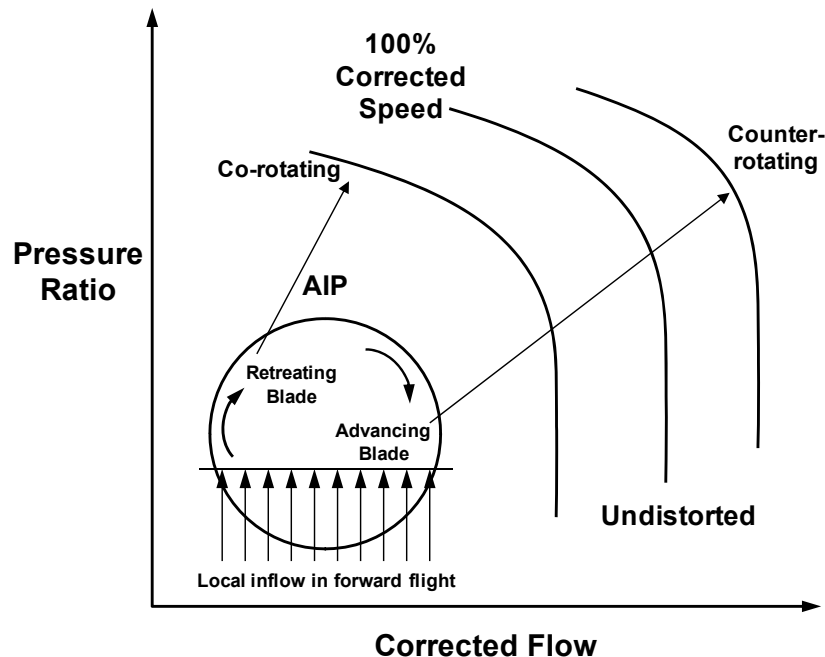


FIGURE 6 - DUAL FAN CHARACTERISTIC AT CONSTANT RPM OF A FAN-IN-WING CONFIGURATION

Non-axisymmetric fan disk loading can cause structural damage and may produce oscillatory thrust during transition flight.

Two case studies are presented in the following subsections to illustrate the effects of cross-flow on system performance and stability. The first case study is a fan-in-wing experiment. The second case study is associated with the Short Takeoff and Vertical Landing (STOVL) version of the Joint Strike Fighter, the F-35B, which uses a lift fan installed in the fuselage.

4.1.3.1 Fan-In-Wing Systems

The case study involving a fan-in-wing lift system may be found in the work by Schuab and Bassett reported in References 3 and 4. The investigation included tests of a wing model that featured a 12-in-diameter lift fan. A schematic illustrating the lift-fan installation in cross section appears in Figure 7. Tests conducted in the 10 ft by 20 ft National Research Council of Canada Propulsion Wind Tunnel simulated cross flows that would be encountered in flight at a number of velocities and angles of attack.

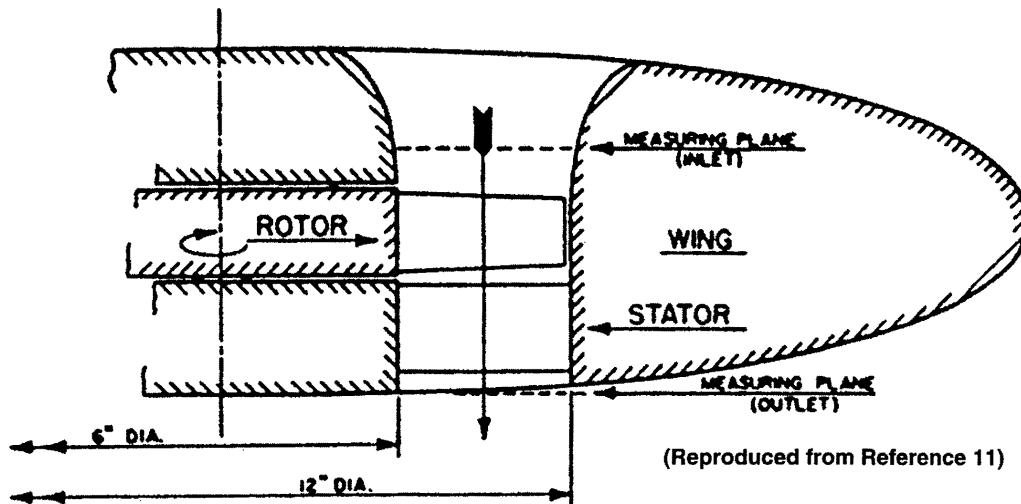


FIGURE 7 - FAN-IN-WING CROSS SECTION SCHEMATIC

Test results included measurements of swirl induced at the fan inlet as well as at the fan exit. The fan-in-wing configuration experienced cross-flow-induced swirl with inlet swirl angle magnitudes proportional to the cross-flow velocity. The angles acted in one direction on the advancing fan blade and in the opposite direction on the retreating blades.

Although the observations of Schuab and Bassett provide valuable insight into cross-flow-swirl distortion, it is likely that the particular results are case-specific. Additional studies of this type of swirl can be found in References 5 to 12.

4.1.3.2 JSF Lift Fan

The STOVL version of the Joint Strike Fighter, the F-35B, provides another case study of a lift fan type cross-flow configuration. In this case, the lift fan is mounted in the fuselage behind the cockpit, as shown in Figure 8. The incoming boundary layer is thicker due to the flow over the fuselage nose and canopy. Again the flow must turn 90 degrees relative to the flight path into a short inlet and again the swirl cross-flow angles are proportional to the cross-flow velocity. This type of inlet-swirl distortion is most severe during transition from flight regimes where the majority of the lift is developed by the fan to flight regimes where the majority of the lift is developed by the main wing. Such transitions involve forward flight with the lift fan still providing a significant portion of the total lift. Although the F-35B lift fan uses IGVs, the high cross-flow velocity produced during transition results in separation on the IGVs. Thus, the swirl distortion is transformed into total-pressure distortion at the inlet to the lift-fan rotor.



FIGURE 8 - LIFT FAN INSTALLATION IN F-35B JSF

Scale-model wind tunnel tests of the aircraft with the lift-fan-inlet configuration, but without swirl probes, showed that the total-pressure distortion measurements at the AIP (IGV leading edge) were inaccurate due to the swirl-induced flow angularity at the tips of the total-pressure probes. The existence of a very strong coupling effect between the inlet (with cross flow) and the lift fan became apparent from these results and from detailed CFD solutions. To reduce risk, it became obvious that some type of ground test with the full-scale lift fan in combination with the cross flow was needed.

An approach that used “stream tubes” derived from CFD for the various critical flight conditions was investigated and adopted. Devices to simulate the stream tubes (see Figure 9) were constructed at each critical flight condition to represent the cross flow over the aircraft forebody and canopy into the lift fan. These “stream tubes” were used to provide the flow to the full-scale lift fan in an engine test facility.

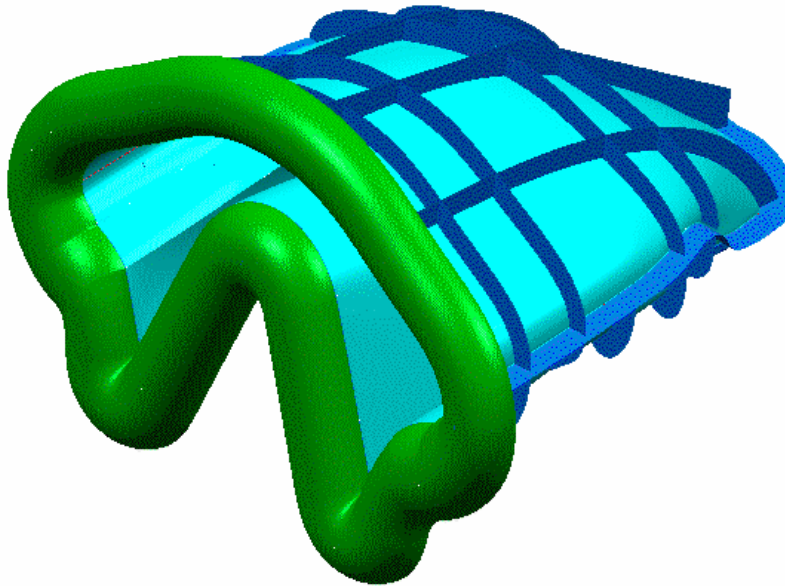


FIGURE 9 - LIFT-FAN STREAM TUBE

To qualify the critical hover flight condition, a representative inlet cowl complete with the aft-hinged, lift-fan door was also built and tested. It should be noted that the aircraft surface effectively represents a stream tube for static conditions. One effect given special attention was the ingestion of tightly-wound vortices produced by the corners of the lift-fan door. This configuration is pictured in Figure 10.

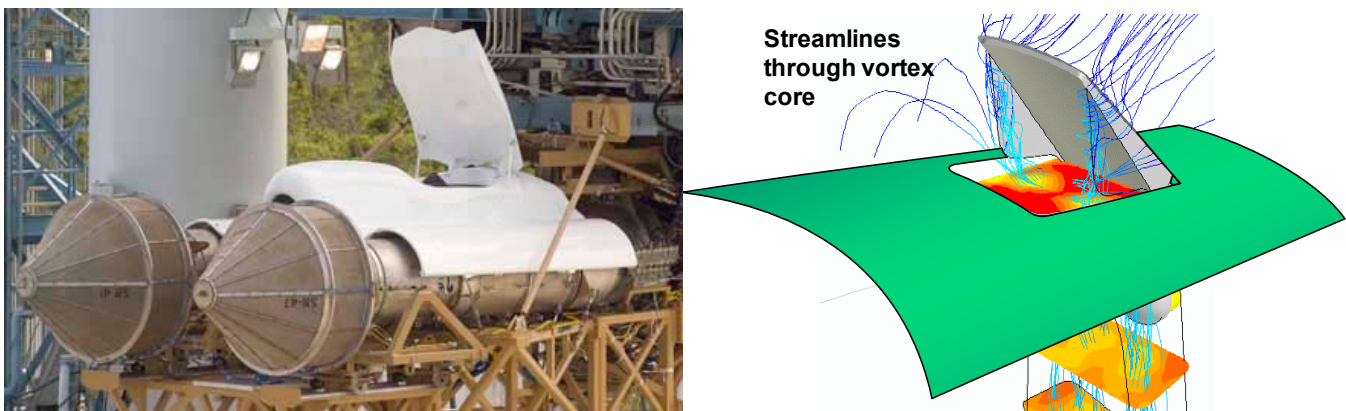


FIGURE 10 - JSF PROPULSION SYSTEM TEST RIG WITH LIFT FAN “STATIC INLET” TO ASSESS THE HOVER FLIGHT CONDITION

As a result of the “stream tube” and hover tests, the propulsion system risk was reduced to an acceptable level, clearing the way for full-aircraft ground tests followed by flight testing.

4.1.4 Thrust-Reverser Experience

For many years the use of thrust reversing to assist aircraft braking after landing has resulted in occasional engine surges. It was generally assumed that hot-gas re-ingestion was the cause of this surge. Motycka conducted extensive tests of engines in thrust-reverser mode (see Reference 13). His investigation, supported by analytical studies, showed that the dominant cause of the engine surges during reverser operation was the existence of a vortex in the inlet air stream. His results also showed that the vortex caused a severe pressure distortion which was the primary cause of surge during reverser operation rather than the temperature distortion.

Motycka reported the comprehensive results of conditions under which a vortex could cause engine surge during thrust-reverser operation. His findings include the following cases:

- a. Case 1: Tests of JT9D installed-engine thrust reverser were conducted on the B-52 Flying Test bed (see Reference 13). After a high-speed taxi run to approximately 120 Kts, the thrust reverser was deployed in the simulation of a normal landing rollout. Thrust-reverser operation was terminated at engine stall or a speed of approximately 20 kts, whichever came first. A sample of pressure and temperature distortion results is shown in Figure 11 revealing the location of a vortex. As the forward speed slowed, the low-pressure core of the vortex tended to move from the fan to the core stream, resulting in the potential for instabilities in the gas-generator compressor as shown in Figure 11.

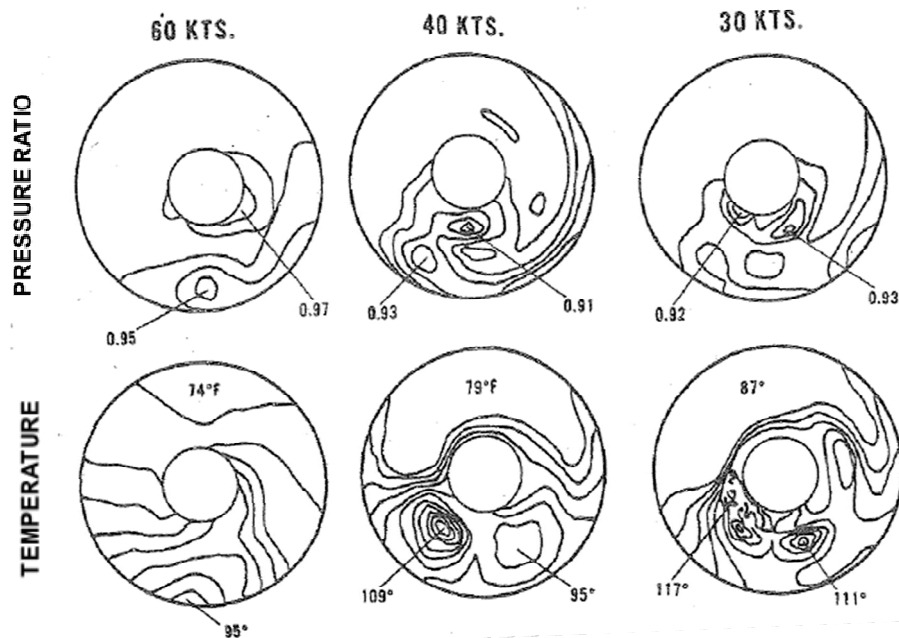


FIGURE 11 - B52/JT9D REVERSER TEST – MAXIMUM INSTANTANEOUS INLET DISTORTION VERSUS GROUND SPEED

- b. Case 2: In 1971, an Air Force C-141 aircraft was flown with high-response inlet-pressure instrumentation. During the thrust-reverser portion of this test, very high instantaneous total-pressure distortion was present during reverser operation shown in Figure 12. A peak level of $(P_{T2Max} - P_{T2Min})/P_{T2Avg}$ between 20 and 25 percent was encountered just prior to the onset of instability.

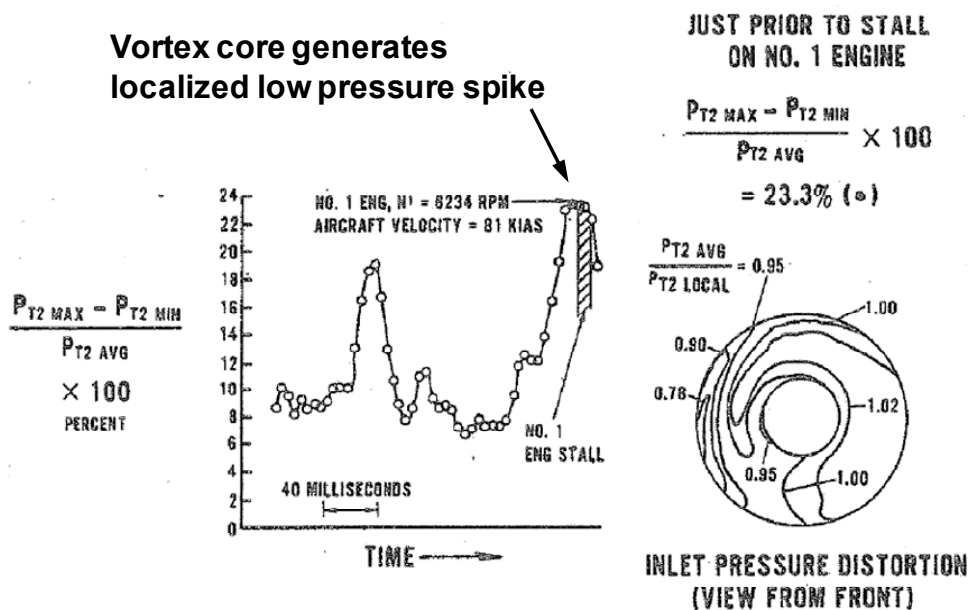


FIGURE 12 - C-141/TF33 INLET DISTORTION SURVEY DURING MAXIMUM REVERSER OPERATION (REFERENCE 13)

4.1.5 Auxiliary Power Unit (APU) Experience

In the case of APUs, swirl is generated by flow turning that occurs locally within the plenum chamber that often is incorporated in the installation, and therefore can occur either statically on the ground or in flight. An example is found in the TSCP 700-5 APU installation in the Airbus A300 transport aircraft. The TSCP 700-5 features a three-stage, low-pressure, axial compressor followed by a single-stage, high-pressure, centrifugal compressor. It is installed in the aircraft tail cone as shown in Figure 13. The installation features an inlet with variable flaps that may be configured for APU operation both in flight and on the ground. The inlet supplies air to a plenum chamber. The flow makes a turn as the engine draws air from the plenum.

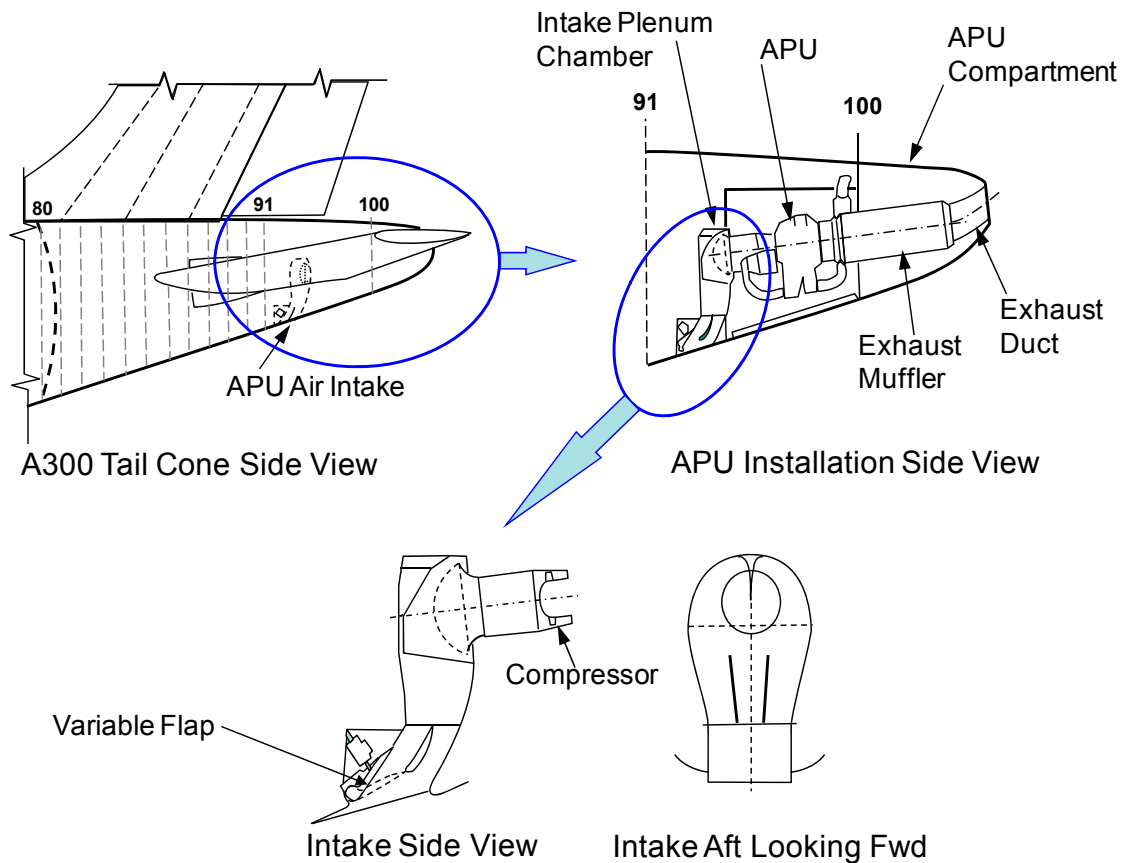


FIGURE 13 - APU INSTALLED IN AIRBUS A300 TAIL CONE (REFERENCE 14)

A series of high-cycle-fatigue (HCF) failures of the axial compressor blades prompted a study by K. W. Lotter and J. Jörg (see Reference 14). Theorizing that the blades were aerodynamically excited at their natural frequencies, the investigators measured the inlet flow field using five-hole probes and the surface flow patterns using oil-flow traces. The results indicated swirl angles of up to 40 degrees were experienced in ground operations while angles as high as 50 degrees were experienced in flight, as shown in Figure 14. The investigators attributed the excitation of blade resonance to the swirl pattern and developed modifications to the intake system that reduced the flow angularity as indicated.

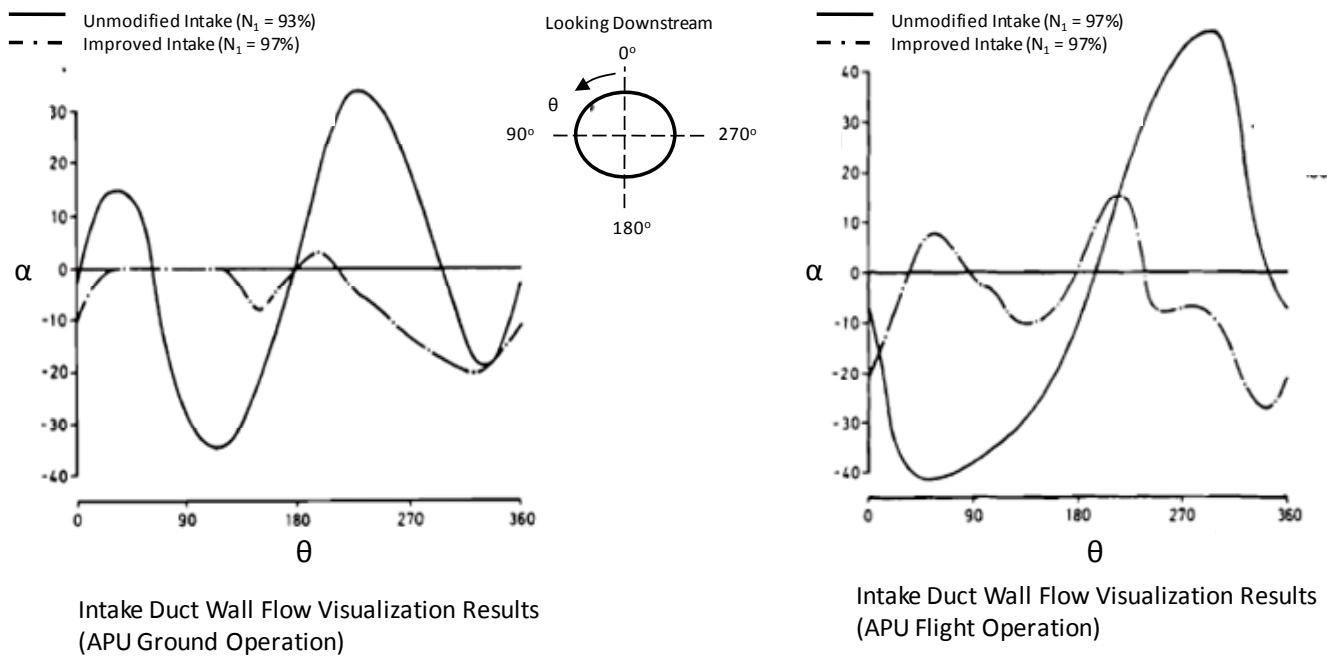


FIGURE 14 - APU INLET DUCT SWIRL ANGLE VERSUS CIRCUMFERENTIAL LOCATION FROM OIL FLOW TEST (REFERENCE 14)

4.1.6 Case Study Summary

The case studies cited in this chapter showed that swirl-distortion issues can arise in aircraft ground and flight operations. The cases included examples spanning the range of flight regimes from fighter-aircraft supersonic-flight operations to APU static-ground operations. The wide variety of inlet-engine configurations examined suggests that swirl distortion can originate from a number of sources, and therefore, a variety of swirl characteristics might be expected. The next section shows that this is, in fact, the case. The various types of swirl encountered in the case studies are categorized and the aerodynamic mechanisms leading to swirl are described.

5. SOURCES AND IMPACT OF SWIRL

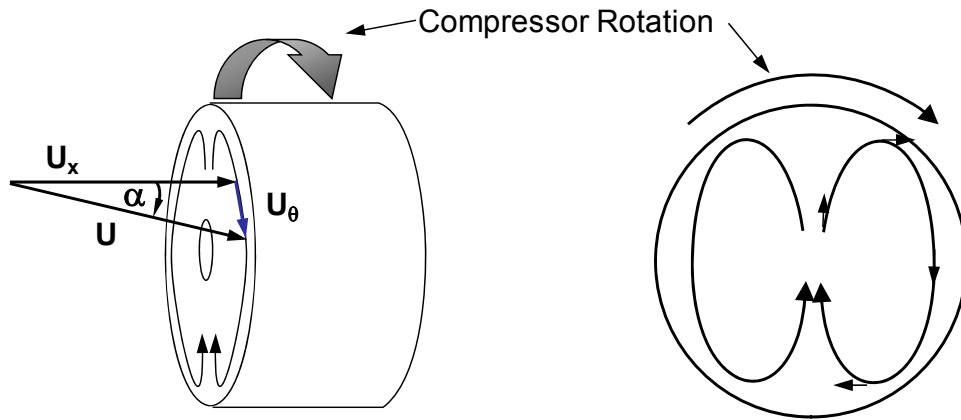
Inlet swirl has been grouped into as many as a dozen different categories. The large number of categories resulted from delineations that included not only the characteristics of the swirl itself but the inlet configuration and the physics that induced the swirl. In this document, swirl is grouped into four fundamental categories based strictly on the characteristics of the swirl pattern. The characteristics that define the four fundamental types of swirl patterns as well as the mechanisms by which various configurations generate swirl are presented. It will be shown that the swirl produced by various configurations fall into one of these categories. It will be subsequently shown, in Section 6, that the basic categories of swirl actually define points on a continuous spectrum of swirl-pattern shapes which can be described using numerical descriptors. Section 5 ends with a brief introduction to the mechanisms by which swirl affects the engine compression system.

5.1 Types and Sources of Swirl

In the following subsections, swirl is grouped into the following four categories: (1) bulk swirl, (2) tightly-wound vortices, (3) paired swirl, and (4) cross-flow swirl. Examples of inlet configurations that most commonly generate each type of swirl are presented to show how the swirl is formed.

The characteristics of the various types of swirl will be illustrated in terms of the swirl angle. The swirl angle, α , is defined at a point as the circumferential angle of flow from the axial direction as calculated in Eq. 1 and shown in Figure 15. A positive swirl angle is in the direction of the fan or compressor rotation. The swirl pattern is representative of the distribution of swirl angle over the AIP.

$$\alpha = \tan^{-1} \left(\frac{U_{\theta}}{U_x} \right) \quad (\text{Eq. 1})$$

FIGURE 15 - DEFINITION OF SWIRL ANGLE α

5.1.1 Bulk Swirl

Swirl distortion is defined as bulk swirl when flow approaches the compressor with the entire flow field rotating in one direction about the rotational axis of the compressor. If the flow is rotating in the same direction as the compressor rotation, it is called a co-rotating bulk swirl. Conversely, if the flow approaching the compressor is rotating in the opposite direction to the compressor rotation, then it is referred to as counter-rotating bulk swirl (also called contra-rotating bulk swirl in some literature). An example flow field (upstream of a compressor) resulting from bulk swirl is illustrated in Figure 16.

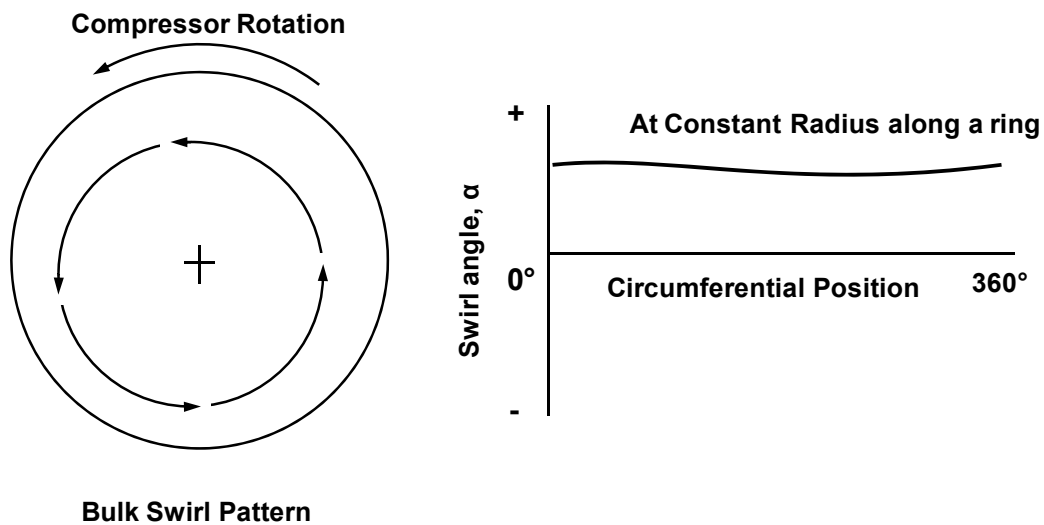


FIGURE 16 - PROJECTED VELOCITY VECTORS PRODUCED WITH BULK SWIRL

Bulk swirl can be generated through a number of mechanisms external or internal to the inlet. For example, bulk swirl can be generated by a large externally produced vortex ingested into a pitot-style inlet system as shown in Figure 17. Such a vortex could be generated by an external component of the airframe. Possibilities include wing-tip vortices or vortices shed from the fuselage in sideslip conditions.

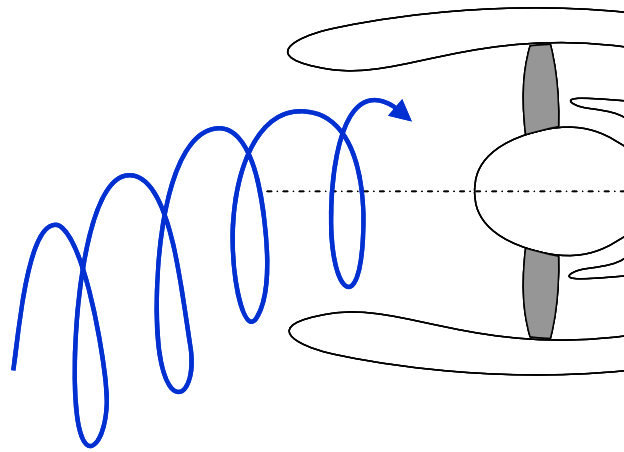


FIGURE 17 - BULK SWIRL GENERATED BY INGESTING A LARGE EXTERNALLY GENERATED VORTEX INTO THE INLET

Internally-generated bulk swirl can be a result of the geometry of the air-induction system coupled with the inlet-flow conditions. For example, bulk swirl can develop in inlets that feature inlet plenums. Such inlets are typical of airplane APU installations as well as marine and industrial engine installations. The development of inlet swirl in an inlet plenum can be visualized by considering the plenum-style inlet in a cross wind. As illustrated in Figure 18, cross-wind flow entering a plenum-style inlet from a direction normal to the rotation axis will result in a bulk swirl at the compressor entrance.

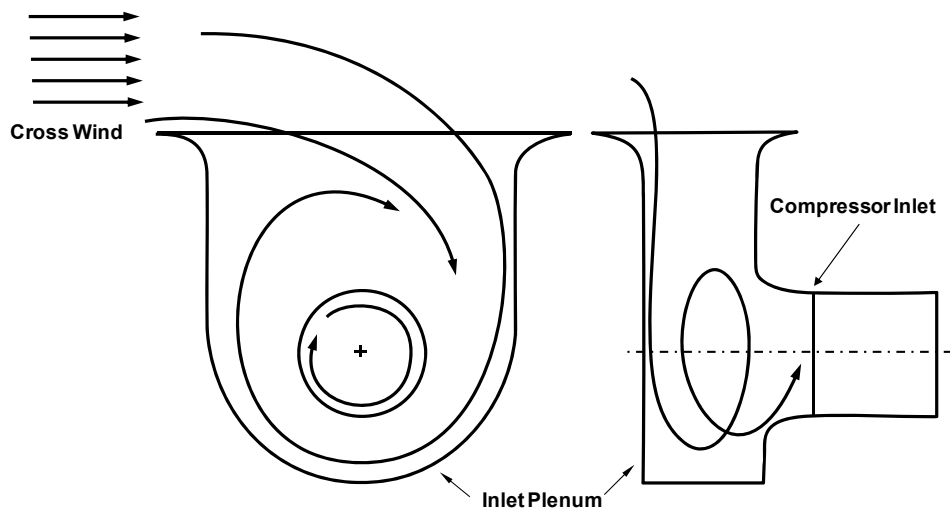


FIGURE 18 - PLENUM-STYLE INLET IN CROSS WIND GENERATES A BULK SWIRL

Bulk swirl also can be generated internally in inlets featuring S-shaped diffuser ducts. Such inlets are found in some fighter aircraft, cruise missiles, and center engines of commercial aircraft. Bulk swirl can result when the inlet flow experiences a non-axisymmetric total-pressure gradient normal to the plane of the turn that interacts with the static-pressure gradient of the S-bend flow. Vorticity associated with the pressure gradient normal to the plane of the turn is a necessary condition for generation of a bulk swirl at the exit of the turn.

The total-pressure gradient that contributes to the initiation of S-duct bulk swirl can originate from local flow separation at the entrance to the duct. A schematic diagram of a vertical S-bend inlet (depicting the Tomahawk-style inlet discussed in Section 4) in sideslip appears in Figure 19. As shown, a low-pressure region due to a sideslip separation (out-of-plane of the vertical-duct turning plane) causes the low-energy flow to migrate circumferentially to the inside radius of the duct turn. This migration sets up a clockwise bulk swirl (forward looking aft). A sideslip in the opposite direction would generate a bulk swirl rotating in the opposite direction. Thus depending on the direction of rotation of the engine, one of the sideslip directions would result in a counter-rotating bulk swirl which would tend to reduce stability margin. This was the mechanism responsible for operability issues in the Tomahawk case discussed in Section 4.

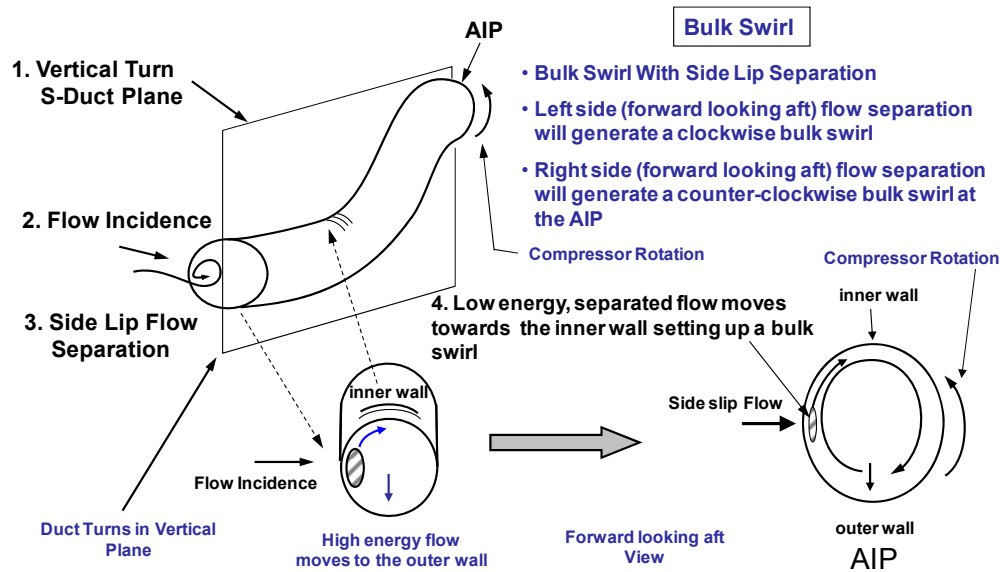


FIGURE 19 - AN INLET DUCT WITH A TURN WILL GENERATE A BULK SWIRL PATTERN IN CROSS WIND DUE TO LOW ENERGY FLOW ENTERING THE WINDWARD SIDE

Another example of an inlet system that could generate bulk swirl would be a side-mounted inlet (with a horizontal-duct turning plane) found in some fighter aircraft such as the Tornado shown in Figure 20. A bottom-lip flow separation can result from the high-flow incidence experienced during a take-off rotation. This bottom-lip flow separation creates a low-pressure region out of plane of the (horizontal) turn and sets the conditions necessary for generating a bulk swirl as this low-pressure, low-energy flow negotiates the inlet-duct turn and migrates to the inside radius. The left and right inlets (aft looking forward) will generate bulk swirls at the AIP, each rotating in the opposite direction because the inlet turns are opposite. Since both left and right engines are rotating in the same direction one of the inlets will generate a counter-rotating bulk swirl, and the other a co-rotating bulk swirl.

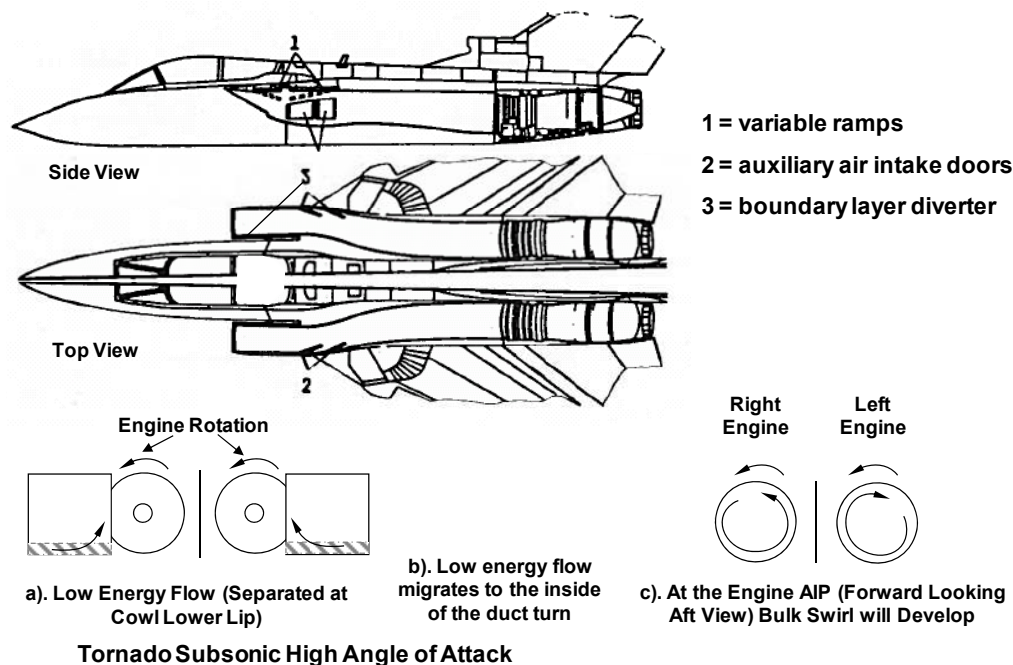


FIGURE 20 - EXAMPLE OF TORNADO SIDE INLETS GENERATING OPPOSITE BULK SWIRL PATTERN DUE TO A LOWER LIP SEPARATION

The same side-inlet configuration with separation on an upper ramp (of a side-mounted inlet) in supersonic operation will generate a bulk swirl rotating in opposite directions from those generated during takeoff. This was the cause of the operability issues discussed in the Tornado example of Section 4. In the example shown in Figure 20, the left engine experienced a counter-rotating bulk swirl when the lower-lip flow was separated at high angle of attack. In the event of upper-ramp flow separation in supersonic operation, the bulk swirls in each inlet reversed direction from what is shown in Figure 20 causing the right engine to experience a counter-rotating bulk swirl.

5.1.2 Tightly-Wound Vortex

Tightly-wound vortices are compact vortices which are generated by a number of mechanisms. Examples of some sources of tightly-wound vortices include tip vortices from upstream aircraft strakes or leading-edge extensions as well as vortices attached to the ground or airframe during ground operations. These vortices tend to be small (on the order of 10 percent of the inlet flow area), highly dynamic in location, and extremely difficult to measure.

A vortex associated with static or near-static engine operation in the vicinity of the ground is sometimes called an inlet-ground vortex or simply a ground vortex. In general, the formation of an inlet-ground vortex requires a flow sink, a ground plane with a stagnation point for vortex attachment, and vorticity in the approaching flow. In the example, shown in Figure 21, the engine inlet provided the flow sink, the taxiway surface provided the vortex attachment point, and the boundary-layer flow along the ground plane provided the ambient vorticity needed. Due to condensation of moisture in the ambient air brought about by the pressure and temperature drops in the vortex, the ground vortex can easily be seen in the photograph.



FIGURE 21 - PHOTOGRAPH OF A TIGHTLY-WOUND GROUND VORTEX DURING THRUST REVERSER OPERATION

Although the tightly-wound, inlet-ground vortex may attach to the ground as shown in Figure 21, it may attach to other surfaces. In fuselage-mounted engines (see Figure 22) which are relatively far from the ground plane but close to the fuselage surface, a tightly-wound vortex can form in aircraft static or near-static operation between the fuselage and the inlet or between the inlet and the upstream wing surface.

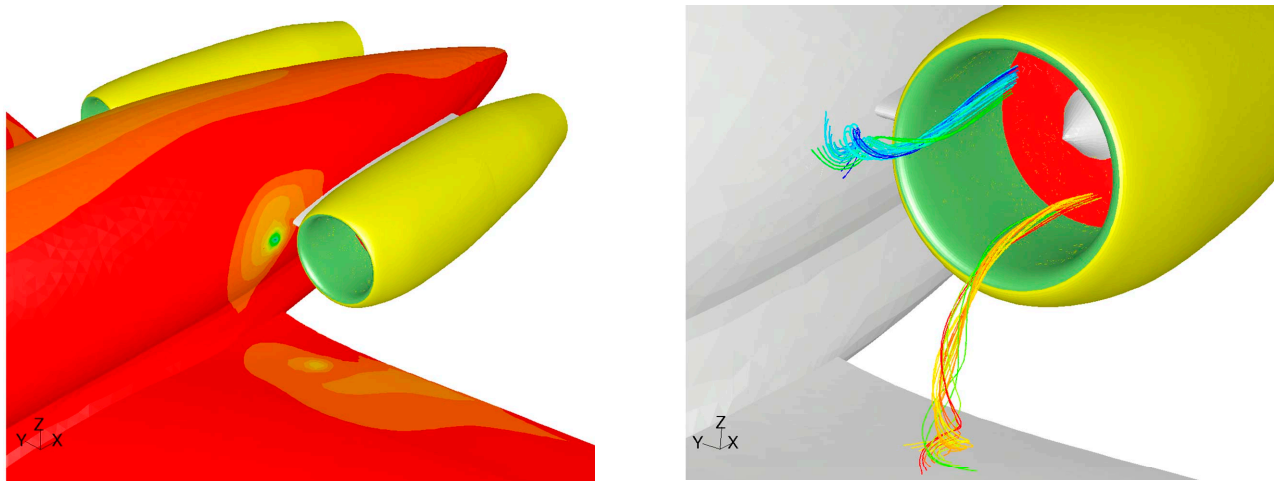


FIGURE 22 - FUSELAGE-MOUNTED ENGINE INSTALLATION

The inlet-ground vortex has caused problems ranging from the ingestion of debris or foreign objects into the engine to engine stability margin loss, such as described in Section 4.1.4. As a result, the formation of the inlet-ground vortex became the subject of many investigations (see References 13 and 15 to 18). These studies report the existence of four different modes of vortex formation each of which fundamentally depends on ambient-vorticity sources, the relative-wind direction, wind strength and the existence of a stagnation point on the ground plane near the inlet for the vortex to form. Ambient vorticity is the shear flow at a far-upstream location created as the wind blows across the ground or if flow approaching the inlet has a vertical or horizontal velocity profile. A ground vortex can form in quiescent (no wind), head-wind, cross-wind and tail-wind conditions.

The vortex formation is dependent on the combination of velocity ratio U_i/U_∞ and the non-dimensional height h/D_i of the inlet above the ground, where U_i is the inlet velocity, at the lip highlight, and U_∞ is the free-stream velocity. This relationship is shown in Figure 23, reproduced here from Reference 18. In particular, increasing the velocity ratio or decreasing the non-dimensional height has been found to result in an increased tendency for vortex formation, or the strengthening of an existing vortex. The need to increase the by-pass ratio of engines in order to increase the propulsive efficiency is forcing lower lips of wing mounted engines closer to the ground and thus to operate in the so called “vortex region” shown in Figure 23.

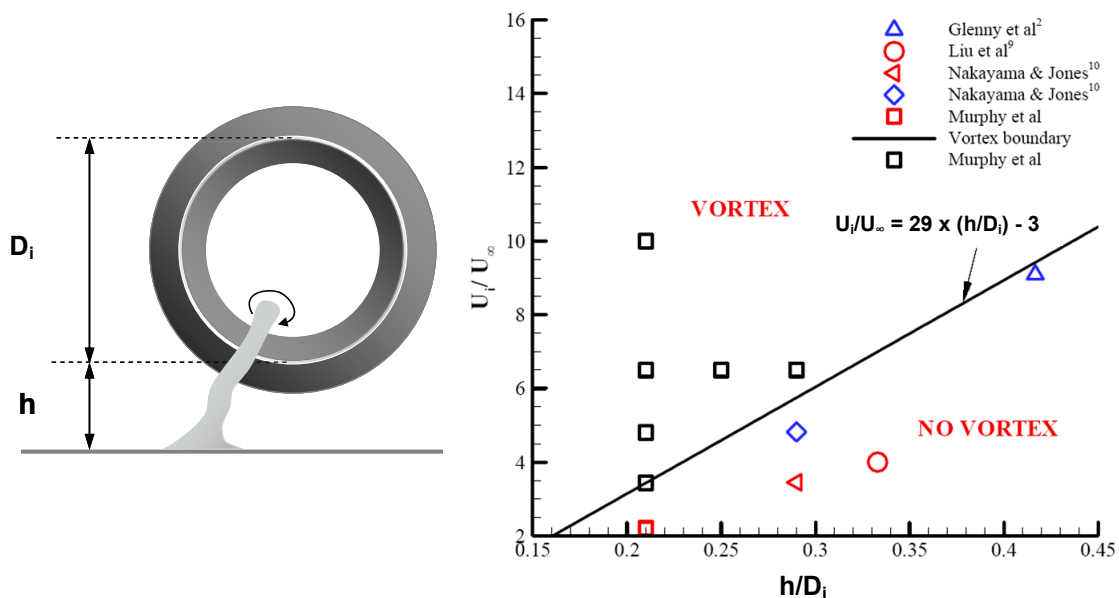


FIGURE 23 - VELOCITY RATIO VERSUS NON-DIMENSIONAL HEIGHT REVEALS A REGION OF VORTEX FORMATION AND NO VORTEX FORMATION (REFERENCE 18)

The magnitude and extent of the ground vortex is also a function of the wind direction. In Reference 18, the investigators conducted tests with a 90-deg cross wind as well as tests with quiescent (no-wind) conditions. A comparison of the total pressure distortion produced by the inlet-ground vortex between the quiescent and the cross-wind conditions appears in Figure 24. With the cross-wind conditions, the vortex was approximately three times stronger, four times larger and resulted in a 20-fold increase in a total-pressure loss compared with the quiescent conditions.

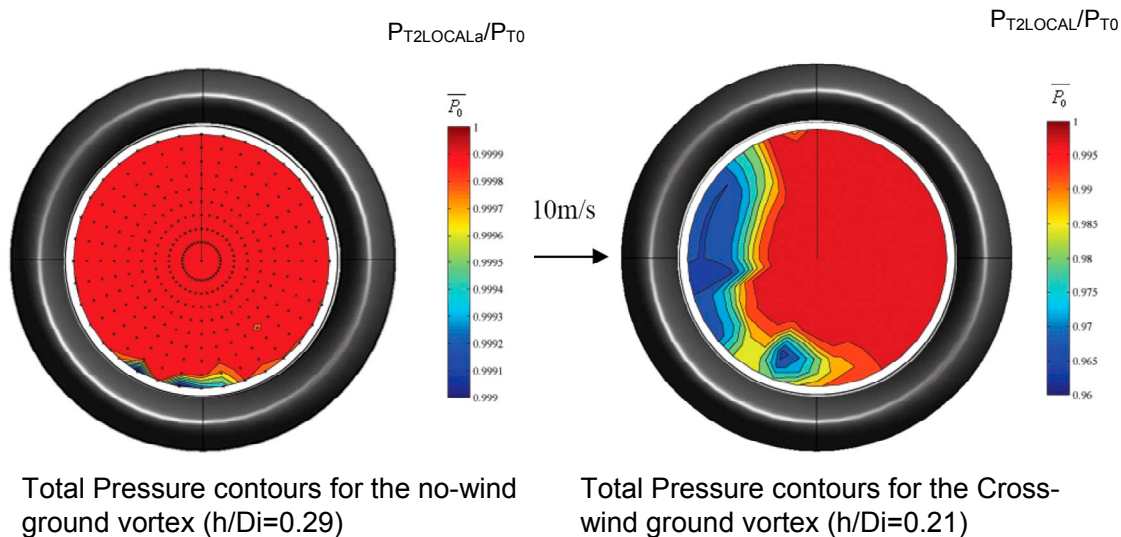


FIGURE 24 - COMPARISON OF GROUND VORTEX WITH AND WITHOUT CROSS-WIND AT SAME INLET FLOW (REFERENCE 18)

In addition to swirl magnitude and extent, wind direction and velocity also influence the position of the tightly-wound ground vortex at the AIP. In Reference 19, the investigators showed an influence of a tailwind on the position of the vortex. For a fixed ground height, increased tail wind causes the foot of the vortex to move ahead of the inlet lip while the head of the vortex moves towards the core stream (the flow that enters the engine core), as shown in Figure 25. This trend was observed in the reverser test of Reference 13. As the forward speed of the aircraft was reduced the relative velocity between the reversed gas and the forward motion of the aircraft produced an apparent increased "tail wind" causing the vortex with low-pressure core to enter the core stream of the engine.

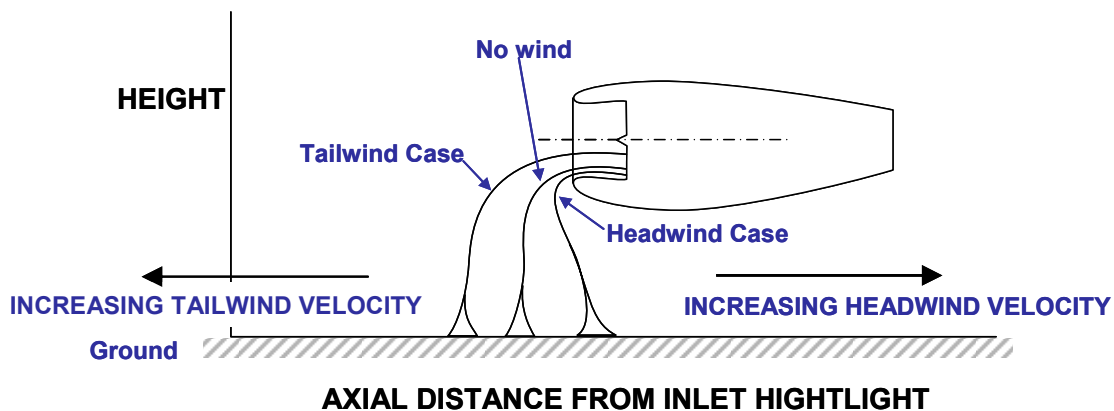


FIGURE 25 - INFLUENCE OF WIND DIRECTION ON POSITION OF VORTEX

The structure of the inlet vortex is very similar to that of an aircraft wing-tip vortex as shown by the Rankine vortex velocity distribution in Figure 26. Here, circulation Γ is the strength of the vortex defined by the tangential velocity as a function of the radius from vortex-core center. There is a rapid rise of the tangential velocity to a peak in the core of the vortex with gradual velocity decay outside the core. The vortex core is also associated with a sharp drop in total pressure seen in Figures 24 and 11.

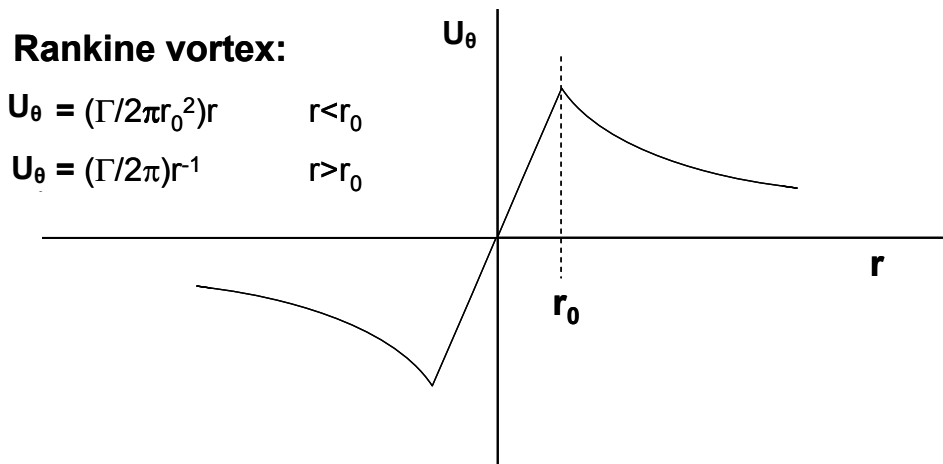


FIGURE 26 - VELOCITY DISTRIBUTION IN A TYPICAL GROUND VORTEX

In general, a tightly-wound inlet vortex produces a flow that has a large-amplitude, local, tangential velocity and decaying lower tangential velocity distortion over a considerable angular extent around the head of the vortex at the engine face. However, there is a significant total-pressure defect (~20%) over a small fraction of the inlet-flow area. As noted in Reference 13, this localized sharp total pressure defect causes a circumferential distortion which is largely responsible for the engine surge and not the swirl in the inlet vortex. Thus the swirl distortion caused by the vortex is indirectly responsible for engine operability issues by creating a sharp low-pressure region.

Although an inlet vortex occupies a narrow circumferential extent, it possesses high swirl angles and large total-pressure deficits. Furthermore, measurements have shown that the position of the inlet vortex is highly unstable leading to time-variant swirl distortion. Some investigations have indicated that there is actually a pair of counter-rotating tightly-wound vortices at the AIP even though only one ground-attachment point is apparent. A further discussion of the structure of the inlet vortex, supported by computational and test results appears in Appendix A. The past practices have been to recommend avoidance, which in practice is achieved via operational procedures such as placing limits on static thrust production or limiting thrust-reverser operation at lower speeds.

5.1.3 Paired Swirl

Paired swirl is the most common type of swirl. The literature contains at least two explanations for the formation of paired swirl, one based on vorticity considerations, and one based on pressure-gradient considerations. The vorticity-based description is depicted in Figure 27. In this description, a paired swirl is produced when a flow containing vorticity normal to the flow direction is turned out of the plane of the vorticity, i.e., normal to the vorticity vector. Referring to Figure 27, flow within a duct has a vorticity vector (1) which is due to the velocity gradient in the wall boundary layer. When this flow is subjected to the duct-turning vector (2), normal to the vorticity vector, it causes the flow to be rotated in a third (3) vector direction (apply right-hand rule). The two vortices in the sides of the duct are oriented opposite to each other. Therefore, when they are turned in the duct, they cause the flow on the two sides of the duct to turn in opposite directions from the outer side of the turn towards the inner side of the turn, thus resulting in a paired swirl at the exit of the duct.