

**Encyclopedia of Aerospace Engineering - Volume 8 - Chapter EAE487**  
**Basic Principles – Gas Turbine Compatibility – Intake Aerodynamic Aspects**

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## 1. ABSTRACT

Engine/intake compatibility covers the mutual dependencies between the aircraft intake and the gas turbine. Flow physical effects in both the intake and/or the gas turbine can reduce stability margins of the propulsion system dramatically, possibly resulting in unstable performance or engine flameout. Besides exhibiting optimal performance it is of utmost importance that stable propulsion operation in the whole flight envelope of a jet aircraft is ensured. In this chapter the sources of possible intake flow distortions will be described. The state of the art for the quantification of intake flow distortion by the use of distortion parameters is presented together with possible methods for measuring the data for the calculation of these parameters. Existing experience and current research efforts with the aim of reducing flow distortion in intakes are highlighted.

Note: Whereas this article concentrates solely on the aerodynamic aspects of intake flow distortions the effects of these distortions on the engine are covered in the companion Volume 8, Chapter eae573.

## 2. INTRODUCTION

There are two aspects that are important at the engine/intake interface. For an optimum propulsion system the intake must deliver the air at the highest total pressures ensuring high engine thrust or shaft power and as uniform as possible (both spatially and time wise) to allow stable engine operation at all flight conditions within the flight envelope. It is this second aspect, that is, the compatibility aspect, this chapter deals with.

During the design phase of an aircraft and its

engine it is important that the compatibility aspects at the aerodynamic interface between the aircraft intake and the engine experiences sufficient consideration because of the implications failures in this area may have. There are examples in the history of aircraft development where design expansion beyond the state of the art of engine and intake resulted in compatibility issues previously unknown. In some cases, extensive and expensive redesigns in order to deliver the specified performance resulted from this lack of knowledge. Lessons learnt from these experiences dictate that mutual understanding of intake and engine characteristics is essential for an efficient development process, requiring early coordination of design efforts between aircraft and engine.

## 3. COMPATIBILITY ASPECTS OF INTAKE DESIGN

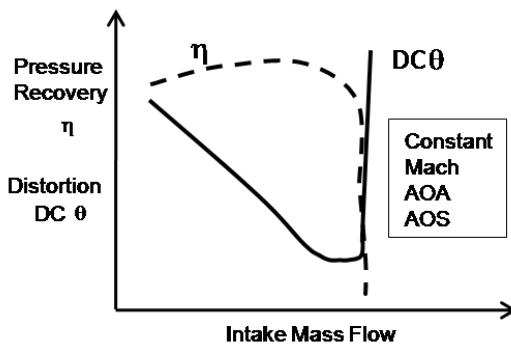
### 3.1 The Task of an Intake and its Performance Descriptor

The task of an intake is to transport the air mass flow required by the engine with as little total pressure losses as possible to the agreed-upon interface plane (AIP). Depending on the flight Mach number this requires either acceleration or deceleration of the air inside the intake in order to match the engine flow condition demands. (There exists only one aircraft that was built in large numbers for which no intake has been necessary, that is, the C-141 Starlifter transport aircraft.) In addition, the flow entering the engine should be as uniform as possible in order to ensure stable engine operation. Because other design aspects for the intake usually require compromises on its geometric design the intake flow of an aircraft can never be ideal for all flight and propulsion conditions with respect to both the efficiency of the intake and the uniformity of the intake flow.

In Volume 2, Chapter eae088 the performance parameters generally used for the intake of a propulsion system have been defined. Two parameters are of interest for this chapter, that is, the total pressure recovery defined as

$$\eta = \frac{P_{tAIP}}{P_{t0}} \quad (1)$$

and distortion (which will be defined in the following).  $\eta$  is a measure for the efficiency of the Ram compression of an intake and is the mean value of the total pressure at the engine entry plane (or an agreed-upon interface plane AIP) divided by the total pressure of the freestream flow. The dependency of total pressure recovery and distortion on intake mass flow is shown in Figure 1.



**Figure 1.** Dependency of Pressure Recovery and Distortion on Intake Mass Flow at Supersonic Flight Mach number

In this example at supersonic flight Mach number distortion exhibits exceedingly high values both at both low and high intake mass flows, indicating unstable intake flows and propulsion performance. Usable working range is limited to the intake mass flows between these two boundaries.

### 3.2 Flow Non-Uniformity – Intake Distortion

The intake flow can be non-uniform in the AIP plane in total pressure, or static pressure, or total temperature or in a combination of some/all of these parameters. These non-uniformities are usually described by "intake distortion" parameters. In addition flow angularity in the AIP, that is, the deviation of the flow direction from the axial engine direction is a further distortion parameter called swirl.

Static pressure distortion in general is a result of vortices entering the intake. The most prominent example is the so-called ground

vortex. Because those vortices depend, among others, on the engine mass flow they can be prevented by engine handling procedures on engine mass flow and will not be dealt with here.

The more important distortion parameters are the total pressure distortion and swirl for all aircraft and, in addition, total temperature distortion for fighter aircraft.

### 3.3 Sources of Intake Distortion

Although experience exists on the distortion behavior of different types of intakes for various aircraft projects, even today the compatibility situation of a new aircraft cannot be predicted with certainty at the start of the design cycles. This is mainly due to the fact that the selection of an intake type, its position on the fuselage and its cross-section variation and longitudinal shape are not only defined by flow physics arguments. Aircraft performance strongly influences this selection as does the internal fuselage structure and available space, for example, inside the fuselage. Aircraft stealth requirements seem to demand highly curved intake ducts that are prone to more or less heavy flow separations. The magnitude of these steady or unsteady flow separations depends on intake/engine mass flow. Today's very stringent cost and weight requirements have led to very compact intake designs exhibiting new risks of possible distortion problems.

#### 3.3.1 Total pressure distortion

The main sources for total pressure distortion are flow separations and wakes. Intake lip and/or sidewall separations can occur especially for thin, drag optimized shapes depending on the intake mass flow, which produce varying local flow angles/conditions around the lip/sidewall.

For subsonic passenger aircraft with optimized engine nacelle geometries on the wing (or top of the aft fuselage) this risk is usually small except for take-offs/landings at high angles of attack and take-offs with strong sidewinds.

This risk is much higher for an agile fighter aircraft whose flight envelope encompasses very high angles of attack and sideslip. Other disturbances for these aircraft with highly integrated intakes could be swallowed wakes from excrescencies or fuselage boundary layers that become separated due to interaction with intake shocks or due to intake

mass flow throttling. At supersonic flight Mach numbers shock/boundary layer separations on the walls or ramps of intakes pose a high risk of excessive distortion. Although this risk can be reduced by the use of wall bleed, passive bleed systems cannot always remove the separated air completely due to configuration limitations (e.g., space). Even relatively straight but very short intake diffusers can be prone to flow separation because the pressure increase from the throat to the AIP can become rather large such that the intake boundary layer cannot handle it for certain mass flows.

Engines of aircraft with a twin-duct intake do not only see distortion as created in two single-duct intakes but have to cope with a thick layer of low-energy air originating from boundary layer on both sides of the splitter between the two ducts. In addition, for those intakes twin duct instability can be a problem.

At supersonic Mach numbers the total pressure downstream of the external intake shock system of axisymmetric intakes at angles of attack depicts a gradient from the lower surface to the upper surface of the compression cone/half-cone because the strength of the oblique shock compression is weakened on the upper surface and strengthened on the lower surface. Depending on the quality of the subsonic diffuser this gradient can become the reason for total pressure distortion at AIP even without any additional flow separations.

Stealth considerations have led to the selection of intakes with triangular cross-section for UAVs. Together with the straight lips this creates extremely small acute angles on the sides of the intake. Boundary layers in these corners are prone to thickening and separation.

All these examples of flow separation can be unsteady to some degree. However, there are disturbances that are inherently unsteady like the wakes of the propeller entering the intake of a turboprop propulsion system. Another unsteady phenomenon is the organ-pipe type fluctuations of the intake/compressor air column during intake buzz (at small intake mass flows). In this case planar pressure waves travel inside the intake affecting the compressor periodically.

### 3.3.2 Swirl

Flow separations result in areas of low flow energy, which in curved intakes will lead to flow angularity according to the same

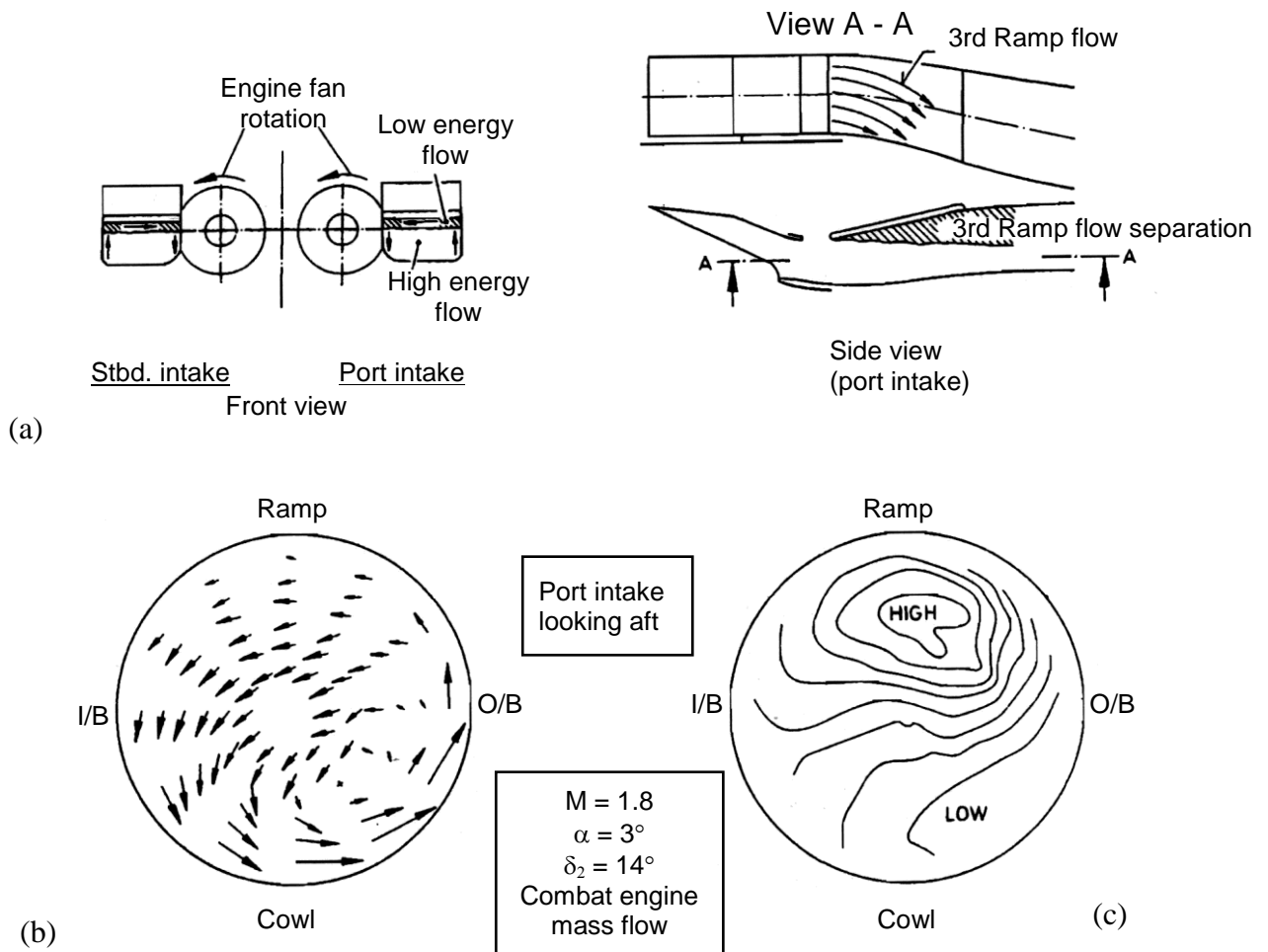
mechanisms that produce rotating flows in pipe bends. Depending on the location of the separation (top or bottom) and the curvature of the intake duct the flow can enter the compressor in either in rotation or counter-rotation direction (see Figure 2), that is, either decreasing or increasing the angle of attack of the compressor blades (or compressor guide vanes) - see Section 3.3.3 in Volume 8, Chapter eae573. This deviation from the axial flow is called swirl. Because highly integrated and compact intakes depict some sort of duct curvature their total pressure distortion is nearly always connected with swirl. Extremely large swirl values must be expected in serpentine intakes. These are the preferred intakes for stealthy vehicles. Intakes for Turboprop engines, auxiliary power units (APUs), helicopters, and even tanks and marine vehicles are prone to produce large swirl angles due to their compactness and duct curvatures.

### 3.3.3 Total Temperature Distortion

Total temperature distortion does not depend on the flow inside the intake but is a disturbance entering the intake from the outside. An example is hot exhaust gas that may be re-ingested under certain conditions on the ground. V/STOL aircraft hovering on their efflux are notorious for swallowing their own exhaust, especially under tailwind conditions. Other possible sources of temperature distortion, especially for combat aircraft, are ingestion of missile exhausts, jet efflux from preceding aircraft during formation flying or steam ingested during aircraft carrier take-offs. Entering of a prohibitive mixture of total pressure and temperature distortion due to gun firing into the intake can usually be prevented by carefully positioning the gun exit with respect to the intake entrance.

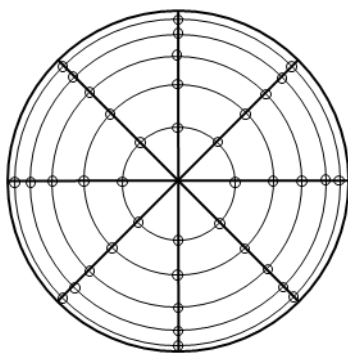
## 3.4 Distortion Descriptors and State of the Art of Distortion Evaluation

The description of the non-uniformity of the flow at AIP depends strongly on the way the basic data are measured. A natural way to do this in the circular AIP is by radial rakes on which measuring probes at the center of equal-area rings are positioned. With this configuration area weighting of the data is accomplished without extra mathematical efforts. It results in a denser clustering of the probes closer to the intake wall. A rake



**Figure 2.** Creation of swirl in curved intake duct. (a) Secondary flows in intake at supersonic Mach numbers and high ramp angles; (b) flow angles at engine/intake interface; (c) isobars at engine/intake interface. Reproduced with permission from Stocks and Bissinger (1981).

arrangement with eight arms on each of which five sensors are positioned is depicted in Figure 3.



**Figure 3.** Possible Rake and Pressure Sensor Arrangement in AIP

### 3.4.1 Total Pressure Distortion

In Figure 2c total pressure isobars are plotted at the AIP. A picture like this visualizes the flow

non-uniformity a blade of a compressor will experience during one revolution. The total pressure defect region can have negative effects on the flow inside a compressor possibly leading to surge or non-recoverable rotating stall (see Volume 8, Chapter eae573). For the determination of surge boundaries of an engine due to distortion, simple and easy-to-handle descriptors are needed, which can be correlated with the distortion sensitivity of the jet engine. These descriptors depend on the specific engine (geometry, compressor design, rotational speed, etc.) and cannot be specified in general. They must describe the sensitivity of the compressor to

- the magnitude of the total pressure defect distinguishing between circumferential and radial defects,
- whether circumferential and/or radial defects occur in the hub, mid-span, or tip regions,

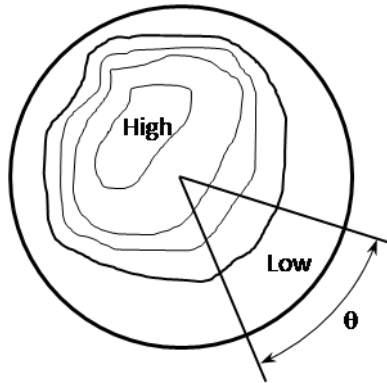
- the time a single compressor blade would spend in the defect region, and
- the number of defects which are encountered by a blade in one revolution.

Historically distortion descriptors differ from engine company to engine company. Next three types of classical distortion parameters, which have been successfully used in various aircraft projects in the past and present, should be described. The three are examples for simple and involved distortion parameter definitions.

**DC60.** This distortion parameter has been derived by Rolls Royce and used extensively in the European fighter programs TORNADO (Stocks, Bissinger, 1981) and Eurofighter (Bissinger, Jost, 2000).

$$DC\theta = \frac{\overline{p_{tAIP}} - \overline{p_{t\theta}}}{q^2} \quad (2)$$

$\overline{p_{t\theta}}$  is the minimum mean total pressure of all sectors of extent  $\theta$  in the AIP, and  $\overline{p_{tAIP}}$  and  $q^2$  are the mean total and dynamic pressures respectively at AIP (see Figure 4). The critical extent  $\theta$  of the low total pressure region depends on the engine design and can be 60° or larger. This distortion parameter is limited to one-per-revolution, circumferential total pressure non-uniformities.



**Figure 4.** Total Pressure Distribution in AIP – Definition of Critical Sector Angle  $\theta$

**KDA.** This is also a relatively simple but radially weighted circumferential distortion parameter. Its definition (AGARD, 1991) also reflects the ring-based geometry of the total pressure instrumentation.

$$KDA = 100 \frac{\sum_{i=1}^m \left\{ \left( \frac{\Delta p_{ti}}{\overline{p_{ti}}} \right)_{\max} \frac{r_{AIP}}{r_i} \theta_i \right\}}{\sum_{i=1}^m \frac{r_{AIP}}{r_i}} \quad (3)$$

where  $\Delta p_{ti} = (\overline{p_t} - p_{tmin})_i$  and  $\overline{p_{t,i}}$ ,  $p_{tmin,i}$  are the mean and lowest total pressure on a ring  $i$ , respectively, and  $\theta_i$  is an extent factor for the low total pressure section on that ring. The number of rings in the AIP is  $m$ .

**IDC and IDR.** In this case, the circumferential and radial distortion is calculated separately (LTH-AT 41 130-01, 1983). The engine distortion sensitivity must be specified using combinations of the two parameters.

For each ring  $i$  in the AIP a factor

$$IDC_i = \frac{\overline{p_{ti}} - p_{tmin,i}}{\overline{p_{tAIP}}} F_{\theta_i} \quad (4)$$

is calculated where  $F_{\theta_i}$  is an empirical weighting factor that is a function of the circumferential extent of the low total pressure on a ring. The value of the distortion parameter IDC is the largest value of the mean of the IDC ring values of two neighboring rings.

$$IDC = \max \left[ \frac{1}{2} (IDC_i + IDC_{i+1}) \right] \quad (5)$$

The radial distortion parameter is calculated by considering the inner ring (hub radial) and the outer ring (tip radial).

$$IDR_i = \frac{\overline{p_{tAIP}} - \overline{p_{ti}}}{\overline{p_{tAIP}}} \quad (6)$$

With  $i = in$  or  $out$  follows

$$IDR = \max (IDR_{in}, IDR_{out}) \quad (7)$$

**Proposal in Reference (SAE AIR1419, 1999).**

Large efforts have been undertaken to collate the state of the art in distortion descriptors and engine stability analysis with respect to surge in reference (SAE AIR1419, 1999). A method for the derivation of distortion intensities and distortion sensitivities of a compressor together with the specification of basic experimental requirements for the measurement of both can be found in the reference.

Distortion descriptor elements are derived from the measurements of total pressure on a rake and probe array in the AIP. Circumferential and radial distortion elements are described on a ring-by-ring basis. (Here only steady state one-per-revolution distortion is considered. Details for instantaneous multiple-per-revolution distortion are given in the reference.)

For a ring  $i$  the circumferential distortion intensity for a one-per-revolution total pressure defect region is calculated as

$$\left( \frac{\Delta P}{P} \right)_i = \frac{(PAV)_{i-} - (PAVLOW)_i}{(PAV)_i} \quad (8)$$

with

$$(PAV)_i = \frac{1}{360} \int_0^{360} P_t(\theta)_i d\theta \quad (9)$$

≡ Ring average total pressure

and

$$(PAVLOW)_i = \frac{1}{\theta_i^-} \int_0^{\theta_i^-} P(\theta)_i d\theta \quad (10)$$

≡ average total pressure in defect region of extent  $\theta_i^-$

For the same ring i the radial distortion intensity is given as

$$\left(\frac{\Delta PR}{P}\right)_i = \frac{(PFAV) - (PAV)_i}{(PFAV)} \quad (11)$$

with

*PFAV* = area-weighted face-average total pressure

$(PAV)_i$  = Ring average total pressure

$\theta_i^-$  = angular extent of defect region on ring i, that is, extent of the region with total pressures below *PFAV*

This reference does not define one specific distortion parameter (called screening parameter) because it is "impossible at this time to develop an inlet flow distortion screening parameter that is universal and quite independent of engine sensitivity parameters". Instead three examples of possible screening parameters are presented.

The first example uses the loss of compressor surge pressure ratio.

$$SCREENING \ PARAMETER = \frac{\Delta PRS}{Allowable \ \Delta PRS} \quad (12)$$

where

$\Delta PRS =$

$$\sum_{i=1}^m \left[ KC_i \left(\frac{\Delta PC}{P}\right)_i + KR_i \left(\frac{\Delta PR}{P}\right)_i + C_i \right] \times 100$$

≡ loss in compressor surge pressure ratio due to distortion

(13)

with

m = number of rings in AIP

$KC_i$  = circumferential distortion sensitivity (empirically determined)

$KR_i$  = radial distortion sensitivity (empirically determined)

$\left(\frac{\Delta PC}{P}\right)_i$  = circumferential distortion sensitivity as defined above

$\left(\frac{\Delta PR}{P}\right)_i$  = radial distortion sensitivity as defined above

$C_i$  = an offset term (empirically determined)

For compressors that are most sensitive to circumferential total pressure distortion (usually downstream compressors) an equation for a family of "screening parameters" is given:

$$SCREENING \ PARAMETER = \sum_{i=R}^S \left(\frac{\Delta PC}{P}\right)_i f(\theta_i^-) f(MPR_i) \quad (14)$$

with

$f(\theta_i^-)$  = extent function (empirically determined)

$f(MPR_i)$  = multiple-per-revolution function (empirically determined)  
- is equal to one in case there is only one defect region on a ring

Both functions may be different for each compressor. The summation in this equation should be performed over the rings that measure the total pressure of the air that passes through the particular compressor and not necessarily over the whole AIP. R and S are the relevant ring numbers.

Another equation is given for a family of compressors that are sensitive to both circumferential and radial intake distortion:

$$SCREENING \ PARAMETER = \sum_{i=R}^S \left\{ \left(\frac{\theta_i^-}{MPR_i}\right)^2 \left(\frac{\Delta PC}{P}\right)_i + b \left[\left(\frac{\Delta PR}{P}\right)_i + C_i\right] \right\} \quad (15)$$

with

$MPR_i$  = multiple-per-revolution number. For definition see reference

$\theta_i^-$  = angular extent of defect region. For multiple defect regions see definition in reference

b = superposition factor describing the ratio of radial distortion sensitivity to circumferential distortion sensitivity

$C_i$  = offset term

The summation again depends on the specific compressor. For example, for hub or tip

sensitive fans the summation would be performed over the inner or outer rings only.

### General Remarks

The distortion parameters above can be calculated for steady state and instantaneous total pressure data. Instantaneous distortion can exceed steady-state distortion drastically and therefore defines the surge-free limit for a propulsion system.

Testing time in a wind tunnel at one data point usually is in the order of 0.5 to 1 seconds. It must be assured that this testing time is sufficient to capture the maximal distortion value (Lotter, Scherbaum, 1992), for example, by statistical analysis of all distortion peaks measured during a test point.

Recommendations concerning instrumentation, data acquisition, data processing, and data scaling (full-scale engine test via large-scale intake model tests) are summarized in references (SAE ARP 1420, 2002; SAE AIR1419, 1999). The most sensitive task for the designers of intake and engine is the definition of an interface plane (AIP) at which data from intake model tests and full-scale engine tests can be matched. It has to be assured that at that plane both in the intake of models and in the full-scale vehicle flow conditions are the same and that the engine does not modify the intake flow at this station. This has been easily possible for relatively long fighter intakes. However, the situation is totally different for very compact configurations like in intakes for helicopter, turbo-prop engines, or auxiliary power units (Lotter, Jörg, 1982; Chamay, Zelazny, 1998). In these cases it is very difficult to design an intake model including its instrumentation that does allow realistic tests. Sometimes full-scale testing together with the engine is the last resort. (The same problem exists for CFD methods for which relevant intake exit boundary conditions have to be found for calculations of such an intake.)

It has become known in the propulsion community that the rake with 40 probes as recommended in references (SAE ARP1420, 2002 and SAE AIR1419, 1999) is not always adequate. In some cases this rake would not catch significant flow details. This could be the case, for example, for a twin-duct intake in which the boundary layer on the splitter plate between the two ducts spans the complete duct height. The wake originating from the splitter plate can only be determined by extremely high effort of scanning it. A fixed

rake would not be able to produce sensible data.

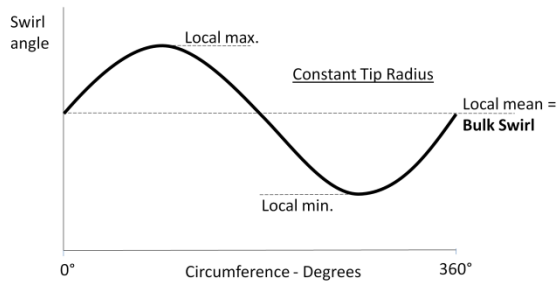
Because of the complexity of total pressure distortion measurements several attempts have been made to estimate total pressure distortion descriptor values from turbulent root mean square (RMS) data of a limited number of pressure probes (Jacocks, 1972; Borg, 1981; Sedlock, 1984; Liang, Zhang, 1992). The results of these methods are good only as long as the distortion level is small and can be applied during early design stages for exploring boundaries of high total pressure distortion flow areas.

### *3.4.2 Swirl*

Up to today no agreed-on methodology exists that deals with effects of swirl distorted intake flows. One reason for that is that the engines of the big American fighter programs did not show sensitivity to swirl, mainly because their inlet guide vanes seem to be able to reduce swirl to an acceptable level. In contrast, European engines without guide vanes show sensitivity to swirl and large efforts have been undertaken on company basis to investigate and quantify swirl effects as well as assure by design and stage matching that sensitivity to swirl distortion is minimized.

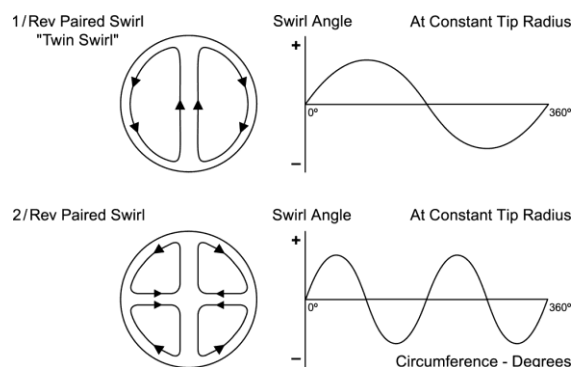
Swirl, as considered here, is a circumferential cross-flow velocity in AIP. If this cross-flow velocity is contra-rotating to the engine then stability can be reduced. Experience in the past has indicated that an engine can be more unstable when subjected to total pressure distortion in combination with swirl than when running with total pressure distortion alone.

The cross-flow velocity distribution in the AIP of the TORNADO project (Stocks, Bissinger, 1981) in general looked like in Figure 2b. Plotting the angle between the circumferential and axial velocity (swirl angle) around the circumference at constant radius (see Figure 5) it can be seen that this swirl pattern can be decomposed into a mean swirl (called bulk swirl in Figure 5) and a 1/Rev Paired Swirl (see Figure 6) called Twin Swirl. It was found that the engine sensitivity was dominated by bulk swirl at a constant tip radius. Because of its simple flow angle pattern, bulk swirl can be simulated rather easily whereas the full cross-flow pattern requires much more effort (see Section 3.7.2 in Volume 8, Chapter eae573).



**Figure 5.** Local Swirl Angles at Constant Radius and Definition of Bulk Swirl

For some intakes, for example, in APUs, this simple bulk swirl parameter can no longer be used. For those intakes swirl can manifest itself in 1/Rev Paired Swirl or even as 2/Rev Paired Swirl and bulk swirl is zero (see Figure 6). For these cases SAE Committee S-16 is discussing this subject and will publish a report that will in the future supplement the reports on total pressure and temperature distortion (SAE ARD50015, 1991; SAE ARP1420, 2002; SAE AIR1419, 1999). At the moment this report does not cope with combined total pressure and swirl distortion (although mentioning it). Also, swirl is considered to be steady state. Unsteady swirl measurements would be extremely involved and costly. There are no data available today that would support the request for dynamic swirl investigations.



**Figure 6.** Generic Paired Swirl Patterns

One proposal for a standardized description of swirl flows and their effects on engine performance is given in Bouldin, Sheoran (2002). A report on a numerical investigation of the effects of twin swirl, bulk swirl, and combined total pressure and swirl distortion on

compressor stages has been published in Davis and Hale (2007).

Flow angles can be measured with five-hole-probes. These probes need careful calibration. In small- to medium-scale intake models a drawback of these probes can be their relatively large size. So blockage at AIP could become a problem. However, due to progress in technology optical measuring methods like Doppler global velocimetry (DGV) are now available (Schodl, et al., 2002), which do not require measuring probes in the intake flow. All three velocity components can be measured with this system. Total pressure and total pressure distortion could then be derived from the measured velocity data.

### 3.4.3 Total Temperature Distortion

Whereas total pressure distortion and swirl are quite often the result of processes originating within the intake, total temperature distortion is caused by external factors (see Section 3.3.3). In the past, negative effects of total temperature distortion (e.g. surge, flameout) have been either avoided or minimized by aircraft configuration design or design modifications or/and operational procedure changes or/and desensitization of the engine by modifications of the engine control laws. Very often such modifications resulted in performance degradations.

With the highly agile aircraft and missiles of today the situation has changed because ingestion of hot gases is highly probable and can be severe enough to lead to engine surge and flameout even with some risk of loss of aircraft. A possible approach of the plume ingestion problem could be a combination of numerical methods for the determination of worst plume ingestion cases (Gleissl, Deslandes, 2005) and engine tests simulating the worst-case temperature conditions (Breuer, 2006) for the determination of the surge boundaries with respect to total temperature distortion. As a conservative approach the maximum increase of the mean total temperature and the temperature rise time at the entrance of the intake during the plume ingestion can be used for the description of the temperature distortion at AIP. Flight tests with exact replication of the total temperature distortion and determination of the derived surge boundary are prohibitively expensive if possible at all. A few in-flight missile firings specially designed to surge the engine are difficult enough for the confirmation of the surge prediction capability of the approach

selected and the proof that possible engine palliatives are working correctly.

The same approach could be used for the case that an engine plume is being swallowed during formation flying of several aircraft. It is the safety aspect of engine surge and not the performance that is of interest here.

Especially for cases for which the performance degradation due to total temperature is of importance, like for hovering/landing VSTOL aircraft, the SAE S-16 Committee has collected (SAE ARD 50015, 1991) in order to start discussions on this subject with the aim to publish an Aerospace Information Report (AIR) or Aerospace Recommended Practice (ARP) report in the future. At the moment the committee is of the opinion that there are "insufficient test data in the available literature to entirely substantiate the guideline procedures".

The guidelines to be discussed for the definition and measurement of the total temperature distortion parameter follow the same route as for the total pressure distortion parameter applied in references (SAE ARP1420, 2002; SAE AIR1419, 1999). It is proposed that total temperatures are measured on radial rakes at the center of equal area rings. A circumferential parameter is calculated on a ring-by-ring basis using the difference between the ring mean and the mean of that ring sector whose total temperatures are higher than ring average. Up to two sectors on a ring can be considered. A radial parameter is calculated on each ring based on the difference between the ring-average and AIP-average total temperatures. Small-scale model tests have to be designed very carefully. It is not always possible to exactly scale all parameters from full scale to model scale. One example is the temperature of the hot gas entering the intake of a VSTOL aircraft during hovering, which can be limited by the test set-up and model instrumentation. Small-scale testing of missile plume ingestion in a windtunnel can hardly be accomplished at all.

With further advances of numerical methods complicated maneuvers like landing of a VSTOL aircraft will be duplicated at correct flow conditions without the need of scaling (Richardson et al., 2006). Attempts have been made to not only calculate the distorted flow inside an intake but to numerically evaluate the effect of distortion on the engine, for example, in (Hale et al., 2004). These methods allow the study of the creation and the effects of total pressure, total temperature, and swirl distortion

and combinations of these distortion phenomena.

### 3.5 Reduction of Intake Distortion Effects

A jet engine propulsion system always requires compromises between vehicle configuration, intake design, and engine design. Appreciable distortion will always occur within the flight envelope of an aircraft at least in some boundary areas of the flight envelope (except maybe for a vehicle flying at one design point only). Therefore, it is necessary very early during the design that both intake and engine engineers carefully evaluate the distortion critical flight regimes and find ways to minimize possible incompatibilities.

Temperature distortion was usually coped with by the engine. Palliatives to desensitize the engine (e.g., by bleeds etc. – see also Volume 8, Chapter eae573) have worked quite well. If those are not sufficient and if, for example, changes in flight procedures during missile firing do not help, flight envelope restrictions will result.

Because the main source for total pressure distortion and swirl are flow separations or wakes it is natural that modifying the intake flow has the largest potential for relieving an incompatibility problem. Fences have reduced swirl in the TORNADO program (Stocks, Bissinger, 1981). In addition to conventional ramp/wall bleed vortex generators, micro jets, mesoflaps, wedges, ramps, bumps, and recirculating flow control devices (grooves) have been investigated for the reduction of separations and unsteadiness (Loth et al, 2004; Young et al, 2005; Holden, Babinsky, 2004) in shock-boundary layer interactions. Aggressive serpentine intake ducts have become of interest in programs like VAATE (Versatile Affordable Advanced Turbine Engines) and UEET (Ultra Efficient Engine Technology) in the USA. These intake ducts need active carefully optimized bleeds (Gorton et al., 2004; Florea et al., 2005) or arrays of vortex generators (Anderson et al., 2003; Jirásek, 2006). Problem areas like icing/deicing, bleed hole blockage by dirt, and material life and strength (mesoflaps) need to be evaluated.

By locally modifying the duct geometry and creating suitable pressure gradients it is possible to accomplish a redistribution of the flow such that at AIP the flow is more uniform (smaller distortion) and/or swirl is reduced. An early report on this was given in Lee and Boedicker (1985). The necessary duct

changes can be found by numerical optimization methods (Lee, Kim, Rho, 2005; Zhang, Lum, 2006). The validation of such approaches is a topic of current research.

Moveable intake lips have proven to be successful in keeping distortion low even at very high angles of attack (Bissinger, Jost, 2000).

The rule of thumb of older intake handbooks that a long subsonic diffuser with little curvature would damp-out all disturbances from upstream can no longer be applied due to configurational restrictions.

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## 5. SYMBOLS AND ABBREVIATIONS

### 5.1 Symbols

A = area

P = pressure

$P_t$  = total pressure

q = dynamic head,  $q = P_t - P$

r = radius

$\eta$  = intake pressure recovery =  $\frac{P_{t \text{ intake exit}}}{P_{t \text{ free stream}}}$

$\theta$  = sector angle/circumferential extent

### 5.2 Subscripts

0 = free stream

### 5.3 Abbreviations

AIP	aerodynamic interface plane (at engine inlet)
AIR	Aerospace Information Report
AOA	angle of attack
AOS	angle of sideslip
ARD	Aerospace Resource Document
ARP	Aerospace Recommended Practice
DGV	Doppler Global Velocimetry
HPC	high pressure compressor
IGV	inlet guide vane
I/B	inboard
LTH	Lufffahrt Technisches Handbuch
LPC	low pressure compressor
Mach	Mach number
O/B	outboard
RMS	root mean square
SAE	Society of Automotive Engineers
UAV	unmanned aerial vehicle
VSTOL	vertical and/or short take-off and landing