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SOME ASPECTS OF INLET/ENGINE COMPATIBILITY

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SOME ASPECTS OF INLET/ENGINE FLOW COMPATIBILITY

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ABSTRACT

This paper discusses some results obtained from test programmes carried out to investigate the effects of simulated total pressure distortion on the performance and stability margins of various isolated multi-stage axial compressors, and on turbojet and turbofan engines. Distortion propagation through the turbomachinery is also discussed. Some of the limitations of such testing are judged against contemporary developments on the inlet/engine compatibility scene. Results derived from the application of some theoretical ideas to the problem of compatibility are discussed briefly. Some comments are made on the choice of suitable parameters for describing inlet distortion.

1 INTRODUCTION

The aim of this paper is to contribute to the growing subject of inlet/engine compatibility a discussion of some of the more interesting results of research and development testing of rig compressors and engines carried out at the Bristol Engine Division of Rolls-Royce (1971) Limited, and to discuss these against a now extensive background literature.

The effects of an inlet system on an axial flow gas turbine are principally on performance, stability and mechanical integrity. In this paper attention is focussed on the effects of total pressure distortion on the compressor system's performance and stability.

II DESCRIPTION OF FLOW DISTORTION

Inlet flow distortion has been limited traditionally to describing the spatial variations of 'time-averaged' or 'steady' total pressure, or of equivalent axial velocity, at the inlet/engine interface. Data are obtained initially from geometrically similar small-scale inlet models tested with or without the surrounding aircraft structure but usually without engine simulation. Attempts to observe dynamic similarity have involved testing at representative flow Mach number and, within facility constraints, Reynolds number.

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Note Figures in parenthesis refer to the references at the end of the paper

For some years it has been recognised that simple total pressure descriptions are deficient in several important respects, namely:

1 High static pressure gradients in inlets having short, highly-curved ducts or lips close to the engine entry plane can cause significant departures from LP compressor entry design flow conditions and can hence cause engine problems. Examples have arisen in straight lift or vectored thrust V/STOL installations, or in conventional subsonic podded installations in crosswinds or during manoeuvres. (1)(2).

2 Time-wise variations in total pressure, representing in-phase (buzz type) or spatially-distorted (turbulence type) perturbations can give rise to considerable 'dynamic distortion' within the inlet. Problems have been encountered in supersonic inlets operating off-design with strong shock/boundary layer interactions, during ground-running, due to inlet lip flow separation or to ground vortex, and during subsonic manoeuvring flight at high positive or negative incidence or in sideslip. (3)(4)(5)(6)(7)(8).

3 The turbomachinery can cause radical changes to the inlet flow field and can considerably modify the interface flow distortion from that defined from isolated inlet testing. The presence of the engine compressor may promote or suppress lip flow separation, modify static pressure gradients and swirl velocities within the inlet. (9)(10)(11).

High static pressure distortion is thought to have caused up to 7% loss of gross thrust on a VTOL lift/propulsion turbofan engine. Dynamic distortion has caused losses of engine surge margin between 1.5 and 3 or more times those associated with steady state distortion. The development of techniques for quantifying the effect of dynamic distortion on stall represents an important advance in compatibility analysis. Simulations of an engine during small-scale inlet tests have shown about 10% reduction in the extent of the lip flow separation region of a zero length pitot inlet in a 90^{o} crosswind. It has been shown that a choked plug downstream of an inlet transforms the flow field at the simulated engine entry in a manner similar to a compressor.

These examples show that the general description of a distorted inlet flow field requires that time as well as space variations of more than one flow parameter needs to be specified if the effect of the inlet on the turbomachinery is to be accounted for properly. Data derived from isolated inlet tests, depending upon the particular installation, may not be sufficient for this purpose.

In formulating a system for studying compatibility problems it follows, therefore, that situations where the distortion may be described adequately by the space-time variations of total pressure alone must be distinguished clearly from those where it may not. This distinction is fundamental, for example, to the selection of flow distortion parameters.

The long straight inlet duct is an example where inlet distortion may be considered sensibly as uninfluenced by the compressor. To date, rig compressor and engine testing, as well as main theoretical developments, have been based largely on this assumption, which implies that inlet/engine compatibility may be described - at least to a first approximation - in terms of total pressure distortion only. Tests with inlet distortion simulated by means of gauze screens, which complement inlet plus engine tests, provide insight into turbomachinery response to distortion and a guide to design short-falls in the inlet in such a case.

The main purpose of testing compressors with total pressure distortion in the first instance is to provide advance information of its effect on compressor performance, stability and distortion - propagation characteristics. For this purpose idealised distortion patterns, representing pure radial or circumferential 'top hat' profiles of different intensities and extent are tested systematically in order to isolate relevant distortion parameters. This testing may be followed by mixed radial-circumferential patterns or by testing of selected inlet patterns - depending on circumstances.

Results from such tests are discussed in the following sections.

III RIG COMPRESSOR TESTS

To examine the effects of circumferential and radial maldistributions of inlet total pressure on a seven-stage high specific flow axial compressor, one stator blade in each stage was fitted with a pitot rake. The gauze system used to generate the pressure maldistribution was mounted on a carrier ring which could be rotated to a number of fixed circumferential positions while the compressor operating point was maintained constant. In this way the average inlet total pressure could be determined accurately and the progress of the maldistribution through the compressor measured with the minimum of additional instrumentation.

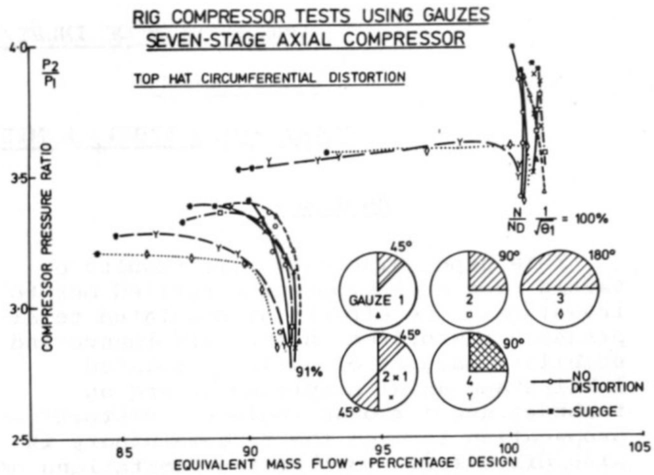


Figure 1

Circumferential Distortion

The effect of five idealised 'top hat' circumferential distortions applied to this compressor is shown in Figure 1. The moderate distortions having spoiled sector angles up to 90°, represented by Gauzes 1,2, and the twin-lobe Gauze 1, all had similar small effects on the compressor surge pressure ratio at design speed. When the sector angle was increased to 180° (Gauze 3) and when the intensity of the 90° sector gauze was increased (Gauze 4), the overall compressor characteristic was transformed by local stalling within the compressor. Although the apparent surge line remained unchanged, operating the compressor along a running line near to surge could result in a mass flow and efficiency loss of 8%. The resulting positive slope constant speed characteristic was found to be stable on both rig and engine, but the massive performance penalty in operating the engine in this region of the compressor map makes it unusable. For this reason, when the results were correlated, only the negative slope part of the constant speed characteristics was taken as usable.

The distortion parameter DC $(\theta)_{crit}$, conceived by Reid (12), was used in the correlation of loss of stall pressure ratio with distortion. Values of θ_{crit} between 0 and 180° were examined, the best correlation being given by $\theta_{crit} = 120°$, as shown in Figure 2. Theoretical values calculated using the parallel compressor hypothesis are also shown. The correlations and agreement with theoretical predictions are seen to be reasonable.

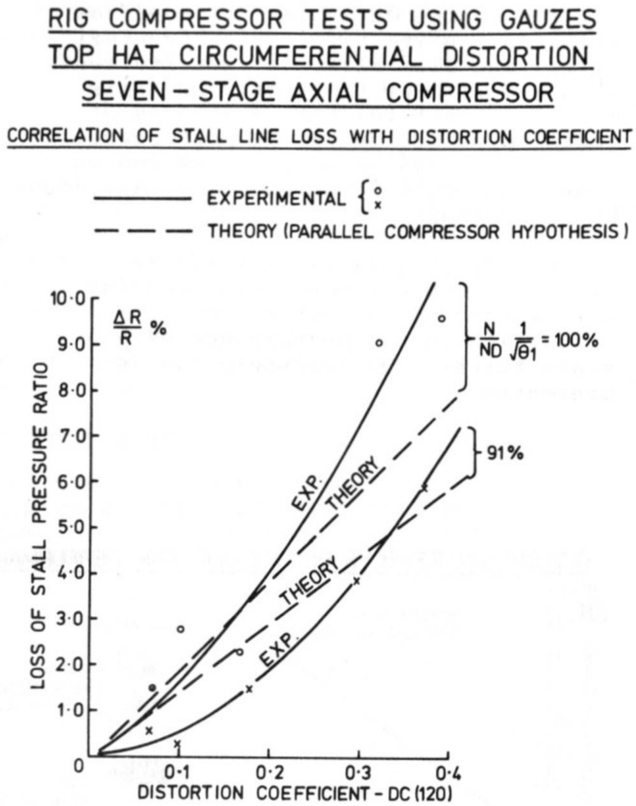


Figure 2

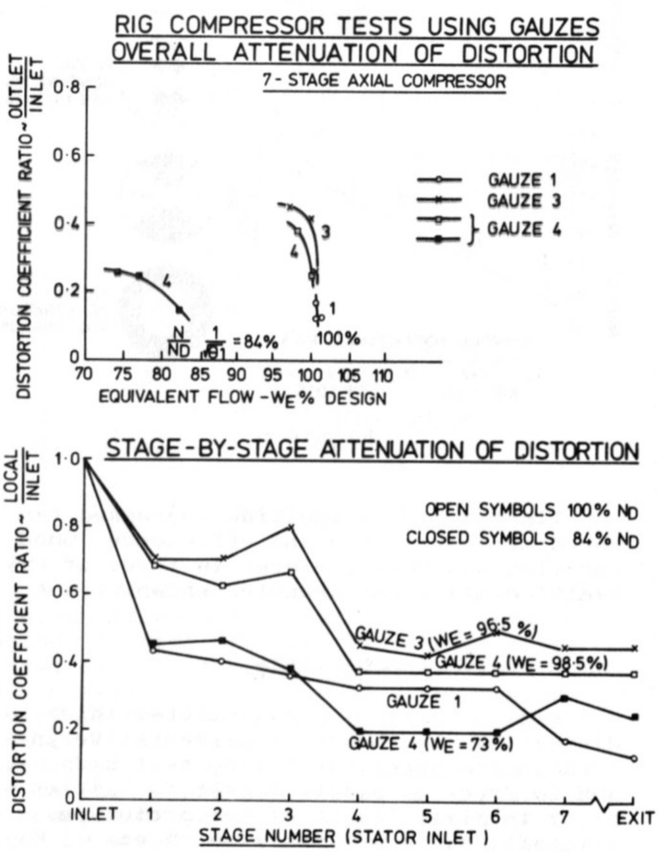


Figure 3

Propogation of Circumferential Distortions through the Compressor

The results given by interstage and delivery pitots and statics were used to calculate local values of distortion coefficients and are shown plotted in Figure 3.

The distortion coefficient ratio, outlet to inlet, as a function of speed and compressor mass flow, has the general appearance of a conventional compressor map. Attenuation is greatest at low rotational speed and high flow. Figure 3 also shows where the attenuation is achieved within the compressor.

With a 0.315 inlet hub/tip ratio it might be expected that this compressor would fall outside the theoretical predictions of Plourde and Stenning (10) whose eloquent actuator disc approach adequately describes the attenuation of circumferential distortion through high hub/tip ratio machines.

The lower attenuation at design speed with Gauzes 3 and 4 is due to local stalling within the compressor. A more sophisticated theoretical flow model would therefore be necessary to predict this result.

The interstage instrumentation showed generally good attenuation at the rotor tips, and poor attenuation at the hub - a result which is anticipated by other elementary theoretical considerations. (13)(14).

It may be seen from Figure 3 that there is a significant attenuation of circumferential total pressure distortion through the compressor. This result, together with the observed static pressure and total temperature distortion created, is important to the overall stability of multi-spool axial gas turbines.

Radial Distortions

The effect of radial maldistributions of pressure on the characteristics of this compressor is shown in Figure 4.

It will be noticed that the surge line was not adversely affected by any of the three radial profiles tested. Low hub pressures resulted in a reduction of flow at a given compressor speed, and low tip pressures resulted in a flow increase.

The result of the combined circumferential and radial profile (Gauzes 2 plus 21) suggest that the radial component determines the compressor response of increased mass flow.

The effect of the tip - low radial distortion in increasing non-dimensional mass flow has also been observed during testing of the engine which contained this compressor as the LP unit. The engine flow capacity at a given speed increased with increasing degrees of tip spoiling. In Figure 5 this is shown by expressing the amount of tip spoiling as a 'boundary layer' thickness, δ , comparing rig and engine results.

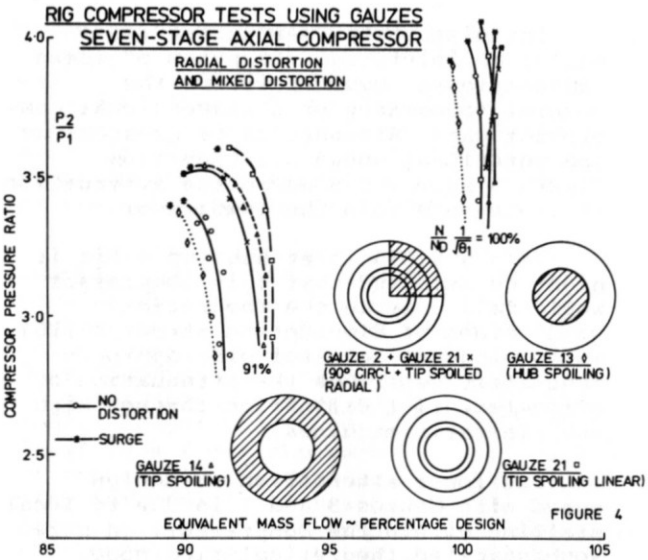


Figure 4

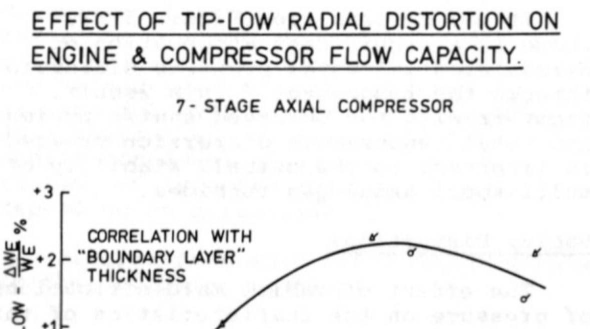


Figure 5

The engine data were derived from tests on the sea-level bench (venturi inlet) and from altitude facility tests with and without tip spoiling. This result illustrates the importance of radial profiles on engine performance. Similar effects have been observed on other engines having transonic fans and LP compressors.

A further example is shown in Figure 6, where a more comprehensive correlation of the effects of distortion on the performance of a $\frac{1}{4}$-scale three-stage transonic fan is presented.

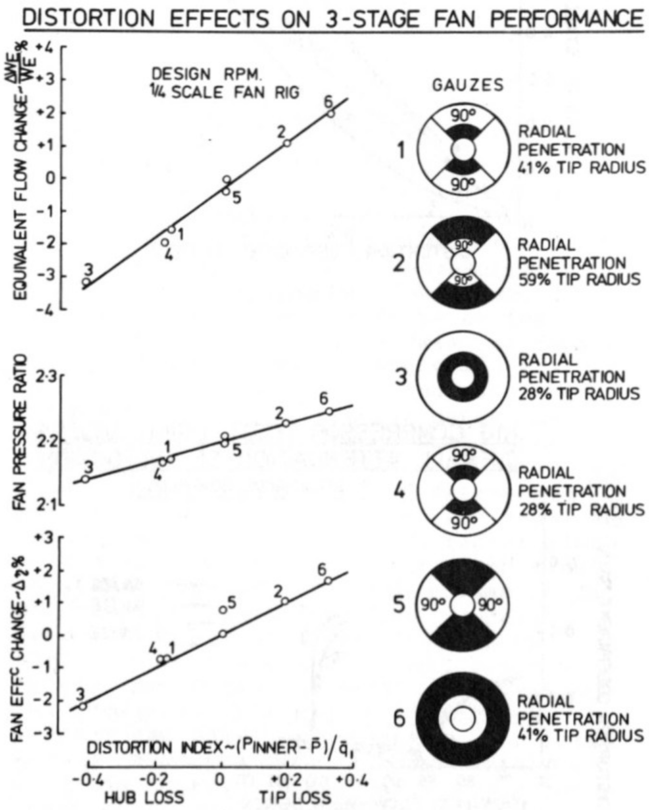


Figure 6

Tip-low radial spoiling increased fan non-dimensional flow and efficiency. Good correlations were achieved in terms of the radial distortion parameter shown.

IV ENGINE TESTS

Engine testing with simulated inlet distortions and behind representative inlets on the bench, in flying test beds, and in free-jet altitude test facilities prior to first flight of the prototype aircraft, minimises the risk of encountering intractable compatibility problems.

Interactions between matched compressors and other powerplant components make engine testing with distortion simulation early in the engine development programme a vital part of compatibility work. Problems in extrapolating rig compressor distortion results to the engine arise in accounting adequately for combined radial and circumferential total pressure distortion, total temperature and static pressure distortion (particularly in close-coupled spool arrangements), rematching of the engine due to component performance changes, and Reynolds number changes between rig and engine.

Turbojet Engine

Figure 7 shows the results of tests of simulated aircraft inlet distortions, using gauzes, on the surge line of an early development of a two-spool turbojet engine.

DISTORTION EFFECT ON 2-SPOOL TURBOJET ENGINE OPERATION

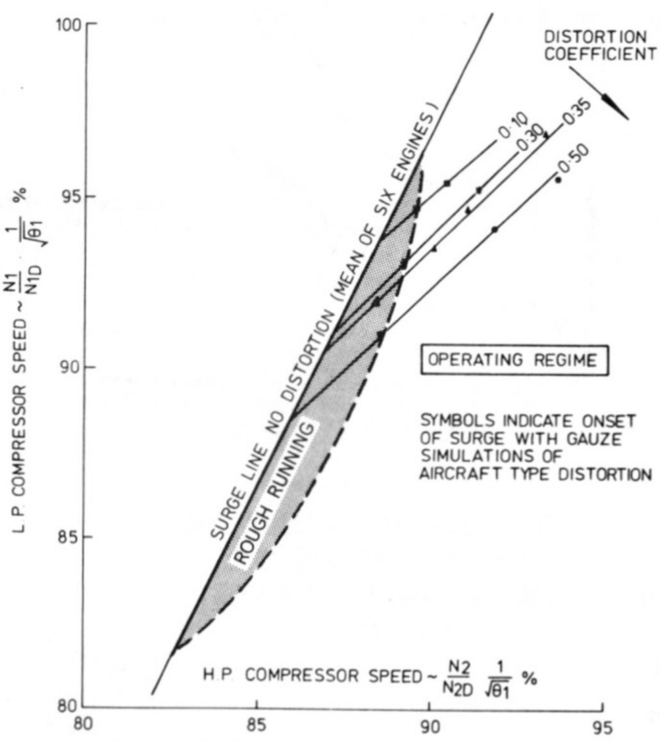


Figure 7

A difficulty in expressing the results of distortion on the stability of such an engine in terms of overall pressure ratio arises because there is no unique relationship between LP and HP compressor speeds. A very convenient method of presenting the results is in terms of the two spool speeds, as in Figure 7. Engine surge margin is then expressed either as changes in HP compressor non-dimensional speed at fixed LP speed, or vice versa.

The engine stability margin may be determined utilising the same distortion simulation technique as used during rig compressor testing by varying the engine final nozzle - so moving the LP compressor operating line towards surge, for example.

Figure 7 shows the progressive loss of effective engine operating speed range resulting from various inlet total pressure distortion simulations of increasing severity. In this case engine surge was induced by the distortion sensitivity of the LP compressor, and hence depended largely on LPC stall margin. At lower speeds the engine could be operated quite near to the LP stall line, without surge, although a zone of rough running occurred close to stall.

Turbofan Engine

Some results from tests on a 2.8:1 by pass ratio turbofan engine, illustrated in Figure 8, are shown in Figures 9 to 13.

2·8 BY-PASS TURBOFAN ENGINE
INSTRUMENTATION LAYOUT

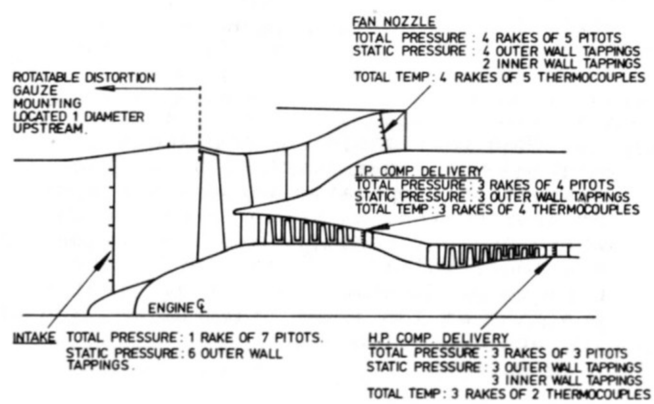


Figure 8

These results were obtained in a manner similar to the rig compressor results described in Section III using a rotatable gauze system upstream of the engine fan. The fixed instrumentation shown in Figure8 enabled the progress of the mal-distribution through the entire compressor system to be measured.

Figure 9 shows a gauze-simulated aircraft inlet distortion pattern typical of those encountered during crosswinds on to subsonic pitot inlets. A region of low total pressure, reflecting local lip flow separation, occurs at the compressor tip.

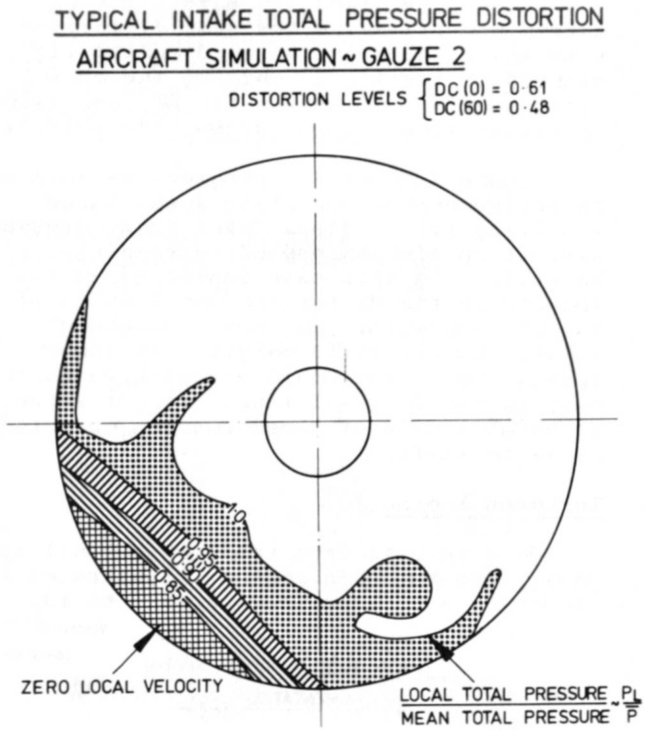


Figure 9

When this gauze was applied to the engine on the sea-level test bed the distortion propagated through the compressor system, as shown in Figure 10 where typical radially-averaged values of the local total pressure profile are plotted as functions of circumferential position at fan inlet, fan outlet, and at IPC and HPC outlet.

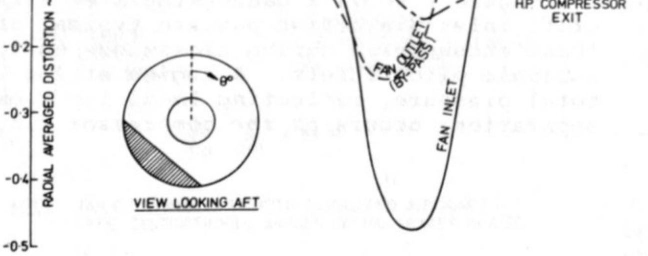


Figure 10

It will be noted that, while good attenuation is achieved in the gas generator section of the engine, only limited attenuation takes place in the fan outer flow.

The trend of distortion propagation through the compressor system over a range of engine speeds is shown in Figure 11.

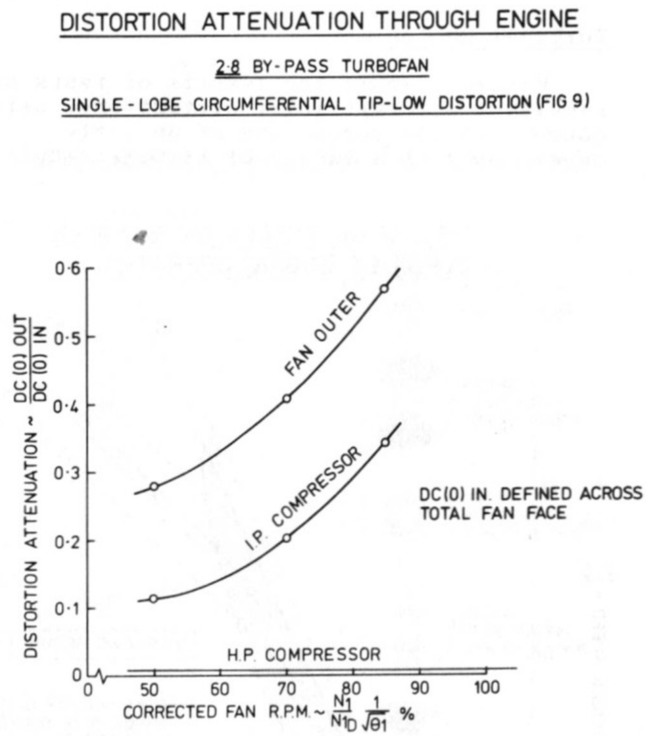


Figure 11

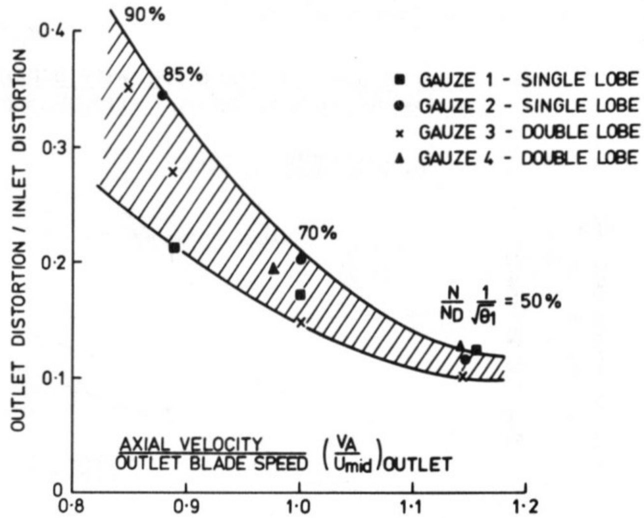
No static pressure distortion was found at HPC exit over the range of fan speeds shown. Since the HP compressor characteristic was almost vertical over its speed range during these tests, the Plourde and Stenning flow model adequately described the almost-uniform exit flow conditions.

Further tests with single- and double-lobe distortions representative of pitot inlet distributions, were carried out using gauzes. The distortion attenuation characteristics were similar to those shown in Figure 11. Typical results across the IP compressor are shown in Figure 12 for four gauze configurations.

DISTORTION ATTENUATION - I.P. COMPRESSOR

2·8 BY-PASS TURBOFAN ENGINE

AIRCRAFT DISTORTION SIMULATION



Note :- DISTORTION AT FAN ENTRY REPRESENTS TOTAL SPAN DISTORTION.

Figure 12

These results are presented in a manner similar to that of Reid using compressor outlet flow coefficient. The curves illustrate the deterioration in distortion attenuation with reducing flow coefficient. As this represents increasing aerodynamic loading of the compressor rear stages, it is seen that distortion attenuation is dominated by rear-stage loading.

LOSS OF SURGE PRESSURE RATIO

2·8 BY-PASS TURBOFAN ENGINE

SIMULATED AIRCRAFT DISTORTION - GAUZE 2

DC (60) = 0·48

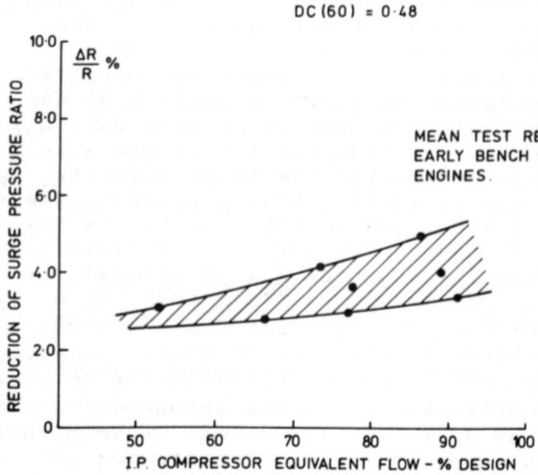


Figure 13

Surge

Surging of this engine was promoted by the effect of distortion on the IP compressor. Figure 13 shows the reduction of IP compressor surge pressure ratio with rpm for Gauze 2, having a fixed distortion coefficient of 0.48. The results were derived from tests on five early bench development engines, moving the IPC working line by varying IPC delivery bleed and increasing rpm until the engine surged, and also by varying hot nozzle exit area.

V. TOTAL PRESSURE DISTORTION PARAMETERS

An important objective of compatibility programmes is to attempt correlations of surge line and performance changes with distortion parameters which are valid for a wide range of distortion patterns. The treatment of other compatibility issues, in particular the question of forced rotor blade vibration - which requires detailed integration of Fourier components of the inlet circumferential forcing function over the blade span in relevant blade vibrational modes, may not be correlated in terms of a simple parameter. Further, there appears to be no fundamental reason why a distortion parameter invented to describe loss of engine stability margin should also be expected to account for performance changes.

Surge-Circumferential Distortion

Reid, in a comprehensive series of rig tests on multi-stage axial compressors suggested that a circumferential parameter of the form $DC(\theta)_{crit}$ defined by

$$DC(\theta)_{crit} = \frac{\overline{P} - P_{min}}{\overline{q}} \qquad (1)$$

should be relevant to the surge problem.

P_{min} represents the average total pressure in a spoiled sector of extent θ_{crit} surrounding the region of lowest pressure in the inlet.

$\overline{P}$ and $\overline{q}$ represent overall mean total pressure and dynamic head, respectively.

It is necessary to evaluate θ_{crit} for each individual compressor and engine type. Where radial distortions are present the pressures represent radially-averaged values.

On this basis a simple application of the parallel-compressor hypothesis, ignoring flow matching, predicts the fractional loss of surge pressure ratio to be:

$$\frac{\Delta R}{R} = \frac{\overline{P} - P_{min}}{\overline{P}} \qquad (2)$$

The concept of a critical sector angle as the minimum angle beyond which further loss of stall pressure ratio for a given distortion intensity is negligible, has since been confirmed experimentally. (5)(13)(15)(16)(17). Figure 2 presents a typical example. Recently, Brunda and Boytos (18), arguing on a 'distortion similarity' basis achieved a good collapse of data using a similar parameter to DC $(\theta)_{crit}$ for purely circumferential distortion. Test data on the J85-GE-13 engine (16) have been correlated on the basis of a critical sector angle of 60^{o}. Figure 14 shows the good agreement between the results of this work and that of Reid.

CORRELATION OF SURGE LINE LOSS WITH 60° SPOILED SECTOR PARAMETER

PURE CIRCUMFERENTIAL DISTORTION

SPOILED SECTOR ANGLE	22½°	30°	45°	60°	90°	180°	270°	315°	
J-85 ENGINE TESTS (NASA TM-X-2239)		•		▲ ▲	□	○			EXPERIMENTAL DATA
R.R. RIG TESTS (ASME 69-GT-29)	◊ ♦		▼ ▼		σ	σ	x	Y	

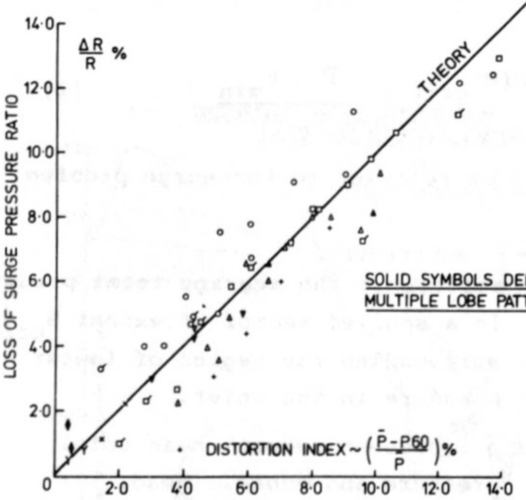


Figure 14

Theoretical predictions using the parallel compressor hypothesis are also shown in this figure. Agreement with experimental results is good.

The results from a turbofan engine having a T-compressor are shown in Figure 15 to correlate with DC (120), as did the data for the 7-stage axial compressor described earlier (Figure 2). No correlation of the turbofan data was found on the basis of DC (60).

CORRELATION OF SURGE PRESSURE LOSS WITH DC(120)
3-STAGE FAN BY-PASS TURBOFAN "T"-COMPRESSOR

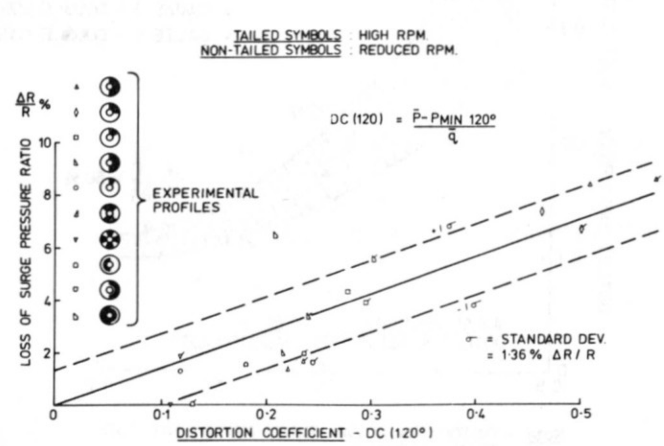


Figure 15

These experimental results show that, in general, each compressor may be expected to respond to a different critical sector angle.

In an attempt to understand the relevance of θ_{crit} to compressors of various designs, the unsteady rotor blade loading caused by a top hat circumferential distortion was examined theoretically. For simplicity the rotor blades were regarded as isolated aerofoils. The spatially-varying portion of the flow field was resolved into velocity components normal and tangential to the mean relative flow vector, and the top hat distortion was expressed as a Fourier series. Upwash and chordwise velocity perturbations then take the form of travelling waves. The lift distribution was then built up by Fourier superposition utilising unsteady loading functions given by Sears (19) and Horlock (20). The result of this calculation is that the rotor lift grows as the blade enters the low axial velocity sector and assymptotically approaches the steady-state value appropriate to the new blade incidence; on leaving the distortion the blade loading decays in a similar manner. The maximum lift reached for a given distortion intensity depends upon the reduced frequency parameter, $\omega C/2V_r$, and the circumferential extent of the distortion. In the absence of a theory of dynamic stall it was decided to adopt a quasi-steady stall criterion to show qualitatively how consideration of blade loading can lead to the idea of a critical sector angle.

Figure 16 shows the results of these calculations.

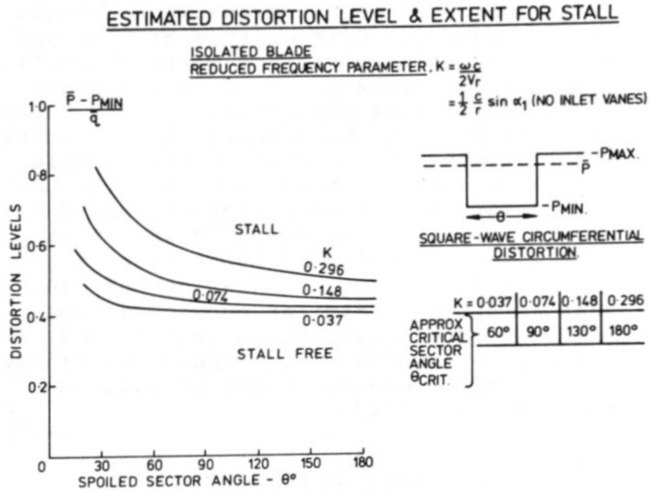


Figure 16

As sector angle increases, a lower distortion level is required to produce stall. At sufficiently high values of spoiled sector angle, changes in distortion level required to stall are negligibly small. The minimum sector angle and the associated level of distortion depend upon the reduced frequency parameter.

Preliminary thoughts on the likely results for cascades based upon the work of Schorr and Reddy (21) suggest that the critical sector angle for cascades might be lower than for isolated aerofoils, as the cascade appears to operate more nearly quasi-steadily.

Surge - Radial Distortion

An interesting correlation of the effects of pure radial distortion on the surge characteristics of a compressor have been derived from the data presented by Calogeras et al (16), Figure 17

In this particular case tip spoiling reduced surge pressure ratio. Hub spoiling caused a gain in surge pressure ratio for values of the radial distortion parameter down to -0.10 to -0.15 (approximately), depending upon engine speed, and thereafter a loss.

This result is completely opposite to that shown in Figure 4, where tip spoiling improved the compressor surge line. The importance of radial matching of the front stages of a compressor in determining its response to radial distortion is clearly illustrated by this comparison.

The use of inter-blade row axisymmetric equilibrium solutions is an obvious tool in the study of these effects.

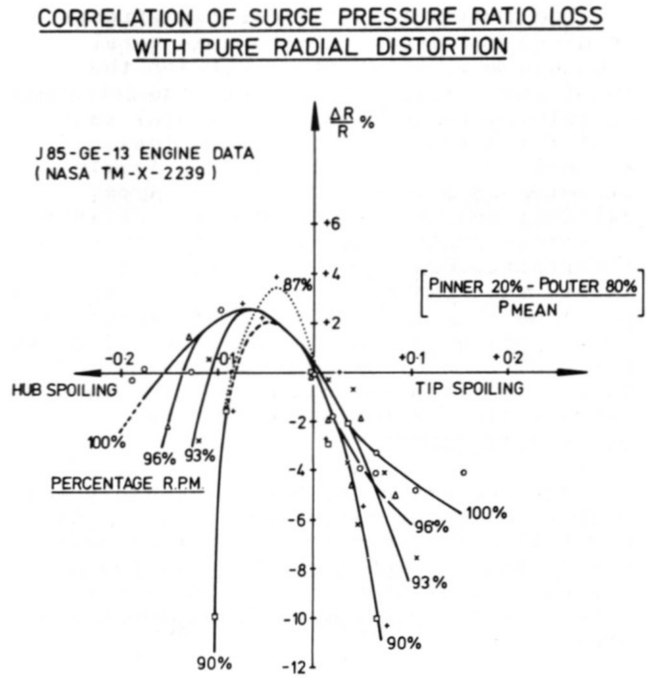


Figure 17

Surge-Mixed Circumferential and Radial Distortion

As far as the authors are aware, no satisfactory distortion parameter which adequately covers the case of combined radial and circumferential distortion has been determined. It is thought that because of radial rematching in the front stages of axial compressors, rig compressor tests with combined radial and circumferential gauzes are necessary to determine the effect of mixed distortions for each particular machine.

Performance

A similar situation arises in using compressor rig characteristics obtained by separate component tests to predict overall performance changes of the engine. Component rematching within the engine dominates the engine performance so that gauze testing of engines is necessary to evaulate performance effects. It is unlikely that analytic techniques capable of accounting for the complex interaction between components will eliminate the need for these ad hoc tests.

The effect of the inlet on turbomachinery performance may be considered in two parts:

1 Changes of one-dimensional performance due to the mean total pressure loss in the inlet.

2 The effect of maldistribution of the total pressure on the component mean non-dimensional characteristics.

The separation of these two effects involves the definition of mean total pressure at the interface between the inlet and compressor, so that the definition of inlet efficiency is fundamental to distortion-induced performance loss accounting. For low distortion levels performance differences arising from distinctions between alternative definitions of intake efficiency are relatively unimportant. For high inlet distortion levels that can arise off-design, very real problems of how to define performance losses arise in practice as a result of the basic difficulty of accounting simultaneously for mass, momentum, and energy conservation in the equivalent one-dimensional flow.

This question has been reasonably well discussed in the literature (22)(23)(24) and will not be considered further here other than to emphasise the need for consistency of definition throughout all phases of the powerplant development programme.

The only thermodynamically consistent definition of intake efficiency is given by the 'availability' or 'entropy' mean value (24):

$$W. \log \overline{P} = \int \log P. \, dW \qquad (3)$$

ie by a mass flow 'weight' of log total pressure. This is cumbersome to apply.

Current practice at Rolls-Royce (Bristol Engine Division) is to use area-weighted mean total pressure definitions.

VI SOME LIMITATIONS OF THEORETICAL PREDICTIONS OF DISTORTION PROPAGATION

Valuable insight into the propagation of circumferential distortion and on the upstream re-distribution of flow distortion caused by the compressor, are obtained by application of mathematical models based upon actuator disc theory. Thus for a simple cosine distribution of total pressure it may be shown for a high hub/tip ratio multi-stage compressor that:

$$\frac{DC\ (\theta)\ \text{exit}}{DC\ (\theta)\ \text{entry}} \simeq (1+\phi)\left(\frac{\overline{\rho}_2}{\overline{\rho}_1}\right)^2 \qquad (4)$$

where ϕ is a compressor slope parameter given implicity by the relationship:

$$\frac{\phi}{1+\phi} = \frac{1}{2}\ \frac{\overline{U}}{\overline{V}_a}\ \frac{\Delta\left(\Delta\overline{p}/\tfrac{1}{2}\overline{\rho}\,\overline{U}^2\right)}{\Delta(\overline{V}a\ /\overline{U}\ )} \qquad (5)$$

On a flat speed characteristic ($\phi = 0$) little total pressure attenuation occurs. On a vertical characteristic ($\phi = -1$) the total pressure distortion is completely attenuated.

Reasonable agreement with experiment has been achieved in applying this estimate to multi-stage compressors where compressor exit static pressure was known to be constant. Difficulties have arisen in applying the prediction where distortion caused a significant change in the shape of the compressor characteristic and hence ϕ . It has also been found that in multi-spool machines the condition that static pressure is constant at exit from the LP compressor, whilst approximately valid for rig compressors, has not held when that compressor was followed by an HP unit, so that the distortion attenuation has been over-predicted. Similar considerations arise in identifying the necessary and sufficient conditions for apply the 'short' and 'long' compressor model of Callahan and Stenning. (11).

VII DYNAMIC DISTORTION

Inlet Turbulence

A detailed discussion of this subject is not undertaken in this paper. It appears, in the surge context, that the major features of turbulence-generated inlet distortion, ie of time-variant distortion, having significant out-of-phase spatial components, can be described in terms of quasi-steady extension of time-averaged distortion ideas to a much shorter time-scale of the order of the time for one rotor revolution. This development, which has helped explain so called 'drift' surges, requires a high degree of sophistication in test measurement, recording and analysis techniques to evaluate 'instantaneous' values of distortion coefficients relevant to surge. High-response equipment, high-speed data processing and careful data editing methods are necessary to obtain and manage the experimental distortion data. Once 'instantaneous' peak distortion levels and patterns have been identified, it appears possible to account for their effects on engine stability, at least to a first order, using steady-state gauze simulations.

In-Phase Inlet Pressure Oscillations

The treatment of in-phase distortion, ie of sensibly one-dimensional variations of inlet total pressure with time, is more amenable. In practice, such oscillations arise as a consequence of inlet buzz or during gun- firing. Theoretical methods derived from early work by Lubick and Wallner (25) have been developed to account for their effects on compressor stability when the frequency of the oscillation is outside the response range of the engine control system. Such methods (26)(27),which are based upon modelling the compressor stage by stage, utilise one-dimensional unsteady continuity, momentum and energy equations, accounting for stage volume lags in lumped or distributed terms, and using steady stage characteristics. Compressor instability then results from dynamic mismatching of the stages. Figure 18 presents the estimated surge line for a version of the 7-stage axial compressor referred to earlier.

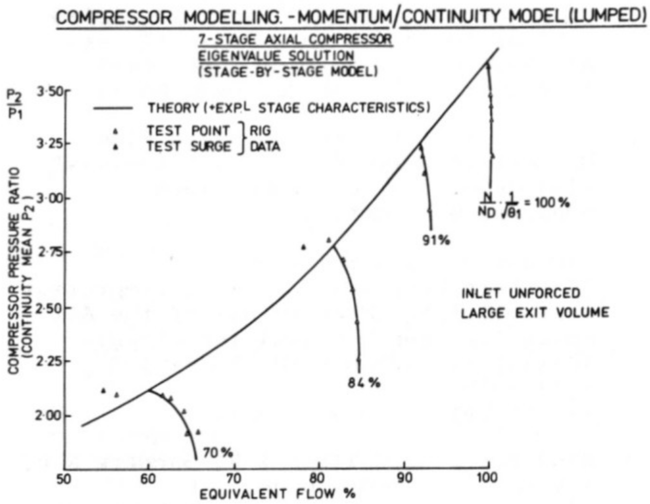


Figure 18

The analytical technique used in this estimate involved the so-called lumped momentum-continuity model (28). Agreement between experimental and predicted surge lines was reasonably good in this case of an unforced inlet.

Figure 19 compares the results of various alternative predictions of surge pressure ratio at 89% non-dimensional rpm for the unforced inlet. There was little to choose between the various models tried at this speed, although some models were better suited than others to predictions over different speed ranges.

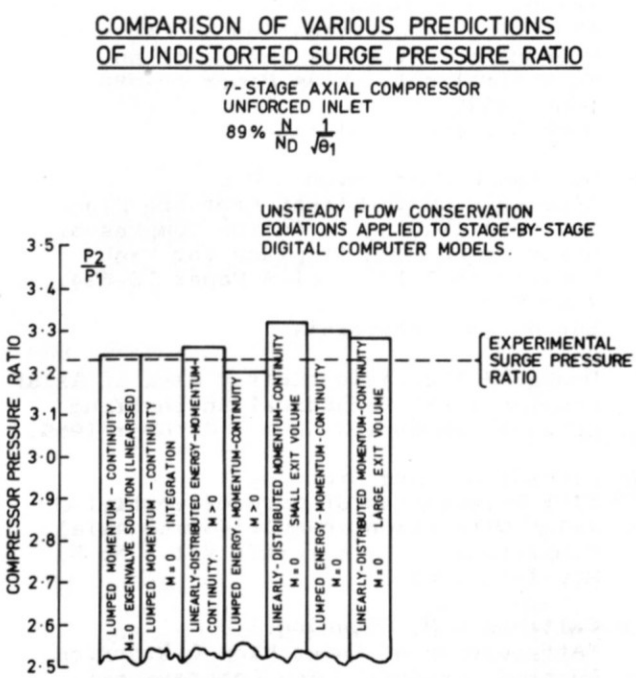


Figure 19

A typical result obtained by applying the lumped momentum-continuity model to estimating compressor sensitivity to a simple harmonic total pressure oscillation of varying frequency and amplitude is shown in Figure 20.

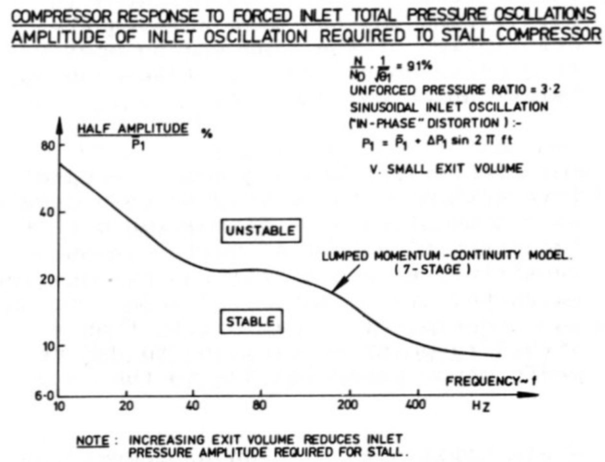


Figure 20

The half-amplitude of the inlet total pressure oscillation, expressed as a percentage of the mean pressure, which is required to stall the compressor, is shown as a function of oscillation frequency. Compressor sensitivity increased progressively with frequency up to 400 Hz or more. For this model the compressor exit volume was very small, consequently the inlet pressure amplitude required for stall was high. Amplitudes required for stall reduce with increasing exit volume as greater phase lags between exit and inlet pressure oscillations can arise.

Because large exit volumes tend to be destabilising, it follows that the dynamic response of a compressor to inlet flow unsteadiness on the rig can be quite different from its response in the engine. Further, large volumes associated with the bypass ducts of turbofan engines also tend to destabilise the fan.

VIII CONCLUDING REMARKS

1 The description of flow distortion at the inlet-engine interface can be extremely complex. Due to flow interactions between inlet and engine flow fields test results from isolated inlet testing may not give an adequate description of the true engine operating environment, eg for close-coupled inlet-engine arrangements.

2 For similar reasons, eg spool to spool interactions, the testing of compressors with simulated inlet distortion whilst important to establish basic component sensitivities and distortion propagation characteristics is not sufficient to ensure powerplant compatibility from a stability point of view, or to define performance penalties due to the inlet.

3 Where total pressure can be identified as the prime distortion variable, for example in the case of a long inlet duct, traditional techniques involving small-scale inlet wind-tunnel testing and compressor rig testing with simulated distortion remain valid provided that distortion is defined on a time-scale of the order of one rotor revolution if the inlet flow field is significantly unsteady. Techniques for dealing with such dynamic phenomenon are complex but are now within the state of the art.

4 As the volume of published empirical and theoretical work on inlet-engine compatibility increases, early hopes of identifying a universal surge distortion parameter fade. While prospects for estimating compressor response to circumferential distortion using a critical sector angle or $DC(\theta)_{crit}$ approach are reasonably good, the unique response of a particular compressor to radial maldistribution inhibits predictions involving combined radial and circumferential distortion and adds considerably to the difficulty of finding general distortion correlation indices.

5 The effect of distortion on engine performance can be dominated by rematching of powerplant components and can be quantified properly only by full-scale engine testing on the basis of a clear and consistent definition of inlet efficiency.

6 Within the current state of the art there is no substitute for the testing of engines with simulated inlet distortion and with the representative aircraft inlet on the bench, in the free-jet altitude facility, and flying test-bed as early as possible in the engine development programme.

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LIST OF SYMBOLS

$DC(\theta)_{crit}$	- distortion coefficient * (Equation 1)
C	- blade chord (ft)
f	- frequency (Hz)
K	- reduced frequency parameter $\left(\frac{\omega C}{2 Vr}\right)$
N	- compressor rpm
P	- total pressure (psi)
p	- static pressure (psi)
Δp	- compressor static pressure rise (psi)
q	- dynamic head (psi)
R	- compressor total pressure ratio
ΔR	- loss of surge total pressure ratio
r	- radius (ft)
T	- total temperature (^{o}K)
U	- blade speed (ft/sec)
Va	- axial velocity (ft/sec)
Vr	- blade relative velocity (ft/sec)
W	- mass flow (lb/sec)
α_1	- blade inlet angle (degrees)
δ	- 'boundary layer' thickness (inches)
η	- efficiency
σ	- standard deviation
ρ	- air density (slug/ft^3)
ϕ	- compressor speed line slope parameter (Equation 5)
θ	- circumferential position (degrees)
θ_{crit}	- critical spoiled sector angle (degrees)
θ_1	- corrected inlet total temperature $T_1/288$
ω	- circular frequency (sec^{-1})

* DC (0) represents radially averaged total pressure at a given circumferential position, θ

Subscripts

1	- compressor entry
2	- compressor exit
D	- design
L	- local

Superscripts

$(\bar{\ })$	- mean or average value