Printed in U.S.A.

69-GT-29

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The Response of Axial Flow Compressors to Intake Flow Distortion

C. REID

Compressor Research and
Development Engineer,
Rolls-Royce Limited,
(Aero Engine Division),
Derby, England.

The response of a lift engine model compressor to inlet pressure distortion is studied in detail to determine the nature and extent of the critical area of spoiling. This is found to be a sector of width between 60 and 90 deg. On this basis a simple distortion index is proposed which implies that only the circumferential pressure gradients of a complex distortion pattern are significant. The "Parallel Compressor" model satisfactorily explains surge and this experience is related to different types of compressors and to complex spoiling patterns. Comments are made on the differences in behavior between compressors operating on rig test and in engines.

Contributed by the Gas Turbine Division for presentation at the Gas Turbine Conference & Products Show, Cleveland, Ohio, March 9-13, 1969, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters December 17, 1968.

Copies will be available until January 1, 1970.

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1 INTRODUCTION

One of the most serious problems associated with the installation of an axial flow jet engine in an aircraft is the poor engine handling characteristics, i.e., inability to accelerate or engine overheating, compressor surge, combustion flame out, and so forth, which result when the air flow at the engine face is nonuniform. This nonuniformity of inlet flow can be due to any one of many different effects, the most common being: (a) break-away from intake lips at high angles of attack, (b) break-away from walls of curved inlet ducts, (c) an intake working well away from the nominal design velocity ratios (d) ingestion of boundary layers, and (e) separation in supersonic intakes caused by shock wave/boundary layer interaction.

These five simple examples could be termed steady-state distortions in that the scale of flow unsteadiness is small in relation to the scale and area of intake loss. However, the engine may also be forced to accept unsteady flow conditions such as: (a) wakes from stalled wings, (b) ground vortices, (c) supersonic intake "buzz," and (d) turbulence.

Whatever the origin of the flow disturbance, the deterioration in engine handling is due to a deterioration in the surge characteristics of the compressor system. Although the engine matching will have originally been arranged to provide a safe margin between the compressor operating line and surge line, any excess reduction in this margin due to inlet spoiling will result in handling problems.

This paper concentrates solely on the "steady-state" type of spoiling and describes some of the work carried out with the objectives of: 1) determining which features of the distorted flow are relevant to the compressor and so attempt to develop a suitable distortion index, and 2) gaining an insight into the mechanism of the compressor's response to distortion.

2 EARLY HISTORY

The most concentrated work on flow distortion was originally (pre-1960) carried out on the first generation of lift engines and compressors (RB.108 and RB.145) where the V.T.O.L. application called for the toleration of extremely high distortion levels. While testing was always of an ad-hoc and complex nature, a good degree of success was achieved in empirically correlating loss

NOMENCLATURE

P = total pressure, psi
p = static pressure, psi
R = total pressure ratio
T = total temperature, deg K
M = mass flow, lb/sec
V_a = axial component of air velocity, fps
U = tip blade speed, fps
q = dynamic head (= $P-p$)
Δ = difference of two levels
η = efficiency
K_p = specific heat at constant pressure, 10,820 ft-lb/lb/deg C
N = compressor rotational speed, rpm
α_o = absolute air angle relative to engine axis
LP = low pressure
IP = intermediate pressure
HP = high pressure

Subscripts

1 = inlet
2 = outlet
p = last stage operating at peak of its characteristic

Superscripts

θ = critical sector angle
60 deg = critical sector angle = 60 deg
- = area mean
R_p = overall R when last stage is operating at its peak pressure rise
ΔR = unspoiled surge R - spoiled surge R
$\Delta R'$ = R_p - spoiled surge R

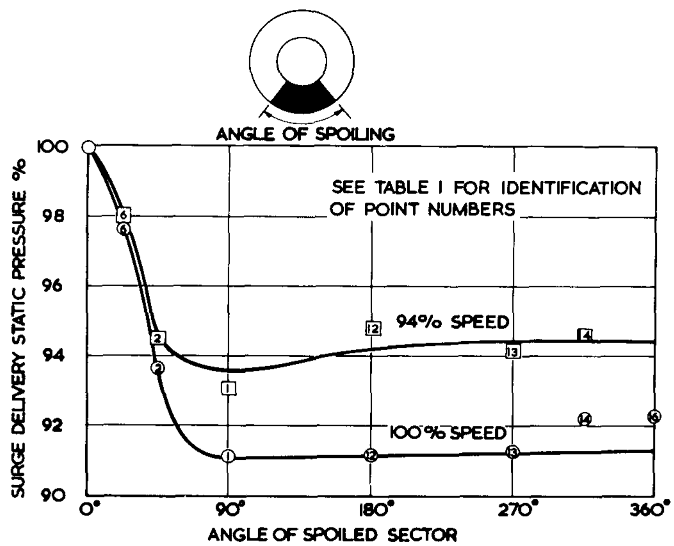

Fig.1 Effect of varying circumferential angle of spoiling on VTOL model compressor

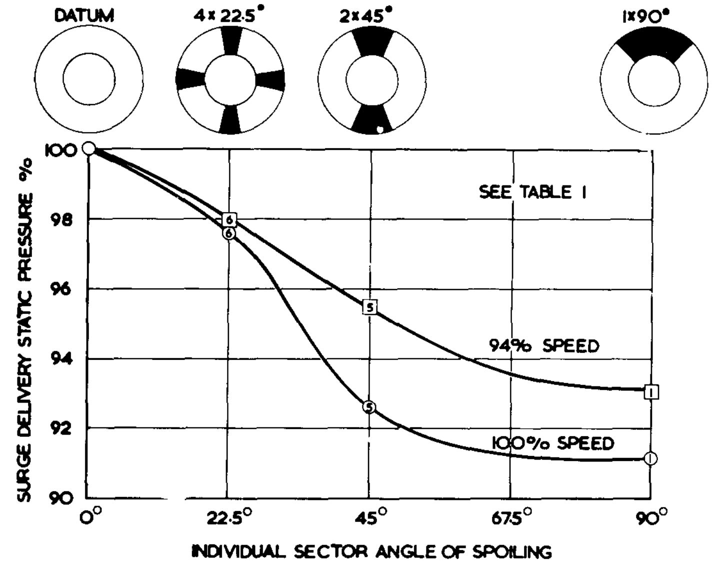

Fig.2 Effect of dividing spoiled sector angle on VTOL model compressor

of surge margin with intake conditions. Two valuable observations were: (a) Radial distortions were much less detrimental to surge line than circumferential distortions; and (b) Despite the complexity of the spoiling patterns, the critical inlet pressure appeared to be the lowest area mean total pressure to be found in any 60 deg sector in the compressor face.

Encouraged by these results, it was decided to do some basic research on a 15 in.-dia model of a second generation lift compressor by systematically varying inlet pressure patterns and levels.

3 RESEARCH TESTING

Compressor Design Parameters

The leading design parameters for the model lift compressor were:

Overall pressure ratio	= 4.25
Number of stages	= 6
Stage reaction	≃ 55 percent, constant radially
Inlet hub-tip diameter ratio	= 0.431
Length-diameter ratio	= 0.825
Rotor 1 tip blade speed	= 1100 fps
Flow per unit frontal area	= 31 lb/sq ft/sec

Spoiling

Spoiling was by means of stationary gauzes (0.080 dia wire) placed about 1/4 compressor diameters upstream of the inlet guide vanes.

Instrumentation

1 Inlet Total Pressure, P_1. Rotating rakes with 5 radial probes traversed at 10-deg intervals circumferentially.

2 Inlet Total Temperature, T_1. Six resistance thermometers upstream of spoiling plane.

3 Mass Flow, M. Calibrated airmeter upstream of inlet throttle and spoilers.

4 Delivery Static Pressure, p_2. Five at inner and 5 at outer wall, one annulus height downstream of outlet guide vanes.

5 Delivery Total Pressure, P_2. Sixteen Kiel probes equi-spaced around annulus (only used for defining delivery distortion).

6 Total Pressure Ratio, R. Ratio of delivery total pressure (as computed from outlet statics, mass flow, and continuity) to $\overline{P}_1$.

4 DEFINITION OF CRITICAL AREA OF SPOILING

While many of the distortion parameters in popular use depend on the local minimum and maximum pressures or velocities at the engine face, it seems logical to expect the response of the compressor to be dependent on a finite area of spoiling. To determine the significant area of spoiling for purely circumferential patterns, the VTOL model compressor was tested with a range of spoiled sector angles covering 22 1/2, 45, 90, 180, 270, 315, and 360 deg. The mesh of spoiling gauze was the same in each case, thus giving approximately the same ratio of pressure in the spoiled and unspoiled sectors. The reduction in outlet static pressure at surge with the various angles of spoiling is plotted in Fig.1 for the highest two speeds

Table 1 Description of Spoilers Included in Reserach Program

(Note: Spoiler Nos. correspond to Point Nos. in Figs.1 to 6)

Spoiler no.	Description	P_1 min / P_1 max at 100% N	$\Delta\bar{P}_1 60°$ / $\bar{q}_1$	Remarks
1	1 x 90 deg	0.933	0.402	
2	1 x 45 deg	0.931	0.387	
3	1 x 22 1/2 deg	-	-	Test curtailed by failure
4	1 x 11 1/4 deg	-	-	Not tested
5	2 x 45 deg	0.930	0.281	
6	4 x 22 1/2 deg	0.936	0.036	
7	2 x 22 1/2 deg	-	-	Not tested
8	1 x 90 deg	0.870	0.860	
9	1 x 90 deg	0.967	0.178	
10	360 deg tip	-	-	Test curtailed by high stage 1 rotor stresses
11	360 hub	0.952	0	
12	1 x 180 deg	0.927	0.287	
13	1 x 270 deg	0.923	0.146	
14	1 x 315 deg	0.925	0.059	
15	180 deg hub + 180 deg tip	0.925	0.185	
16	360 deg	1.0	0	Covered whole annulus

tested. As the spoiled angle was increased from 0 to 90 deg, the surge delivery static pressure fell rapidly and then stabilized at a constant minimum value from 90 to 360 deg. This demonstrates that, at least for this particular compressor, there is a critical sector of spoiling between about 60 and 90 deg, confirming the indications of earlier experience of testing complex patterns on other VTOL compressors.

5 EFFECT OF DIVIDING THE SPOILED AREA

Since the compressor was shown to be sensitive to a critical angle of spoiling (60 to 90 deg), it was of significance to determine if this critical angle required to be located within a single area, or if the compressor's response would change as the angle was divided into a number of smaller elements. This is relevant to those cases where an intake generates more than one region of low energy, e.g. twin inlets feeding a single engine or high incidence break away from both the intake lip and the hub bullet.

The surge delivery pressure with the single 90-deg sector was, therefore, compared to that with 2 x 45-deg sectors and 4 x 22 1/2-deg sectors, the intensity of inlet loss remaining the same. As shown in Fig.2, the surge delivery pressure is, in fact, related to the size of the individual sector, the shape of the curve being the same as that obtained for the single areas of spoiling (Fig.1). This observation can provide additional clues to the nature of the compressor's response to spoiling.

Two possible explanations are:

1 The propagation and onset of stall or surge is dependent on the duration of time each blade passage is operating in the low pressure region, so that splitting the spoiled area into small elements would reduce the tendency of individual passages to stall (1).[1]

2 The true critical area exists at the stage controlling overall surge rather than at inlet. At the high speeds being considered, this would be the rear stage, so the critical area may be smaller than 60 deg if some tangential mixing has taken place. Due to the increased number of shear surfaces between the high and low pressure regions for the multiple spoiling cases, the total

[1] Numbers in parentheses designate References at the end of the paper.

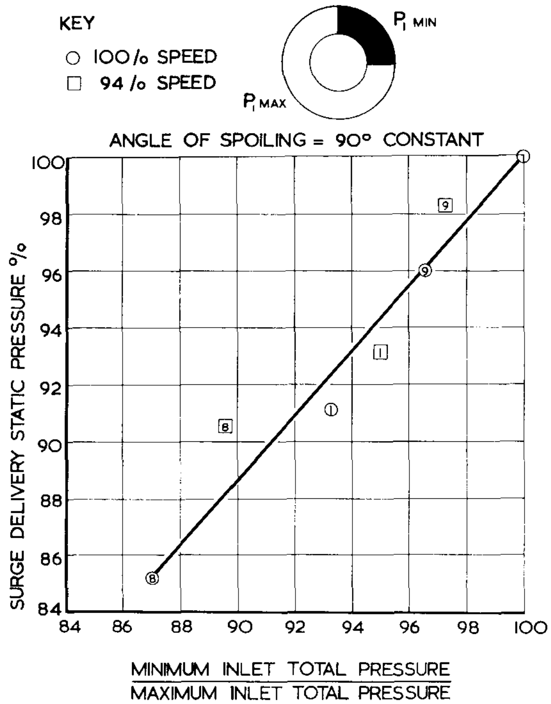

Fig.3 Effect of varying intensity of spoiling for a fixed pattern on VTOL model compressor

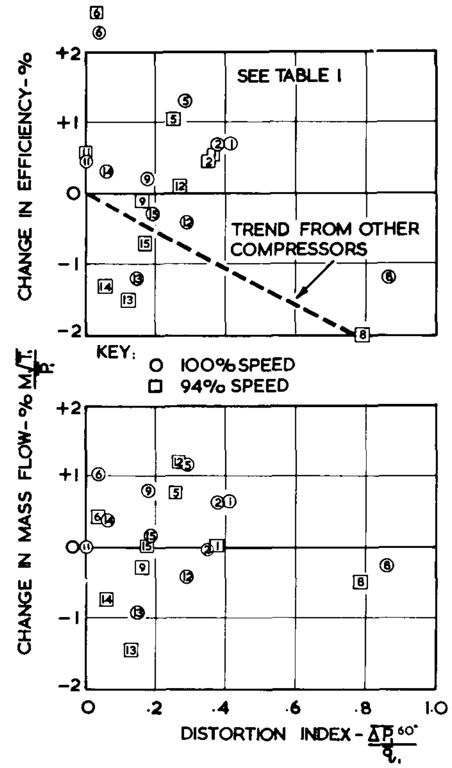

Fig.5 Effect of spoiling on flow and efficiency on VTOL model compressor

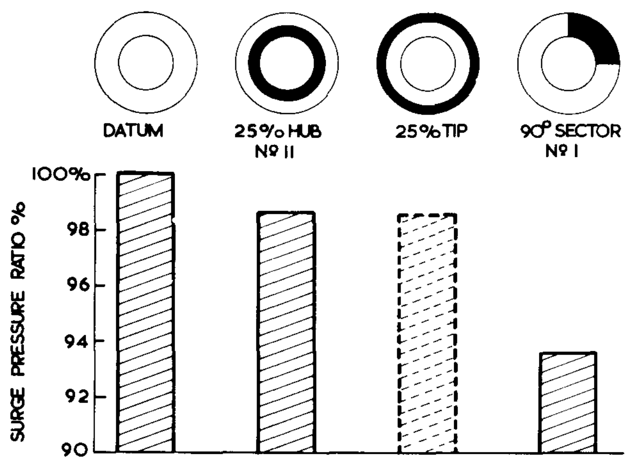

Fig.4 Comparative effects of radial and circumferential spoiling on VTOL compressors

area of spoiling at the rear stages is likely to have decayed to a smaller value than that existing with the single area. This effect could, of course, combine with the first explanation.

6 EFFECT OF VARYING INTENSITY OF SPOILING

As would be expected, for a fixed pattern of spoiling (90-deg sector), the surge delivery pressure was almost directly proportional to the level of spoiling (P_1 min/P_1 max) (Fig.3).

7 COMPARISON OF RADIAL AND CIRCUMFERENTIAL DISTORTIONS

Fig.4 shows that radial distortion effects were much less severe than circumferential. A radial spoiler, covering 25 percent of the annulus area, gave only one-fifth the loss of surge pressure ratio caused by a 90-deg sector of the same spoiling intensity. Unfortunately, on this compressor tip spoiling induced high stresses in Stage 1 rotor blading, due to positive incidence stalled flutter, and prevented a direct surge line comparison being obtained for hub and tip spoiling. To complete the picture, therefore, the tip spoiling result (shown by the broken line in Fig.4) has been taken from a test on another lift engine compressor, of which the response to spoiling was generally similar to that of the model compressor.

Presumably the greater facility for mixing to occur in the radial direction allows a compressor to deal more easily with, and to correct, radial flow distortions. After all, substantial radial gradients of pressure and temperature normally exist within a compressor. However, it is quite possible that sensitivity to radial distortion would be influenced by the aerodynamic design features, e.g., vortex flow assumptions, stage reaction, radial variation of work, loss and stall

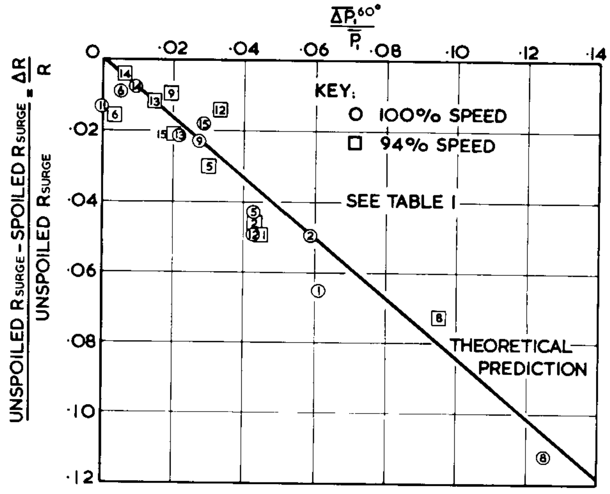

Fig.6 Comparison of theoretical and measured loss of surge pressure ratio for VTOL model compressor

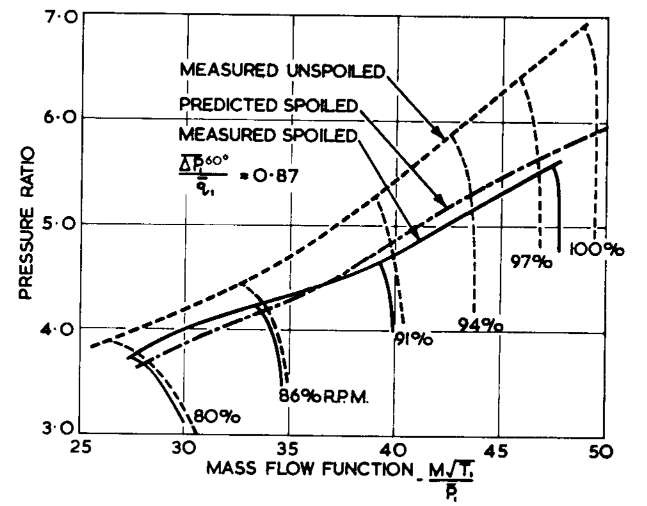

Fig.7 Performance map of VTOL engine compressor, nine stages, hub-tip ratio = 0.39

margin. The general experience of a large range of compressors with inlet guide vanes, and designed mainly with constant reaction stages, is that radial distortion is much less detrimental to surge line than circumferential distortion (but not necessarily less detrimental to flow and efficiency). More limited experience also suggests that free vortex, zero α_0 machines behave similarly.

8 DISTORTION EFFECTS ON FLOW AND EFFICIENCY

By far the greatest effect of distortion on engine performance is a deterioration in weight flow, and hence thrust, at a speed, due to the reduction in mean inlet pressure. In other words, the main performance loss is a result of a reduction in intake efficiency. Compressor nondimensional performance, i.e. corrected weight flow and efficiency, is usually little affected, particularly with predominantly circumferential distortions.

The changes in non-dimensional mass flow $M\sqrt{T_1}/P_1$ and efficiency measured on the lift engine model are shown in Fig.5, related to the distortion index $\overline{\Delta P}_1^{60\ deg}/\bar{q}_1$ (see Appendix 1 for definition of this distortion index). No real correlation exists. Variations of flow and efficiency are generally within plus or minus two percent of the undisturbed values. The scatter of points really demonstrates the difficulty of making accurate measurements with nonuniform flow. For the levels of distortion normally encountered by civil aircraft ($\overline{\Delta P}_1^{60\ deg}/\bar{q}_1$ less than 0.3), the nondimensional performance changes are usually small. They can, however, be significant in military applications, particularly VTOL and super-

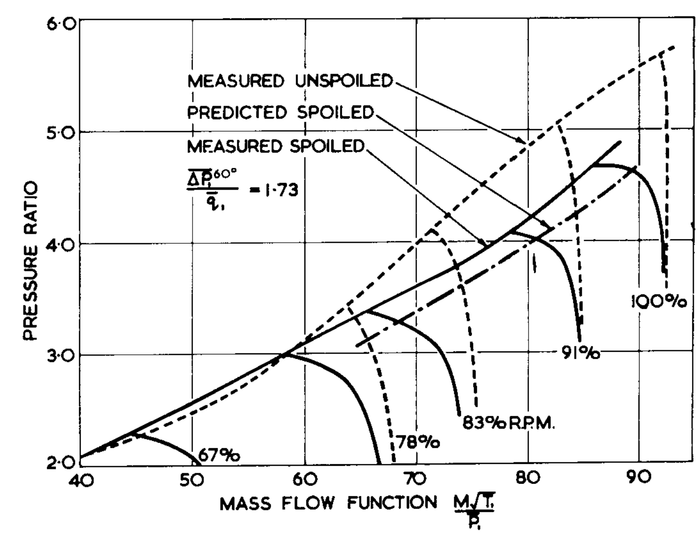

Fig.8 Performance map of HP compressor from two-shaft, by-pass engine, nine stages, hub-tip ratio = 0.73

sonic aircraft, where the distortion levels can be very severe ($\overline{\Delta P}_1^{60\ deg}/\bar{q}_1$ as high as 1.0). It must also be remembered that additional performance losses will occur if it is found necessary to derate the compressor working lines to provide adequate surge margin for dealing with inlet distortion.

The observation of little change in nondimensional maximum mass flow is significant. As proposed by Pearson and McKenzie (2), it indicates that the compressor must be tending to induce a constant air inlet velocity, thereby creating an inlet static pressure gradient in sympathy with the gradient of total pressure.

This supports the "Parallel Compressor Mo-

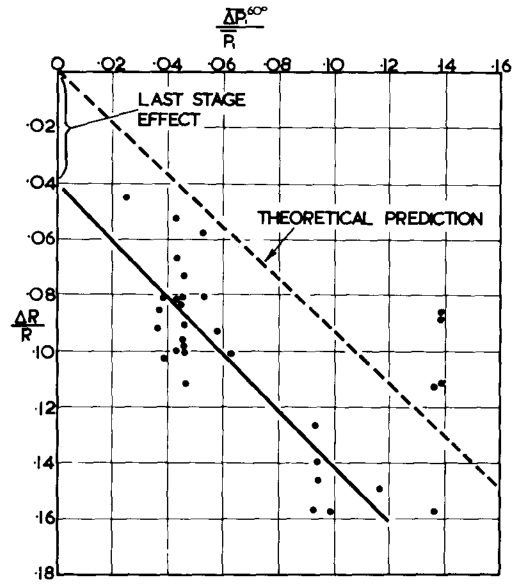

Fig.9 Effect of spoiling on multi-stage LP compressors compared to standard theoretical prediction

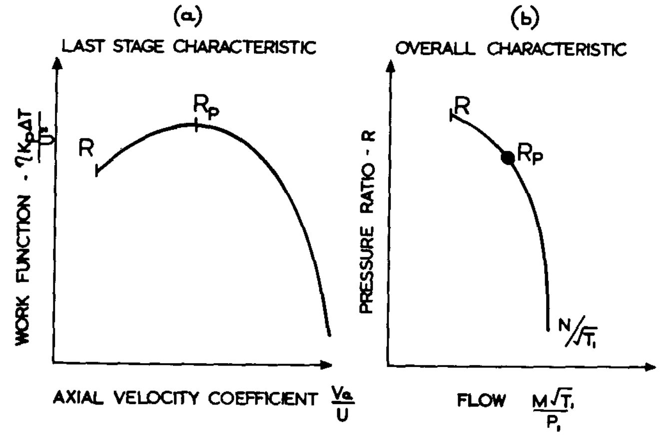

Fig.10 Diagrammatic representation of last stage and overall characteristic for a multi-stage LP compressor

del" assumption that the spoiled and unspoiled sectors are operating on a unique characteristic, at least away from stall at maximum flow (see Appendix 2 for explanation of "Parallel Compressor Model"). Due to the compressor's tendency to operate with constant inlet velocity, one must be careful in the interpretation of air flow suction tests on model intakes and in the calibration of distortion simulating screens [also commented on in reference (3)]. Without the presence of the compressor, a constant static pressure will prevail in the entry plane. However, a simple method of approximating to the presence of the engine is to place a close mesh gauze in the plane corresponding to the engine face. By designing for the gauze to be choked at the relevant flow, a static pressure profile will be created by the constant, choked velocity.

9 CORRELATION OF COMPRESSOR SURGE WITH "CRITICAL SECTOR ANGLE"

If the concepts of a "critical area" and "Parallel Compressor Model" are sound, then the loss of surge margin ($R_{unspoiled} - R_{spoiled}/R_{unspoiled}$) should be directly proportional to the reduction of inlet pressure in the critical sector, $\overline{\Delta P}_1^{60\ deg}/\bar{p}_1$. The results of the model lift compressor tests are related in this way in Fig.6, assuming 60 deg to be the critical sector width.

It can be seen that there is quite a good straight-line correlation, agreeing with the theoretical prediction. A complex spoiling pattern, (Point No. 15), combining radial and circumferential pressure gradients (180-deg hub + 180-deg tip spoiling) also satisfies the correlation, demonstrating that the prediction system works for patterns other than the "square wave" type. To obtain confidence in the prediction system, it is necessary to put it to the test on other engine compressors tested with complex spoiling patterns.

As typical examples of low and high hub/tip ratio machines, performance characteristics are shown: a) in Fig.7 for another single shaft VTOL engine compressor, and b) in Fig.8 for the hp compressor of a two-shaft by-pass engine. Despite the complexity and severity of spoiling patterns, the measured and predicted results agree tolerably well.

10 DEVIATIONS FROM "PARALLEL COMPRESSOR MODEL"

The foregoing section demonstrates how the application of the simple "two compressors in parallel" theory explains surge over a range of high-pressure ratio compressors ($R > 4{:}1$). However, some compressors have been found to deviate from the principle, in being either more or less sensitive than predicted. In many cases, inspection of the individual stage characteristics, or stage matching, has revealed the cause of the deviation. Once the cause is understood, the prediction method can be modified to explain further behavior of that particular type or family of compressor. More important, in the case of a highly sensitive compressor, having identified the mismatching, or rogue stage, which causes premature surge, the fault can be corrected and the compressor's sensitivity to spoiling improved.

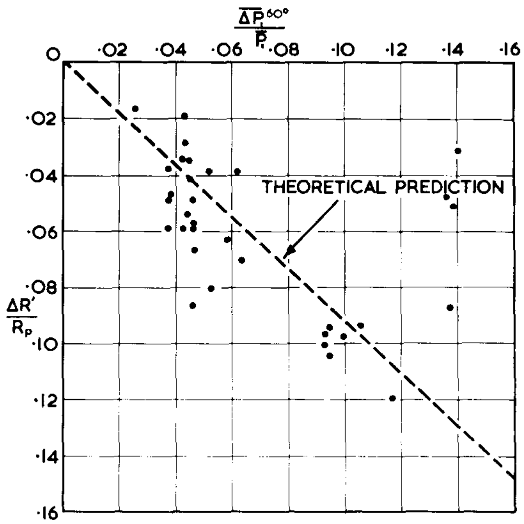

Fig.11 Effect of spoiling on multi-stage LP compressor compared to prediction modified for "last stage effect."

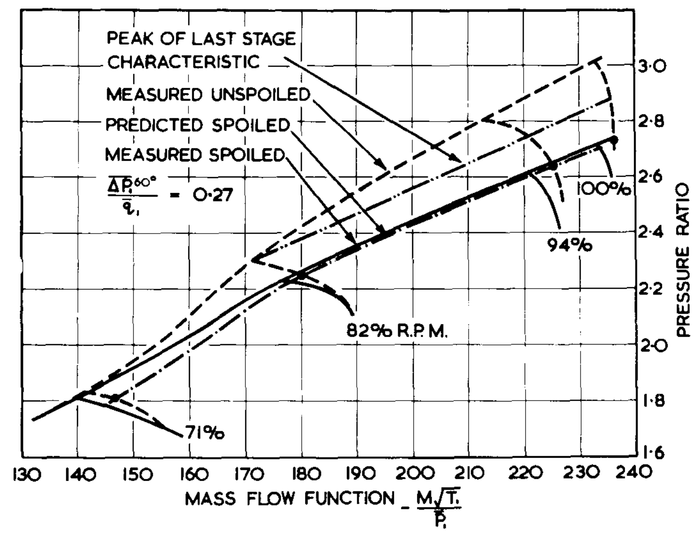

Fig.12 Performance map of LP compressor from two-shaft by-pass engine, five stages, hub-tip ratio = 0.32

Compressors Intolerant to Distortion

Low Pressure Multi-Stage Units. It had been observed that multi-stage low pressure units (R < 4:1) often suffered two or three times the expected loss of surge pressure ratio. The results of 32 tests on 9 LP compressors are shown in Fig.9. The general mass of measured surge points is well below the predicted line indicating high sensitivity to spoiling.

The large amount of scatter of points is understandable when it is considered that

(a) Different aerodynamic designs were tested, though, in fact, all but two were to the same general design philosophy (with subsonic, constant reaction stages) but subsequently developed in different ways. One would therefore expect some differences in their sensitivity to spoiling.

(b) All of the inlet distortion patterns were very complex in nature and such a simple distortion parameter, which takes no account of radial variations, cannot completely define inlet conditions (e.g., on Figs. 9 and 11 those points at $(\Delta P_1 60\ /P_1)$ 0.14, which are above the general level, consist mainly of an intense pressure loss at the tip section, indicating that this particular compressor is relatively insensitive to tip spoiling).

(c) The distortions were produced by a variety of methods, viz., gauzes, flat plates, and swirl vanes placed at different distances from the compressor. These would produce a different "character" of flow, such as varying degrees of turbulence level, and probably have different rates of decay.

(d) The distortions were applied during routine development testing and inlet instrumentation was often barely adequate to assess accurately the inlet pressure variation.

In the investigation to determine the reason for the oversensitivity to spoiling of these compressors it was noted that one feature in which they differed from HP compressors was that the characteristic of pressure rise in the last stage, as a function of flow, $[(\eta K_p \Delta T/U^2)$ versus $(V_a/U)]$ peaked and changed slope before high speed surge occurred, as is shown by Fig. 10 (a).

With H.P. compressors high-speed surge usually occurs when the last stage reaches the peak of its pressure characteristic. In the LP case it has been postulated that, since the positive slope portion indicates that the stage is operating in a relatively stalled condition, the compressor will only operate stably in this region when conditions are ideal, i.e., when inlet conditions are uniform.

The success with which the modified prediction technique can be applied is shown on the overall performance map (Fig.12) of a five-stage LP compressor from a two-shaft by-pass engine. Having recognized the "last stage effect," this particular compressor's unspoiled surge line and tolerance to distortion were able to be improved by unstalling the last stage in a re-matching exercise.

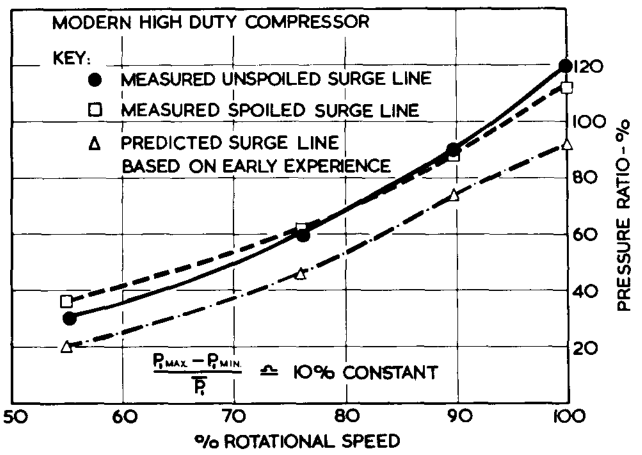

Fig.13 Performance map of modern high duty compressor showing increased distortion tolerance relative to early experience

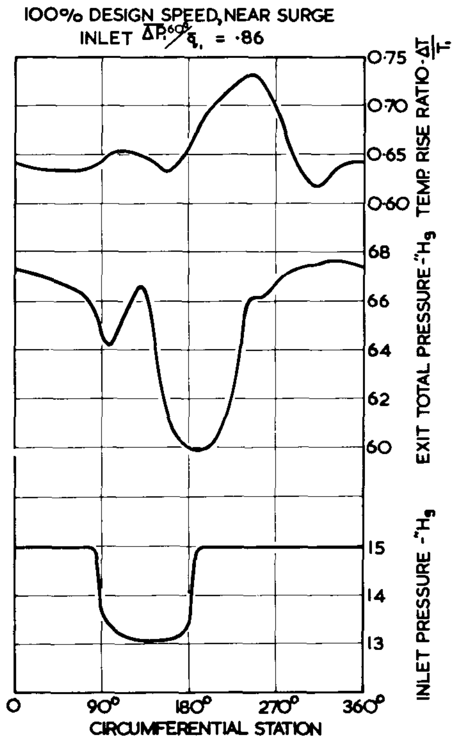

Fig.14 Extreme case of compressor failing to attenuate inlet distortion

Compressors Tolerant to Distortion

As a result of many years experience in dealing with flow distortion problems in a variety of intake/engine installations, a number of aerodynamic and aero/mechanical techniques have been developed to increase compressor tolerance to distortion. Often this has required intensive development effort, if, for example, an existing civil engine had to be adapted for military applications where more severe intake conditions existed. At one time it was feared that advancement of compressor design technology, leading to designs with higher and higher stage loadings, would result in the new generation of compressors being oversensitive to flow mal-distribution. However, the reduction in number of compressor stages, resulting from increased pressure ratio per stage, allowed blade chords to be lengthened, always providing the mechanical designers could be restrained from attempting to take full advantage of the reduced stage numbers to obtain the proportionate reduction in compressor length and weight. As shown in reference (1), long chord blades can increase tolerance to distortion on the basis that blade stall is dependent on the time the blade is operating in the high incidence condition.

The influence of the "time element" also points to high reaction stages being favorable for distortion tolerance, since that part of the stage which is doing the majority of the pressure rise and is controlling the surge point (viz., the rotor) is protected against local stall by its rotational movement through the spoiled area. While the stator row is not protected in this way, it does not contribute so significantly to the pressure rise or overall stage loss. Provided it succeeds in achieving its design air deflection when stalled, and this it can do at high solidity, it is not likely to influence the surge free operational range of the machine.

The overall outcome is that the new generation of advanced technology engines are likely to have improved tolerance to intake distortion. In some instances, this is evident by the fact that the critical sector of spoiling is substantially increased, e.g., from 60 to 120 or 180 deg. As an example, Fig.13 shows the characteristics of a modern high duty engine compressor tested with realistic flow patterns over the operating range. While early experience with low duty compressors, untreated for distortion tolerance would have indicated that there should be significant surge line deterioration, the surge line, in fact, is hardly disturbed.

11 DISTORTION OF COMPRESSOR EXIT CONDITIONS

The "Parallel Compressor Model" predicts that, when inlet conditions are nonuniform, there will also be a circumferential variation of delivery total pressure and temperature. Usually the inlet disturbance is attenuated as it travels through the compressor ($^1/_3$ is a typical attenuation figure for many engine compressors). However, certain cases have been found where amplification has actually occurred, the exit pressure distortion

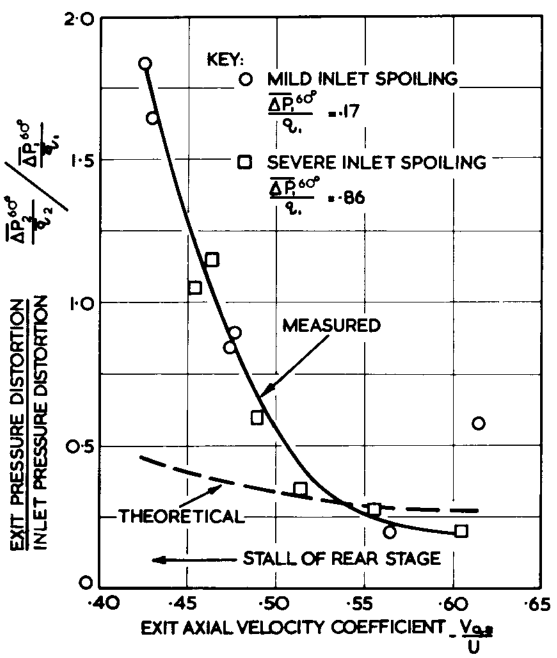

Fig.15 Extreme case of inlet distortion being amplified at exit as operation approaches stall

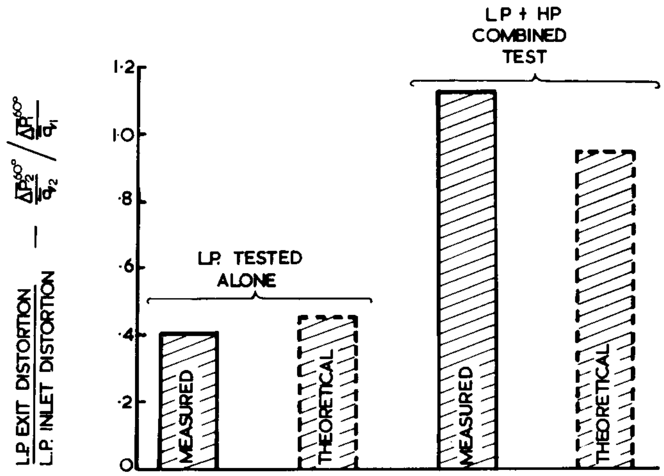

Fig.16 Influence of HP compressor presence on LP compressor exit distortion

rising to 1.5 to 2.0 times that at inlet, together with an associated large circumferential temperature gradient. Such an extreme case is shown in Fig.14. Incidentally, it will be observed here that there has been little circumferential mixing between high- and low-pressure regions, verifying one of the assumptions of the "Parallel Compressor Model" and substantiating the same observation made in references (3) and (4).

Fig.15 relates the ratio of exit to inlet distortion to the exit axial velocity coefficient, this being intended to be representative of the operating condition of the rear stage. The degree of attenuation, or amplification, appears to be dependent on the proximity of the operating point to stall and presumably to the slopes of the individual stage characteristics (4). The theoretical attenuation, as calculated by the "Parallel Compressor Model" is achieved at the maximum flow end of the characteristic but, as stall is approached (decreasing V_a/U) and the rate of negative slope of the last stage characteristic reduces, (perhaps going to a positive value), the exit distortion increases well above the theoretical value. This obviously exposes a weakness in the simple model, in that its assumptions may no longer apply when some stage, or stages, are operating stalled. The situation is sometimes anomalous in that, although the surge point may be successfully explained, the associated variation of exit conditions is inconsistent with the prediction.

The amplification of inlet distortion may create additional problems for the engine. In a multi-compressor engine, if the low-pressure fan amplifies the intake distortion then the intermediate or high-pressure compressors may be forced into surge. Until this phenomenon was recognized, there was difficulty in understanding the reason for HP compressor surge in some twin-spool engines, when operating with intake distortion. Obviously, serious combustion and turbine problems can also result from HP compressor delivery distortion.

12 DIFFICULTIES IN RELATING RIG TESTS TO ENGINES

At an early stage in the launching of a new engine project, it is essential that the individual compressor components be tested with intake distortion to anticipate intake/engine compatability problems. If possible, flow patterns representative of the actual intake should be used, but if these are not known then valuable information can still be obtained by using either classical distortion patterns or ones vaguely representative of the intake. Development, or redesign, can then be directed toward improving the tolerance of any particular compressor, or compressor stage, which appears to be oversensitive to distortion.

However, even when a good background of compressor distortion testing has been established for the new engine project, it is by no means an easy task to interpret rig data in such a way as to make quantative predictions of engine surge margins and handling capabilities. Since the observations on compressor response to distortion outlined in this and many other technical papers are based on rig tests, it may be advisable to remind the reader of some of the difficulties in applying these observations to engines.

1 Differences in Reynolds number between

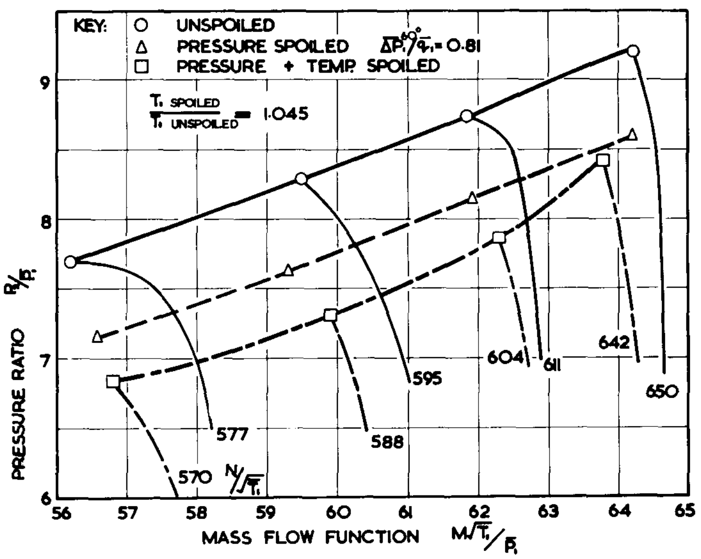

Fig.17 Combined effect of pressure and temperature spoiling on HP compressor of two-shaft by-pass engine, 12 stages, hub-tip ratio = 0.68

rig and engine tests will cause changes in performance, including surge margin, for which allowance will have to be made (5). For example, it is not unusual for HP compressors to be tested at between 1/5 to 1/10 the Reynolds number levels experienced in the engine at sea level conditions. For a 7:1 pressure ratio compressor the surge point at a non-dimensional speed may, therefore, be changed by as much as 1.0 pressure ratio. Surge margins, therefore, need to be measured, or estimated, with varying Reynolds number to cover engine operating conditions over the whole aircraft flight envelope.

2 Unlike the situation on rig test, the engine internal layout may not encourage circumferential equalization of static pressure at compressor delivery, due to the close proximity of the separate compressors, to the combustion system, or to the presence of radial struts in the inter-compressor ducts. The delivery conditions which control surge on the rig would not, therefore, apply in the engine environment, and surge line measurements or prediction techniques learned from rig tests would have to be modified.

3 Strong interaction can occur between compressors with close axial spacing, changing the attenuation properties of the upstream compressor. Fig.16 shows how the attenuation of an LP compressor (delivery distortion/inlet distortion) can be changed from a favorable 0.4 to a potentially embarrassing 1.1 by the close presence of the HP compressor. In this case, the HP compressor has to experience the full magnitude of intake distortion, a fact that could have been overlooked from isolated rig tests. It is shown that, in both situations, the "Parallel Compressor Model" can predict quite well the LP total pressure delivery distortion by alternately assuming equalization of outlet static pressure: a) at LP delivery when tested alone, and b) at HP delivery when the HP is present. Therefore, if facilities do not exist for testing the compressors in series, it may be safer to rely on theoretical predictions of distortion attenuation rather than on isolated rig test measurements.

4 Pressure distortion at inlet is also converted to a temperature distortion at outlet, and allowance has to be made for this additional effect on the following compressor. An example of the serious deterioration of surge line, which can result from the combined effects of pressure and temperature spoiling, is shown on Fig.17. Once again, the parallel compressor model has been found to predict quite well the effect of steady temperature distortion on surge line. In this case, it is assumed that the disturbed and undisturbed sectors operate at different inlet temperatures and, hence, correspondingly different non-dimensional speeds ($N/\sqrt{T_1}$), surge being determined by the lower speed characteristic. So far, the indication of limited experience is that the sensitivity of a compressor to steady temperature distortion will be quantitatively similar to its sensitivity to pressure distortion, i.e., if it is tolerant to one type it will be tolerant to the other.

5 In interpreting distortion results obtained from testing fans of by-pass engines, there may be difficulty in deciding whether the by-pass (tip) or the gas-generator (hub) sections will be a source of trouble for the engine. With a high by-pass ratio single stage fan surge of the by-pass section may be easily identified, but it may not be possible to surge the hub section, since the tip will support the hub when operating well on the stalled side of its characteristic. Therefore, in this case, particular attention must be paid to the distortion of conditions delivered by the hub to the following compressors, due consideration being given to inter-compressor interaction effects.

13 CONCLUSIONS

Based on experiments carried out on a compressor of moderate pressure ratio (R = 4.25:1) and low hub to tip diameter ratio (h/t = 0.431), the following conclusions can be drawn:

1 As the design speed of the compressor was approached, the loss of surge pressure ratio, due to inlet flow mal-distribution, was mainly depen-

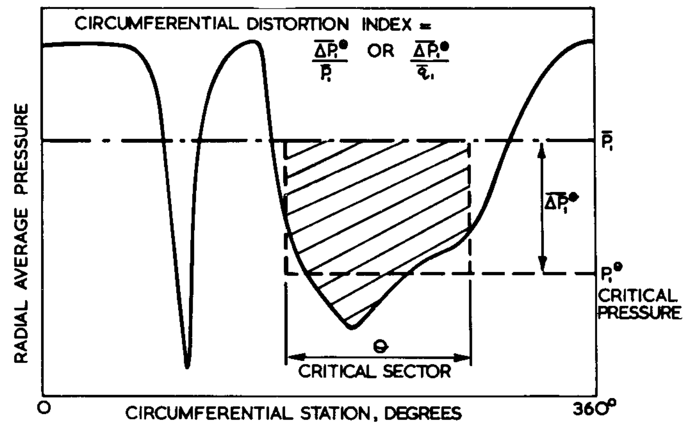

Fig.18 Definition of distortion index $\overline{\Delta P_1}^\theta/\bar{q}_1$

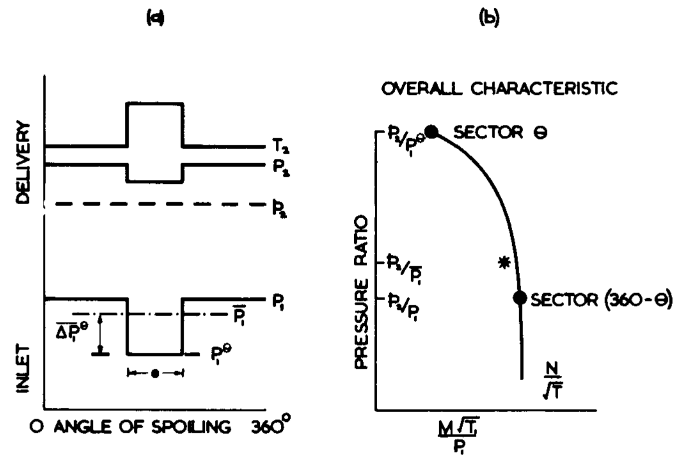

Fig.19 Diagrammatic representation of "Two compressors in parallel theory"

dent on the circumferential variation of inlet total pressure.

2 Radial variations of total pressure caused less loss of surge pressure ratio than the equivalent area and levels of circumferential spoiling.

3 The loss of delivery surge static pressure increased rapidly as the sector angle of spoiling was increased from about 20 to 60 deg and then leveled off to a constant value between 60 and 90 deg, the minimum value then being maintained right up to 360 deg. This suggests that a compressor is sensitive to a critical, minimum area of spoiling which will induce the maximum loss of surge pressure ratio.

4 It was found to be beneficial to divide the spoiled region into a number of small areas, each below the critical sector size. The loss of surge pressure then depended on the individual size of the small areas.

5 Non-dimensional mass flow and efficiency were only slightly affected by distortion.

These observations support the porposal of a simple distortion index $\overline{\Delta P_1}^\theta/\bar{p}_1$ which defines the critical inlet pressure as being the lowest average pressure to be found within the critical sector angle, θ. An angle of 60 deg is recommended.

6 The "Parallel Compressor Model" can provide a good basis for understanding the response to distortion of compressors covering a wider range of pressure ratio ($R > 2.6:1$) and hub to tip diameter ratio ($h/t > 0.32$) than has generally been believed, particularly if individual stage characteristics and stage matching are considered. The model also holds for complex distortion patterns.

7 Little tangential mixing of circumferential distortion takes place within a compressor. While the disturbance is generally attenuated by the compressor there are cases, probably associated with local stall within the compressor, where the distortion may be increased at compressor delivery.

8 Inlet pressure distortion also causes distortion of delivery total temperature.

9 There are indications that long chord blades and high reaction stages provide greater tolerance to flow distortion.

10 Within the operational environment of an engine, the response and attenuation characteristics of a compressor may be significantly changed from those experienced on rig test.

APPENDIX 1

BASIS OF A SIMPLE INLET DISTORTION INDEX

Over the years, airframe and engine people (to say nothing of the airline or service customer) have had great difficulty in finding a mutually acceptable inlet distortion index as a basis for guaranteeing intake and engine performance. In view of the complexity of the problem, this is not surprising. It has, however, often developed into a "numbers game" with the engine manufacturer trying to explain his engine behavior in a particular installation by various complex circumferential and radial weightings of pressure or velocity. Although the numbers derived in this way can work well for one engine/intake installation, they rarely read across to another.

While making no pretense at its being a completely satisfactory solution, a simple and relevant index to allow for steady-state distortions can be derived on the basis of the tests described in sections 4 to 7 of this paper [and also from Fig.10 of reference (6)] as follows:

1 In principle, neglect radial gradients on the following basis: a) They are generally

less harmful than the equivalent circumferential gradients. In realistic patterns there is usually a circumferential component of the distortion which takes precedence over the radial component. b) Their effect is dependent on the individual compressor design rules, and to some extent can be taken care of in the normal aerodynamic design processes. Therefore, any attempt to allow for them would involve different radial weightings for each new compressor or engine. This is the engine man's responsibility, and it would be unfair to the airframe man to expect him to cope with complex parameters and to guarantee contractually his intake performance based on parameters which he cannot readily appreciate or predict for his intake.

A compromise may be advisable in the case of high by-pass ratio engines where the by-pass and gas generator flows may be analyzed separately and the radial gradients neglected within each stream.

2 Define the critical sector angle (θ) for the compressor on the basis illustrated in Fig.1. Then, for a complex pattern, plot the radial average of total pressure circumferentially as in Fig. 18 and find the lowest average pressure (P_1^{θ}) contained within any sector of width θ. This is assumed to be the critical pressure and its depression ($\overline{\Delta P}_1^{\theta}$) below the average pressure ($\tilde{p}_1$) can be related to either $\tilde{p}_1$ or to the mean inlet dynamic head ($\bar{q}_1$), whichever is convenient, so defining the index as:

$$\text{Circumferential distortion index} = \overline{\Delta P}_1^{\theta}/\tilde{p}_1 \text{ or } \overline{\Delta P}_1^{\theta}/\bar{q}_1$$

$\overline{\Delta P}_1^{\theta}/\bar{q}_1$, is akin to a loss coefficient and has the advantage of remaining fairly constant over a wide range of mass flow for a distortion simulator screen or for a fixed geometry intake operating at constant incident conditions.

It is significant to note that this parameter was originally derived from analysis of a large number of complex flow patterns and not from simple idealized "square wave" patterns. Since 1962 it has been used successfully to predict and explain engine/intake behavior in many civil and military installations.

In a large number of cases, 60 deg has been found to be the critical sector angle and may be recommended for the distortion index $\overline{\Delta P}_1^{60\text{ deg}}/\bar{q}_1$. Apart from this, 60 deg also represents a reasonable compromise between engine and intake interests. A smaller angle might unduly restrict the intake designer in attempting to confine the minimum loss within a small area at off-design conditions, and a larger angle would not give the engine designer sufficient protection against extreme local variations in pressure.

APPENDIX 2

SIMPLE MODEL EXPLAINING SURGE INDUCED BY SPOILING

Two Compressors in Parallel Theory

The concept and observation that a compressor is responsive to a critical area of spoiling combines ideally with one simple model used to explain surge induced by spoiling. This model, first suggested by Pearson and McKenzie in reference (2), is known as the "two compressor in parallel theory."

For simplicity, consider the compressor to be operating with a stepped change in the circumferential variation of inlet total pressure as shown by Fig.19(a).

Assume that the spoiled sector is equal to, or greater than the critical sector width (θ). Then it is assumed that the two separate compressors operate in parallel, one with an undisturbed inlet pressure (P_1) and the other with a throttled inlet pressure (P_1^{θ}) without any cross flow taking place. The two compressors exhaust to a common and constant outlet static pressure and operate on the same nondimensional characteristic [Fig.19(b)] which, in fact, is the same as that measured on the whole compressor with completely uniform inlet conditions. It is assumed that surge will occur when the pressure ratio (outlet static/inlet total) across the spoiled sector reaches the level which is the normal surge pressure ratio of the completely undisturbed compressor.

It should be noted that, due to the higher pressure ratio of the spoiled sector and to the difference in delivery dynamic head between the two points on the overall characteristic, there will be a variation of delivery total pressure and temperature.

When dealing with a realistic, complex pattern of spoiling, the model may still be used if the critical sector angle θ is defined as in Appendix 1.

ACKNOWLEDGMENTS

The author wishes to express his thanks to the Directors of Rolls-Royce Limited for their permission to publish this paper, to the Ministry of Technology, who supported the research work, and to J. H. B. Rushton for his assistance in conducting the research test program.

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