UNSTEADY 3D FLOW IN A SINGLE-STAGE TRANSONIC FAN.
PART I: UNSTEADY ROTOR EXIT FLOW FIELD

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ABSTRACT
Detailed unsteady aerodynamic measurements have been taken in a single-stage transonic fan with a very high stator-hub loading. 2D dynamic yawmeters probes, capable of measuring mean and fluctuating levels of stagnation pressure, static pressure and yaw angle have been traversed at rotor exit, and downstream of the stator along with several types of pneumatic 3D probe. Part I of this paper describes the dynamic yawmeters and their performance, and presents ensemble-averaged stagnation pressure and random stagnation pressure unsteadiness measurements taken at rotor exit. These are used to illustrate the salient features of the rotor flow field, and the effects of compressor aerodynamic loading. Part II presents measurements taken at stator exit.

INTRODUCTION
It is required that future aeroengines be lighter and have a reduced cost of ownership, while achieving improved levels of performance. When applied to compressors, these goals dictate that designs become more compact and that higher levels of aerodynamic loading and Mach numbers are allowed. For military applications in particular, the use of low aspect blading is preferable. These trends increase greatly the complexity of the compressor flow field and make it more difficult to design machines that achieve their design performance with adequate stability margin. It is anticipated that to design such machines to achieve optimum performance in future, design tools that take account of aspects of the flow field ignored by current methods will be employed. In particular, the effects of blade row proximity and flow field unsteadiness need to be modelled. However, it is only in recent years that transient instrumentation capable of withstanding the arduous environment in high-speed compressor flows has become available. Therefore, there is little with which to assess the integrity of predictions made by the growing number of time-accurate CFD codes.

Ng & Epstein (1985) and Gertz (1986) have presented flow field unsteadiness measurements taken behind the rotors of three different transonic fans. All three fans showed the same characteristics, i.e. large amplitude fluctuations in stagnation pressure and temperature within the inviscid core flow between the rotor wakes. The frequency of these oscillations was three to four times that of rotor passing, and was attributed to rotor shock system movement driven by periodic vortex shedding in the blade wakes, see Epstein et al (1988). However, Cherrett & Bryce (1992) presented similar phenomena in measurements taken behind the first three rotors of a core compressor, where strong rotor shock systems were not present. This anomaly showed that there is some way to go to understand fully the mechanics of the flow field unsteadiness.

Part I of this paper describes the high frequency yawmeters and their performance, and presents unsteady flow field measurements taken at rotor exit. These measurements are used to illustrate the salient features of the viscous flow field associated with the rotor.

Part II of the paper presents steady and unsteady area traverse measurements taken behind the stator row of the fan. Unlike the rotor exit measurements (which were taken during a traverse in the radial direction only) the stator measurements illustrate the time-dependence of both the circumferential and radial variations of the flow field, and are able to shed light on the effects of blade row interaction on the development of the flow phenomena within the stator passage.

THE C148 TRANSONIC FAN
The C148 single stage transonic fan was derived from an existing Rolls-Royce multi-stage fan designed in the early 1980's and its design concept and major aerodynamic features are described by Bryce et al (1993). The fan was designed to have

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a rotor tip inlet relative Mach number of 1.5 and a high aerodynamic stage loading at the hub which resulted in near sonic Mach numbers at inlet to the stator hub and high deflection through the stator (>57° turning to axial at stator exit).

The stage is illustrated in Fig 1 where it can be seen that it has a small, but engine-relevant, rotor/stator gap of around 20% of rotor axial chord in the inner half of the annulus. Geometric and aerodynamic information relevant to this paper are given in Table 1. Bryce et al showed (using surface oil-flow visualization and pneumatic stator exit traverse measurements) that the stator hub flow is dominated by a large endwall corner stall. A significant high loss region is associated with the corner stall, and a region of high total pressure (and Mach number) is found between adjacent high loss regions. A smaller corner stall was also found at the stator casing. Although the stator flow was dominated by 3D viscous effects, the rotor flow was found to be modelled with reasonable success using essentially 2D S1-S2 methods.

The overall performance of the fan is shown in Fig 2. This paper will concentrate on detailed flow field measurements taken at two operating points on the design speed characteristic, i.e. at peak efficiency (A) & at near surge (C) and at peak efficiency operation (B) on the 80% speed characteristic. Part II will concentrate on measurements at point A only.

<table>
<thead>
<tr>
<th>Number of rotor blades</th>
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<tr>
<td>Rotor pitch/ chord ratio (mid span)</td>
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<tr>
<td>Number of stator blades</td>
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<tr>
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<td>Stage pressure ratio</td>
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<td>Stage hub loading (ΔH/ΔU²)</td>
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<td>Rotor inlet tip diameter (mm)</td>
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<td>Stage inlet hub/tip ratio</td>
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<tr>
<td>Stage exit hub/tip ratio</td>
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</tbody>
</table>

**TABLE 1 C148 PARAMETERS**
FIG 3 A DYNAMIC YAWMETER

Dynamic Yawmeter

Construction

Fig 3 shows a dynamic yawmeter of the type developed at Rolls-Royce, with UK Government support, by Cook (1989). Two identical yawmeters were used in C148. The wedge-shaped cross section of the probe head has an included angle of 30° and an axial chord of 5.6mm. Three semiconductor pressure transducers (designated P1, S2 & S3) are contained within the sensing head of the probe. The transducer for measuring stagnation pressure (P1) is a Kulite type XCQ-062, while the two static pressure transducers are Kulite type LQ-047. All transducers used in the C148 yawmeters had a range of 344 kPa absolute and were coated with a 0.05-0.08mm layer of silastomer rubber for protection. The two static pressure transducer diaphragms lie flush with the probe surface.

Yawmeter aerodynamic calibration

The aerodynamic characteristics of both dynamic yawmeters were determined during calibrations carried out at the Whittle Laboratory, Cambridge University, which are reported fully by Cherrett et al (1992). The calibrations were carried out at Mach numbers of 0.2, 0.5, 0.7 & 0.9, and showed that the operating incidence (yaw angle) range of the probe was approximately ±35°. At highest incidences the flow separated completely from the leeward wedge surface. At lower incidence settings, i.e. between 10° and 25°, the flow on the leeward side of the probe-wedge was characterized by a separation and re-attachment; where the point of re-attachment moved rearwards on the wedge surface with increasing incidence. Although this introduced flow field unsteadiness close to the probe, the amplitude of the resultant pressure fluctuations was small compared to those that would occur in a high-speed compressor.

The calibrations also showed that Reynolds number effects were negligible in the range 36x10³ to 90x10³ (based on a wedge length of 5.7mm) where the mid-span Reynolds numbers at the rotor and stator exit were 55x10³ to 65x10³ respectively in C148. The yawmeters were also calibrated at pitch angles of -5°, 0°, +5°, 10° & 15°. This revealed that the blockage associated with the probe stem caused fluid to move 'radially inward' toward the sensing head of the probe.

An identical pneumatic yawmeter was also calibrated in great detail. This mirrored the performance of the dynamic probes, and provided further confidence in the integrity of the dynamic probe calibrations. The pneumatic yawmeter was not used in C148.

Frequency response

The frequency response of transducers coated with silastomer rubber, similar to those used in the yawmeters, have been shown to be flat to 100 kHz while displaying negligible phase-angle lag, see Ainsworth et al (1990). However, this is not the only issue affecting the yawmeter measurement bandwidth. Transducer spacing needs to be taken into account and related to how the flow around the probe head behaves during rapid changes of direction and velocity. Such effects may be complex, especially if vortices are shed from the wedge apex. It is not known what effect such phenomena may have on the yawmeter's performance, nor how valid it is to use the steady-state aerodynamic calibration in a highly unsteady compressor flow field. More work is required to investigate these issues.

Transducer thermal compensation and temporal drift

Compensation for the temperature sensitivity of the pressure transducers was achieved using a system developed at DRA, which has been described in detail by Cherrett & Bryce (1991). Implementation of this system requires that the transducers be calibrated over a given pressure cycle, at a series of constant temperatures. Therefore, the transducer pressure sensitivity (Vₚₕ) and null-pressure output (V₀ₑ) can be expressed as a function of the transducer's diaphragm temperature. By monitoring the voltage (Vₚ) across a thermally stable resistor placed in series with the transducer, Vₚ can be correlated with the diaphragm temperature. Therefore, when used in the compressor, the transducer's pressure output voltage (Vₚₑ) is converted to pressure using the following equation.

\[ \text{pressure} = \frac{(Vₚ - V₀ₑ)}{V₀ₑ} \]

Where V₀ₑ and V₀ₑ are determined for the diaphragm temperature derived from the Vₚ output.

The yawmeter transducers were calibrated repeatedly during a
one year period, including immediately before and after being used in C148. This showed that the transducer's V<sub>oz</sub>, V<sub>oz</sub>, and V<sub>s</sub> changes occurred when the yawmeters were used in C148. While the largest changes were found in V<sub>oz</sub> (which were potentially correctable via periodic reference to barometric pressure), the experience did highlight the need for regular and frequent calibration to monitor changes in the other transducer characteristics.

Analysis was carried to assess the impact of these changes. This showed that, as long as corrections for V<sub>oz</sub> drift were made by daily reference to ambient barometric pressure levels, transducer measurement accuracy could generally be maintained to within ±0.3% to ±0.4% of full scale deflection. This could have been reduced by calibrating more frequently within the C148 test series, although this was not undertaken in order to minimise risk of damaging the yawmeters during repeated probe installation. Similarly, the effects of drift could have been reduced further by using smaller range transducers, as the 344kPa range transducers were somewhat oversized for C148 in order to allow their use in other compressors.

Yawmeter accuracy

Because each of the yawmeter transducers were prone to drift, resulting in pressure measurement uncertainty, further analysis was undertaken to assess the consequences for Mach number, yaw angle, stagnation pressure and static pressure measurement accuracy. The results are shown in Fig 4, for different levels of transducer measurement uncertainty; where the analysis assumed that the pressure levels were compatible with those found at stator exit in C148, and that the same magnitude of pressure measurement uncertainty applied to each of the three transducers. (An average value of uncertainty was derived considering all possible permutations of the error between the 3 probe sensors).

The figure shows that Mach number and yaw angle accuracy are strongly dependent on the flow field Mach number, especially below Mach 0.5, while stagnation and static pressure accuracies are more acceptable. The ±1.2 kPa (±0.35% FSD) data are the most representative yawmeter performance, whilst the curves for the two smallest levels of pressure measurement uncertainty (ie. ±0.1 kPa and ±0.5 kPa) are equivalent to very good pneumatic system performance, and significant errors arise even here.

While the above analysis is useful to assess the order of magnitude and qualitative variation of measurement accuracy, it can be pessimistic because it is unlikely that the same degree of uncertainty would affect all three transducers at the same time. In order to gain further confidence in the yawmeter performance, the measurements were compared with those taken with two types of 3D pneumatic probe design at condition A at stator exit (plane Y). These data are presented in Part II and show that the yawmeter measurements compare very favourably with the pneumatic results.

Data capture and processing

All of the unsteady aerodynamic signals were amplified at the rig and transmitted over 20m cables to the facility control room. Here, the data were recorded on a high-speed digital data acquisition system that has been described in detail by Cherrett & Bryce. The data were sampled in two modes. That is, either as continuous records, or as multiple 'discontinuous' records captured in response to a once-per-revolution trigger signal. The latter were processed on-line to determine the following parameters.

a) Ensemble averaged signal:

\[ P(t) = \frac{1}{N} \sum_{n=1}^{N} P(n, t) \]

b) Average random unsteadiness:

\[ \overline{R(t)} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (P(n, t) - \overline{P(t)})^2} \]

Where: \( P(n, t) \) is an instantaneous AC coupled signal.

N is the number of consecutive rotor revolutions during which phase-locked data capture was carried out in response to a once-per-revolution pulse, normally 128.

\( t \) is the temporal duration of each of the segmented data records (typically 512 or 2048 samples depending on the recorder module capacity).

Processing data in this manner is a well established technique that accentuates the periodic unsteadiness correlated with the rotor. As the data are captured in response to a once-per-revolution signal, the rotor is in the same position each time the
recording cycle is initiated and differences in the flow field associated with individual rotor passages are retained.

The trigger pulse was generated by a small magnet located in one of the rotor blade tips passing underneath a shorted bar in the FM grid intended for blade vibration monitoring during the tests. Because of uncertainty concerning the circumferential position of the shorted bar, it was not possible to position the rotor blades relative to the stator blades on receipt of each trigger pulse. While this did not affect the integrity of the measurements, ie. the pulse was very sharp and repeatable, it would have been useful to know the actual rotor position relative to the stator frame of reference.

**ROTOR EXIT FLOW FIELD**

The rotor exit flow field is illustrated in this paper using:

1. steady-state stagnation pressure measurements taken with Pitots mounted proud of the leading edge of an otherwise standard stator;
2. time-varying stagnation pressure measurements derived from the yawmeter transducer. During the 17-point yawmeter traverses the probes were set at the mid-span design inlet flow angle. Additional measurements taken at six span-wise positions, showed that the characteristics of the dynamic pressure signals did not change significantly when the yawmeters were set at ±10°,±5° & 0° to the mid-span flow angle.

In order to gain confidence that the yawmeter results were not corrupted by the cut-back stator interference problem, the yawmeter data were compared with measurements taken by dynamic pressure transducers fitted to an otherwise standard single-blade stator cassettes. Although not shown in this paper, these data were in excellent agreement with the yawmeter Pitot transducer results.

**Time-averaged measurements**

Fig 5a compares the pneumatic leading-edge stagnation pressure measurements taken at condition A, with the corresponding time-averaged yawmeter measurements. The intended design pressure distribution is also shown. Fig 5b shows the time-averaged random unsteadiness measurements derived from the yawmeter. The pressure measurements have been expressed as a ratio of fan inlet stagnation pressure, while unsteadiness has been expressed as percentage of the local stagnation pressure level.

The pneumatic measurements and yawmeter data are in good agreement (a characteristic which was also seen in the condition B & C data). This gives further assurance that the yawmeter measurements were not adversely influenced by the probe-stator interference problems. Over much of the span the measurements are in good agreement with the design intent. However, toward the hub, between 0% and 30% span, it is evident that the stagnation pressure levels exceed those intended in the design. As Bryce et al (1993) explain, evidence from S1-S2 modelling of C148 indicates that this phenomenon is due primarily to low blade row performance, and arises from shortcomings in the deviation corrections employed when the rotor was designed in the early 1980's. In the tip region, at approximately 90% span, there is an additional increase in measured stagnation pressure which, although small, is clearly evident at all operating conditions. This is associated with the tip-leakage vortex flow.

Fig 5b shows that the span-wise distributions of time-averaged random unsteadiness increase toward the hub and casing, where the viscous end wall flow phenomena dominate. These are illustrated more fully in the following section.

**Unsteady flow field measurements**

As an illustration of the unsteady measurements taken at mid-span, Fig 6 shows the random unsteadiness and ensemble-averaged stagnation pressure variations while operating at condition A. At this condition and considering the random unsteadiness data first, the rotor wakes occupy approximately 30% of the rotor passing period and are the singularly most notable flow feature. Unsteadiness levels within the wakes are three-to-four times those found elsewhere within the rotor passage. However, weaker peaks in random unsteadiness level are seen to be centred at approximately mid-pitch.

The ensemble-averaged pressure measurements are considerably more complicated than the idealised view (often reinforced by low-speed compressor measurements) of wake perturbations punctuating an otherwise monotonic pressure variation from one side of the passage to the other. In the wake region, the stagnation pressure rises rapidly from a pressure trough on the suction surface side of the rotor wake, to reach a pressure peak on the suction surface side of the wake. The magnitude of this peak relative to the mean level is two-to-three times that of the pressure trough. The point in the wake region where the stagnation pressure increases above time-averaged value corresponds approximately to the position of maximum random unsteadiness.

The stagnation pressure field within the rotor passage (ie. between the rotor wakes) is very active. A second stagnation
pressure trough occurs on the suction surface side of the wake followed by a peak (to rival the strength of that attained within the suction surface side of the rotor wake) at approximately 40% rotor pitch. This is followed by a rapid fall in stagnation pressure to reach the minimum value at approximately 75% rotor pitch. The extent of the region bound by the mid-pitch excursion from pressure peak to trough corresponds approximately to the aforementioned region of increased intra-passage random unsteadiness. These data are discussed in more detail later, following a more complete presentation of the measurements at this, and the other, operating conditions. That is, rather than view the data as individual time-histories, they have been presented below to represent the complete rotor exit flow field.

Random unsteadiness. The random unsteadiness field at the three operating conditions is shown in Fig 7. The time dependant results are plotted in a form representing the 2D rotor-locked pressure field which sweeps past the 'radial' traverse line. The 'radial' traverse positions are shown as well as the loci of the rotor trailing edges. In order to position these loci circumferentially relative to the observed phenomena two assumptions were made at mid span. Firstly that the wake could be identified with peak unsteadiness in the measured data and secondly that the wake lay along an extension of the stagger line. The positions of the trailing edge loci relative to the wake at mid span were then estimated (as shown in Fig 1) by projecting the stagger line of the mid-span rotor sections to intersect the plane where the measurements were taken. This procedure was adopted because of the uncertainty in the circumferential position of the once-per-revolution trigger pulse that triggered the data acquisition system. The data are shown such that rotor is viewed from behind looking upstream while rotating clockwise, and the non-symmetrical shape of the annulus segments arises because the measurement stations were situated along a line approximating to the stator leading edge which is not a truly radial line. The data shown document the passing of three rotors, although the total available data set documented 22 of the 25 rotor blades. There were quantitative differences in the data from passage to passage of the rotor, although these were generally small and the different rotor flow fields were in excellent agreement. The data were sampled at 500 kHz which resulted in 90 samples across a rotor passage.

The random unsteadiness measurements give an immediate insight into the extent of the viscous flow field features where random unsteadiness levels are highest. However, caution must be exercised when interpreting the data as it must not be assumed a priori that the positions of peak levels of random unsteadiness correspond precisely to the centres of the viscous flow features they appear to indicate. That is, the highest levels of random pressure unsteadiness may occur in viscous shear layers bounding high-loss (viscous flow) regions and adjacent (inviscid) passage flow. In addition, the positioning of the sensors relative to the stator needs to be taken into account. Studies using unsteady
predictions have shown that pitch-wise positioning of a sensor can affect the measurements greatly, see Epstein et al (1989) for example. All of the unsteady measurements reported here were taken by sensors close to the stator leading edge, and consequently where potential interaction effects between the rotor and stator rows are likely to be strong (see later).

At the hub, there appear to be endwall corner stalls causing high levels of unsteadiness, the amplitude and size of which grow with increasing stage loading. The extent to which these structures lie close to the endwall and spread across the passage in the pitchwise direction is quite different to corresponding measurements taken by the authors in a multi-stage core compressor (see Cherrett & Bryce 1992). In the core compressor, the corner stalls tended to extend up the blades in a span-wise direction.

The rotor wakes show the expected broadening with increasing span. This is in part due to increased axial spacing between the probe and rotor trailing edge with increasing span. However, the greater shock strength toward the rotor tip, and the accompanying interaction with the blade surface boundary layer, would also be expected to result in broader wakes. It is interesting to note that between 20% and 35% span the wake unsteadiness levels increase above those found at span-wise positions immediately below and above. This is outboard of the region of excess rotor pressure rise, but it corresponds to the region where rotor relative inlet Mach numbers approach unity. The locally near sonic flow conditions, and the necessity for reasonably high degrees of turning, causes very high values of diffusion factor in this region. Consequently, the blade sections are more difficult to design, and the measurements illustrate how the design tools employed in the early 1980’s were unable to resolve these problems satisfactorily.

At the casing, the random unsteadiness distribution is characteristic of the tip-leakage vortices. Under-turning of the tip leakage, and that the measurements were taken some way downstream of the tip leakage, results in the vortices being positioned close to the pressure surfaces of the subsequent blade wakes. The unsteadiness regions associated with tip leakage flow become larger with increasing stage loading, although the amplitude of the unsteadiness does not increase accordingly. These observations are consistent with expected tip-leakage flow development, although the work that has studied leakage flows most thoroughly has been confined to low-speed flows, eg. Inoue & Kuroumaru (1989).

At all operating conditions the inviscid rotor passage flow regions are characterized by low unsteadiness levels, except near mid-pitch in the upper part of the annulus; where there is a ridge of increased unsteadiness that lies almost radially. The unsteadiness levels within this feature increase with increased stage loading. This important feature is discussed more fully later.

**Ensemble averaged pressures.** Attention is now turned to the ac-coupled ensemble averaged pressure measurements in Fig 8. The use of ac-coupling means that the significant radial profile seen in the time-averaged measurements is suppressed in Fig 8. During interpretation of these data it is particularly important to remember that they were taken in the stationary frame of reference. In the stationary frame it is possible for stagnation pressures to be higher on the suction, rather than the pressure, surface side of the passage, and for a wake (pressure deficit) in the relative frame to appear as a jet (pressure excess) in the stationary frame. As such the data are not easy to interpret because it is intuitive to think of the flow field in rotor relative frame. Because of the cut-back stator interference problem, it was not possible to transpose into the relative frame using the unsteady yaw angle information (accepting that unsteady 3D angle measurements may be necessary to avoid the risk of introducing significant errors).

In order to relate these data to the salient features identified in the random unsteadiness measurements, the rotor trailing loci have been superimposed. This shows that pressure levels are greater on the suction surface side of the rotor wakes than on the pressure surface side, and that very large pressure changes occur on either side of the wake between 20% and 30% span; where the rotor inlet Mach numbers approach unity. Otherwise, the data show little change in amplitude with increased compressor loading at the same speed. In this respect, and in their qualitative form, the data are very similar to the measurements reported in other high-speed compressors. The stagnation pressure oscillations mentioned
earlier are evident as the 'radial' regions of high pressure extending up the inviscid core flow. However, it is difficult to appreciate the full complexity of the intra-passage oscillations using the coarse contour plots in Fig 8.

**DISCUSSION**

An explanation is needed for two of the phenomena seen in these data. Firstly, the cause of the mid-pitch ridge of random unsteadiness needs to be identified. Secondly, the mechanism causing the high-frequency stagnation pressure oscillations needs to be discussed.

**Mid-pitch unsteadiness.** Fig 7 shows that this feature increases in strength with increasing span, and compressor aerodynamic loading. As such, it is thought to be related to the rotor shock system. The spatial position of the feature, relative to the blade wakes and the estimated trailing edge loci, indicates that it occurs during the part of the rotor passing period when the rotor trailing edge passes the stator leading edge region. With the small rotor/stator gap in C148 and the relatively severe gradients likely to occur in the stator flow-field near the leading edge, this is when strong potential flow interaction between the rows might be expected. The potential interaction between the blades will induce changes in rotor circulation and lift and perturb the rotor shock. The shock perturbation may in fact accentuate the potential interaction between the blade rows. Because of turbulence and effects such as vortex shedding, such events will not be precisely repeatable from one revolution to the next, giving rise to unsteadiness as observed.

If this hypothesis were true, it would be expected that the strength/occurrence of the ridge would depend upon the circumferential position of the sensor relative to the stator leading edge. The C148 rotor exit measurements were taken very close to this position, and it was not possible to take measurements at mid-pitch to see if the feature subsided. However, it is noteworthy that similar features were not seen in the random unsteadiness data reported by Cherrett & Bryce (1992), where the measurements were taken at mid-stator pitch. Similarly, Alday et al (1993) showed no evidence of mid-passage unsteadiness in their measurements taken behind a transonic civil fan rotor. However, in the former case strong shocks were not present and in the latter case the measurements were taken someway downstream of the rotor in the by-pass duct. It would be interesting to re-evaluate the Ng & Epstein (1985) and Gertz (1986) data to look for similar behaviour, as random unsteadiness data were not presented in these cited publications. Clearly it is difficult to confirm this hypothesis without corroborative data.

**Stagnation pressure oscillations.** Fig 6 shows that there is a spatial correlation between the mid-pitch pressure peaks and troughs in the ensemble-averaged data, and the random unsteadiness ridge. In this instance it is likely that the phenomenon discussed above is responsible for both features. However, at other span-wise positions and operating points, it is not easy to relate the stagnation pressure oscillations to the random unsteadiness data, and it is not so easy to explain the behaviour.

Epstein et al (1988) presented a hypothesis that suggested that the frequency of the oscillations was determined by vortex shedding in the rotor wakes. It was envisaged that the periodic changes in circulation which accompanied the shedding caused the rotor shock system to jitter, thus amplifying the perturbations and causing the substantial pressure oscillations in the flow field. While this is a plausible argument, the measurements taken at DRA suggest inconsistencies in the hypothesis. Firstly, the core compressor measurements reported by Cherrett & Bryce (1992) were qualitatively and quantitatively very similar to those measured in C148, and those reported by Ng & Epstein (1985) and Gertz (1986). However, the core compressor rotors were not transonic, and therefore devoid of strong shocks. Secondly, frequency domain analysis of continuously sampled data (i.e. not ensemble averaged) captured in the core compressor and C148 does not show any peaks at frequencies that cannot be attributed to the blade passing frequencies or their harmonics. If vortex shedding were responsible, the characteristic frequencies are likely to be determined by the displacement thickness of the rotor wake, and therefore not correlated directly to blade passing, unless there is a mechanism for locking them in. No such mechanism yet appears to have been clearly identified.

Clearly, the analysis of the rotor exit data presented in this paper is restricted by fact that the measurements were taken in only one meridional plane. In Part II of the paper, stator exit measurements taken on a 2D traverse grid are presented. Analysis of these data showed that it was difficult to understand individual pressure time-histories without making reference to the perturbations occurring elsewhere on the 2D traverse grid. It is recommended that a similar approach be adopted for dynamic rotor exit traverse measurements in future, and that much of the current difficulties in interpreting the rotor exit data could be alleviated if a more complete view of the complex flow field were available.

Finally, the salient features of the viscous flow field associated with the rotor are clearly evident in the random unsteadiness data, and this semi-quantitative information is of potential benefit to the development and validation of steady-state 3D viscous flow solvers. However, the fact that the measurements were taken in only one meridional plane may also be significant for these data. That is, as the measurements were taken close to the stator leading edge, the data were gathered when the potential interaction between the blade rows was likely to be strongest, and this may augment the rotor viscous flow field development locally. It is not clear whether this could explain the tendency for the rotor hub corner stall to spread circumferentially, rather than radially.

**CONCLUSIONS**

A dynamic yawmeter probe, capable of measuring fluctuating stagnation pressure, static pressure and yaw angle, has been used extensively in a transonic single stage fan. Using a method to compensate for semiconductor pressure transducer temperature sensitivity it was possible to obtain absolute pressure measurements from the sensors. However, the measurement accuracy was compromised by drift in the transducer characteristics with time and more work is required to ascertain...
the cause of these changes and to alleviate their magnitude. Even so, with careful and frequent transducer calibration, it was possible to obtain time-averaged yawmeter measurements that compared very favourably with 3D pneumatic probe measurements.

Interference between the yawmeter and the adjacent stator meant that only accurate stagnation pressure measurements could be obtained at rotor exit. These were processed to reveal the random unsteadiness and ensemble averaged unsteady pressure fields associated with the quasi-steady flow field locked to the rotor. This revealed the following.

1) Viscous blade-wake, over-tip leakage, and rotor-hub corner stalls were clearly identified in the random unsteadiness measurements. The changes in size and intensity of these features were commensurate with expected behaviour. However, the hub-corner stalls extended in a pitch-wise direction and lay close to the hub endwall, which is quite different to the behaviour seen elsewhere in low-speed and high-speed compressor rotors.

2) An almost radial ridge of increased random unsteadiness was seen at mid-pitch in the upper portion of the annulus. This feature became more pronounced with increased stage loading and it is suspected that it is a consequence of interaction of the rotor and stator flow fields influencing the rotor shock system. More work is required to investigate more fully the nature of this interaction.

3) The ensemble averaged pressure measurements showed that, away from the viscous endwall and wake flows, the rotor passage flow was characterized by stagnation pressure fluctuations at several times blade passing frequency. Similar measurements in other transonic fans have been attributed to rotor shock system unsteadiness. However, in part II of this paper it is shown that similar measurements at stator exit can be related to global changes in stator exit stagnation pressure during the rotor passing period.

4) It is suggested that radial traverses behind high-speed compressor rotors are unable to provide sufficient information to explain the rotor flow field fully. 2D area traverse are recommended in future.

A vast amount of unsteady aerodynamic measurements have been accumulated in some 350 hours of testing the C148 transonic fan. Some of the measurements taken at stator exit are reported in part II of this paper, while other measurements, including on-blade stator-surface pressure and thin-film gauge measurements will be reported in future.

ACKNOWLEDGEMENTS

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