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ACCURACY OF FAST-RESPONSE PROBES IN UNSTEADY TURBINE FLOWS

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ABSTRACT

Accurate measurement of flow conditions in high frequency oscillating flows is still an unresolved problem. This is because a probe placed in the unsteady flowfield represents a solid boundary and the surface pressure at each point on its surface therefore contains inertial terms. Calibrating probes in steady conditions is relatively easy but calibration in dynamic conditions is at present considered experimentally impossible due to an inability to determine the true instantaneous flow conditions.

Over recent years a variety of fast-response aerodynamic probes have been developed with the aim of measuring the unsteady flows that occur in turbomachines. These types of probes have mainly fallen into two groups, prismatic and cylindrical probes.

One method of determining the dynamic measurement error of various geometries is by low speed testing at low frequency in water (Humm et al. [1]). These experiments usually involve rotating the probe rather than the fluid. The results reported by Humm et al indicated that in turbine representative flows the dynamic measurement error can often exceed the amplitude of the unsteady quantity of interest (ie the pressure change across the blade trailing edge shock). It was also concluded that cylindrical probes have a much lower dynamic measurement error than prismatic probes.

Slow speed testing in water has two major problems. Firstly rotating the probe instead of the fluid requires a non-inertial change of reference frame, which alters the pressure field around the probe. Secondly the experiments do not simulate all the errors incurred by the probe in a real engine. These include steady error sources such as probe blockage and the effects of compressibility and unsteady error sources such as shock and wake interaction.

The aim of this paper is to gain an understanding of the size of the total measurement error incurred by prismatic probes mounted in turbomachines. To simulate the correct engine conditions testing was undertaken by placing two fast-response aerodynamic probes downstream of a cold flow transonic turbine stage. The size of the total measurement error was varied by changing both the angle at which the probe was mounted and the geometry of the probe. It should be noted that both steady and unsteady measurement errors are strong functions of both angle and geometry.

The measurements presented in this paper are insufficient to accurately determine the magnitude of the total measurement error. They do, however, allow the composition and order of magnitude of the total measurement error to be investigated in a true engine representative environment. No large dynamic measurement errors, such as those encountered by Humm et al., were found to occur in the range of flow conditions over which the probes were used. The results are used to show both the range of flow conditions over which prismatic probes can be used and the measurement accuracy that can be expected.

INTRODUCTION

The measurement of unsteady flows in turbines is extremely difficult. The blade passing frequencies are between 5kHz and 20kHz and to resolve the flowfield requires probes with a bandwidth of up to 100kHz. Probes are also subject to variations in angle and the impingement of shocks wakes from upstream blade rows.

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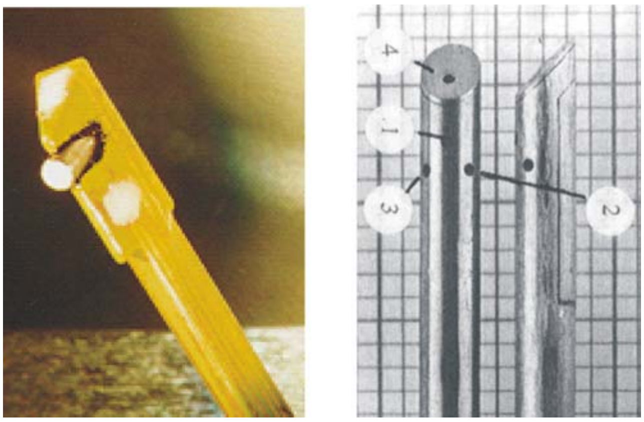

Fig. 1 Four sensor wedge probe and cylindrical probe

In the literature two types of fast-response aerodynamic probe have been reported. Prismatic probes (ie wedge and pyramid), with surface mounted pressure sensors (ie Ainsworth et al. [2]) and cylindrical probes, with the pressure sensors mounted in recessed pockets (ie Humm et al. [1]). A photograph showing an example of each type of probe is shown in Figure 1. It should be noted that the circumferential spacing of the sensors is similar in both designs, ~1.5mm for the wedge probe and ~1.8mm for the cylindrical probe.

Traditionally most probes used in the turbomachinery industry have been of a prismatic geometry. This has been due to their high sensitivity to changes in flow angle and their insensitivity to Reynolds number (Dominy and Hodson [3]). For unsteady flows, however, a number of research papers have concluded that, in unsteady flows, cylindrical geometries of probe incur a lower total measurement error (ie Humm et al. [1]).

The total measurement error incurred by aerodynamic probes in unsteady flows can be split into two groups: those that occur in steady flow fields (steady flow errors) and those that are the result off unsteadiness in the flow (dynamic errors). These two groups are summarized below:

<u>Steady flow errors</u>

1. **Velocity gradients**. If there is a velocity gradient parallel to the line between the yaw angle sensor the probe measures an apparent change in flow direction, Bryers and Pankhurst [4].
2. **Reynolds number effects**. The locations of boundary layer separation points move as the Reynolds number is changed. This influences the pressure field around the probe.
3. **Probe blockage**. Introduction of the probe into a turbomachine causes the effective flow area to be reduced. This raises the local flow velocity.

<u>Dynamic errors</u>

1. **Inertial effects.** The pressure field around the probe is altered by the inertia of the fluid in which it moves.
2. **Circulation induced lift.** When the probe is subjected to a time-varying angle of attack its circulation and thus lift is altered.
3. **Dynamic boundary layer effects.** In dynamic flow thin layers of reversed flow, on the probe surface, may exist without disturbing the outer flow. This may cause the location of the separation points to vary in time.
4. **Dynamic stall.** Dynamic stall is caused by a separated leading edge vortex propagating rearward, causing a transient pressure distribution.
5. **Shed vortices.** The shedding of vortices alters the unsteady pressure field around the probe causing measurement errors. When the frequency of the flow is close to the natural shedding frequency of the vortices the two can synchronise (coupling of shed vortices) amplifying the unsteady pressure fluctuations.

Extensive experimental measurements have been undertaken at ETH (Humm et al. [1]) to investigate the effects of unsteady flows on both prismatic and cylindrical probes. The model probes were tested at low frequency by dropping the speed of the flow. This allows the correct reduced frequency (fD/v) to be set. The Reynolds number was then set by testing in water. For convenience the probe was oscillated instead of the fluid. An example of the dynamic response of a 60 degree wedge under yaw angle oscillations of varying amplitude and a four sensor cylinder probe under pitch angle oscillations of varying amplitude are shown in Figures 2 and 3. The testing was carried out at a reduced frequency of 0.1. The results clearly show both probes diverging from there steady flow calibration and in the case of the wedge probe a large dynamic stall. The results indicate that when making measurement in unsteady flows dynamic measurement errors are often larger than the amplitude of the unsteady flow in which the measurements are being made.

The research undertaken in Humm et al. was undertaken with the probe rotating and the fluid stationary. In the real case the probe is stationary and the fluid is moving. Changing the

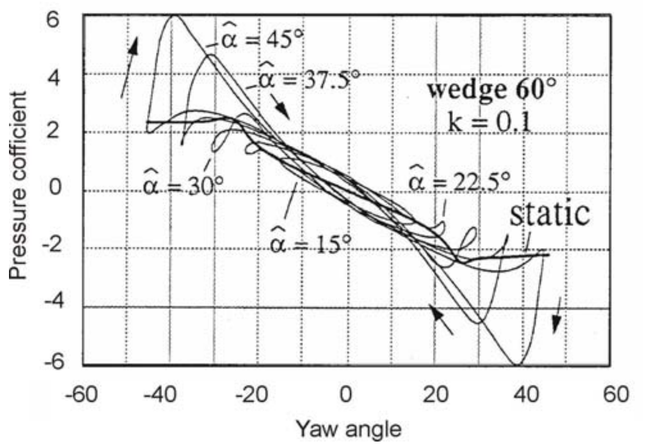

Fig 2. 60° wedge probe subject to yaw angle oscillations of varying amplitude

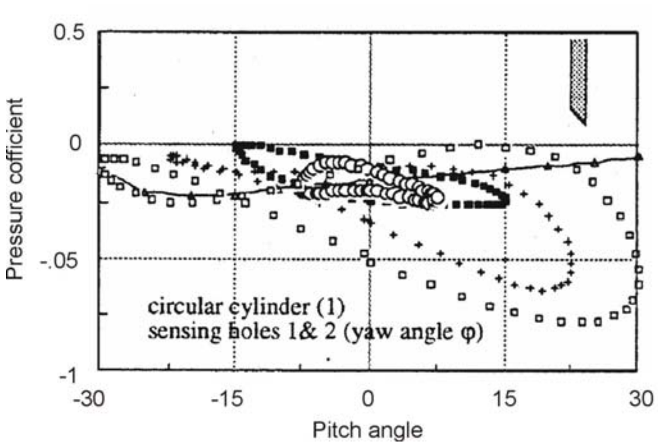

Fig. 3 Four sensor cylinder probe subject to pitch angle oscillations of varying amplitude

frame of reference from one fixed to the probe to one fixed to the fluid is not simple. This is because the frame of reference is moved from one that is stationary to one that is accelerating either linearly or rotationally with the probe. This causes a change in the pressure field experience by each sensor. In addition to this difference the real flow that is experienced in a transonic turbine stage is compressible and contains both wakes and shocks. It is thus likely that the dynamic errors predicted by water tank experiments are significantly different to those that occur in the real machine.

At present it is considered impossible to simulate a controlled reference environment, similar to the flow experienced in a turbomachine, in which to calibrate a probe. The aim of this paper is to investigate the measurement error of a probe by making measurements in a real transonic turbine stage. This is done by varying parameters that are known to have a strong effect on both the structure and strength of the measurement error.

NOMENCLATURE

D	Diameter
f	Frequency
p	Pressure
Θ	Angle around sphere
v	Velocity
ρ	Density

Subscripts

o	Stagnation value

2. METHODOLOGY

The aim of the experimental research described in this paper is to investigate the accuracy of fast-response aerodynamic probes in turbine flows. As has been discussed in the introduction, changing the frame of reference from a stationary to an accelerating frame in a fluid with temporal variations in velocity and angle changes the static pressure field experienced

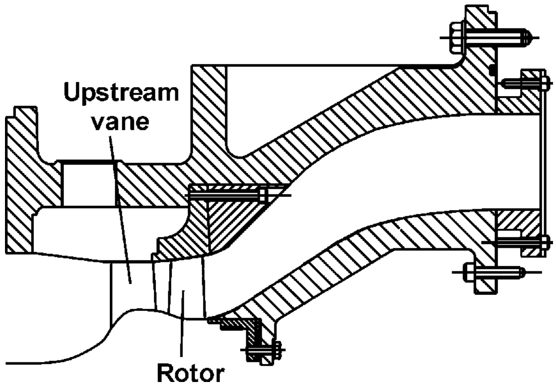

Fig.4 Working section

by the probe. It was thus decided that the experiments would be done with a stationary probe in an oscillating flow field. The problem with this is that generating a well described unsteady flow field in which to calibrate the dynamic performance of the probe is difficult. It was thus decided that testing would be carried out in an unknown unsteady flow field and that parameters that affected the magnitude of the dynamic measurement error would be varied.

As discussed in the previous section the dynamic errors incurred by an aerodynamic probe are all related, directly or indirectly, to the inertia of the fluid and the temporal velocity gradients of the flow. To understand how the pressure field around an object is alters in a time varying flow it is of use to examine the analytical solution for a sphere traveling with a time dependent velocity in a stationary incompressible irrotational fluid, Lamb [5].

$$\frac{p - p_0}{\rho} = \frac{1}{4}\left(-5 + 9\cos^2\vartheta\right)\frac{V^2}{2} + \frac{1}{2}a \times \cos\vartheta \times \frac{dV}{dt}$$

It should be noted however, that this is the case for the probe oscillating not the fluid. A non-inertial transformation is required to obtain a full understanding of the pressure field experience by a stationary probe in an oscillating flow. The first term in the solution gives the pressure field that would occur around a sphere in steady motion. The second term gives the change in the pressure field caused by temporal changes in the probe velocity. If a spherical shaped probe was used to make measurements in a fluid then the first term would represent the steady probe calibration and the second term the dynamic measurement error caused by the inertia of the fluid. The magnitude of the second term is altered by three parameters, the geometry of the probe, its angle relative to the flow and the temporal velocity gradient of the flow.

In the experiments described in this paper the flow in which the probe is placed is the exit flow from a transonic turbine stage. The flow is therefore not well described and the temporal velocity gradients of the fluid at each location relative to the upstream rotor are fixed but unknown. Systematically altering the dynamic measurement error incurred by the probe can only therefore be achieved by either altering the angle, relative to the probe, at which the flow is measured or by changing the geometry of the probe. The two experiments described in this paper involve varying each of these two parameters independently.

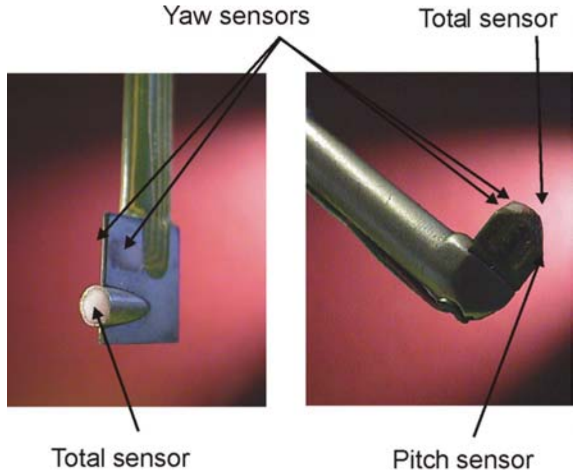

Fig. 5 Fast-response wedge and pyramid probe

Two experiments were undertaken. The first involved using a single geometry of probe mounted at a number of angles relative to the flow. The second involved the measurement of the same flow with two different geometries of probe. The measurements were both made with the probes mounted downstream of a transonic turbine stage. In addition to providing a flow with the correct temporal velocity and angle variations the flow also simulated the correct wake and shock interaction. The effect of wake and shock interaction on the accuracy of probe measurements does not appear in the literature. If the correct total measurement error is to be gauged then it was considered necessary to simulate both correctly.

A schematic of the working section of the facility in which the measurements were made is shown in Figure 4. The upstream row of vanes had 36 blades with an exit Mach number of 0.95 and an exit Reynolds number, based on axial chord, of 1.55×10^6. The rotor disc had 60 blades with an exit Mach number of 0.98 and the rotational speed of the rotor disc was 8910 rpm. The temperature ratio between the stage inlet gas and the blade surface was 1.4.

Two fast-response aerodynamic probes were used, a wedge probe and a pyramid probe (Figure 5). The first probe was a three sensor wedge probe. This probe was designed so the circumferential sensor spacing is small, giving the probe good spatial resolution. The wedge probe can measure yaw angle, Mach number and total pressure. The angle between the two sides of the wedge is 30° (probe half angle of 15°). It should be noted that a radius was manufactured on the probe leading edge to avoid flow separation. The wedge probe has a reduced frequency (fD/v), based on sensor spacing, of 0.1. The second probe was a four sensor pyramid probe. This probe had a larger circumferential spacing between the sensors than the wedge probe and thus has a worse spatial resolution. The pyramid probe can measure pitch angle, yaw angle, Mach number and total pressure. Both probes were calibrated in a steady flow calibration facility. The wedge probe was calibrated between yaw angles of ±24° and a Mach number of 0.2 to 0.7. The pyramid probe was calibrated between pitch angles of -24.8° to +32°, yaw angles of -28.8° to +28.8° and a Mach number 0f 0.1 to 0.9. The measurements made with each pressure sensor were compensated for variations in temperature. More information on the steady flow calibration and temperature compensation of probes can be found in Ainsworth et al. [2].

3.0 CHANGE IN PROBE ANGLE

The flow downstream of the turbine stage was measured with a fast-response probe set at a number of fixed angles relative to the flow. The experiment described in this section makes use of the strong variation of dynamic measurement error with probe relative flow angle. The sources of dynamic measurement error that are particularly sensitive to probe relative flow angle are the inertial effects, circulation induced lift, dynamic stall, and dynamic boundary layer effects. These effects are split into two groups. The inertia and circulation induced lift effects result in a measurement error that slowly changes as a component of the probe's angle to the flow. Dynamic stall and dynamic boundary layer effects exhibit a strongly non-linear behavior causing a sudden large rise in the measurement error. An example of dynamic stall at flow angles exceeding 20° is shown in Figure 2. It should be noted that the half angle of this probe is 30° and the half angle of the probe in the tests described in this section is 15°. By comparing measurements made at the exit of a transonic turbine with a probe mounted at a number of different angles it should therefore be possible to examine both the structure and size of the dynamic error.

The probe was mounted in a removable cassette mechanism 30% X/C_{ax} downstream of the rotor exit. The turbine was run six times with the probe set to six angles of yaw, -10°, -4.5°, 0°, +4° +8 °, and +12° with an accuracy of ±0.1°. The results were then blade to blade ensemble averaged over two rotor revolutions. In the limit of ensemble-averaging averaging infinite events the non-blade periodic component of the flow is completely removed from the measurements. Ensemble averaging over two rotor revolutions (120 rotor passing events) was found to reduce the uncertainty of the Mach number and the Yaw angle measurements to 0.005 and 0.65° respectively. The ensemble averaged yaw angle is shown in Figures 6. The yaw angles measured by the probe with its fixed probe angle removed and the Mach number are shown in Figure 7. The wedge probe's static calibration limits are ±24° in yaw and 0.2 to 0.7 in Mach number. Any flow conditions outside these

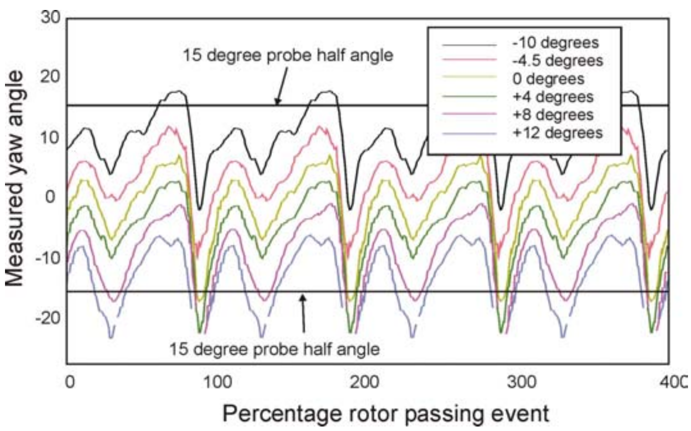

Fig. 6 Raw yaw angle measured at six set angles

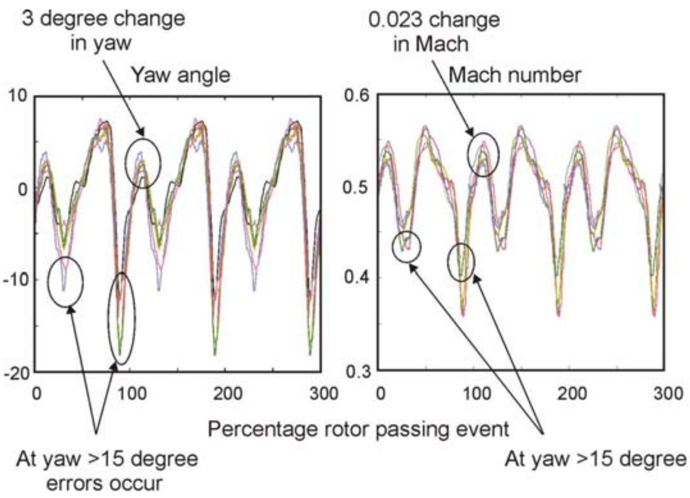

Fig. 7 Analyzed yaw angle and Mach number

limits result in measurements falling outside the probe calibration and thus gaps in the measured results.

As the set angle of the probe was altered the structure of the measured flow was found to show no sudden change in structure. The largest deviation in flow angle was found to occur at 30% and 90% rotor relative phase. At these locations a change of 6° was found in the flow angle. As is shown in Figure 14, these two regions of increased measurement error coincide with the flow angle exceeding the probe probe's half angle (15° for the wedge probe). At 30% rotor relative phase the measured flow was found to exceed the probe's half angle when the probe was set at fixed angles of 8° and 12°. At 90% rotor relative the measure flow angle was found to exceed the probe's half angle when the probe was set at fixed angles of 0°, 4°, 8° and 12°. At both locations the flow exceeding the probe's half angle was found to cause the measured angle to be overestimated. The effect of the flow angle exceeding the probe half angle on the measured Mach number can be seen in Figure 7. At 30% rotor relative phase the Mach number is underestimated and at 90% it is overestimated. The reason for this difference is at present not understood.

The overestimation of the measured flow angle, at flow angles above those of the half angle of the probe, allows for measurements below and above the probe half angle to be simply differentiated. This allows flow conditions at angles above the half angle of the probe to be rejected if higher measurement accuracy is required. If the probe was found to underestimate the angle of the flow then it would be impossible to distinguish between measurements in flows with angles below and above the half angle of the probe.

Below the half angle of the probe a small systematic change in the measured flow angle and Mach number is observed as the probe relative flow angle is changed. An example on this can be observed at 10% rotor relative phase. The measured yaw angle changes by 3° and the Mach number by 0.023 as the probe angle is changed from -10° to 12°.

The presence of severe dynamic effects such as dynamic stall or dynamic boundary layer effects would cause a large sudden rise in measurement error. This would be observed to occur at a particular flow angle relative to the probe. Humm et al. [1] found that wedge probes were particularly prone to dynamic stall. An example of dynamic stall for a wedge probe with a half angle of 30° is shown in Figure 2. It was concluded by Humm et al that for an oscillating wedge probe the flow measurements were affected by dynamic stall at angles significantly below the half angle of the probe. It is unlikely that dynamic boundary layer effects will have a significant effect on a prismatic probe. This is because the locations of the separation points are fixed at the corners of the probe. No sudden large rises in the probe measurement error similar to those shown in Figure 2 were observed. This indicates that neither dynamic stall nor dynamic boundary layer effects occurred around the probe. This is of interest because for the -10°,+8°and +12° tests the flow angle relative to the probe exceeded the probe half angle by up to 9°.

The largest measurements errors were found to occur at angles in excess of the probes steady flow stall angle. The cause of the small measurement errors that occurred over most of the rotor passing cycle is not at present understood. The systematic nature of this error is, however, consistent with an inertial effect. The results indicate that even though the flow exceeds the probe half angle, for part of each rotor passing event, when the measured flow angle is below the half angle of the probe the measurement error is in the order of 15% of the amplitude of the unsteadiness in the flow.

The amplitude of angle variation expected in the stationary frame of reference behind this rotor is ±9° at mid-height, ±25° close to the hub wall due both to overturning and vane-rotor hub interaction (Miller et al. [6]) and ±50° through the rotor tip leakage flow. A wedge probe at a fixed angle is therefore sufficient for making measurements in the mid-height exit flow of the rotor. Close to the hub wall multiple measurements with the probe set at a number of angles would be required to accurate measure the flow. It is thought likely that the angle variations in the rotor tip leakage flow are too large and the wedge probe is likely to incur large measurement errors.

4.0 CHANGE IN PROBE GEOMETRY

Two geometries of probe were used to measure the flow downstream of the turbine stage. The probes were mounted in a removable cassette mechanism 25% X/C_{ax} downstream of the rotor exit. The aim of the experiment was to determine whether two completely different geometries of probe measured the same flow conditions. The different size of the probes and the different orientation of the pressure sensor results in very different causes of both steady flow and dynamic measurement errors. A comparison of the two measurements is discussed.

Before examining the measurements in detail the structure of the flowfield in which the measurements were made must be discussed. The probes where mounted in the stationary frame of reference and so their structure is very different from that expected downstream of a cascade. A schematic showing the idealized structure of the rotor mid-height exit flow alongside a schlieren photograph of the same geometry of rotor blade (Mee. et al. [7]), is shown in Figure 8. The first schematic shows the total pressure in the rotor-relative frame. It is assumed that the idealized wake profile is Gaussian with a width and depth equal

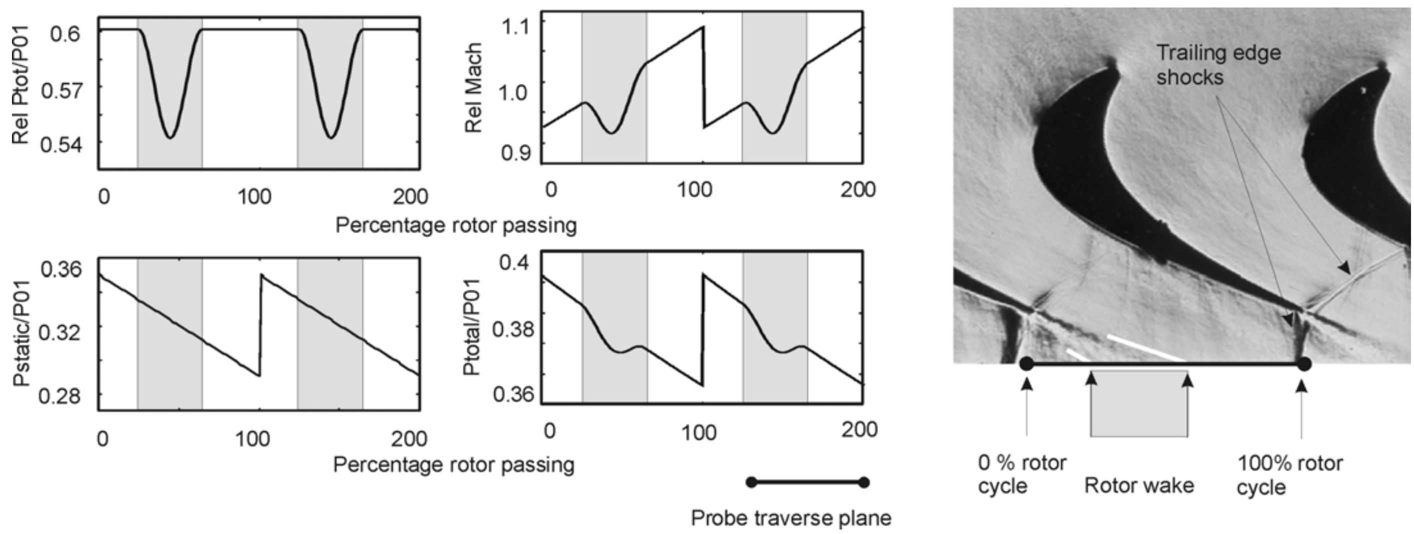

Fig. 8 Idealized structure of rotor exit flow

to that measured by Mee in his cascade experiments. Loss generation (entropy production) in the rotor wake corresponds to a drop in total pressure (irreversible adiabatic steady flow processes result in a drop in total pressure). In the rotor-relative frame the rotor trailing edge shock has no visible effect on the blade exit total pressure field (drop of only 0.01%). The second and third schematics in Figure 8 show the rotor-relative Mach number and static pressure at rotor exit.

Across the shock the static pressure rises and the Mach number drops. To determine the total pressure in the stationary frame both the static pressure and the Mach number in the stationary frame are required. The static pressure is unaffected by the frame in which it is observed and the static pressure rise across the shock is thus the same in both the stationary and relative frames of reference. In the rotor relative frame a drop in Mach number accompanies this rise in static pressure such that the total pressure only changes by 0.01%. In the stationary frame of reference the Mach number is lower than in the relative frame (Stationary 0.45, relative 0.98). The change in Mach number across the shock in the stationary frame is thus lower than in the rotor relative frame and results in a rise in total pressure in the stationary frame across the rotor trailing edge shock. The structure of the total pressure profile in the stationary frame showing the combined effect of both the rotor wake and shock is shown in the final schematic in Figure 8.

It must be noted when comparing the measurements made with the two probes that the differences can be caused by a number of effects other than inertia. Firstly the probes have different spatial resolutions due to the circumferential spacing of the sensors. Secondly the wedge probe is not calibrated for variations in pitch angle and therefore measurement errors occur in flows with a significant pitch angle.

A comparison between the experimentally measured flow field made with the two probes and the idealized flow conditions (total pressure and Mach number) are shown in Figure 9. The measurements made by each probe are dominated by the presence of the rotor shock and wake. Three main differences were observed between the two sets of measurements.

- The wedge probe measurements have a higher temporal resolution than the measurements made with the pyramid probe.
- The Mach number deficit associated with the wake measured by the wedge probe is deeper and sharper than that measured by the pyramid probe. The total pressure deficit associated with the wake is, however, similar for the two probes. It should also be noted that the phase of the total pressure wake deficits differs by approximately 5% of rotor phase.
- The change in Mach number across the shock measured by the pyramid probe is larger than that measured by the wedge probe.

The difference between the temporal resolution of the two probe is caused by the difference in the circumferential spacing of their sensors. The wedge probe has its sensors mounted in a smaller circumferential spacing than the pyramid probe. A circumferential difference in the location of the sensors corresponds to a time delay between the pressure measurements made by each sensor. This limits the frequency response of the probe. It should be noted that the frequency response of the measurement of a particular fluid quantity, such as pressure or Mach number, is dependant on the spacing of only those sensors that are particularly sensitive to that quantity. Total pressure measurements are a strong function of the measurement made by the front sensor and therefore both probes make total pressure measurement that are of a similar frequency response. Mach number measurements, however, are equally sensitive to measurements made by all the sensors on the probe and therefore the two probes make Mach number measurements of significantly different frequency responses.

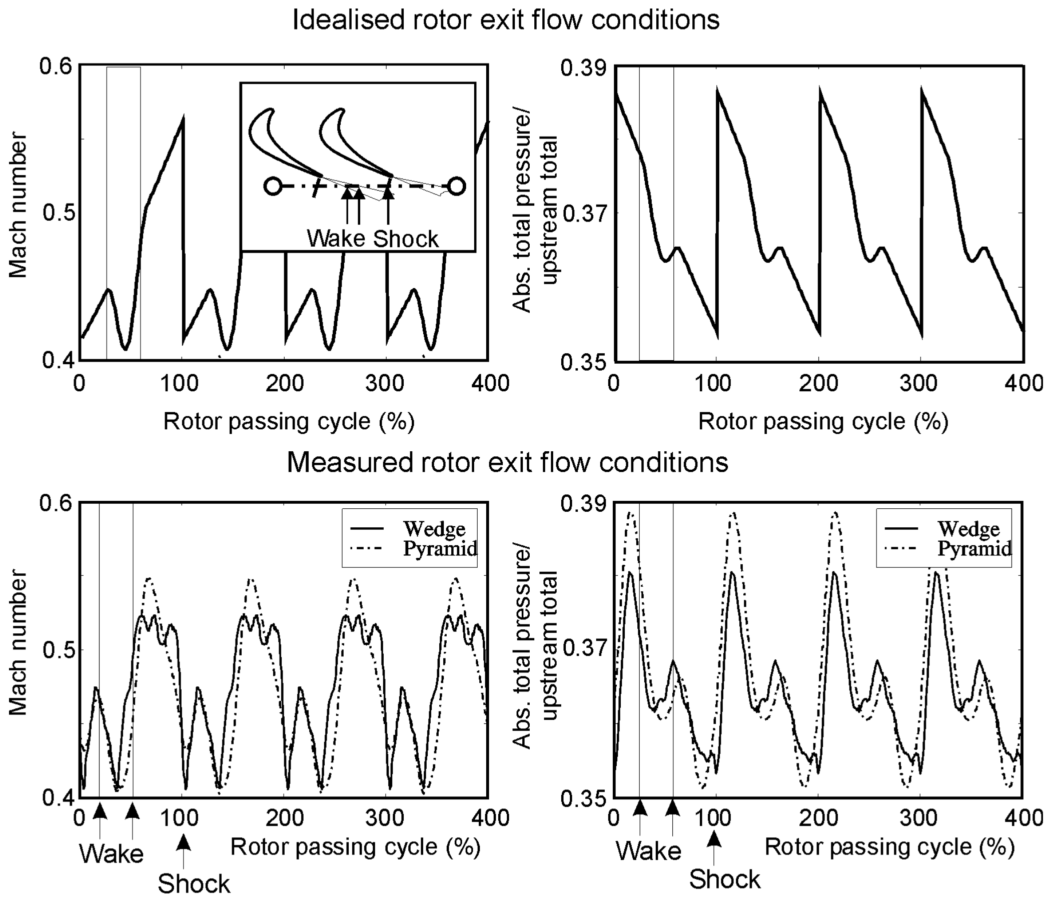

Fig. 10 Comparison of idealized and measured rotor exit flow condition

The difference between wake measurements made with each probe is complex to understand. The difference in the Mach number deficit in the wake could be caused either by the lower frequency response of the pyramid probe or by a radial migration in the wake causing the flow to have a significant pitch angle and thus causing an error in the wedge probe measurements. The difference in the phase of the total pressure deficits measurements in the wake region is caused by a difference in the axial location of the two probes. The pyramid probe was located 0.5mm (2.5% X/Cax) downstream of the location of the wedge probe. As can be seen in Figure 7 the relative rotor phase at which the wake is measured is heavily dependent on the axial location of the measurements. Assuming the flow direction in the relative frame is the same as the blade exit metal angle, a 0.5mm axial movement in the probe, causes the rotor wake to move circumferentially by 5.4% of a rotor passing cycle.

The difference between the strength of the trailing edge shock measured by both probes can't at present be explained. The frequency response of the total pressure measurements made by each probe should be similar and thus the same total pressure change across the shock would have been expected.

A comparison of the measurements made by the two geometries of probe indicates that the flow fields measured by each probe are dominated by the presence of the rotor shock and wake. Significant differences in the measurements made by each probe were observed. A number of these differences can be explained by differences in the probe mounting and frequency response but a number cannot. No evidence was found for the large inertial measurement errors indicated in the Humm et al. [1].

6. CONCLUSIONS

This paper described two tests designed to investigate the composition and magnitude of the measurement error incurred by prismatic fast response probes used in transonic turbines. The experiments invested the effects of both probe mounting angle and probe geometry.

From the first experiment a number of conclusions can be drawn. At flow angles below the half angle of the probe the deviation in the measured yaw angle was 3° and the deviation of Mach number was 0.023. This indicates that the measurement error is of the order of 15% of the amplitude of the deterministic unsteadiness in the flow. The results indicate that no dynamic stall occurred even though flow angles exceeded the half angle of the wedge probe by 9°. The results indicate the wedge probe, set at one fixed angle, can be used to measure the mid-height exit conditions of a transonic turbine. Close to the hub wall a number of measurements with a probe set at a number of fixed angles are required. It is thought likely that the angle deviation through the rotor tip-leakage vortex is too great to allow accurate measurement with this design of fast-response probe.

From the second experiment it is more difficult to interpret the source of measurement errors. The mean values and the unsteady structure of the measurements made by each probe are in good agreement, but a significant measurement discrepancy is observed. It is difficult to determine the cause of the discrepancy in measurements made by the two probes. The difference could be caused by a number of factors, such as a small difference in the location of the head of the probe, the effect of the inertia of the fluid, the difference in their spatial resolution or the inaccuracy of the wedge probes in regions were the flow has a significant angle of pitch. The two probes have very different geometries, sensor locations and stem design. This test is therefore a good guide to the absolute accuracy with which a fast-response prismatic probe can used in a transonic turbine.

No evidence for the large measurement errors indicated by the model testing in water, described in Humm et al. [1], was found. In both experiments the change in the measured flow conditions caused by the total measurement error was found to be much smaller than that of the measured flow phenomena, such as shocks and wakes. The results indicate that the type of probe used in these tests can be usefully used by turbine experimentalist to measure the time-resolved flow within turbomachines. As has been discussed the causes of measurement error when fast-response probe's are used in unsteady flows are numerous and difficult to quantify. The only certain method by which the total measurement error is likely to be significantly reduced is by a reduction in probe size.

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