Fast-Response Aerodynamic Probes
Paper 10

AN ULTRA-HIGH SPEED TRAVERSE SYSTEM FOR FAST RESPONSE AERODYNAMIC MEASUREMENTS IN TRANSIENT FLOW FACILITIES

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Abstract

This paper discusses the problems of obtaining time-resolved area aerodynamic surveys in transient flow facilities. It describes the design, construction and testing of a rapid traverse mechanism for the purpose of making unsteady aerodynamic measurements along circumferential arcs in the Oxford Rotor Facility. A compilation of these measurements over several tunnel runs at different radial heights allows an unsteady area contour to be constructed. The advantages of this novel design of traverse are its high speed compared with existing techniques, its controlled acceleration and deceleration providing protection for instrumentation, its precise initiation of movement, and its small size, with consequently limited 'filling-time' effects where run-times are small.

The development of this rapid traverse mechanism has allowed high bandwidth area aerodynamic traversing to be completed in a transient flow facility for the first time, allowing full time-resolved area surveys, which would have taken over four hundred tunnel runs with a fixed position probe, to be completed in ten facility operations.

Nomenclature

D_{nk}	Fourier Coefficients
L	Blade Pitch
m	Mass
M	Mach Number
N	Speed
P	Pressure
t	Time
T	Rotor Passing Period
T	Temperature
x	Displacement
V	Velocity

Subscripts

1	NGV Inlet
2	Rotor Inlet
3	Rotor Exit
n	Nozzle Guide Vane
r	Rotor
p	Probe
^	Unit Vector

Introduction

In recent years, aircraft gas turbine engine designers have become increasingly interested in unsteady effects on turbine blade performance. Numerous studies have been published indicating that unsteady flow phenomena in turbine stages have significant effects on blade performance. As a result a significant level of research activity has recently been directed towards the development of unsteady three-dimensional viscous Computational Fluid Dynamics (CFD) codes. Many experimental programmes are underway to provide data for validation purposes or to aid interpretation of the complex three-dimensional unsteady flow phenomena involved. Much of this experimental work has been carried out in short duration facilities as these enable engine conditions to be correctly modelled at a fraction of the cost of continuous facilities, (Dunn et al (1988), Esptein et al (1984), Ainsworth et al (1988)). A comprehensive review of the role of short duration facilities in gas turbine research is given in Schultz et al. (1987) and in Jones et al. (1993). One type of transient facility is the Isentropic Light piston Tunnel (ILPT) which was devised at Oxford University specifically for turbine testing (Jones et al. 1973). Facilities to test a full turbine stage have been built at Oxford University (Ainsworth et al.,1988), at the Von Karman Institute, Brussels, and at DRA Pyestock (Hilditch et al.,1994). The advantage of these facilities is that the results from them show excellent agreement with continuous cascades while total power demands are substantially reduced, lowering significantly the time and cost involved for aerodynamic studies at engine representative operating conditions.

The development of reliable two and three dimensional fast response aerodynamic probes in recent years has enabled unsteady aerodynamic measurements to be made in short duration facilities, when traditionally they have only been possible with hot wire and optical techniques (Ainsworth et al (1990)). These fast response aerodynamic probes have been used to make measurements of Mach number and flow angle at fixed positions downstream of the HP turbine in the Oxford rotor facility and have shown good agreement with 2D unsteady CFD solutions (Ainsworth et al. (1994)).

However, in order to aid understanding of the complex unsteady blade row interaction phenomena, and to validate new three dimensional unsteady viscous CFD codes, time-resolved area surveys of the aerodynamic flow-field are required. Such measurements have hitherto proved impossible due to the short run time characteristic of these facilities and their transient nature. The intention of this paper is to discuss the problems of obtaining time-resolved area surveys in transient flow facilities, and to describe the design, construction and testing of an ultra-high speed traverse system for this purpose, thus allowing time-resolved area surveys to be made using a 2D fast response aerodynamic wedge probe downstream of the HP rotor exit.

Oxford Rotor Project

The Oxford Rotor Facility consists of a single stage 0.5m diameter shroudless turbine mounted as the working section of the ILPT. The high pressure turbine stage consists of 36 nozzle guide vanes (NGVs) and a turbine blade ring containing 60 rotor blades. A schematic of the facility is shown in Figure 1.

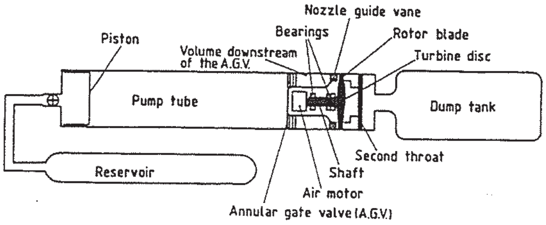


Figure 1 Oxford Rotor Facility

The ILPT is consists of a long tube containing a light piston which is driven forward by high pressure air. The tube is separated from the working section by a fast acting Annular Gate Valve (AGV), and the air ahead of the piston is isentropically compressed. At a pre-set compression ratio the AGV is explosively opened, allowing test gas to flow through the working section. Before firing the ILPT the working section is evacuated to a pressure of about 20kpa and the turbine spun up to a speed of 7500 RPM using an airmotor. The flow is transient in nature, and the turbine accelerates unbraked through the design speed of 8910 RPM to 10000 RPM in the 200ms of ILPT run time. A turbine speed versus time plot for a typical run is given in Figure 2. At the turbine design speed the facility simulates engine representative Mach and Reynolds number, as well as the relevant rotational non-dimensional groups. Details of the tunnel's operating point are shown in Table 1. As the turbine accelerates the rotor exit flow angle decreases. The Oxford Rotor Facility is considered to be sufficiently close to the simulation of the design conditions (shown in table1) when the rotor exit flow angle is within ±1 degree of the design rotor exit flow angle. This change in flow angle corresponds to a change in rotor speed of 220 RPM. The time taken for the turbine to accelerate through 220 RPM is 15ms, and the rotor is said to be on design condition for this period of time.

Tunnel monitoring consists of both fast and slow data acquisition. Throughout the 200ms run time both turbine speed and quasi-steady pressures and temperatures are sampled at 10kHz on 64 channels simultaneously. This data is used during subsequent analysis to determine the time at which the design condition was achieved. The output from fast response instrumentation such as aerodynamic probes is measured, using a 64 channel simultaneously sampled data acquisition system. This data acquisition system allows the sample rate of each channel to be raised from 10kHz to 500kHz over the 15ms period the facility is on operating condition.

Table 1

Mass Flow Number $\frac{\dot{m}\sqrt{T_0}}{P_0}$	7.04e-4
Specific Speed $\frac{N}{\sqrt{T_0}}$	435.88
Stage Pressure Ratio $\frac{P_{01}}{P_3}$	3.075
NGV Exit Reynolds Number	2.7e6
Rotor Exit Flow Angle	-23.7°
NGV Exit Mach Number	0.935
Upstream Total Temperature	374.4 K
Upstream Total Pressure	8.04bar

Fast Response Aerodynamic Instrumentation

The use of aerodynamic probes for measurements of Mach number and flow direction within transient rotating turbine simulation facilities is proving to be a powerful and robust technique. Recent work at Oxford has concentrated on the design and construction of fast response aerodynamic probes where semiconductor sensors are directly mounted on the surface of the probe. A photograph showing the four fast response aerodynamic probes used in the present traverse programme of testing is shown in figure 3. Before a fast response aerodynamic probe can be used to make measurements in the Oxford Rotor Facility a series of calibrations must take place (Ainsworth et al. (1994)).

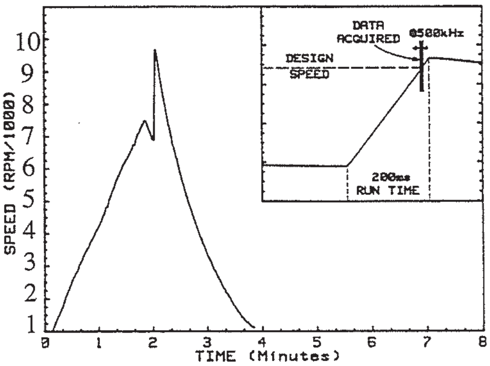


Figure 2 Operation of the Oxford Rotor

Each semiconductor sensor is electrically calibrated to establish pressure sensitivity, temperature sensitivity, and temporal stability. Compensation techniques for these effects can then be applied using software. A dedicated aerodynamic probe calibration facility is then used to calibrate the fast response aerodynamic probe. In this facility the probe is placed in a free jet and the incidence angle of the probe and flow Mach number are systematically varied to generate an aerodynamic calibration grid.

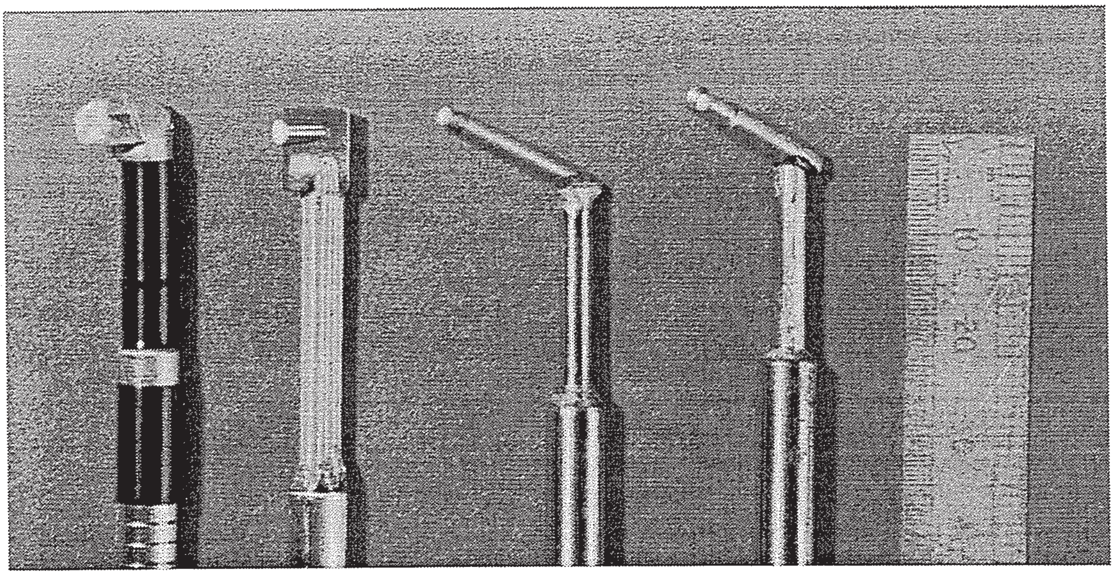


Figure 3 Fast Response Instrumentation(left to right: pyramid, wedge, total, bell-mouth total)

Extensive testing using a variety of 2D and 3D fast response aerodynamic probes have been made at fixed positions downstream of the rotor exit in the Oxford Rotor Facility.

Measurements made using a fast response aerodynamic wedge probe of 30 degree included angle, were made downstream of the rotor exit by Ainsworth et al. (1994). This probe had a pitot-type extension, a radiused leading edge, and yaw sensors mounted as close to the leading edge of the wedge as possible. The wedge probe was inclined at the mean flow angle to the axial direction at a fixed position downstream of the HP turbine in the facility.

The unsteady measurements of Mach number and yaw angle showed good agreement with 2D unsteady CFD predictions. It was thus decided that initial traverse testing would be made using a fast response aerodynamic wedge probe of identical geometry. Traverse measurements done using this probe will be presented in this paper.

The present programme of testing also includes measurements made with 1D and 3D fast response aerodynamic probes traversed downstream of the rotor exit. The purpose of using all three probes is that each probe has its own advantages and a comparison of all three will give the fullest picture of the unsteady rotor exit flow. The two main benefits of the 1D pitot probe are its small size (which enabled traverse measurements to be taken much closer to the wall) and its relatively long neck, which minimises stem blockage effects. Measurements made with the 1D fast response pitot probe should therefore help significantly in understanding the flow phenomena in regions close to the hub and tip. As outlined above the benefit of the 2D wedge probe is that it has been used to make extensive measurements downstream of the rotor exit and has showed good agreement with 2D unsteady CFD. The main benefit of the 3D pyramid fast response aerodynamic probe is that it allows the highly 3D unsteady structure of the rotor exit flow to be measured.

Aim Of Research

In order to obtain a time-resolved area survey of the rotor exit flow on a specified plane, a time history of the flow conditions at each point on that plane needs to be measured. To give an indication of the repeatability of the rotor exit flow conditions in subsequent Nozzle Guide Vane (NGV) passages, it was decided that measurements should be taken over a circumferential distance of 2.5 NGV pitches. Making measurements over such a circumferential distance means that, at any given moment in time, it is necessary to describe the aerodynamic flow field over 4.1 rotor exit passages (shown in figure 4). It was considered that for a rotor exit area survey to have reasonable resolution, a grid of at least 10 by 10 measurement points over each rotor exit passage would be required. To obtain a time history of each point over a circumferential distance of 4.1 rotor pitches with a conventional fixed probe would therefore necessitate in excess of 400 facility runs.

During the 15ms period of time the facility is on operating condition the rotor disc describes 2.5 revolutions and a fixed probe mounted downstream of the rotor exit measures 150 rotor passing events.

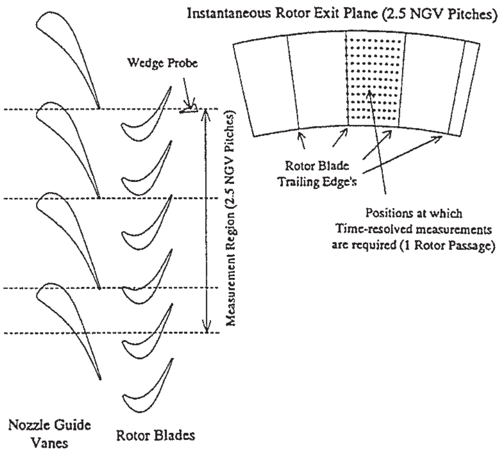


Figure 4 Measurement Requirements

The design of a rapid traverse mechanism would allow each rotor passing event to be measured at a different position relative to the upstream NGVs. Considering one radial height, this device would allow the time history of the rotor exit flow to be determined at 150 points along a circumferential arc. Then over ten runs, the radial position of the probe would be adjusted from tip to root.

Design Requirements

Traverse speed

As mentioned above, the rotor accelerates un-braked throughout the run-time of the facility, causing the flow angle at rotor exit to change continuously during the run. The rotor exit flow is also affected by pressure oscillations caused by the finite mass of the piston and driving gas in the ILPT (Schultz et al. 1977). The frequency components of the unfiltered signal clearly show that the variations in the operating point of the facility occur entirely at frequencies below 20Hz.

When considering the speed at which traversing ought to occur in transient flow facilities, it is important to consider the unsteady periodic nature of the flow field, both in time and space, in which the measurements are being taken. The flow field, measured by a fast response aerodynamic probe traversed at rotor exit, varies periodically both with the rotor passing frequency relative to the probe and with the nozzle guide vane passing frequency of the probe. To allow the effects of variation in the facility's operating point to be cleanly removed from any traverse measurements without its complex unsteady structure being affected, it is important that the measured frequency components of the unsteady flow field are significantly above 20Hz (the maximum frequency component of operating point variations).

Any flow parameter at rotor exit, measured at a fixed radial height, can, ignoring random unsteadiness and the variation in signature between the rotor passages, be described using a two dimensional Fourier series.

$$F1(x,t)=\sum_{n=-\infty}^{\infty}\left(\sum_{k=-\infty}^{\infty} D_{nk}\, e^{j2\Pi k\frac{x}{L_n}}\right) e^{j2\Pi n\left(\frac{t}{T}+\frac{x}{L_r}\right)}$$

The signal measured by a fast response aerodynamic probe, traversed at constant velocity V at a fixed radial height downstream of the rotor, can therefore be described by the one dimensional Fourier series

$$F2(t)=\sum_{n=-\infty}^{\infty}\sum_{k=-\infty}^{\infty} D_{nk}\, e^{j2\Pi\left(k\frac{V}{L_n}+n\frac{V}{L_r}+\frac{1}{T}\right)t}$$

This clearly shows that the two fundamental frequency components of any traverse measurements taken at rotor exit are the probe nozzle guide vane passing frequency (V/L_n), and the probe relative rotor passing frequency $(1/T-V/L_r)$. The frequency components of a constant velocity traverse are shown in figure 5. To recreate *F1(t,x)* from the traverse signal *F2(t)* with a high degree of spatial resolution requires that

$$\frac{2K_{\max}V}{L_n} << \left(\frac{1}{T}-\frac{V}{L_r}\right)$$

where $K_{\max}$ is the highest harmonic of the probe nozzle guide vane passing frequency to have a spectral coefficient greater than that of background noise. The value of $K_{\max}$ will depend on the spectral coefficients of the nozzle guide vane exit flow and the transfer function of the rotor. However, traversing in the Oxford rotor has shown that the rotor acts as a low-pass filter removing all but the fundamental frequency component of the nozzle guide vane exit flow ($K_{\max}=1$). The Fourier coefficients of the mid height rotor exit flow are shown in figure 6.

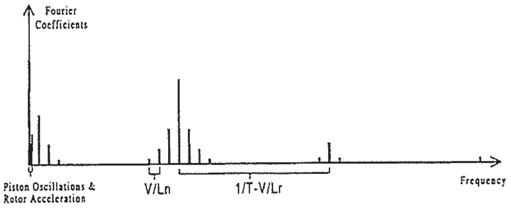


Figure 5 Frequency components of a constant velocity traverse

The chief criterion when designing a traverse for time-resolved area surveying downstream of a rotor in transient flow facilities is that the speed of the traverse must be chosen such that the nozzle guide vane passing frequency of the traverse probe is an order of magnitude greater that the maximum frequency component of variation in the operating point of the facility. However, further increasing the traverse speed above this would not improve the quality of the measurements, since to do so might reduce the spatial resolution of the time-resolved area survey.

As outlined above, the variations in operating point of the Oxford Rotor facility have a maximum frequency component of 20Hz. The nozzle guide vane passing frequency of the traverse probe was therefore set at 200Hz. Since the mid-height nozzle guide pitch of the Oxford Rotor Facility is 46mm, this resulted in a traverse design speed of $10\,ms^{-1}$.

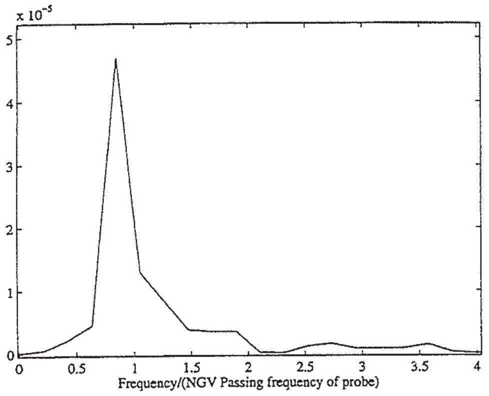


Figure 6 Fast Fourier Transform of traverse data

Mechanical design requirements

Any mechanism designed to traverse a probe in the said facility is restricted by the following requirements:

- The mechanism must fit into the existing cassette system which allows a 40 degree sector of the rotor exit annulus to be removed.
- The mechanism must traverse the probe across more than two NGV pitches within the 15ms period the facility is on design condition
- The traverse's acceleration and deceleration must be minimised to avoid damaging the Kulite semiconductor pressure transducers on the fast response aerodynamic probes .
- The mechanism must trigger with an accuracy of within ±1ms so that the entire traverse length is completed within the 15ms period of time the facility is on design condition.
- The pressure cavity attached to the main annulus in which the traverse mechanism is fixed must be sufficiently small to allow it to fill well in advance of the facility reaching its operating condition. This is to avoid any inflow or outflow from the specified cavity.

The $10\,ms^{-1}$ design speed will easily allow the traverse to cross the required 2.5 NGV pitches during the 15ms period of time the facility is on operating condition. The acceleration of the probe to this design speed in the existing cassette arrangement requires the traverse to have an acceleration of $2200\,ms^{-2}$ for 5.7ms.

Design of Traverse Power Supply

The following were considered as actuating mechanisms :

- **High speed pneumatic cylinders**

To obtain the required acceleration would mean using extremely large cylinders. Experimental testing of the triggering accuracy of such large pneumatic cylinders showed that they cannot produce the required triggering accuracy. This was mainly due to the compressibility of the working fluid and the switching time of valves. The piston seals in high speed low friction cylinders are rated up to a piston velocity of $1\,ms^{-1}$. The $10\,ms^{-1}$ design speed of the traverse would thus be impossible.

- **Linear Motors**

Commercially available linear motors will reach the required speeds and can be triggered with extreme accuracy. However, to obtain high levels of acceleration, an extremely large motor with high power consumption would be required. The consequence of this would be that any suitable linear motor would have to be controlled by a high current thyristor switched power supply, which would in turn result in high noise levels in the facility instrumentation.

- **Hydraulics**

A consequence of the incompressibility of the working fluids used in hydraulic cylinders is that energy cannot be stored in the fluid itself and the power source would still require a high power energy storage device to operate the cylinder.

- **Springs**

With a sufficiently high stiffness constant, a spring can easily develop the speed and acceleration levels required by the traverse. However, it was not at first apparent whether a spring could be triggered with the required degree of accuracy.

Having considered the above power sources, it was decided to use a high stiffness compression spring. Having chosen an amplitude of oscillation and a peak velocity, a second order differential equation showed that a spring with a stiffness of 5.2KN/mm was required. By fixing one end of the compressed spring so that it could operate in tension as well as compression, the spring could also be used to decelerate the traverse thus minimising the maximum acceleration applied to the probe. A displacement time history of the spring used in the traverse is shown in figure 7.

The design requirements of the triggering system are that the delay between a trigger pulse being applied to the trigger mechanism and the traverse starting to move must be less than 120ms, and that the triggering time is repeatable to within 1ms. This is because the Oxford Rotor Facility takes ~120ms to reach its operating speed after being fired. Since even high power solenoids. will not produce levels of force comparable with those stored in this strength of spring, and explosive based firing systems are expensive to run, a trigger mechanism which is initiated by a solenoid, but which uses the force stored in the spring, is preferred. The mechanism chosen is shown in figure 8. The solenoid pushes the central joint of the trigger arm past dead centre and the force of the spring is then used to open the trigger. Testing of the trigger accuracy showed that the mean triggering delay was 37.5ms with a trigger accuracy within ±1ms.

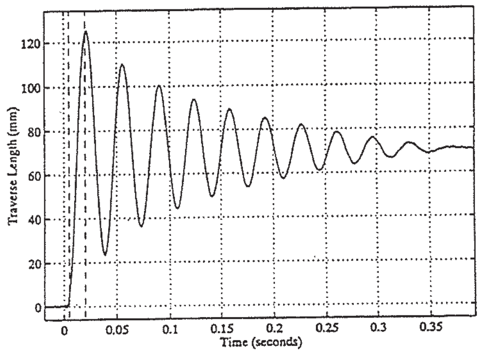


Figure 7 Displacement time history of Traverse

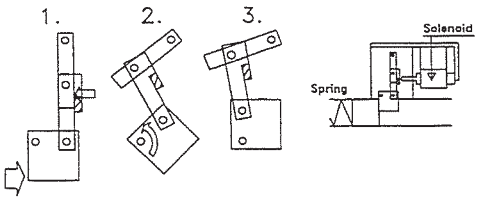


Figure 8 Traverse triggering system

Design of Traverse Mechanism

The linear motion of the traverse gun must be converted into the circumferential motion of the probe in the annulus. The chief criteria for the design of this mechanism are that it has an extremely low weight, since a heavy mechanism would lower traverse probe acceleration, and that it is mounted in a pressure cavity of low volume. The final design of this mechanism can be seen in Figure 10. With the objective of reducing the volume of the pressure cavity, it was decided that the power source should be mounted outside the sealed pressure cavity. The force could then be transmitted to the traverse mechanism by means of a silver steel rod running through the pressure cavity, sealed by PTFE O-rings. It was found that the roller bearing assembly used on many existing traverse mechanisms to move the traverse probe circumferentially would be too large and heavy. The solution to this limitation was to use a CNC-cut square section circumferential rail. The probe was mounted on a plain bearing lined with ®Turcite, a bronze loaded PTFE type material which has very low levels of friction and good wearing properties under heavy loading.

Traverse Triggering

The facility produces an almost constant torque and so the rotor discs acceleration is constant throughout the run time. This allows the time at which the tunnel will reach operating speed to be predicted with great accuracy. The repeatable nature of the traverse gun's triggering system allows a new lower trigger speed to be predicted. The new trigger sequence is shown in figure 9. The fast data acquisition system is triggered by a delayed pulse such that the sample rate is raised to 500kHz for the period of the first oscillation of the traverse gun.

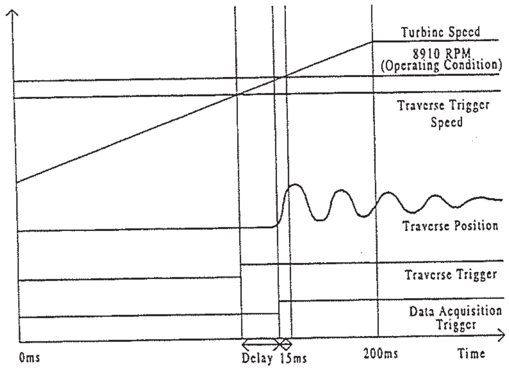


Figure 9 Triggering sequence of traverse

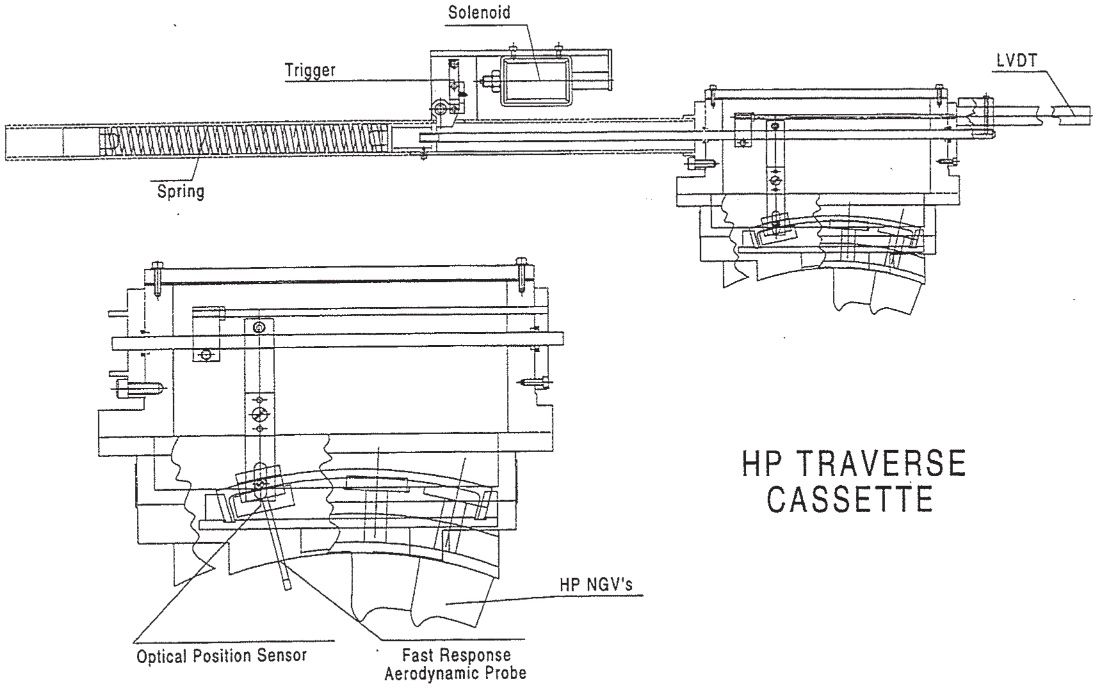


Figure 10 HP Traverse Cassette

Optical Position Sensor

During the 15ms of traverse time, a fast response probe, mounted in the traverse mechanism, measures 150 rotor passing events in the probe-relative frame. The phase of each of these in the absolute frame must be preserved and thus the position and the velocity of the probe tip must be known precisely. During testing of the traverse, it was found that the measurements of the probe position made by the Linear Variable Displacement Transducer lagged behind the probe's actual position, even though the levels of acceleration and velocity produced by the traverse were within the manufacturer's limits. Several optical devices were tried but finally it was found that to measure the probe's position with sufficient accuracy an optical sensor had to be mounted on the probe mounting block, a photograph of which is shown in figure 11. The miniature optical sensor consists of an infrared emitting LED and a phototransistor. The phototransistor responds to radiation from the diode reflected off a CNC-machined circumferential rail mounted in the traverse cassette. This optical device allows the probe's position to be measured to an accuracy of less than 0.05% of a NGV pitch.

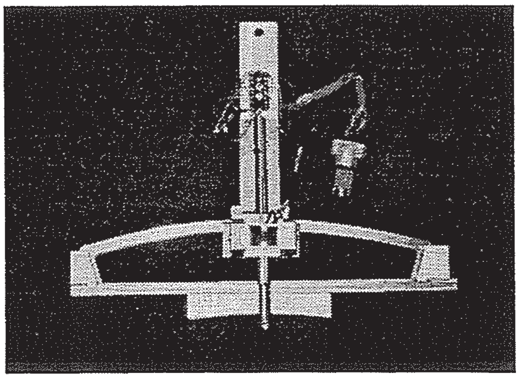


Figure 11 Fast response pyramid probe mounted on the circumferential rail.

Traverse Analysis

Overview

The data analysis techniques outlined in the following section have been developed so that time-resolved rotor exit surveys can be obtained from raw data produced by probes mounted in the rapid traverse mechanism. The initial development of this software has been completed using a wedge probe traversed 4mm downstream of the rotor trailing-edge. An example of the raw data measured by one of the sensors mounted on a fast response pressure probe is shown in figure 12.

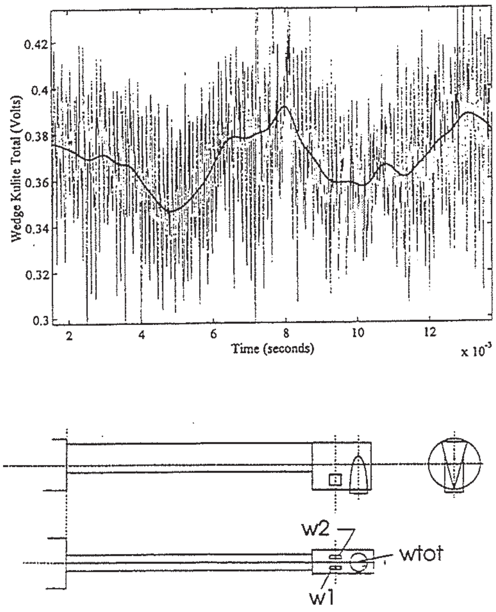


Figure 12 Raw signal measured by the wedge total sensor

Transforming the Data to the Absolute Frame of Reference

The raw data from the traversed fast response aerodynamic probe is initially converted to Mach number, yaw angle, and total pressure using the probe's aerodynamic calibration grid and the pressure and temperature sensitivity of each semiconductor chip. This produces flow measurements in the probe relative frame and compensation for probe velocity must be made to transform the data to the absolute frame of reference. Accurate measurement of traverse speed and rotor speed during the facility run time allows the traverse data to be compensated for this effect using an iterative technique designed by Martin Oldfield (Oxford University).

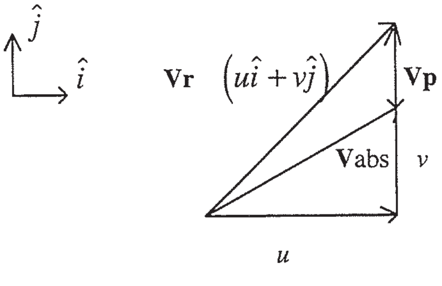


Figure 13 Compensation for probe speed

True velocity **V= Vr + Vp**,

or $\mathbf{V} = u\hat{i} + \left(v - v_p\right)\hat{j}$

Define Mach number vectors as **M** = **V**/a

Then since a is the same in both the probe and tunnel frames of reference, the velocities can be written in terms of Mach number.

M=Mr+Mp,

The probe measures the Mach number in the probe relative frame (**Mr**), static pressure (P) and relative total pressure (P_{0r}). Absolute Mach number **M** could be calculated given a knowledge of the probe Mach number (**Mp**). In turn **Mp** could be calculated from probe velocity and the local static speed of sound, which can be related to the local total speed of sound. However the local total speed of sound can only be calculated if the absolute Mach number (**M**) is known.

Solution: Use $\frac{T_o}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right)$

to give $\frac{a_0}{a} = \sqrt{\left(1 + \frac{\gamma - 1}{2} M^2\right)}$

Using $M_r = M_x\hat{i} + M_{yr}\hat{j}$ then

$$M^2 = M_x^2 + \left(M_{yr} - M_p\right)^2 = M_x^2 + \left(M_{yr} - \frac{v_p}{a}\right)^2$$

Thus

$$M^2 = M_x^2 + \left(M_{yr} - \frac{v_p}{a_0}\sqrt{\left(1 + \frac{\gamma - 1}{2} M^2\right)}\right)^2$$

This equation, which contains M on both sides, can be solved iteratively to find M, using M_r as an initial guess if the total temperature is known. Unsteady measurements of total temperature made with an aspirating probe downstream of the rotor exit in the Oxford Rotor Facility have shown that the periodic total temperature variations due to rotor passing is ±7.5°K, and the mean rotor exit temperature is 288°K. Iterating to obtain the absolute Mach number, assuming the rotor exit total temperature is a constant 288°K results in a 2.8% difference between the probe relative

Mach number and the absolute Mach number. Including the ±7.5°K unsteady variation in rotor exit total temperature and repeating the iteration procedure results in a 0.07% correction in the absolute Mach number. The effect of unsteady total temperature on the absolute Mach number is therefore small, and for analysis purposes the rotor exit total temperature was assumed constant.

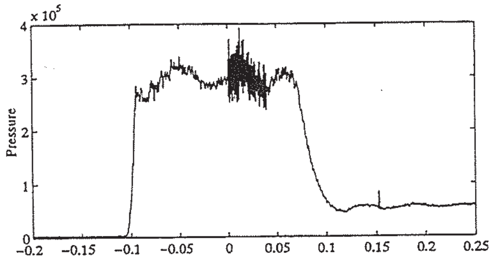
In practice only two iterations are required. Once *M* is calculated, all other parameters, such as total pressure and flow angles can be calculated.

Variations in the facility operating point caused by the acceleration of the rotor and by pressure oscillations resulting from the finite mass of the piston in the ILPT must be removed from any measurement before analysis of the traverse data may take place. An example of the rotor exit total pressure measured with a fast response aerodynamic wedge probe is shown in figure 14a. The data is sampled at 10kHz for the entire run time with the exception of a 40ms period surrounding the operating point during which the sampling rate is raised to 500 kHz. The piston oscillations and rotor acceleration have frequency components below 20Hz, and can thus be removed by high pass filtering. The high pass filtering process is shown in figure 14.

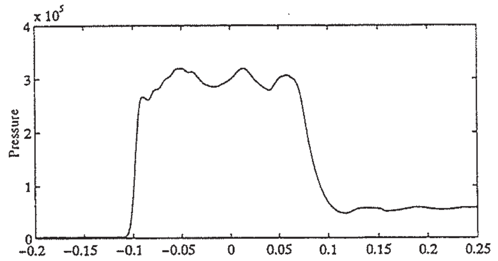
Local Averaging

The development of reliable fast response aerodynamic probes has allowed each rotor passing event to be measured to a high degree of accuracy. However, each rotor passing event has its individual passage signature and a degree of random unsteadiness. If each rotor passing event is to be used to describe the time history of a specific point down stream of the rotor exit then these effects must be removed.

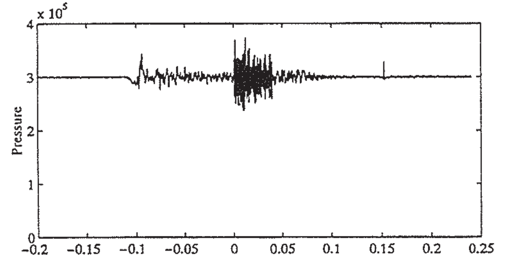
This was done using a technique called local averaging which involved cutting up the rotor passing events using the signal from the 60 line shaft encoder and knowledge of the position time history of the traverse. Each of the 150 rotor passing events measured by the traverse probe is used as a time history of the rotor exit flow at the position (relative to the HP NGVs) at which it was measured. The phase integrity of each of these rotor passing events in the absolute frame is therefore of obvious importance. A highly accurate position measuring device was therefore required to allow the signal to be cut up into individual rotor passing events. Each of the 150 rotor passing events is then interpolated onto a standard 100 point grid to normalise its time base which has been distorted by variations in traverse speed and rotor speed.



A - Unfiltered Data



B - Low Pass Filtered Data



C - Data with ILPT Operating Point Variations Removed

Figure 14 Rotor exit total pressure (measured with a fast response aerodynamic wedge probe)

To calculate the local mean rotor passing event for any of the 150 rotor passing events, each of the nine rotor passing events surrounding it is divided into 100 bins, and a mean taken. This local averaging procedure for wake N is shown in figure 15. This technique acts as a spatial filter and involves a compromise between removing the unwanted variations between rotor passing events and the spatial resolution of the data must be sought.

The result of applying the local averaging technique to traverse measurements of Mach number made at a radial height 11% of the passage height from the hub is shown in figure 17. The spatial periodicity of the data as the traverse probe is moved over a distance of 2 NGV pitches can be clearly observed.

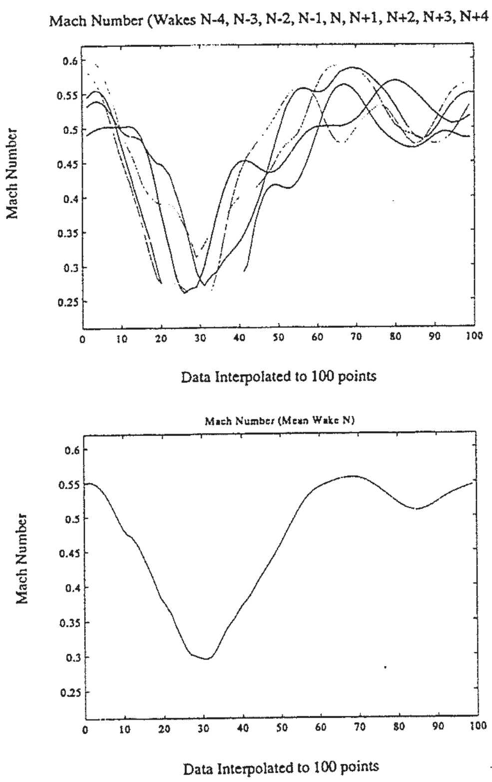


Figure 15 Local averaging technique Producing Time-Resolved Rotor Exit Survey

The rotor passing time history of Mach number, yaw angle, and total pressure in the absolute frame is now known at 150 points along a circumferential arc of length 2.5 NGV pitches at rotor exit. The points along the traverse arc at which the rotor exit time history is known and an example of two time histories is shown in figure 16. Twelve operations of the Oxford rotor have been made with the probe mounted at 12 circumferential heights. This resulted in the time history of the rotor exit flow being known at each point on a 150 by 12 grid (i.e. 1800 positions.). A time-resolved rotor exit area survey can now be constructed from this data. A rotor exit area survey of Mach number in the absolute frame at a fixed moment in time is shown in figures 18. For a full time-resolved rotor exit flow there are 100 such time frames and these have been animated into a movie. These area surveys are constructed with traverse data measured at 12 radial heights. Analysis of the spatial variation of the mean level, phase, and shape of a rotor passing event with NGV relative position is still in progress and it is expected that a detailed understanding of these interaction phenomena will be achieved.

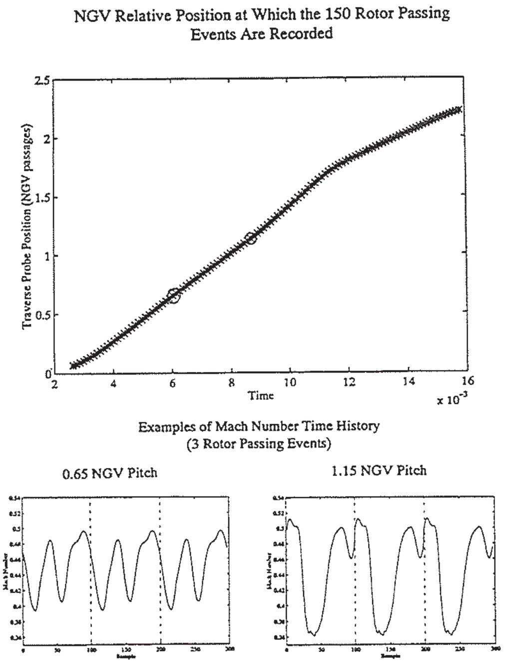


Figure 16 Probe position relative to NGVs; probe Mach number histories at two probe positions

Conclusion

The development of a rapid traverse mechanism has allowed high bandwidth area traversing to be completed in a transient flow facility for the first time. This allows full time-resolved area surveys, which would have otherwise taken over 400 facility operations, to be completed in 10 facility operations. The initial analysis of the traverse data has demonstrated that the reliability and accuracy of the fast response aerodynamic probes is sufficient to allow full time-resolved rotor exit area surveys to be constructed from 150ms of data recorded over 10 facility operations.

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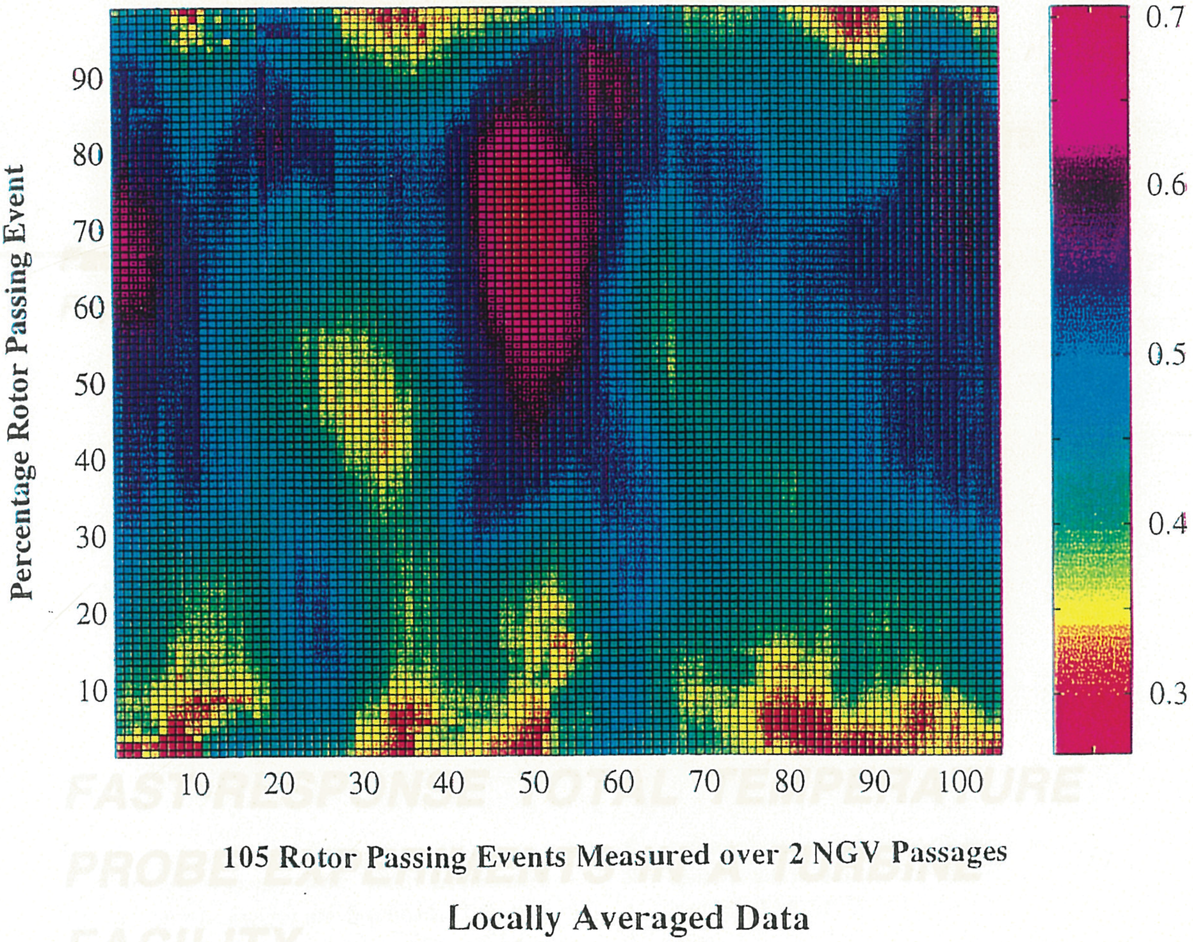

Figure 17. Mach number in the absolute frame measured by a traversed fast response aerodynamic wedge probe (11% from hub)

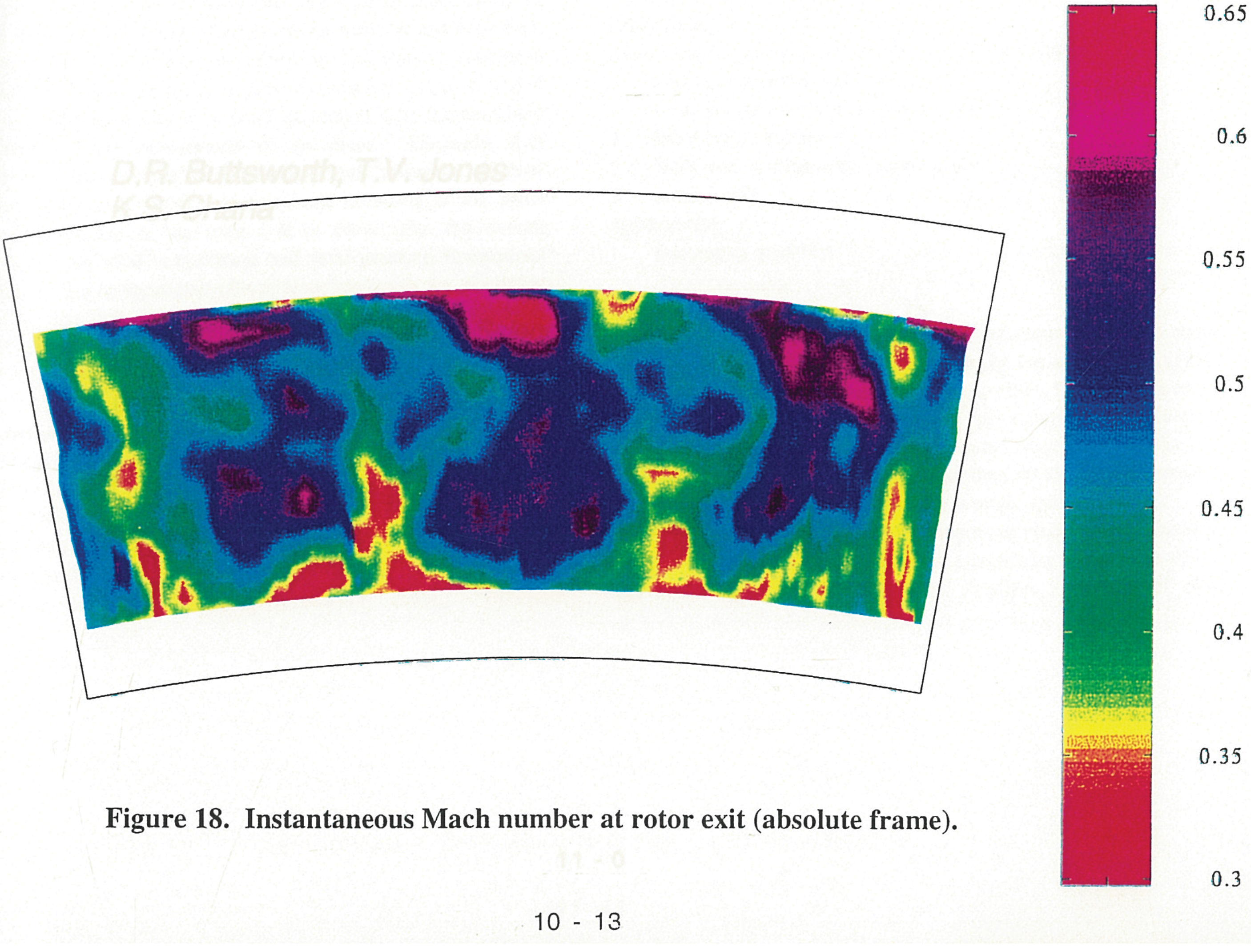

Figure 18. Instantaneous Mach number at rotor exit (absolute frame).