HOT WIRE ANEMOMETRY AT HP ROTOR EXIT IN SUPPORT OF TRENT 500 MODEL HP TURBINE RIG TEST

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1 ABSTRACT

Hot Wire Anemometry is extensively used by Rolls-Royce in turbine rig testing to obtain time resolved data for the validation of unsteady CFD models. The technique has recently been employed to determine flow velocities (and angles) in the HP turbine rotor exit plane of Trent 500 HP 76% scale turbine rig at design point condition.

A statistical analysis of the differences between the Cobra (pneumatic) probe velocities and whirl angles and the hot wire time averaged data is presented

Steady (time averaged) and unsteady hot wire data are presented illustrating deterministic and random unsteadiness.

The hot wire probe was calibrated in the rig environment, to ensure representative Reynolds numbers and densities. A pneumatic probe was used as the calibration reference. The calibration method is described in detail, including assumptions made concerning the performance of the pneumatic probe, the resonances of the hot wire support prongs, and the stability of the characteristics of the wire during use. Some limitations of hot wire sensors are discussed along with assumptions and uncertainties associated with the data analysis.

2 NOMENCLATURE

E	hot wire output voltage
E_o	hot wire "zero flow" output
B	King's Law "gain" constant
n	King's Law "linearity" constant
v_{eff}	effective velocity
v_{Cobra}	velocity from pneumatic probe
k	hot wire Champagne constant
θ	hot wire yaw angle
θ_{off}	hot wire yaw angle offset
a,b,c	empirical constants
U_{opr}	once-per-rev averaged axial velocity
V_{opr}	once-per-rev averaged tangential velocity
U bar	time averaged axial velocity
V bar	time averaged tangential velocity
U_{det}	deterministic unsteadiness in axial velocity
U_{rey}	random unsteadiness in axial velocity

3 INTRODUCTION

Traditionally, most experimental applications of Hot Wire Anemometry have been confined to relatively benign test vehicles, with low temperatures, low velocities, or short test durations. In simple configurations, the fragility of the sensors is mitigated by both the short duration and the ease of access to the sensors for replacement.

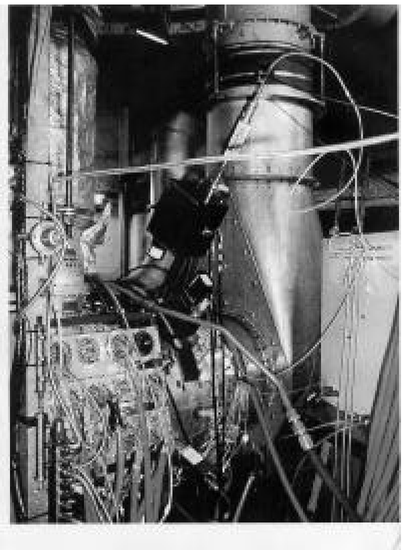
Increasingly there is need for time resolved velocity data to further understand the complex interaction between components in a gas turbine. Though compressor rig tests at Rolls-Royce routinely use LDA (laser doppler anemometry), optical access in the turbine rig geometry prohibits this approach.

HWA data has been obtained in the rotor exit plane of a 76% scale High Pressure Turbine Rig at its design point condition. A pragmatic approach has been required to obtaining data in these challenging conditions, and a detailed analysis of the results was essential to validate this approach.

4 TEST FACILITY DESCRIPTION

The cold flow turbine rig test facility is located at the Rolls-Royce Derby UK site. The facility can accommodate two model test rig configurations; a two shaft HP/IP turbine and a single shaft HP turbine (the configuration used for the test described). Although engine-parts rigs can be tested, in the case considered the rig was 76% scale, representing an annulus height of approx. 48mm. The system is an open type, taking air from and eventually discharging to atmosphere. The turbines are tested at low inlet pressures - approximate total pressure and temperatures in the HP rotor exit are in the order of 15.4 psia and 360K.

Figure 1: Hot Wire Probe installed in Test Facility

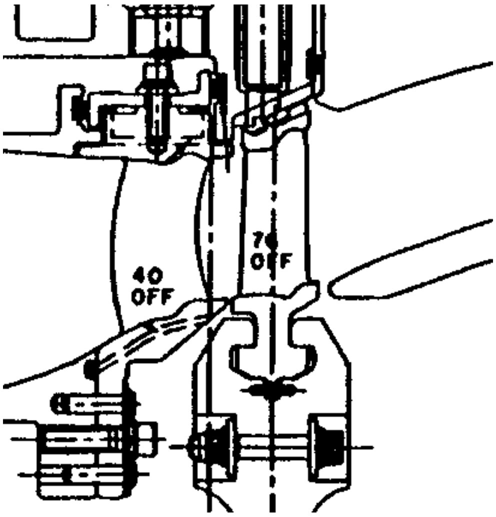


5 RIG CONFIGURATION

HP NGV:	40 off
HP rotors:	76 off
nominal speed:	8400 rpm

The blades are of shrouded construction.

Figure 2: Schematic diagram of the rig



6 EQUIPMENT DESCRIPTION

6.1 Test equipment

Dantec 55P11 single element hot wire anemometer probes were employed. The sensing elements were 5 micron diameter platinum plated tungsten.

6.2 Setting of overheat

An overheat of 1.65 was employed, producing an overheat of approximately 180°C (estimated maximum flow temperature of 90°C). The overheat was adjusted at the first point on each circumferential traverse - to attempt to account for radial temperature distribution.

6.3 Once-per-rev signal conditioning

A Scanamatic optical probe was employed on the HP shaft. The conditioning for this probe allows TTL out, so this signal was acquired directly using the A/D card. Once-per-rev averaging on the HPR exit test data was carried out against the HP signal.

6.4 Turbine Rig Installation

To facilitate the area traverse, an in-house design of radial traverse unit is mounted onto a similarly sourced circumferential rack. The HWA probe was mounted in a retractable carrier which fits into the radial traverse mechanism. This holder allows the retraction of the probe inside a shielding tube, such that in the event of wire failure, the probe holder may be withdrawn from the radial traverse rack and the wire replaced. The probe may then be re-inserted into the rig whilst retracted and re-deployed once positioned within the rig annulus. This eliminates the need to remove the circumferential base in the event of a wire failure, which incurs considerable delays in the rig running programme.

A distance of 3.2 inches on the circumferential rack is approximately equivalent to one nozzle guide vane pitch.

The single element holder is radially datumed in the rig by touching the holder (with the probe withdrawn) to the rig inner wall. The holder is then retracted to a safe height and the probe deployed by a known radial "throw".

The angular position of the hot wire is approximately 90° to the rig axis at 0° indicated yaw. Any discrepancies in the indicated whirl angle in relation to that indicated by the Cobra probe data were corrected for post-test as described below.

Figure 3: Photograph of Hot Wire Probe Holder

6.5 Semi-automated traverse

An automated traverse interface system has been developed by Sci-Tek Consultants for use with the Rolls-Royce Mk III three-axis traverse controllers and the StreamWare® software.

7 EXPERIMENT DEFINITION

At each test point (and calibration point), the two wire outputs and once-per-rev signal were logged simultaneously (achieved via a sample and hold option in the A/D card) at a sample rate of 250kHz for one second.

This provided approximately 100 rig revolutions of data from which once-per-rev averaged hot wire signals could be produced.

At each radial immersion, the probe was presented to the flow at two orthogonal positions, such that the mean flow direction was incident at approximately 45° within the hot wire probe "quadrant". This was done to minimise any prong interference effects, by attempting to contain the flow angle variations away from the extremes of angle. Thus, at each radial immersion, the corresponding (or nearest) Cobra probe data were examined to determine the mean flow angle and thus the hot wire probe angular positions.

The hot wire was traversed over twenty-one circumferential positions at nineteen radial immersions. Each radial immersion was traversed with a fixed yaw position and then repeated with the wire positioned in the orthogonal yaw orientation.

7.1 Hot Wire Calibration and Data Acquisition

The probe was calibrated (velocity and angular offset) in-situ on the rig, against Cobra probe data obtained from a previous run. The probe is calibrated in-situ in order to calibrate in representative densities, temperatures etc. and as shifts in calibration are usually anticiapted during the course of the test.

A five point calibration was carried out at the start of the test. It is standard practice to do a calibration at the end of the test and after any breaks in running the rig (e.g. end of day's running), to assess any drifts in the hot wire characteristic due to stress relief, oxidation, etc. It was not possible to repeat the calibration at the end of the test due to wire failure. However, some running was carried out on the day before the main hot wire area traverse, but time limitations resulted in only a limited wire calibration being carried out. These calibration data agreed very well with the data taken the next day immediately prior to the main traverse, which increased the confidence in the stability of the wire calibration. From previous test experience, such stability is unusual as significant shifts in the wire calibration characteristics are typically encountered during the course of hot wire testing.

Previously, the “King’s Law” curve fit to the calibration data (velocity from Cobra probe vs. hot wire output) has only been based on the peak output at each calibration position. This unfortunately gives very sparse coverage over the velocity range. To attempt to improve this, a “first pass” calculation was carried out to establish a series of nominal calibration constants. These data were then used to establish the nominal yaw offsets at each calibration point (i.e. actual yaw angle of maximum and minimum hot wire outputs). These data were then used to generate a plot of approximate “effective” velocity, where an angle of 90° was equivalent to a flow perpendicular to the wire, thus generating the maximum output. Iteration is required in order to do this, but the resulting data are shown in figure 4. It is apparent that this method gives far greater coverage over the entire velocity range and therefore is a better basis for the King’s law curve fit. The equations used to calculate the effective velocities etc. are as follows:

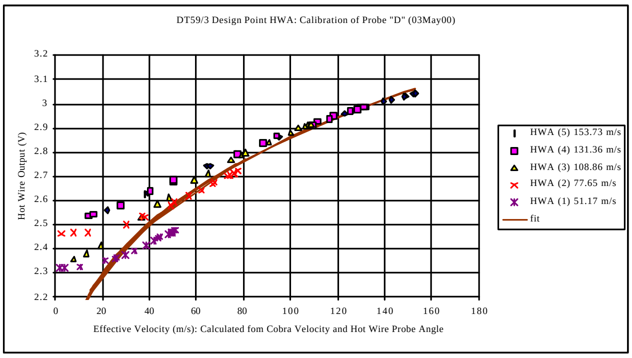
$$E = \sqrt{E_o^{\,2} + B \cdot v_{eff}^{\;n}}$$

$$v_{eff} = v_{Cobra} \cdot \sqrt{\cos^2(q - q_{off}) + k \cdot \sin^2(q - q_{off})}$$

E = hot wire output (V)
E_o = hot wire "zero flow" output - determined by iteration
B = hot wire "gain factor" - determined by iteration
n = hot wire "linearity" constant - set to 1/2.2

v_{eff} = effective velocity
v_{Cobra} = velocity calculated from Cobra probe traversing
k = hot wire "Champagne" constant - set to 0.03
θ = hot wire yaw angle (as positioned in rig)
θ_{off} = hot wire yaw angle offset, such that when $(\theta - \theta_{off})$ = 0°, flow is perpendicular to hot wire. θ_{off} is calculated for each calibration velocity (by a crude initial iteration) and a mean offset is calculated. In the data shown in figure 4, the "individual" offsets are utilised.

Figure 4: Calibration of Hot Wire Anemometer



This approach also differs from the previous method in that a fixed value of the "k factor" was used. This value is an estimate based on previous laboratory testing of 55P11 hot wire probes in a steady jet. The reason for this new approach follows a revision of the calibration methodology, in which it became apparent that the use of the k-factor determined within the rig is not appropriate. This is because the flow is obviously fluctuating in the rig and so when the flow is nominally perpendicular to the wire, there will be instances where it is not. Thus, a lower mean hot wire output will be measured than if the flow were completely steady. Similarly, where the rig flow is nominally parallel to the hot wire, the mean output will be higher than if determined in a steady flow.

Thus, the k-factor determined directly from calibration in the rig will be unrepresentative (and high).

The peak hot wire outputs used to determine other hot wire constants will be lower than if determined in an equivalent steady flow, so these data are also in error, but there is no other simple method of determining these constants, given the differences in flow temperature and density from those that can be readily generated in the laboratory.

The ratio of the effective velocities calculated from the wire outputs in the two orthogonal angular orientations is used to determine the flow angle. If k=0, then theoretically, the relationship between ratio and flow angle is ratio = tan(90-angle). If k is non-zero, then the relationship is more complicated. A further curve fit to these data is employed, for ease of analysis, in the form:

ratio = b.exp$^{(\text{angle}/a)}$ + c, where a, b and c are empirical constants.

These curve fits are shown in figure 5.

Figure 5:

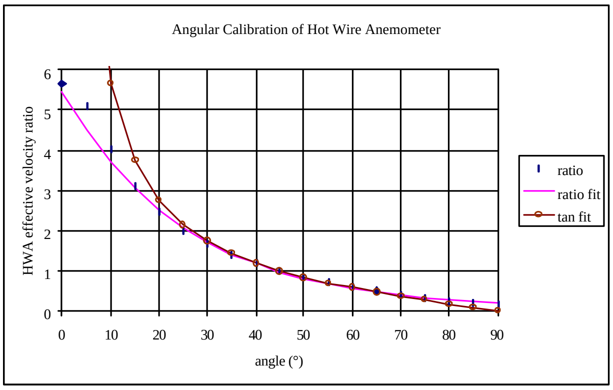


Table 1: Hot Wire Anemometry Calibration Constants

Cal. Coefficient	design point cal. used
Eo	1.614
B	0.6884
n	0.4545
k	0.031
a	-25.531
b	5.408
c	0.4369
yaw corr.	+6.0

8 TURBULENCE ANALYSIS

This type of analysis is still being trialled and as such is incomplete. It is designed to give an estimate of the deterministic and random unsteadiness (turbulence levels). It should be noted that only the velocity components (not density) are considered.

Deterministic: Once per rev averaged velocity data were resolved into axial and tangential components (U_{opr} and V_{opr}). The mean of the resolved opr averaged data was then calculated (U bar and V bar).

The following equations were used to calculate $U^2_{\det}$,$V^2_{\det}$ ($U^2_{\det}$ shown) and $UV_{\det}$:

$$U^2_{\det} = \frac{\sum\left(U_{opr} - \overline{U}\right)^2}{\text{Number of samples in 1 rev (interpolated)}}$$

$$UV_{\det} = \frac{\sum\left(U_{opr} - \overline{U}\right).\left(V_{opr} - \overline{V}\right)}{\text{Number of samples in 1 rev (interpolated)}}$$

Random ("Reynolds"): Instantaneous velocity data was calculated from a single instantaneous data 'pair' (HW volts) using King's law and Champagne's Law (coefficients as for wire calibration). It is important to note here that the two sets of data are not taken simultaneously, the set with the smallest number of elements is interpolated up to the other sets number of elements.

The velocity from this 'pair' was then resolved into axial and radial components. This data set was then interpolated with the number of elements processed in the once per rev averaged case. The following equations were then used:

$$U^2_{\mathrm{Re}\,y} = \frac{\sum\left(U_{inst} - U_{opr}\right)^2}{\text{Number of samples in 1 rev (interpolated)}}$$

$$UV_{\mathrm{Re}\,y} = \frac{\sum\left(U_{inst} - U_{opr}\right).\left(V_{inst} - V_{opr}\right)}{\text{Number of samples in 1 rev (interpolated)}}$$

Further work is required to incorporate more than just one "revolution pair" of instantaneous data to calculate the random unsteadiness and error trapping routine should be inserted to reject data obtained with a faulty OPR signal. At present the routine merely states the number of samples contained in each of the rev. pairs, so any "missed" OPR pulses are highlighted in this manner. Also the effect of interpolating the instantaneous data "up" to the number of (interpolated) OPR averaged data points requires assessment. At present the routine provides a useful tool for qualitatively assessing the distribution of turbulence levels over the traversed area.

9 PROBE RESONANCES

In previous hot wire tests, the data has suffered from vibrational modes which were observed in the hot wire frequency spectra that were not integral orders of the blade passing frequency. To minimise the risk of future occurrences of this problem, all remaining 55P11 probes have been crudely characterised in a free jet exhausting to atmosphere. Many of the probes exhibited strong modes in the 20kHz to 40kHz range. Only a few probes exhibited a relatively flat response to 100kHz (any modes were of relatively low amplitude at frequencies in excess of 50kHz).

Probe "D" was employed in this test, which had recently been repaired by Dantec. Air jet testing indicated that modes at approximately 40 kHz were likely to be observed.

Observation of FFT data from the probe whilst the rig was running indicated that a relatively "clean" signal was obtained. FFTs of typical "raw" and once-per-rev averaged signals are shown in figures 6 and 7. Note that there appeared to be very little activity above third harmonic.

Figure 6: FFTs of "raw" signal - to 50kHz only

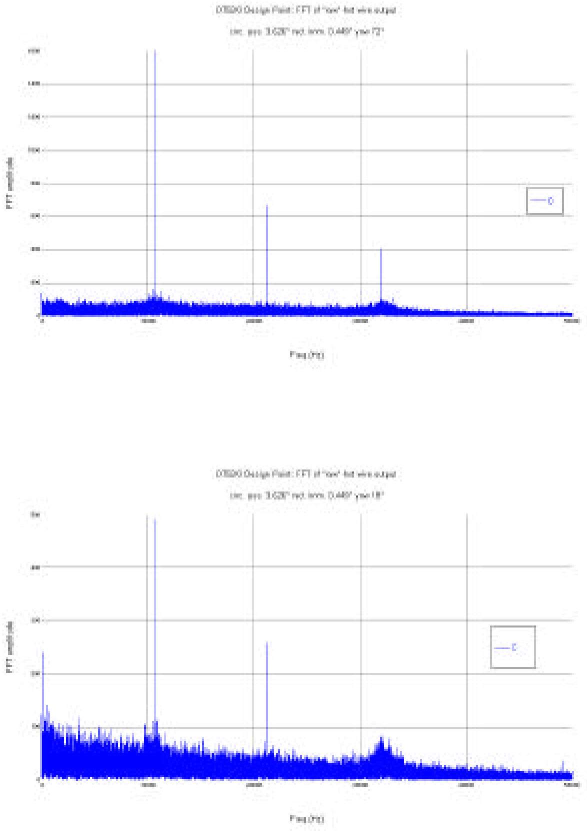
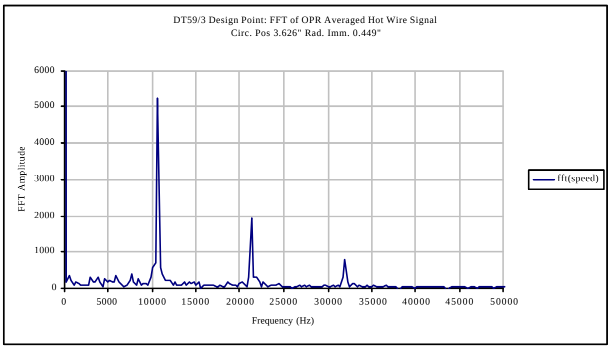


Figure 7: FFT of once-per-averaged signal - to 50kHz only



10 WIRE LIFE

Hot wire anemometry is renowned for short-lived sensors. Due to the nature of rig testing, where the probe is built into the radial traverse rack, which must be in place for the rig to run and the 30-45minutes stabilisation time required before measurements are taken from the rig, HWA can be a fraught business. Reduction of the overheat and use of the robust platinum plated tungsten wire material (rather than the use of other physically weaker alloys with higher temperature capabilities), together with the retractable probe holder, has resulted in an average sensor life of 9 hours continuous rig running. With the automated traverse control system allowing one measurement every 24 seconds, including calibration and rig stabilisation, around 450 measurements can be made in one days (double shift) running.

On this particular test, probe "D" failed after approximately 8.5 hours of testing, just prior to the recalibration operation. Data from other hot wires testing has shown that calibration can drift during the testing operation, in that significant shifts are apparent (which must be corrected for) in the measured data.

11 DATA OBTAINED

As the purpose of this paper is to comment on and demonstrate the capabilities of the technique and data processing, complete data sets are not presented. Instead, contour plots of the time averaged and dynamic data will be presented.

11.1 Figures 8 & 9: Time averaged data as a contour plot over the entire traverse plane, absolute whirl and velocity only.

Figure 8:

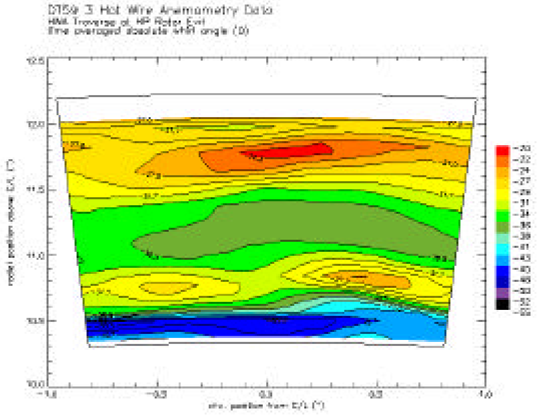
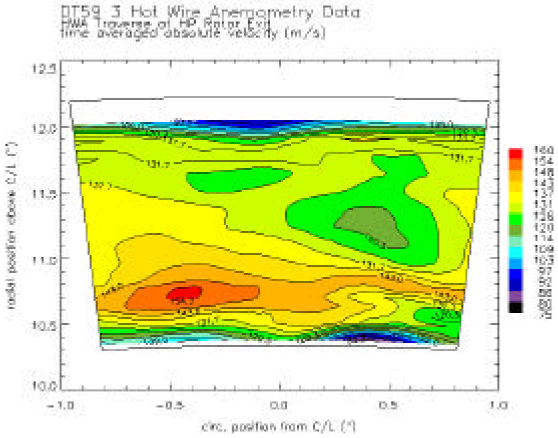


Figure 9:



11.2 Figures 10 to 12: Time averaged data as x-y plots at six circumferential positions, absolute whirl and velocity only, showing comparison with "equivalent" Cobra probe data.

Figure 10a: Velocity Comparison (m/s)

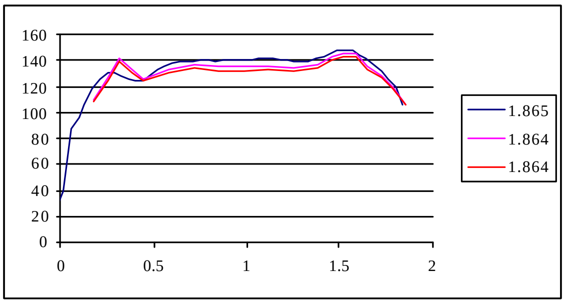


Figure 10b: Yaw Comparison (°)

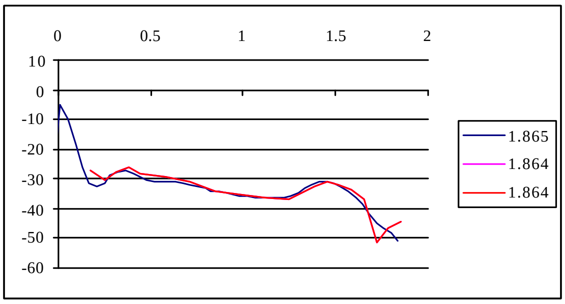


Figure 11a: Velocity Comparison (m/s)

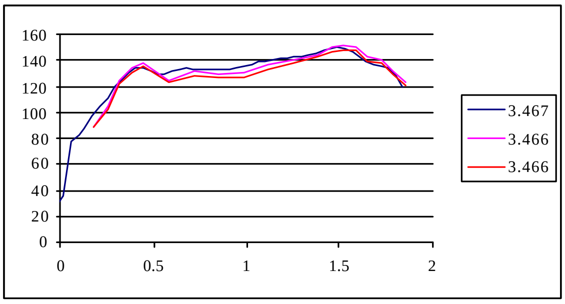


Figure 11b: Yaw Comparison (°)

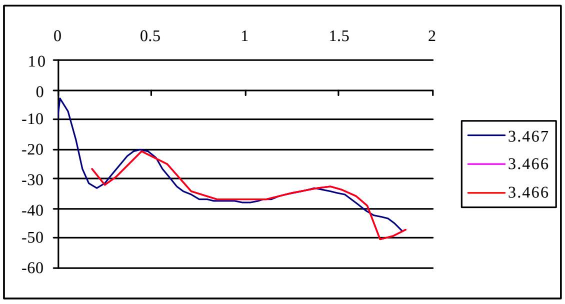


Figure 12a: Velocity Comparison (m/s)

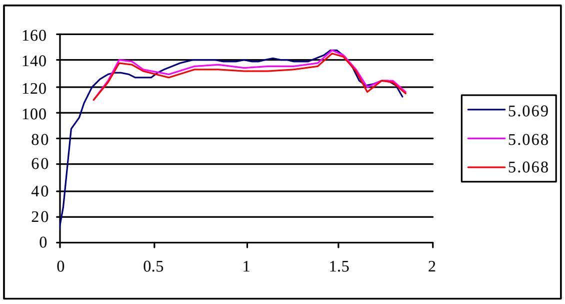
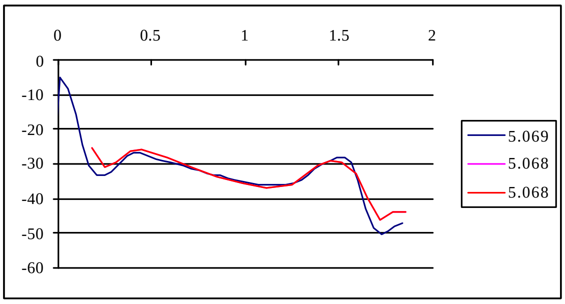


Figure 12b: Yaw Comparison (°)



Blue = Cobra Data
Magenta = Hot Wire Data
- Time Average of "Raw" Data
Red = Hot Wire Data
- Time Average of "once-per-rev averaged" Data

X axes = radial immersion in inches
Y axes = engineering units (m/s or ° as appropriate)
Legend shows circumferential position in inches

11.3 Figures 13 to 16: Dynamic data (first 200 data points only) plotted as circumferential profiles at four radial immersions, absolute velocity only.

Figure 13:

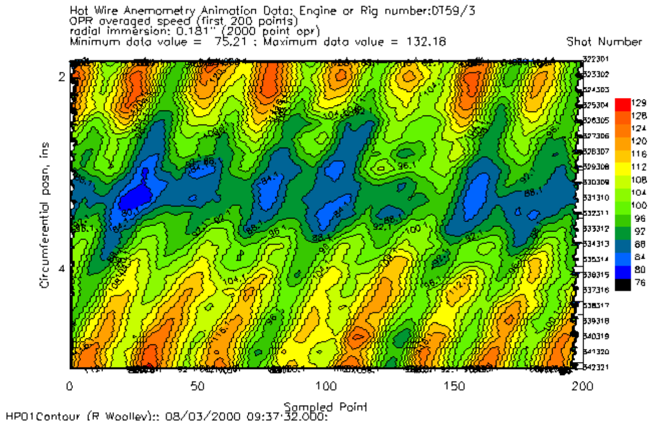


Figure 14:

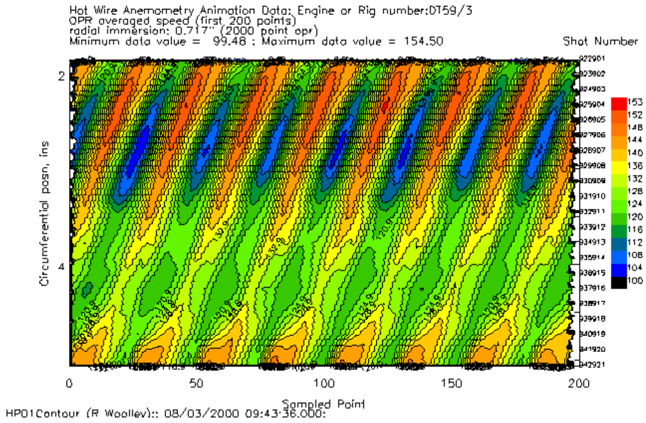


Figure 15:

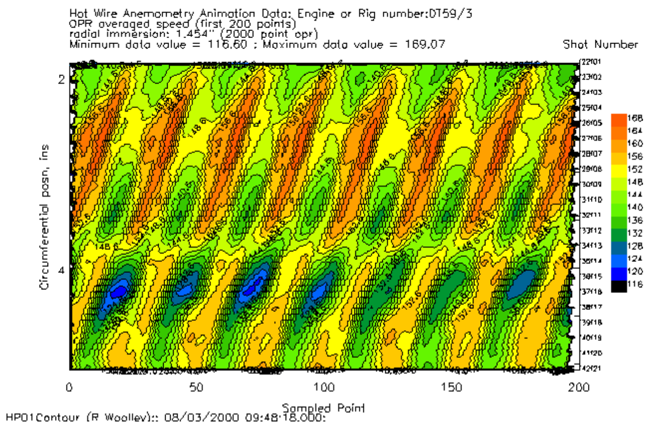
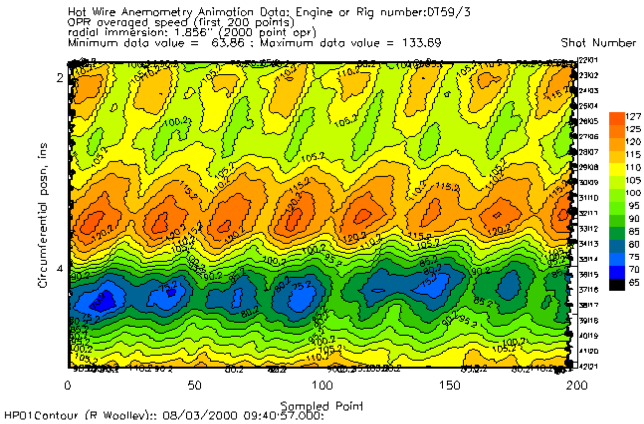


Figure 16:



11.4 Figures 17 & 18: Deterministic and Random Unsteadiness contour plots, axial and tangential velocity components only. Note the provisos with these data detailed in section 8.

Figure 17a: Deterministic unsteadiness in axial component of velocity (m/s) in absolute frame

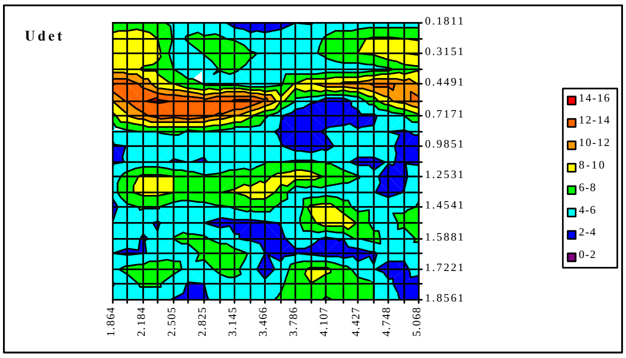


Figure 17b: Deterministic unsteadiness in tangential component of velocity (m/s) in absolute frame

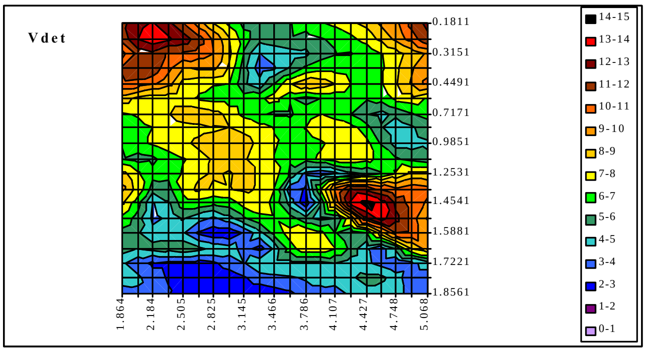


Figure 18a: approximate random unsteadiness in axial component of velocity (m/s) in absolute frame

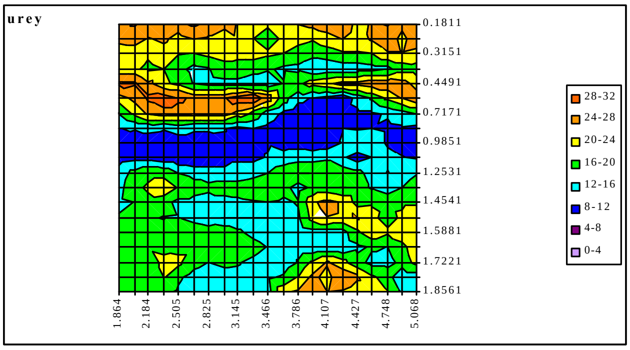
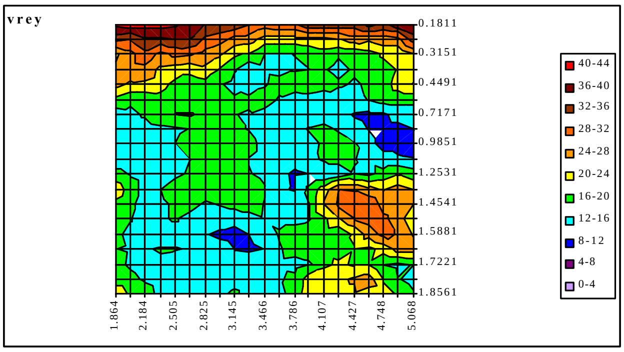


Figure 18b: approximate random unsteadiness in tangential component of velocity (m/s) in absolute frame



X axes = circumferential position in inches
Y axes = radial immersion in inches

12 MEASUREMENT UNCERTAINTIES

12.1 Note that fluid density, viscosity and bulk fluid temperature are frozen into each calibration point. Thus, errors will result if these parameters vary significantly over the area of measurement.

J. Prato et al presented a paper at the 1998 ASME conference suggesting that bulk density effects could be accommodated by a modification to Kings Law:

$E^2 = E_0^2 + Bv^n$ - King's law
$E^2 = E_0^2 + br^m v^n$ - modified King's Law

where E = HW Volts, E_0 = HW Volts offset (Volts at zero flow), v = velocity, ρ = density; n, m, B, b are constants.

The King's law application is described above. The effects of density were assessed in hot wire data taken on a previous build of this turbine rig, in the rotor exit plane. Densities at the calibration points were calculated from Cobra data and wall statics and the hot wire calibration data were re-examined using the modified King's law.

Prato et al found m = 0.78 for their data. Applying the technique to the DT59 build 1a rotor exit calibration data, the best fit was obtained with m = 0 i.e. the standard King's Law.

A 2.2% variation in density (2 sigma) was measured (Cobra data) over the five hot wire calibration points taken for this test. The mean density was 0.955 kg/m^3.

12.2 Similarly, dynamic variations in density, viscosity and temperature will affect the hot wire output, but will appear as velocity variations in the analysed data.

12.3 Comparison with Cobra data

A comparison was made between the hot wire time averaged data and the Cobra data. The comparisons were made at approximately equivalent circumferential and radial positions (data are taken at more circumferential positions with the hot wire and a finer radial traverse is carried out with the Cobra probe).

A grid of 133 points results over which comparisons between the two measurement methods can be made as shown in figures 10 to 12. The statistical variation between hot wire and Cobra positions is as follows:

radial variation (mean ± 2 sigma):
+0.001" ± 0.025" (hot wire - Cobra)
circumferential variation (mean ± 2 sigma):
-0.001" ± 0.087" (hot wire - Cobra)

A statistical analysis of the deltas yields the following:

yaw angle variation (95% confidence):
± 5.7° (mean delta of 1.2°)

velocity variation (95% confidence):
± 10.4 m/s (mean delta of -1.0 m/s)

12.4 As stated above, the hot wire overheat is only set at the first circumferential position. Thus a circumferential variation in temperature will appear as a velocity variation. The level of this effect was investigated in data from a previous hot wire test and indicated that the differences observed between the Cobra and hot wire velocity data cannot be conclusively linked to the circumferential temperature differences.

12.5 Also note that additional errors in the hot wire data may result from run to run temperature profile repeatability and also run to run traverse gear positional accuracy/repeatability. The level of these potential errors have not been assessed.

13 CONCLUSIONS

In summary, although the hot wire technique is best considered as a flow visualisation "qualitative" technique, rather than a technique to be used for precision measurements and despite the concerns and shortcomings listed above, the pragmatic approach adopted in the use of the technique for flow visualisation has proved to be extremely useful to Rolls-Royce in CFD validation.

Confidence in the data is increased as the time-averaged data obtained using this technique often exhibits surprisingly good correlation with pneumatic probe data.

Although concerns remain with the fragility of hot wire sensors, given the challenging environment in which they are employed and the delays that repeated failures could cause in the rig testing activity, wire survival times of typically over eight hours of continuous rig operation are now anticipated.

The technique is now routinely used by Rolls-Royce during model and engine parts turbine rig testing.

14 ACKNOWLEDGEMENTS

The permission of Rolls-Royce plc to publish this paper is gratefully acknowledged, as is the support of many colleagues involved in the turbine design and testing.

15 REFERENCES

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