ON THE USE OF HOT FILM SENSORS IN THE INVESTIGATION OF FLUID DYNAMIC PHENOMENA IN THE NEAR WALL REGION

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ABSTRACT

The authors have extensive experience in the use of hot wire and film sensors in cascade applications. In this paper the relationship between the signals from each of the sensors when they are in close proximity is addressed.

The primary data presented is for a spatial correlation between a wire and adjacent film as the wire is traversed through the suction surface boundary layer of a turbine blade in a linear subsonic cascade. An objective of this work is to find out how a hot film responds to turbulent fluctuations in the boundary layer. Theoretically these fluctuations approach zero at the wall. It was found after some processing of the data, that the wire and film signals approach a correlation of one as they are brought closer together, thereby implying that both are responding to the same physical phenomenon.

Some discussion is also presented in the form of Wavelet Analysis on the same data. Fourier methods have been the traditional technique employed for spectral analysis of experimental data. Although such methods are highly effective at identifying periodic flow phenomena, they are ill suited to the analysis of intermittent or transient data. Wavelet techniques however, offer a compromise between temporal and spectral description of the signal and can even be used to decompose turbulent velocity data into their respective components and scales. The similarity between the observed frequencies from both the surface mounted hot film and hot wire placed in the near wall region is illustrated in figure 8.

The authors have not however been able to resolve the question of how a hot film responds. This indeed is a challenge to the perceived view of turbulent boundary layer structure.

NOMENCLATURE

c_p	Specific heat capacity of the fluid	$Jkg^{-1}K$
$\mathbf{C}_{\omega,\tau}$	Matrix of wavelet coefficients for all frequencies and times	-
E	Anemometer voltage	V
f	Frequency	Hz
k	Thermal conductivity of the fluid	$Wm^{-1}K$
Pr	Prandtl Number $=\left(\frac{c_p\mu}{k}\right)$	-
Re_c	Reynolds number based on blade chord $=\left(\frac{uc}{\nu}\right)$	-
t	Time	s
S	Suction surface length	m
Tu_∞	Turbulence intensity based on upstream velocity $=\left(\frac{100u'}{U_\infty}\right)$	%
Tu_δ	Turbulence intensity based on local free stream velocity $=\left(\frac{100u'}{U_\delta}\right)$	%
u	x -direction component of velocity	ms^{-1}
v	y -direction component of velocity	ms^{-1}
x	Distance from the leading edge in the flow direction.	m
x_0	Distance from leading edge at which heating starts.	m
y	Wall-normal co-ordinate	mm
y^+	Inner wall co-ordinate $=\left(\frac{\rho u_\tau y}{\mu}\right)$	-

Greek

δ	Velocity boundary layer thickness	m
δ_t	Thermal boundary layer thickness	m
μ	Dynamic viscosity	Nsm^{-2}
ρ_{12}	Correlation coefficient between measurements at point 1 and 2 in a flow	-
τ	Time shift of the wavelet function	s
ω	Dilation or frequency shift factor for the wavelet function	Hz
$\psi(t)$	Analysing wavelet function	-
$\Psi_{(\omega,\tau)}(t)$	Matrix of detector functions corresponding to all frequencies and times of interest	-

INTRODUCTION

Heated thin-film gauges by virtue of their small size (and high frequency response) are robust non-intrusive sensors, ideally suited for boundary layer investigations in turbomachinery. The high frequency response associated with the sensors has led to their extensive use in unsteady aerodynamics, particularly with investigations into the effects of wake passing in multistage turbine tests (Hodson *et al* (1994).

Earlier flow investigations with heated thin-film sensors were primarily focussed on the development of quantitative wall shear stress calibration techniques. Despite the inherent difficulties associated with calibration of the sensors for direct measurement of the wall shear stress, their use in a qualitative role has formed a key part in the determination of intermittency, transition location and separation. Owen (1968, 1970) demonstrated that the onset of boundary layer transition can be readily identified by a peak in the root mean square average of the output from a CTA bridge. The authors (Griffin *et al*, 2002) have previously used arrays of hot-film sensors to show the onset and extent of boundary layer transition in subsonic and transonic cascades. This can easily be achieved by calculating the skewness of the fluctuating sensor output voltages.

Even though modern manufacturing techniques have led to the development of sensors with a thickness substantially less than micron scale, the question still remains as to how these sensors respond to fluid dynamic phenomena. The fact that flush-mounted sensors respond to velocity changes contradicts the classical view of turbulent boundary layer structure by Klebanoff (1955). In a turbulent boundary layer velocity fluctuations are known to have zero values at the wall and maximum values in the near-wall region as shown in figure 1:

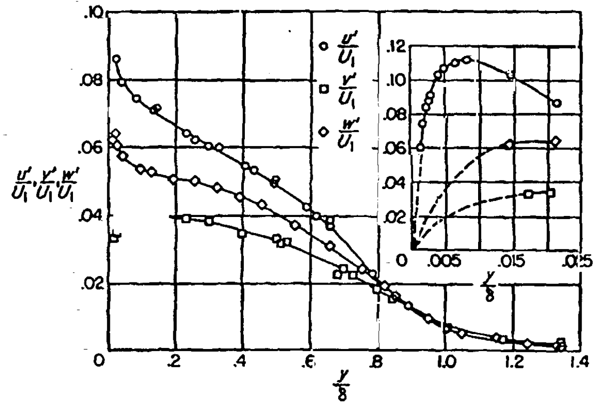

Figure 1: Distribution of turbulence intensities in a turbulent boundary layer for a flat-plate at zero incidence (from Klebanoff, 1955).

As previously mentioned, this paper does not resolve the issue as to how a heated thin-film sensor responds to turbulent fluctuations, but merely provides evidence for such, through the use of a spatial correlation between measurements throughout the boundary layer. The correlation is further complimented with time-frequency representations of these simultaneous signals.

EXPERIMENTAL METHODS

Experimental Apparatus & Instrumentation

The University of Limerick medium speed wind tunnel, subsonic cascade and associated instrumentation was previously described in detail by O'Donnell (2000). The cascade consists of seven aluminium blades, each of 92.6 mm chord, 300 mm span and spaced 70.44 mm apart. The cascade and hot-wire traversing apparatus is illustrated below:

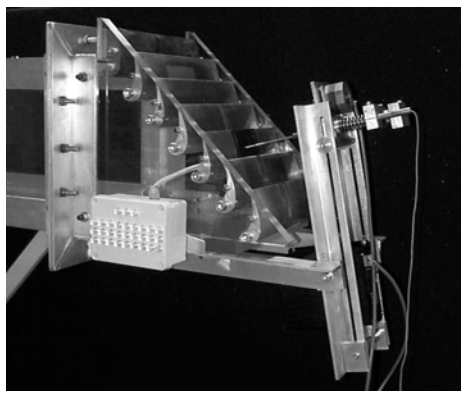

Figure 2: Subsonic Turbine Cascade and Hot-Wire Traverse Assembly.

The suction surface of the central blade in the cascade is instrumented with a custom designed array of Senflex™ (Tao Systems, VA, USA) nickel heated thin-film sensors, which respond to velocity fluctuations in the near-wall region. The sensors are spaced equally in the streamwise direction every 5 mm corresponding to 3.5% increments of suction surface length.

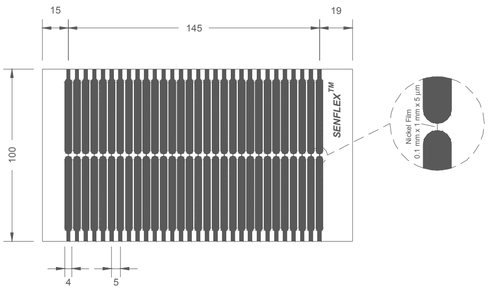

Figure 3: Senflex™ heated thin film sensor array.

The sensing elements (1.25 mm long, 0.1 mm wide) are electrodeposited onto a 0.1 µm polyimide substrate. Atomic force microscopy (AFM) was used to determine the surface roughness of the nickel-sensing element, which was found to be less than 20 nm.

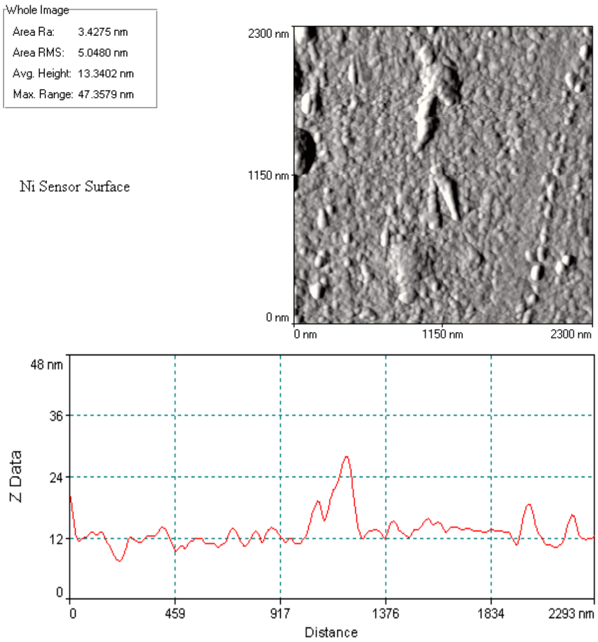

Figure 4: AFM Surface texture analysis of the nickel-sensing element on the Senflex™ array.

Detailed measurements within the boundary layer were obtained using a stepper motor driven traverse system, that permitted movement of a single sensor hot-wire probe (Dantec type P11, Platinum/Tungsten sensor 1.25 mm long, 5 µm diameter), in the wall-normal direction. The sensor was initially placed at a distance of 10 µm from the blade surface and traversed normal to the surface initially in 10 µm steps to accurately resolve the near-wall region. Further out into to the boundary layer this resolution was reduced to 100 µm steps.

Both sensors acquired data simultaneously and were operated in constant temperature mode using Dantec 56C17 CTA bridge units. Two different overheat temperatures were used; the hot-films were operated at 130°C, whereas 250°C was chosen for the hot-wires. Data was sampled at 20 kHz by a five channel 16-bit A/D converter (DSPACE GmbH). The digital output was passed to a standard Intel PII PC with the necessary software for real-time visualisation of results and subsequent data reduction.

Wire-Film Correlation

A spatial correlation between the fluctuating anemometer output voltages from a hot-wire and film sensor was carried out in the turbulent boundary layer at chord Reynolds number of 76,000, with a free stream turbulence intensity of 5.2%. The normalized correlation coefficient (ρ_{12}) is defined as (Schlichting, 1979):

$$\rho_{12} = \frac{\overline{u_1' u_2'}}{\sqrt{\overline{u_1'^2}} \cdot \sqrt{\overline{u_2'^2}}} \qquad (1)$$

and has values varying from 0 to 1.

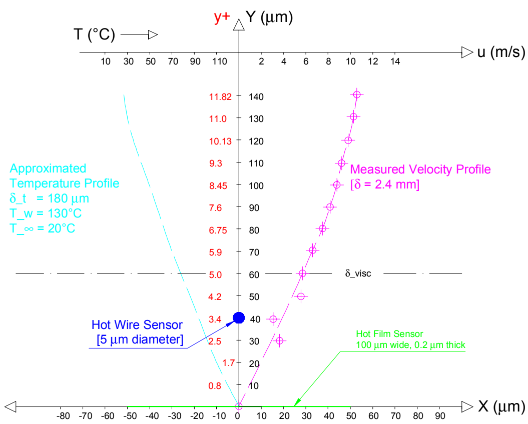

Figure 5: Scaled drawing of the relative dimensions of the hot-wire and film sensors in comparison to the near-wall region.

Figure 5, illustrates the small scales involved in the problem, in which the size of the hot-film and wire sensors can be seen in respect to the thickness of the viscous-sublayer at the measurement location. In addition the actual measured velocity values in the near-wall region are included, showing measurements from well inside the viscous-sublayer. If the frequency associated with turbulent structures in a flow increases with decreasing size, it would appear that a hot-wire has a much higher frequency response than a film, by virtue of its size.

Prior to acquiring the correlation data it was necessary to assess how much of an effect the thermal boundary layer from the hot-film would have on the measured hot-wire data. As the measured thermal boundary-layer profile was not available it was necessary to use a flat-plate approximation (Holman, 1997):

$$\frac{\delta_t}{\delta} = \frac{1}{1.026}\mathrm{Pr}^{-1/3}\left[1-\left(\frac{x_0}{x}\right)^{3/4}\right]^{1/3} \quad (2)$$

Using the velocity boundary layer thickness established from previous measurements at the test location, the maximum thermal boundary layer thickness was estimated as 180 µm from equation (2). Further inspection of the correlation data showed thermal boundary layer effects only having an influence within 60 µm of the wall; therefore all data below this point were rejected.

Wavelet Analysis Techniques

In contrast to conventional Fourier analysis, wavelet techniques permit the localisation of intermittent experimental data both in time and frequency domain. In a similar approach to Fourier methods, which convolute the time series with sinusoids of varying frequency, wavelet methods extract frequency information using compressed and dilated forms of a detector function commonly referred to as the “Mother Wavelet” $(\psi(t))$. Wavelet techniques have initially been used in the analysis of vibrational and geophysical data and have only recently shown promise in the field of turbulence. The wavelet itself can be any real or complex valued function that is localised in time and satisfies the *admissibility criterion* (Farge, 1992). This simply requires that its average is zero:

$$\int_{-\infty}^{+\infty} \psi(t)\, dt \quad (3)$$

The detector function is compressed, dilated and time shifted to yield a matrix of analysing functions corresponding to the range of possible frequencies and times occurring in the signal:

$$\Psi_{(\omega,\tau)}(t) = \frac{1}{\sqrt{\omega}}\psi\left(\frac{t-\tau}{\omega}\right) \quad (4)$$

These analysing functions are used to determine how the signal of interest ($E(t)$) corresponds to the different predefined frequencies and times. Applying the continuous wavelet transform involves convoluting the integral of the signal with the array of analysing functions to yield a matrix of wavelet coefficients ($\mathbf{C}_{\omega,\tau}$), each localised in frequency and time.

$$\mathbf{C}_{\omega,\tau} = \int_{-\infty}^{+\infty} E(t)\,\Psi_{(\omega,\tau)}(t)\, dt \quad (5)$$

The choice of wavelet function depends largely on the application and an extensive review is given by Farge, (1992) on the use of wavelet transforms with specific applications to fluid dynamics and turbulence. Many authors (Volino, 2002 and Lewalle, 1998) have preferred the use of relatively simple functions for flow analysis. Following this, the Marr or Mexican Hat wavelet was chosen as the analysing function for all data in this paper. The Marr wavelet is the second derivative of the Gaussian distribution and when it incorporates the dilation factor ω, is defined as:

$$\psi(t) = \left[(\omega t)^2 - 1\right]e^{-(\omega t)^2/2} \quad (6)$$

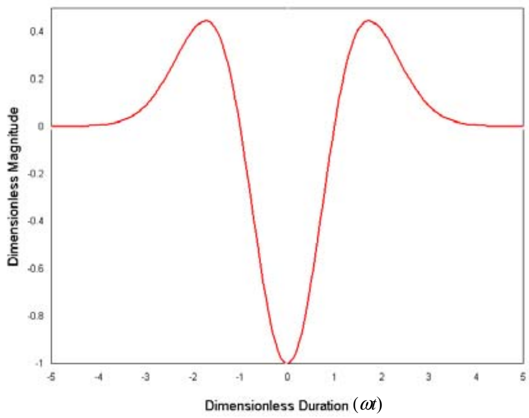

Figure 6: Marr Wavelet.

The constant ω in equation (4) is defined as $2\pi f\,(2.5)^{-0.5}$ specifically for the Marr wavelet by Higuchi *et al.* (1994). In this study 41 frequencies spaced evenly on a logarithmic scale were considered in the range of 5 to 5 kHz at all times (2000 time records from 0 to 0.1 s) in the signal, resulting in the generation of three-dimensional time-frequency representations of $\mathbf{C}_{\omega,\tau}$.

EXPERIMENTAL RESULTS & DISCUSSION

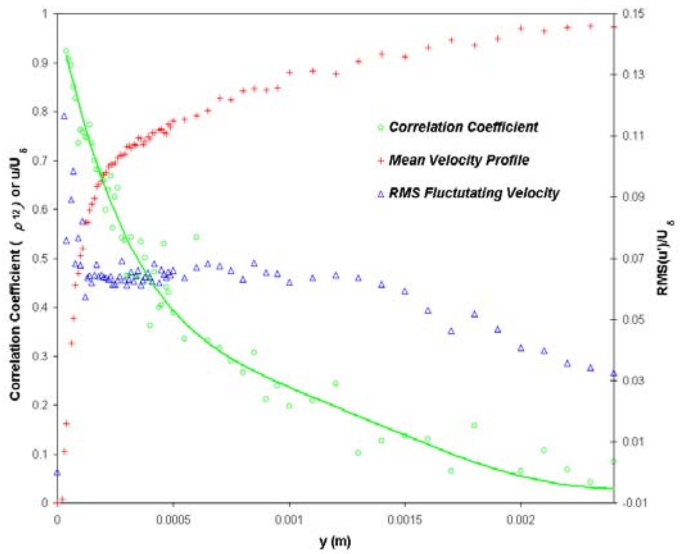

Figure 7: Spatial correlation between the fluctuating voltage signals from a surface mounted hot-film and wire traversing through a turbulent boundary layer (x/S = 0.766) at Re_c = 76,000 and Tu_∞ = 5.2%

Using equation (1), the correlation between measurements of fluctuating voltages from hot-film and wire sensors was evaluated. Figure 6 above, illustrates a distribution of the correlation coefficient (ρ_{12}) over the entire boundary layer thickness (δ = 2.4 mm) at the test location. Subsequent processing the hot-wire data permitted the evaluation of distributions of mean ($\overline{u}$) and fluctuating velocity (u') through the boundary layer. These distributions (normalized on the local free stream velocity U_δ) are presented in the same figure. Both the measured mean and fluctuating velocity profiles exhibit typical turbulent boundary layer behavior, with a high gradient of velocity and maximum velocity fluctuation in the near-wall region.

Cleary visible from figure 6 is the very strong correlation between the wire and film signals in the near-wall region with correlation coefficient values tending towards unity at the wall and gradually decorrelating (tending to zero) further out into the boundary layer. This would indicate that the hot-film is responding to the same fluid dynamic phenomena as the hot-wire in the near-wall region.

The integrity of the correlation between the measurements through the boundary layer is further strengthened, when time-frequency representations of the signals from each sensor are considered. Given that turbulent flows contain many frequencies occurring at different times, time-frequency representations of the data at different locations in the boundary layer should be unique.

Computing a time-frequency representation of a data series is made possible through the use of the Continuous Wavelet Transform (CWT), previously described by equations (3) to (6). In the region where there is a strong correlation between measurements from both sensors, some similarity would be expected between their respective wavelet spectra. Likewise, further out into the boundary layer where the signals decorrelate, dissimilar spectra should be observed.

Figure 7, on the next page illustrates the comparison between the spectra of the hot-wire signals at various locations in the boundary-layer (y/δ = 0.1, 0.3 and 0.5 respectively) and the simultaneously acquired hot-film data. Most striking from the data set considered nearest to the wall (y/δ = 0.1) is very close similarity between the wire and film spectra. Many of the frequencies observed at a particular time by the hot-wire sensor in the flow are also simultaneously sensed by the hot-film. However, in all cases the spectra derived from the hot-film measurements are much lower in amplitude than their hot-wire counterparts.

Moving out into the boundary layer, as the value of the correlation coefficient decreases, the similarity between corresponding spectra disappears. The likeness of the hot-wire signal at y/δ = 0.3 to the film is not as evident, while at y/δ = 0.5, both signals are dissimilar.

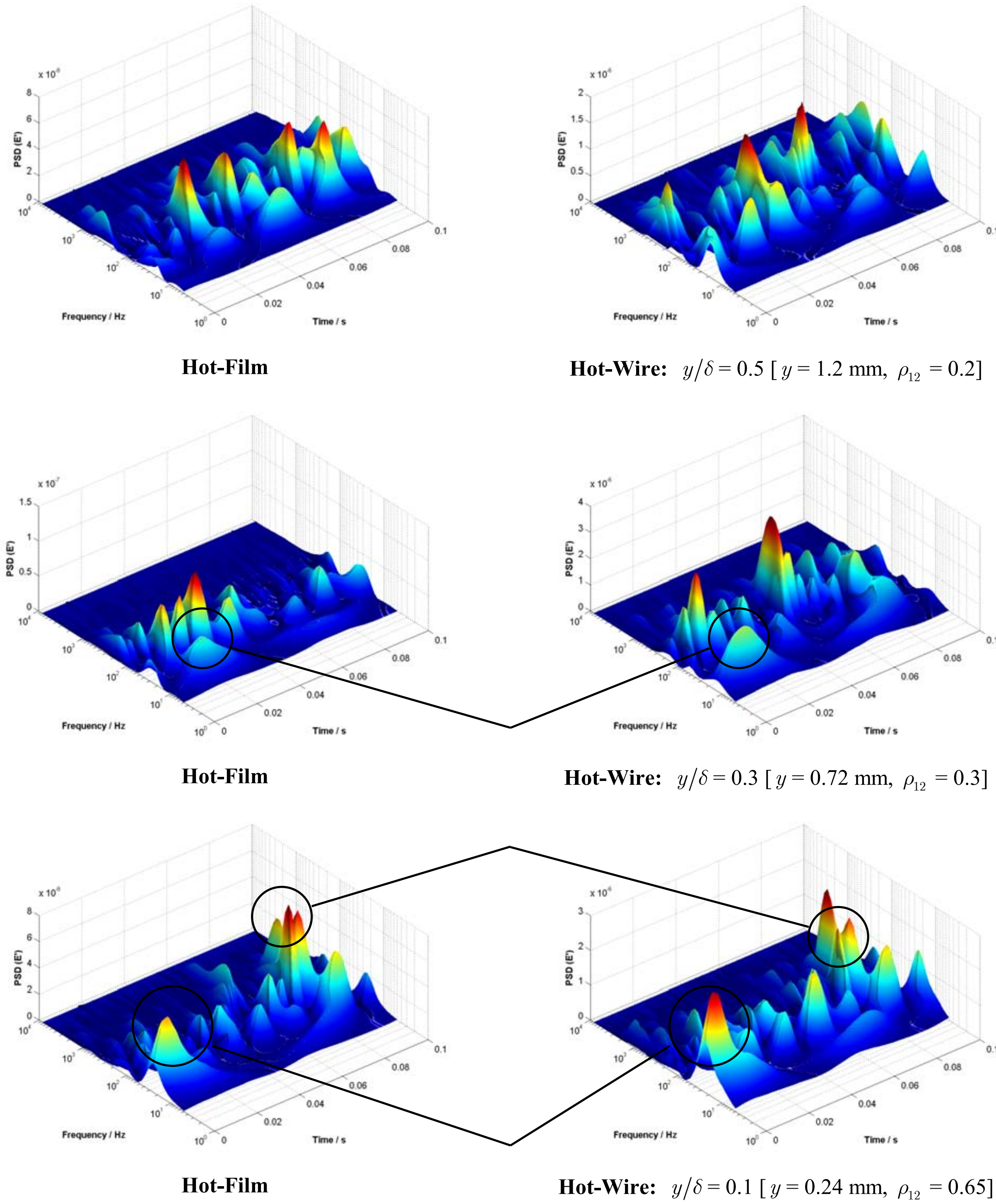

Figure 8: Continuous wavelet transforms of simultaneously sampled hot-wire and film data in a turbulent boundary layer (x/S = 0.766) at Re_c = 76,000, Tu_∞ = 5.2%. Comparison is made between fluctuating output voltages from the wall mounted film and a hot-wire placed in the boundary layer at y/δ = 0.1, 0.3 and 0.5 respectively. Values of $\mathbf{C}_{\omega,\tau}$ are expressed in terms of PSD (E').

CONCLUSIONS

- Hot-film and hot-wire measurements correlate in close proximity to the wall. This suggests that the surface mounted film is responding to the same phenomena as the wire in the near-wall region.
- The strength of this correlation is further verified from wavelet transforms of the experimental data, which show similarity in frequency and time in the near-wall region.
- No similarity exists between the wire and film signals further out from the wall.

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