Paper 10

Session 3 - Hot Wire Measurements

COMPARISONS BETWEEN TURBULENCE SPECTRA MEASURED WITH FAST RESPONSE PRESSURE TRANSDUCERS AND HOT WIRES

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ABSTRACT

Small, fast response, pitot probes offer a means of measuring turbulence spectra in flows which destroy hot wire probes.

This paper describes the response to turbulent flow of a pitot probe using a 1.5 mm diameter flush mounted Kulite pressure transducer, and compares the spectra with those from a hot wire probe. The performance of the probe was studied with regard to its suitability for measuring turbulence in high temperature flows typical of turbomachinery, for which some form of thermal barrier in front of the diaphragm is desirable.

The pitot probe and hot wire agree well below 8 kHz, but differ markedly in response at high frequencies in a manner that changes with flow velocity. This difference has been characterised in terms of two phenomena: the effect of the probe diameter to wavelength ratio, and the resonance of the diaphragm and thermal barrier system.

A correction strategy is described and shown to be effective for transducers with different combinations of coatings and screens.

NOMENCLATURE.

f	frequency (Hz)
$F(f)$	function of frequency, derived by calculation, that describes the transducer resonant response.
$G(k)$	function of wavenumber that describes reduction in sensitivity at small wavelengths.
$H(\bar{U})$	function of velocity that describes effect of Reynolds and Mach numbers on probe sensitivity.
k	wavenumber (1/m) $= 2\pi f / \bar{U}$
p	static pressure (N/m^2)
P_o	total pressure (N/m^2)
φ	velocity potential, such that $U = \partial\varphi/\partial x$, $V = \partial\varphi/\partial y$.
$M(k)$.	measured power spectral density $= d(u'/\bar{U}) / dk$
$S(k)$	true power spectral density
ρ	density (kg/m^3)
U, V, W	velocity in axial and transverse directions (m/s)
u'	fluctuating component of axial velocity (m/s)

Superscripts: $\bar{\ }$ time-mean component,
$'$ fluctuating component.

INTRODUCTION

Knowledge of the turbulence level and spectrum of turbomachinery flows is essential for the accurate prediction of boundary layer behaviour, in particular the heat transfer to first stage turbine components.

In low temperature flows turbulence may be easily measured using a hot wire probe. This however is not possible in hot or dirty flows that would melt, oxidise or break the wire.

In these conditions there are two main alternatives to using hot wires: laser anemometry and pressure transducer probes. Each of these has advantages and disadvantages.

Laser anemometry is non-invasive and can take measurements in two or three dimensions over a long period. To measure the higher frequency components of the turbulence however very dense seeding is required, which may not be possible or desirable, and reduction of the data to give a frequency spectrum may not be easy. Also, variations in refractive index through flows with large temperature gradients may cause focussing difficulties.

Miniature fast response pressure probes have the capability to measure streamwise turbulence spectra up to frequencies and wavenumbers limited mainly by diaphragm resonance and tip diameter. They will withstand fast, hot flows provided that either they are cooled or the exposure time is kept short to avoid excessive transducer temperatures (which sets a lower frequency limit on the measurements). Suitable transducers are available commercially.

Pressure transducers and microphones have been used in the past to measure the turbulence characteristics of flames. Ebrahimini (1967) and Mizutani et al (1975) used a long tube to feed a remote transducer that was out of the flame; this limited the frequency response to a few kHz.
Le Bot et al (1977) and Mauer and Liu (1987) used relatively large transducers that could survive exposure to the flame (through cooling or the use of high temperature materials) but because of their size did not have a very high frequency response or wavenumber resolution.

This paper demonstrates that it is possible to measure the streamwise component of turbulence to a higher frequency than this using a flush mounted sub-miniature pressure transducer in a pitot probe. These measurements can be corrected to agree with measurements of $u'/\overline{U}$ obtained using a single hot wire probe.

TEST FACILITY.

The testing was done in the open circuit wind tunnel shown in figure 1, with four fans sucking air via an inlet bell mouth into a 150 mm square working section which held a turbulence generating grid and the probes. This tunnel is also used for transient heat transfer measurements, and can be rapidly started by using a flap valve and bypass duct.
A grid of ten parallel 6mm bars spaced at 15 mm pitch was positioned 144 mm in front of the probe and produced a turbulence intensity of about 8.7%. This configuration was chosen using correlations for grid turbulence spectra from Roach (1987). The probe was in line with one of the bars. Velocities of up to 90 m/s were achieved with the grid in place.

INSTRUMENTATION.

Three pressure transducer configurations were tested:
1. A Kulite XCW-062/15 transducer with no screen but with a layer of RTV silicone rubber covering the diaphragm. The rubber is thought to be about 0.5 mm thick.

2. An XCW-062/15 transducer with a layer of rubber and a screen made from phosphor-bronze gauze.
3. A standard XCS-062/15 transducer with an "M" screen consisting of a foil sheet in front of the diaphragm with a central 0.35 mm hole and 10, 0.2 mm diameter holes at 0.6 mm radius around this.

In each case the transducer was 1.5 mm diameter.
These were held in a pitot tube so that the front of the screen, rubber or gauze was flush with the end of the tube as shown in figure 2.

The kulite signals were amplified, passed through a high pass (>70 Hz) filter and an anti-alias filter giving a -10dB response at 100kHz , and sampled at 200kHz by the 12 bit A-D converter in a Datalab DL1200 Waveform Recorder. The digitised data was then stored on an AT-compatible computer, for analysis.

A Dantec 55P11 hot wire, with a 1.25 mm length of 5 µm Pt-plated tungsten wire connected to a 55M01 constant temperature anemometer was used to measure the streamwise $u'/\overline{U}$ turbulence spectrum. The anemometer output signal was filtered and digitised in the same way as the pressure transducer signals.

The wire was calibrated in a low turbulence flow at velocities from 10 to 130 m/s, which allowed the instantaneous velocity to be calculated from the wire voltage measurements.

DERIVING TURBULENCE FROM PRESSURE MEASUREMENTS.

It was assumed that the ideal response of a fast pitot probe would be described by the unsteady form of Bernouilli's equation (Bradshaw, (1971)):

$$p + 1/2\,\rho(U^2 + V^2 + W^2) + \rho\frac{\partial\varphi}{\partial t} = constant$$

Defining P_0 as the pressure acting on the transducer at the stagnation point where $U = 0$ and assuming that V, W and $\partial\varphi/\partial t$ are unaffected by the presence of the probe gives:

$$P_0 + 1/2\,\rho(V^2 + W^2) + \rho\frac{\partial\varphi}{\partial t} = p + 1/2\,\rho(U^2 + V^2 + W^2) + \rho\frac{\partial\varphi}{\partial t}$$

$$P_0 = \overline{p} + p' + 1/2(\overline{\rho} + \rho')(\overline{U} + u')^2$$

Hinze (1975) suggests that p' can be approximated by $0.7\rho u'^2$.

The equation can then be reduced to a time-mean component:

$$\bar{P_o} = \bar{p} + 0.7\bar{\rho}\overline{u'^2} + 1/2\,\bar{\rho}(\bar{U}^2 + \overline{u'^2}) = \bar{p} + 1/2\,\bar{\rho}\bar{U}^2 + 1.2\bar{\rho}\overline{u'^2}$$

and a fluctuating component:

$$P_o' = (\bar{\rho} + \rho')\bar{U}u' + 1/2\,\rho'(\bar{U}^2 + u'^2) + 1.2\bar{\rho}(u'^2 - \overline{u'^2})$$

such that $P_o = \bar{P_o} + P_o'$.

At the Mach numbers available in this tunnel (≤ 0.25) the ρ' terms are insignificant and may be ignored. This gives:

$$P_o' = \bar{\rho}\bar{U}u' + 1.2\,\bar{\rho}u'^2 - 1.2\,\bar{\rho}\overline{u'^2}$$

or

$$\frac{P_o'}{\bar{\rho}\bar{U}^2} + 1.2\overline{\left(\frac{u'}{\bar{U}}\right)^2} = \left(\frac{u'}{\bar{U}}\right) + 1.2\left(\frac{u'}{\bar{U}}\right)^2 \quad \text{---------(1)}$$

At low levels of turbulence the $1.2\,\bar{\rho}\overline{u'^2}$ and $1.2\,\bar{\rho}u'^2$ terms may be ignored; the turbulence level is then derived simply by scaling the pressure data. This is illustrated by figure 2 which compares an analysis using equation (1) with one using equation (2).
The 0.7 constant in $p' = 0.7\rho u'^2$ is therefore not critical.

This gives

$$\frac{u'}{\bar{U}} = 1/2\,\frac{P_o'}{(1/2\,\bar{\rho}\bar{U}^2)} = 1/2\,\frac{P_o'}{(\bar{P_o} - \bar{p})} \quad \text{----------(2)}$$

The data was captured as a number of 32768 point files that were cut into sequences of 2048 points and multiplied by a Hamming window. The Fast Fourier Transforms of these were then averaged and smoothed slightly, and scaled to convert to turbulence intensity for plotting as a power spectral density such that the area under the curve (if plotted on a linear scale) would equal the total turbulence level. The results presented here are typically the average of 64 FFT's.

The frequency response of the anti-alias filters and signal amplifiers was measured and the power spectra have been corrected to allow for this.

CHARACTERISTICS OF GRID GENERATED TURBULENCE.

The streamwise turbulence spectrum was initially measured at three velocities using a hot wire. When plotted against frequency the power spectrum appears different for each case (figure 4). If the same spectra are described in terms of wavenumber ($2\pi f/\bar{U}$) the curves are very similar (figure 5). This indicates that, regardless of the mean velocity, at a given ratio of wavelength to grid bar diameter the grid always produces the same fractional velocity fluctuations $u'/\bar{U}$. This grid produces turbulence that is nearly independant of Re.

The streamwise turbulence spectrum was then measured at several velocities using a pressure transducer pitot probe. When these are plotted against frequency (figure 6) they are again all different. This would be expected from the hot wire data.
Figure 7 shows the pressure transducer spectra plotted against wavenumber. They are clearly different to the hot wire spectra both in level at high wavenumbers and in the way that they do not all follow the same line.

It will now be shown that both of these effects may be determined, and that having done this the genuine spectrum can be found from the measured spectrum at any reasonable test velocity.

CALCULATION OF FREQUENCY AND WAVENUMBER RESPONSE.

It was assumed that the hot wire measurement of the turbulence frequency spectrum as seen in figure 5 was correct, and that Reynolds and Mach number effects on the wavenumber spectrum were negligible, so that the same (wavenumber) power spectrum would have been produced by the grid at all velocities. The small step in the spectra seen in the 60 and 88 m/s spectra in figure 5 has been assumed to be a wire or support resonance and the spectrum above this point has been ignored. The hot wire anemometer settings (filter 3, gain 5) should give a practically flat frequency response up to 100 KHz at these velocities according to the Dantec manual.

If the turbulence spectrum measured by the pressure transducer is a function of velocity as well as wavenumber ($M(k, \bar{U})$), which appears to be the case from figure 7, and the genuine turbulence spectrum is a function of wavenumber only ($S(k)$ from figure 5), it is reasonable to suppose that

$$M(k, \bar{U}) = S(k)\,F(f)\,G(k)\,H(\bar{U}) \qquad \text{where } f = \frac{k\bar{U}}{2\pi}$$

ie. that we have a resonance function $F(f)$, a change in sensitivity with wavenumber $G(k)$, and a Reynolds and Mach number effect $H(\bar{U})$.

Figure 7 shows that at low wavenumbers the effects of velocity are small, so $H(\bar{U}) \approx 1$. The differences in level here are so small that an accurate determination of $H(\bar{U})$ would not be possible over the velocity range obtainable with this tunnel, so it has been assumed that $H(\bar{U}) = 1$ and thus

$$M(k, \bar{U}) = S(k)F(f)G(k).$$

If two tests are done at velocities $\bar{U}_1$ and $\bar{U}_2$ then

$$S(k) = \frac{M(k, \bar{U}_1)}{F\left(\frac{k\bar{U}_1}{2\pi}\right)G(k)} = \frac{M(k, \bar{U}_2)}{F\left(\frac{k\bar{U}_2}{2\pi}\right)G(k)}$$

$$\therefore \quad F\left(\frac{k\bar{U}_1}{2\pi}\,\frac{\bar{U}_2}{\bar{U}_1}\right) = \frac{M(k, \bar{U}_2)}{M(k, \bar{U}_1)}\,F\left(\frac{k\bar{U}_1}{2\pi}\right)$$

If $\bar{U}_2 \gg \bar{U}_1$ and it is assumed that $F(0) = 1$ the function F may be found by iteration from the two measured spectra M.

This technique is very sensitive to the level of the initial part of the curve. If this is only slightly different from 1.0 the resulting resonance curve will diverge rapidly. This was avoided (having obtained an initial estimate of the resonance amplitude ratio) by assuming that no resonance effects could be present at frequencies where the increase in amplitude was less than 1% of the peak increase at resonance. Values of $M(k, \bar{U}_2) / M(k. \bar{U}_1)$ between 0 Hz and here were blended in by multiplying by a cosine window function such that the 0 Hz point was at 1.0 and the 1% point was at its genuine value (figure 8).

Once $F(f)$ has been found using this technique, $G(k)$ is found from

$$G(k) = \frac{M(k, U_1)}{S(k)\,F\left(\frac{k\bar{U}_1}{2\pi}\right)}$$

assuming that the true spectrum $S(k)$ is that measured by the hot wire.

RESULTS

Figure 9 shows the resonance characteristics of the three transducers.

Kulite 1 (with just the RTV rubber layer) appears to have a resonance at above 100 kHz. This is expected as the natural frequency of the silicon diaphragm (250kHz) will be reduced to perhaps 130 kHz by the mass of the rubber.

Kulite 2 (with rubber plus gauze screen) has a very severe resonance at 70 kHz. The useful frequency response here is limited not just by the accuracy with which the resonance curve can be calculated (which depends on assumptions about the low frequency part of the curve) but also on the effects of gas temperature on the resonant frequency. The natural frequency will vary as the square root of the temperature of the air behind the screen and this could be difficult to measure during a transient test in a hot flow.

Kulite 3 (with the standard "B" screen) has a resonance peak at 52 kHz.

Figure 10 shows the roll-off of sensitivity as the wavelength of the turbulence ceases to be large compared to the probe diameter. Kulite 1 suffered from drift due to thermal expansion of the rubber with changing temperature which prevented an accurate DC calibration from being done, so a calibration has been assumed that gives the same low wavenumber sensitivity as the other two transducers.
The sensitivity is constant up to $k \approx 1000$, which corresponds to a wavelength $\lambda \approx 6$ mm which is 2.5 × the probe tip diameter and 4 × the transducer diameter.

The analysis of kulite 2 was based on data taken at 30 and 64 m/s. As proof of the validity of the technique, figure 11 shows data taken at 18, 30, 64 and 88 m/s corrected by F(f) and G(k) and compared with the power spectrum measured by a hot wire.
These corrections enable the pitot probe to measure turbulence spectra in environments that would destroy a hot wire.

CONCLUSIONS.

1. Sub-miniature pressure transducers are well suited to measuring turbulence at high frequencies in hostile environments.

2. An analysis of the type described here is essential to correct the probe response for frequency and wavenumber effects.

3. The best frequency response is obtained if transducers are protected only by a layer of rubber. One should avoid a perforated screen unless this can be placed so close to the diaphragm that the the natural frequency of the air in the cavity is well above the frequency range of interest.
If accurate DC pressure measurements are required however it is better to use a screen instead of a layer of rubber to avoid drift problems.

4. This type of probe has a flat response down to wavelengths of about 4 × the transducer diameter (or 2.5 × the probe tip diameter) once it has been corrected for resonance effects.

ACKNOWLEDGEMENTS

The authors wish to thank Rolls-Royce plc and the Royal Aircraft Establishment (Pyestock) for funding this work.
We are also very grateful to Mr T. Norman, Mr D. R. Stayt, Mr E. Woodward and Mr J. Gills for building the probes and working section.

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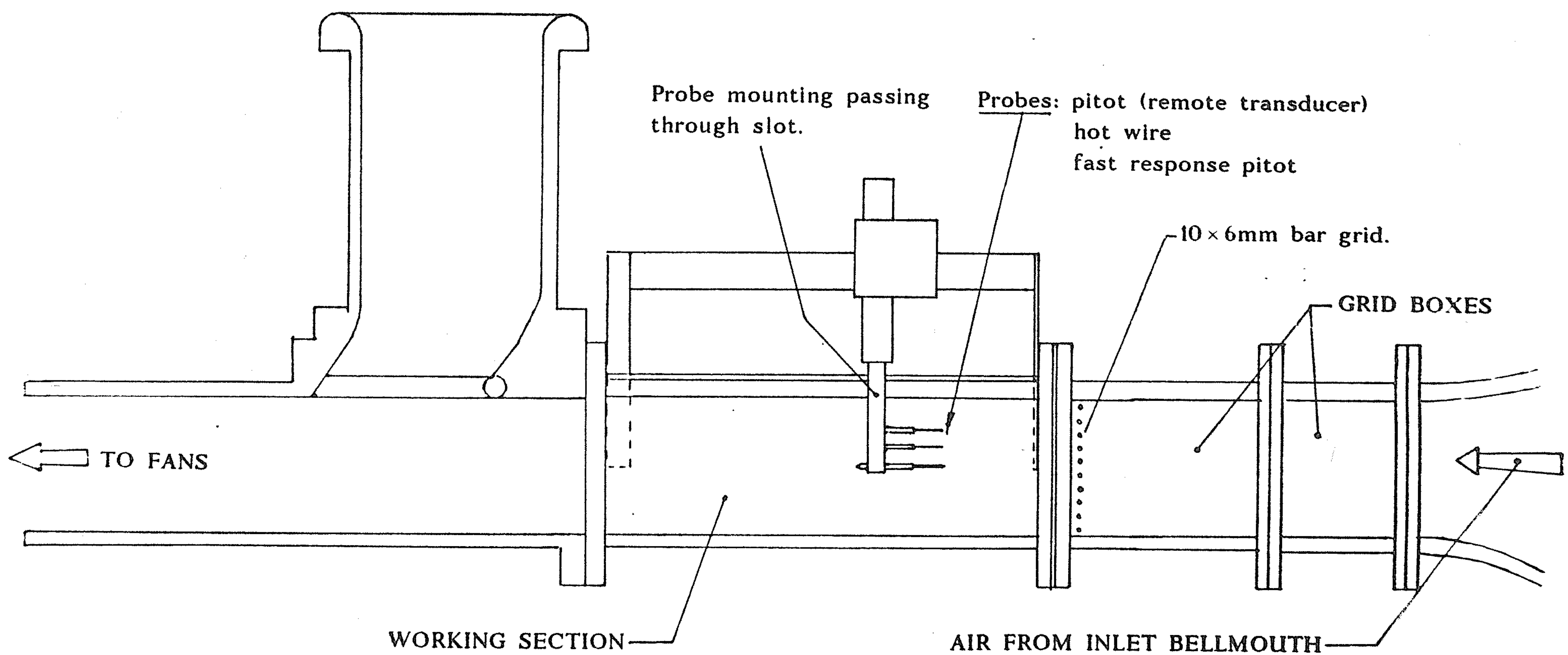
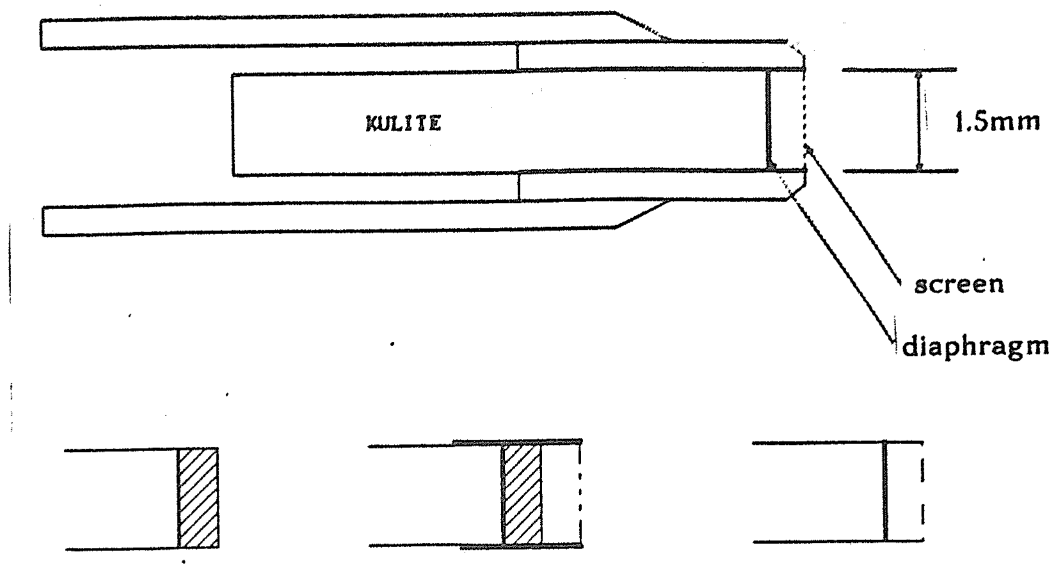


FIGURE 1.

Wind tunnel working section and grid box.



KULITE 1
0.5mm of RTV rubber over diaphragm.

KULITE 2
0.5mm of RTV rubber plus screen of bronze gauze (0.1mm wires at 0.25mm pitch, 22 holes open).

KULITE 3
Standard XCS062-15 transducer with "B" screen.

FIGURE 2

Probe tip and transducer screen configurations.

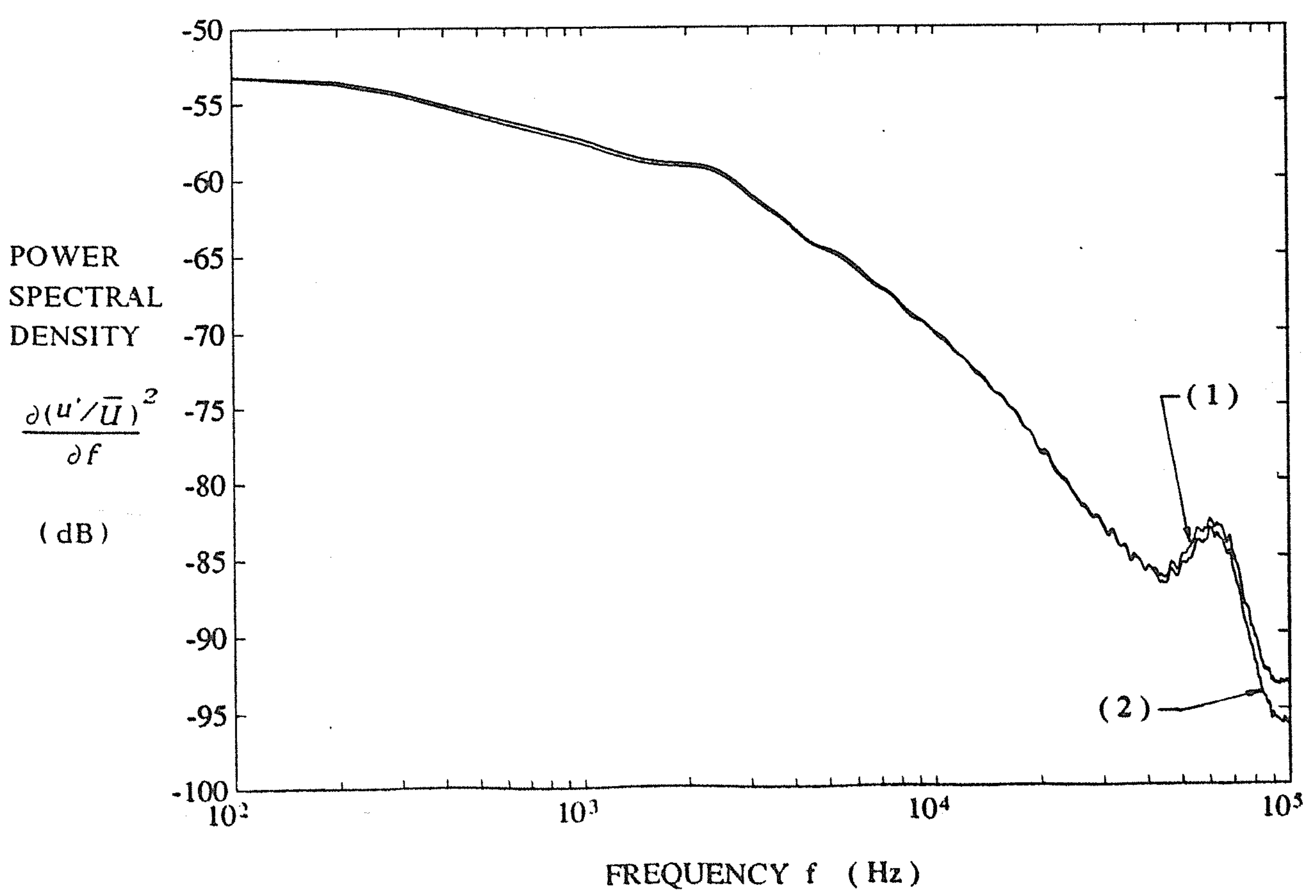


FIGURE 3.

Comparison of quadratic solution (1) and linear solution (2) when deriving grid turbulence spectrum from total pressure measurements.

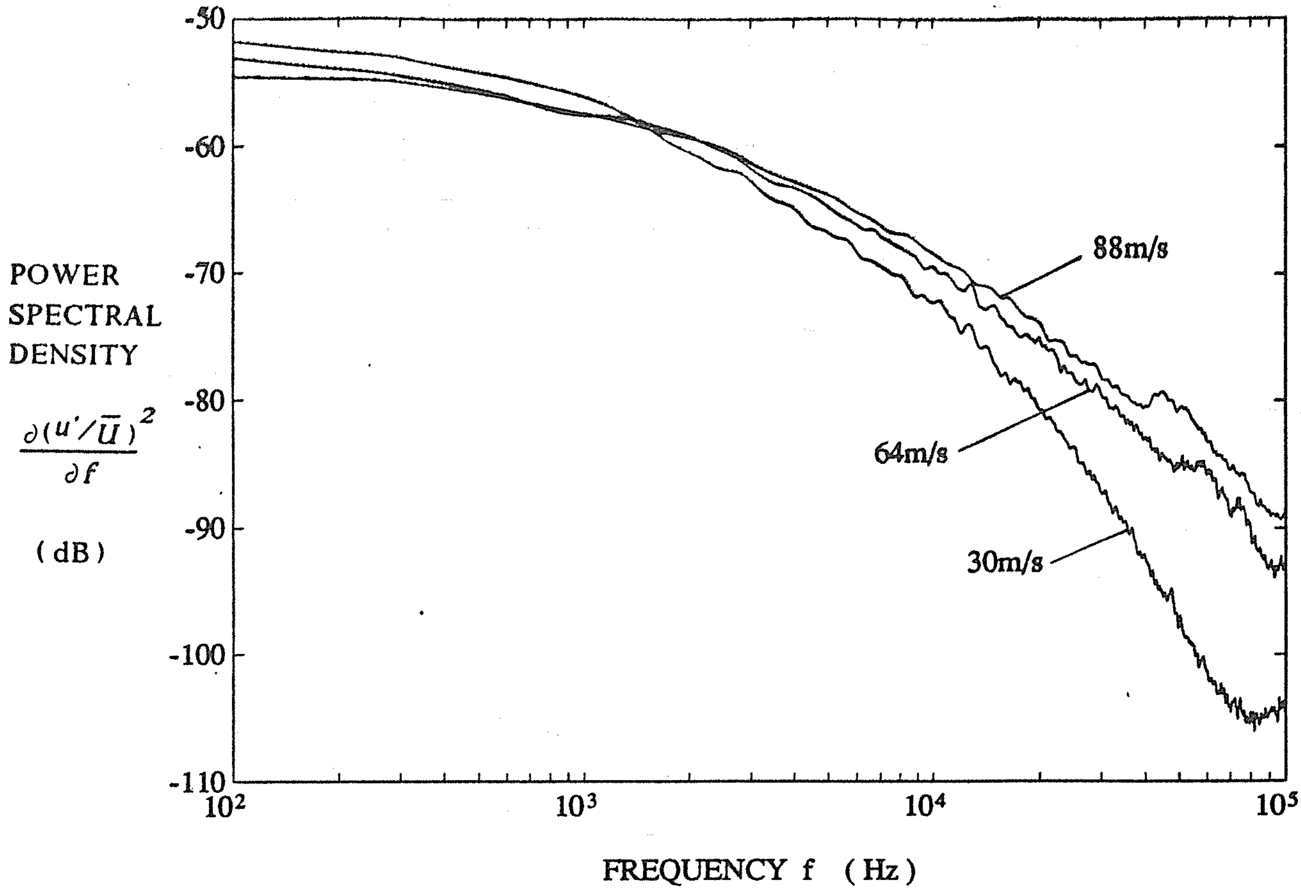


FIGURE 4.

Grid turbulence spectra at various velocities, measured by a hot wire and plotted against frequency.

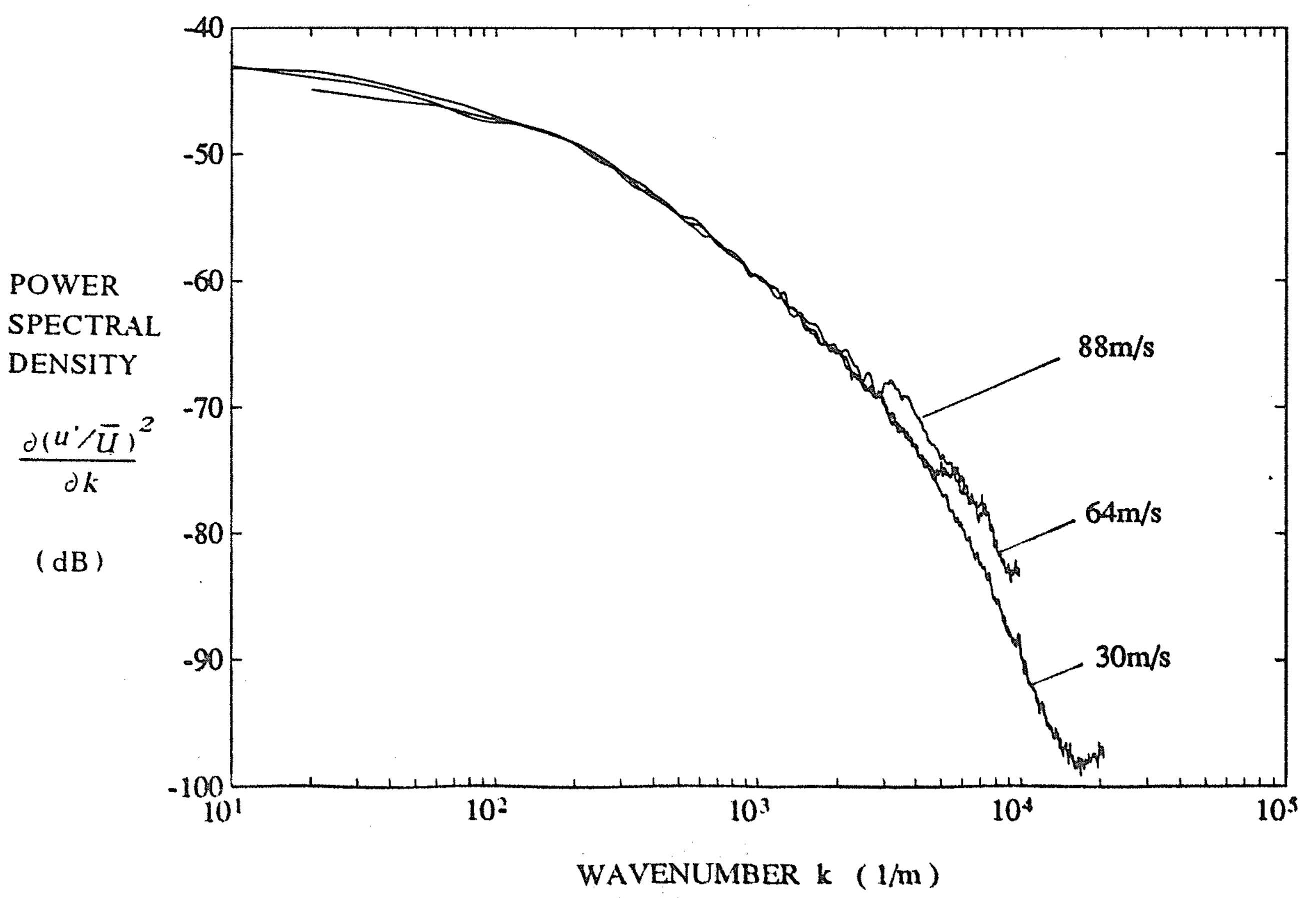


FIGURE 5.

Grid turbulence spectra from figure 4 plotted against wavenumber

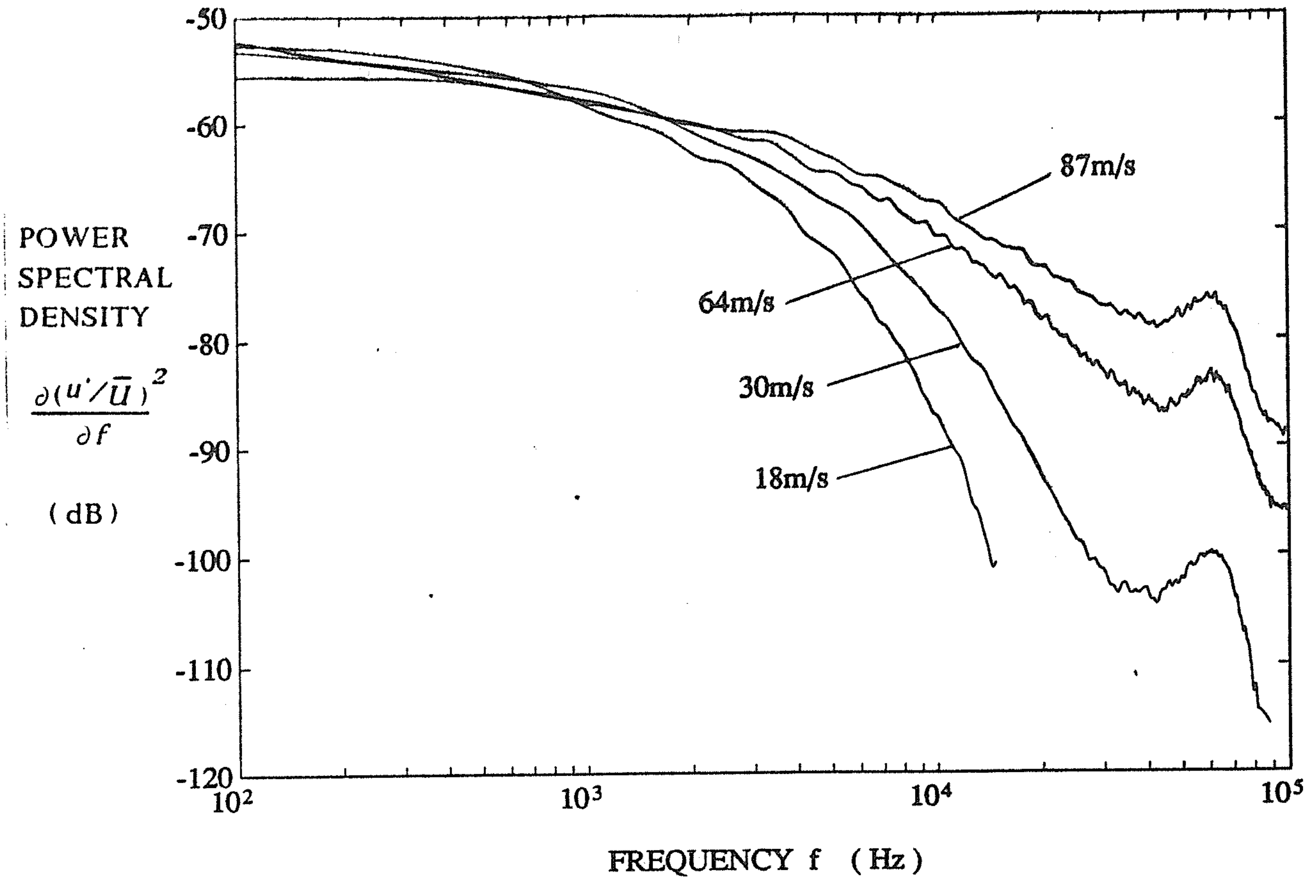


FIGURE 6.

Grid turbulence spectra measured by kulite 2 at various velocities and plotted against frequency.

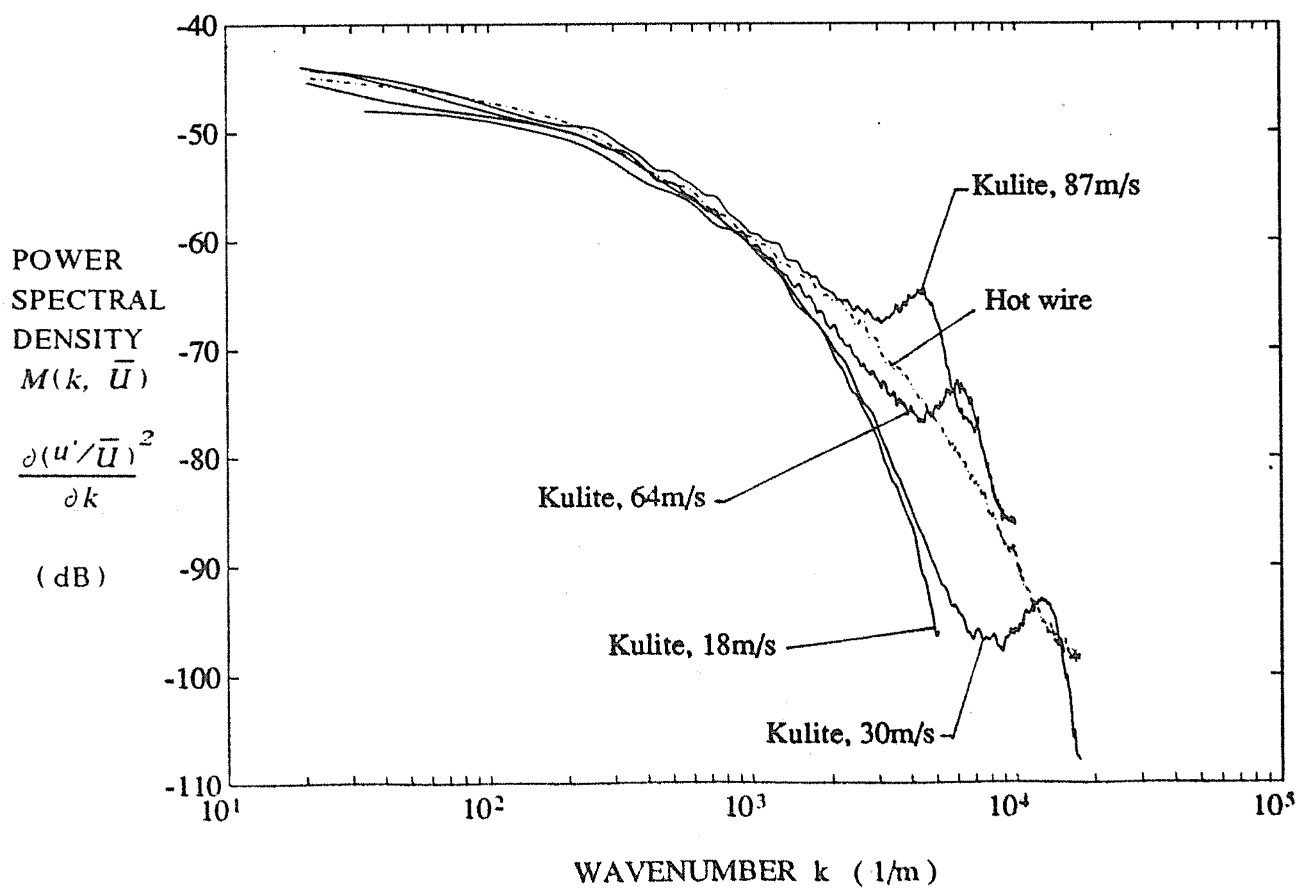


FIGURE 7.

Grid turbulence spectra from figure 6 plotted against wavenumber and compared with 30m/s wavenumber spectrum measured by a hot wire.

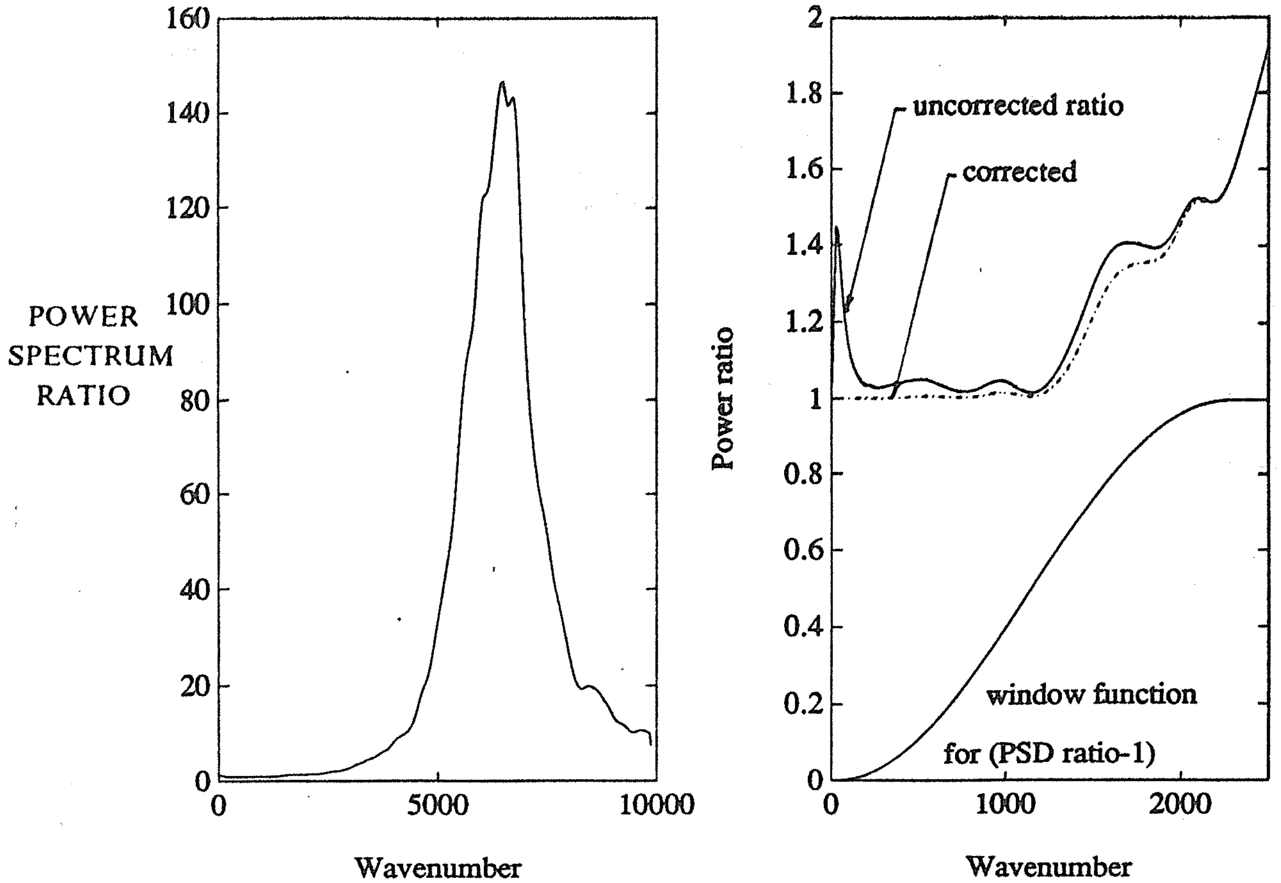


FIGURE 8.

(a) Ratio of 64m/s and 30m/s kulite 2 curves from figure 7,
$M(k,\ 64m/s)\ /\ M(k,\ 30m/s)$.

(b) Attenuation of this curve at low wavenumbers to avoid analysis errors.

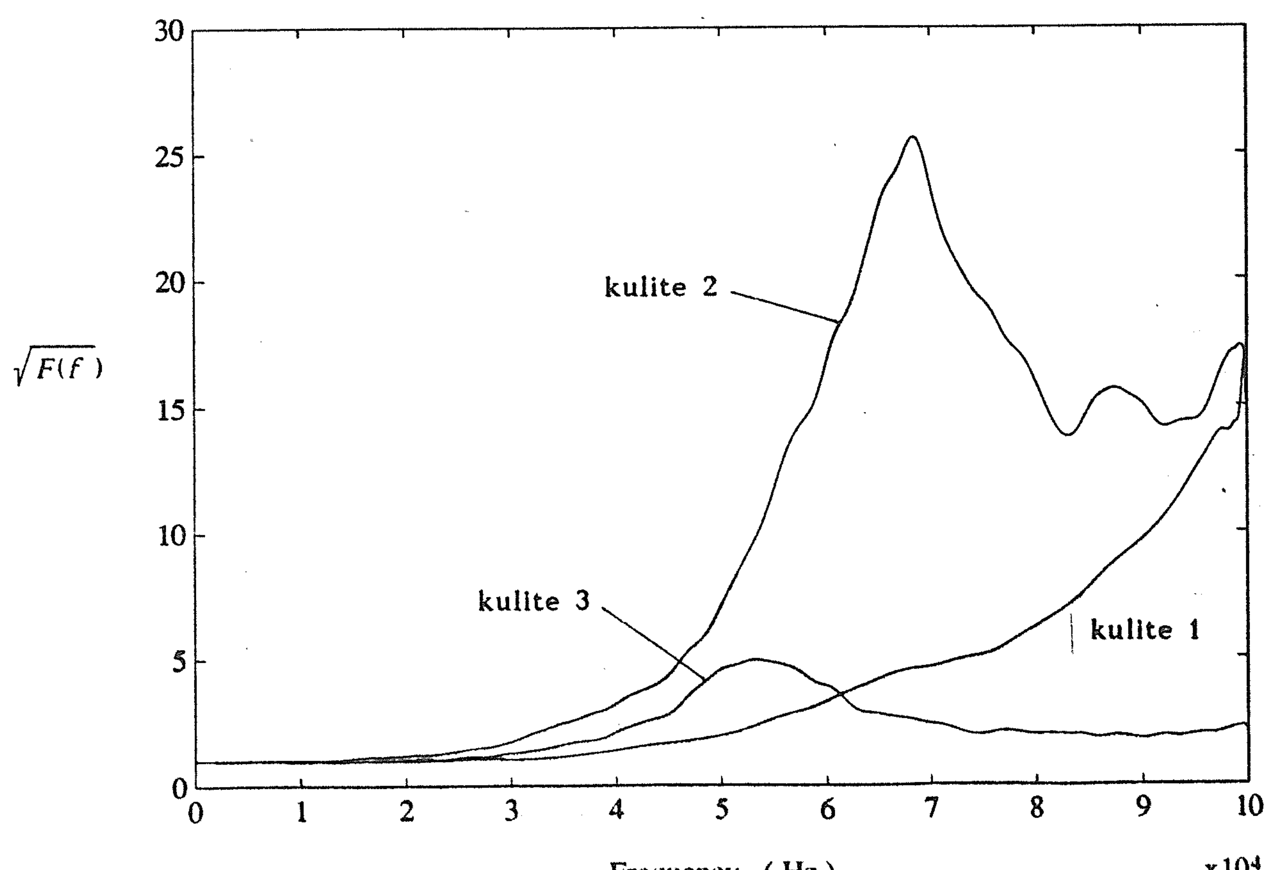


FIGURE 9.

Analysis results: resonance function $F(f)$ for each kulite derived from ratio of 64 and 30m/s measured turbulence spectra.

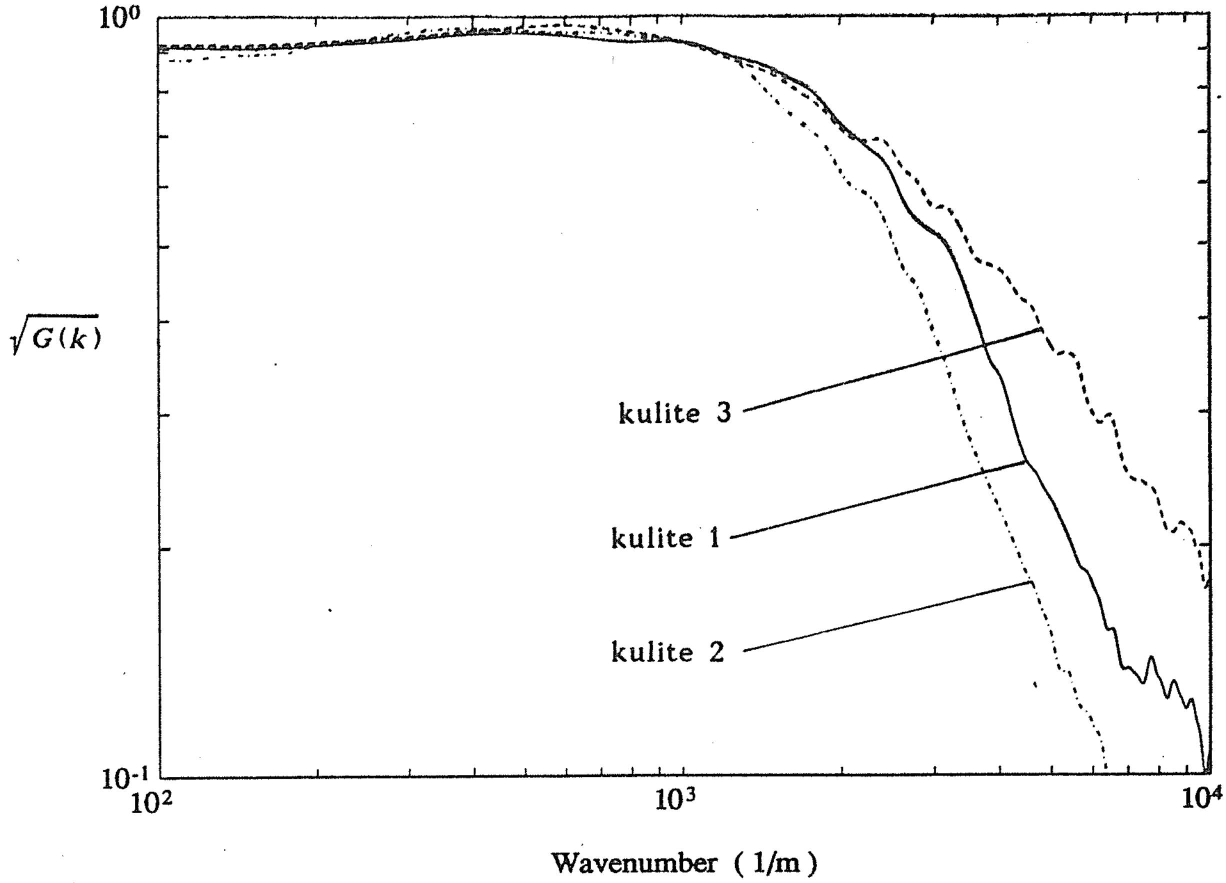


FIGURE 10.

Analysis result: wavenumber sensitivity function $G(k)$ calculated as the ratio of the kulite data (having corrected for resonance) to the true (hot wire) spectrum.

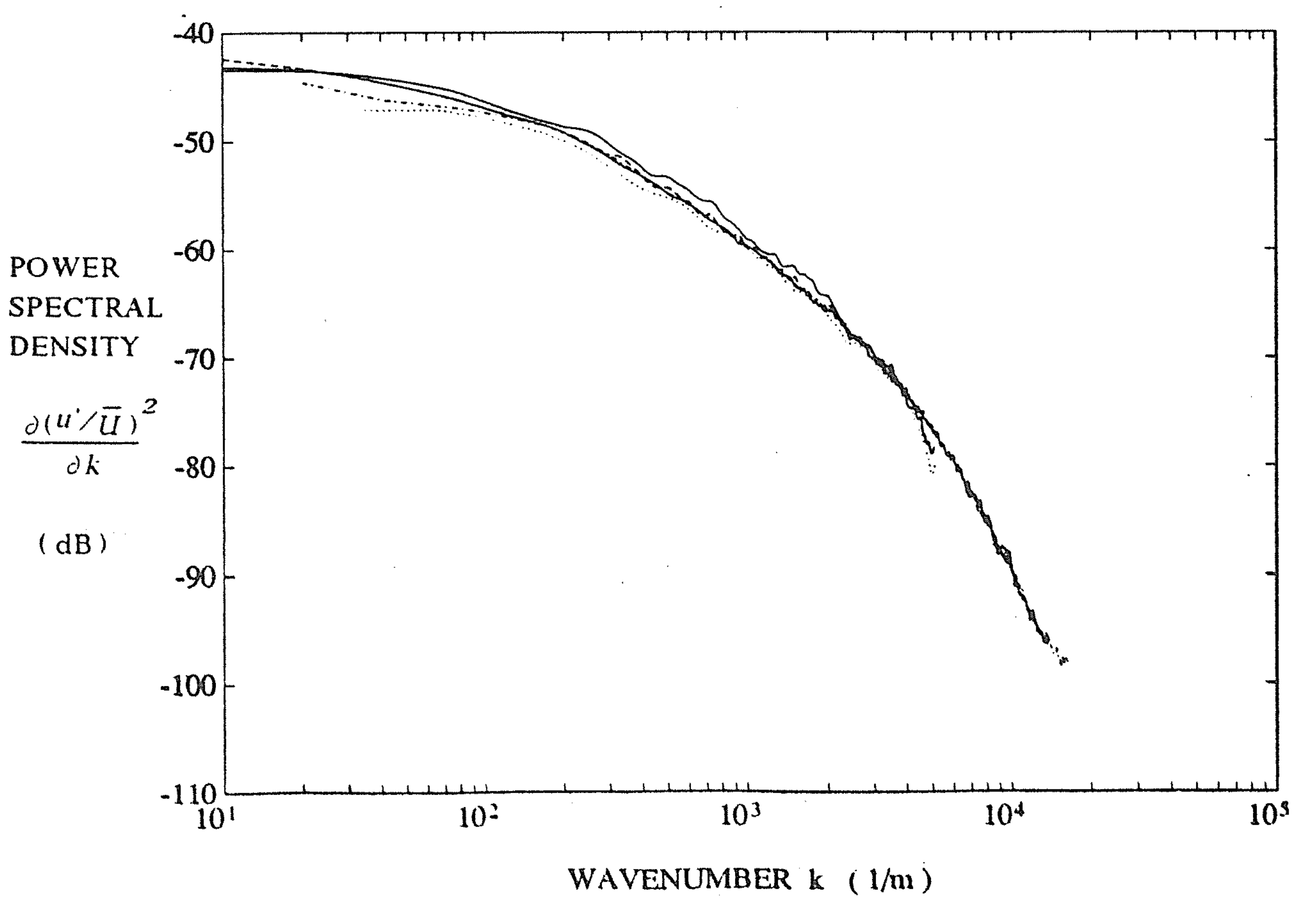


FIGURE 11.

Kulite data from figure 7 corrected for resonance and wavenumber effects and compared with hot wire spectrum.