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FLUID MOTION SUB-COMMITTEE

Some Observations on Vortex Shedding and Acoustic Resonances

- By -

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SUMMARY

Vortex shedding from cylinders and plates has been studied to explain various phenomena reported by R. A. Shaw. His observations suggested forms of acoustic resonance excited by votex shedding. The present work shows that very powerful resonances can be produced, but that these are determined by the dimensions of the wind tunnel and not solely by the model as proposed by Shaw.

1. Introduction

Shaw (1949(a), 1949(b)) proposed an acoustic theory to explain a variety of unsteady fluid dynamic phenomena on aerofoils and bodies. He suggested that certain features of real flows, such as transition, separation and shock wave position, react together and arrange themselves in resonant systems. He postulated that acoustic pulses travelled between these 'centres of disturbance' in such a way that a resonance was excited. It was suggested that the frequencies of vortex shedding from bluff bodies could also be predicted by such a theory if one considered the interaction between the separation points and the vortex wake, and in particular he correctly predicted the Strouhal-number ~ Reynolds-number behaviour of a circular cylinder using some almost plausible assumptions. The theory received no support and it was left to Shaw to provide experimental evidence. In a later paper Shaw (1951) described two experiments which he felt presented irrefutable evidence in favour of his theory. In the first experiment the surface pressure fluctuations on a circular cylinder were investigated. The acoustic theory predicted the existence of high frequency oscillations in addition to the usual low frequency Strouhal signal. Narrow band spectra did in fact show small sharp peaks at the 'acoustic frequency', or rather two peaks either side of this frequency, separated by twice the Strouhal frequency. This is just the result one might expect if the high frequency mode were modulated by the shedding process. The theory predicted the observed frequency to within 1%. The second series of experiments concerned the unsteady flow past an aerofoil model fitted with a trailing edge spoiler. It was found that the fluctuating pressures on the model surface were increased over certain bands of tunnel speeds and that the predominant frequencies, which generally increased almost linearly with flow velocity, locked onto a fixed value over the same speed range. The frequencies of these resonant 'pauses' coincided quite well in some cases with the theoretical frequencies for acoustic modes based on the model chord.

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* Replaces NPL Aero Report 1311 - A.R.C.31 829

The experiments to be discussed in this report were carried out to investigate the validity of Shaw's experiments. It was felt that the experimental data showed good agreement with a theory that was basically unacceptable. The author is aware of a number of other experimenters who have also looked into this work, but the results have generally been of a negative nature and have not been published.

2. Circular Cylinder Experiments

Detailed pressure fluctuation measurements were made on a number of circular cylinders in the 2.44m × 1.83m (8ft × 6ft) low speed tunnel at the College of Aeronautics by Smith and Rogers (1962). The surface pressure fluctuations were detected by a Brüel and Kjaer probe microphone adjusted to have a flat frequency response from 16Hz to 12KHz. The microphone signals were analysed by a Marconi narrow-band (4Hz) double hetrodyne wave analyser type TF.455 D-D/1.

Experiments on a 153mm (6in) diameter model showed a pressure spectrum at the station 90° to the stagnation point which not only had a strong peak at the Strouhal frequency, but also showed weak signals at 1190Hz plus and minus the Strouhal frequency - exactly as Shaw had found on his 130mm (5 1/8in) dia model. Similar results were obtained for a range of windspeeds and angles of rotation. Identical results were also obtained with a 305m (12in) and a 76.1mm (3in) dia model, which according to Shaw's theory should have generated acoustic frequencies at half and double this value respectively.

Dr. Hodgson and the author continued the investigation to determine the cause of this high frequency signal. In fact, it was not difficult to trace these signals to the Marconi analyser. The instrument indicated two spurious peaks when fed with a low frequency sine wave, the frequencies being 1190± the frequency of the discrete signal. The power in these high frequency peaks was about 10^{-6} below that of the low frequency signal. In most experiments such a wide dynamic range is not needed and no difficulties would be experienced with this analyser, but in the present case where weak high frequency signals were being searched for extra care is needed. Removal of the low frequency part of the spectrum by a high pass filter prior to detailed analysis at high frequency by the Marconi instrument eliminated these spurious modes.

It is worth recording that Shaw used an identical instrument to analyse the pressure fluctuations in his cylinder experiments.

3. Plate Experiments

3.1 College of Aeronautics

A thin flat plate with an elliptic extension to the trailing edge was used to investigate the resonance reported by Shaw. A hot-wire probe positioned just outside the turbulent wake was used to detect shedding. After broad-band filtering the signals were matched with a sine-wave on a dual-beam oscilloscope, the oscillator frequency being read off a frequency meter. In this way it was possible to determine the shedding frequency to about ±½%. Fig.1 shows the relationship between tunnel velocity and shedding frequency obtained. There was no observable resonance over the speed range investigated either side of the conditions for resonance predicted by the acoustic theory.

At/

At Mr. Shaw's request a further model, with a circular trailing-edge extension, was also tested. Although the hot-wire signals were less regular in this case, and the frequency harder to define, the resulting plot of frequency versus tunnel speed again failed to show any deviation from the almost linear relationship between velocity and frequency. However, at certain speeds a clear tone could be heard outside the wind tunnel. This signal was sensed by a hand-held microphone and was found to be of the same frequency as the hot-wire signal. When the two signals were compared on an oscilloscope it was found that they also had a fixed phase relationship. The plate length was changed from 456mm (18in) to 381mm (15in) to see if this resonance was connected with the model chord, as suggested by Shaw, but the frequency of the acoustic signal hardly changed from 204.5 to 205Hz. Fig.2 shows the frequency ~ velocity data for the two plates of different chords; both show slight kinks or 'pauses' at about 205Hz although more data are needed to confirm this. The 381mm (15in) chord model was wire braced to check that mechanical vibrations were not producing the phenomenon.

At resonance the hot-wire and microphone signals were locked in phase over a range of probe positions along the span and it therefore seemed clear that the shedding process must be well correlated along the span. Correlation measurements between two hot-wire probes at different spanwise stations along the trailing edge confirmed the above conjecture; at resonance the correlation length was increased by a large factor. However, this work will not be discussed further here since the more detailed work recently completed at the NPL described in the next section shows the same phenomenon more markedly.

The observed resonance concerned some interaction between sound waves generated by the flat plate and the vortex shedding in such a way that the vortex motion became organized over the entire span. Rough calculations suggested that there could be a standing wave pattern normal to the plate across the 2.44m (8ft) dimension of the working section of the wind tunnel and the further experiments at the NPL were carried out to determine the acoustic field in the working section at resonance.

3.2 NPL experiments

3.2.1 The resonance

The model, consisting of a flat plate 406mm (16in) by 6mm (¼in) thick fitted with a 31.8mm (1¼in) dia trailing edge, was mounted vertically in the centre of the 2.14m × 2.14m (7ft × 7ft) tunnel. Initial experiments showed that there was a resonance similar to the previously observed at Cranfield, but arising at a slightly higher wind speed and much more powerfully - the sound outside the working section reached an almost painful level. A hot-wire probe placed at the edge of the wake close behind the trailing edge was again used to detect shedding.

The frequency of the shedding signal was obtained from the peak of the spectrum generated by a Nelson-Ross analyser in conjunction with a storage oscilloscope. Fig.3 shows the frequencies obtained for a range of wind speeds: the frequency increased steadily with the flow velocity except for a range over which the frequency remained constant. During this frequency 'pause' the hot-wire signal increased in amplitude and became very regular; also the sound level outside the tunnel reached a maximum level of about 120dB. The levels of the velocity fluctuations at two stations in the tunnel together with output of a microphone positioned at a pressure fluctuation maximum are plotted against flow speed through the resonant speed range in Fig.4.

Two-point/

Two-point correlation between the hot-wire probes detecting vortex shedding near the trailing edge are shown on Fig.5 for two flow speeds: (a) just below resonance and (b) in the condition of strong sound generation. The correlation length changes quite dramatically from something like 100mm (4in) to almost the full 2.14m (7ft) span.

3.2.2 The velocity and pressure fluctuations

Fluctuating velocities and pressures were explored in the working section at the speed where the resonance was most pronounced. A Disa cross-wire probe was traversed across the working section in a direction normal to the trailing edge. Fig.6 shows the measurement obtained from the Disa correlator equipment in terms of the velocity fluctuations in the stream and transverse directions.

Fluctuating pressures were measured by a 12mm ($\frac{1}{2}$in) Brüel and Kjaer microphone fitted with a 4mm conical nose piece directed into the flow. RMS levels were obtained on the analyser as the microphone was traversed across the flow. An additional fixed microphone enabled the relative phases of the signals to be compared on an oscilloscope. The signals were either in phase or 180° out of phase with the monitor probe except in the region close to the wake. A number of traverses were made at various downstream positions and these are plotted in Fig.7 in the form of contours of fluctuating pressure intensity. The fluctuating pressure distribution along one side of the plate was obtained useing a Brüel and Kjaer 4mm probe microphone passing through holes in the model. (see Fig.8)

4. Discussion of Plate Experiments

Figs.3 and 4, which show the frequency 'pause' and the associated high level of sound, clearly indicate that some form of acoustic resonance was taking place. Shaw also observed this type of behaviour on aerofoil models fitted with trailing edge spoilers, but he attributed these effects to an acoustic resonance involving the path length around the model. In the experiments carried out at Cranfield the model chord was changed without any change in the resonant frequency. The observed type of resonance appeared to be controlled by the dimensions of the working section and not by the model chord. Later measurements at the NPL showing velocity and pressure distributors across the tunnel clearly indicated the existence of an acoustic standing wave. The measured velocity fluctuations are compatible with the pressure fluctuations if they both arise from sound. The fluctuating pressure of a sound wave having velocity q' is

$$p' = \rho q' a, \qquad \text{where } a \text{ is the speed of sound.}$$

In terms of a pressure coefficient

$$C_p' = 2\left(\frac{q'}{U}\right) \times \frac{1}{M} \qquad \text{where } M \text{ is the Mach number.}$$

The maximum value of q' measured on Fig.6 at 0.84m ($27\frac{1}{2}$ins) from the model centre lines is 1.55% of the free stream velocity.

$$\text{Therefore } C_p'(\text{RMS}) = \frac{1.55 \times 10^{-2}}{108} \cdot 2.1122 = 0.32$$

This value compares quite well with the pressure fluctuations measured at 305mm (12in) from the model centre line. (see Fig.8)

The standing wave system consisted of $1\frac{1}{2}$ wave lengths across the wind tunnel working section and it may be noted that this wave length is slightly less than that of a plane wave of the observed frequency. Parker (1966-1967) has investigated similar resonance phenomena in cascade systems, and has shown that the chord of the model influences the wave pattern. He has calculated eigen-frequencies for cascade models with different chord to gap ratios for a number of resonant modes.

5. Conclusions

5.1 Circular cylinder experiments

There is no evidence whatsoever to support Shaw's contention that an acoustic resonance between the wake vortex structure and the model determines the Strouhal frequency. The work at Cranfield revealed that the high frequency resonant mode detected by Shaw was spurious and arose through the type of spectrum analyser used.

5.2 Plate experiments

Experiments on plates with bluff trailing edges have shown that powerful resonances can occur between the vortex shedding and an acoustic wave pattern in the wind tunnel. At resonance the shed vortices are not only stronger but are also correlated over the whole span so that the oscillating lift becomes very large. This in turn provides a strong acoustic source which excites the standing wave pattern in the tunnel. It is clear that the observed resonance is not the result of acoustic pulses passing around the model as suggested by Shaw. It seems likely that the resonances observed by Shaw were of the above type.

One of the original criticisms of Shaw's theory was that insufficient sound could be generated by the wake of a rigid model at low Mach number to influence the flow. However, the present experiments have shown that sufficient sound is generated by the oscillating lift on the section when this becomes correlated over the whole span. The unsteady forces produced on the model are very large under these conditions and could cause structural failure. It is suggested that resonances of this type can be one cause of trouble in boiler tube arrays.

6. Acknowledgement

The author acknowledges the assistance given by Mr. P. Jones.

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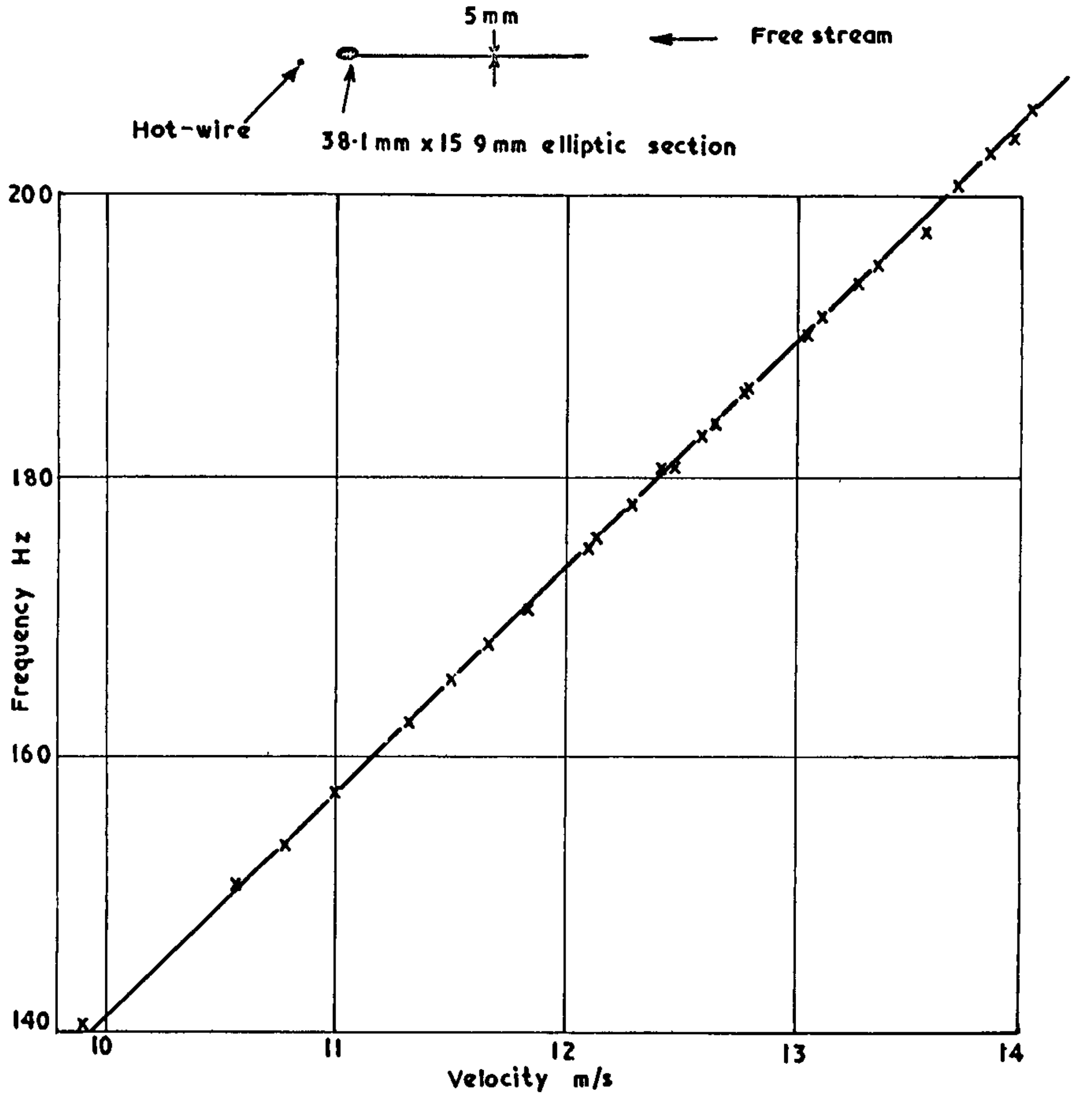
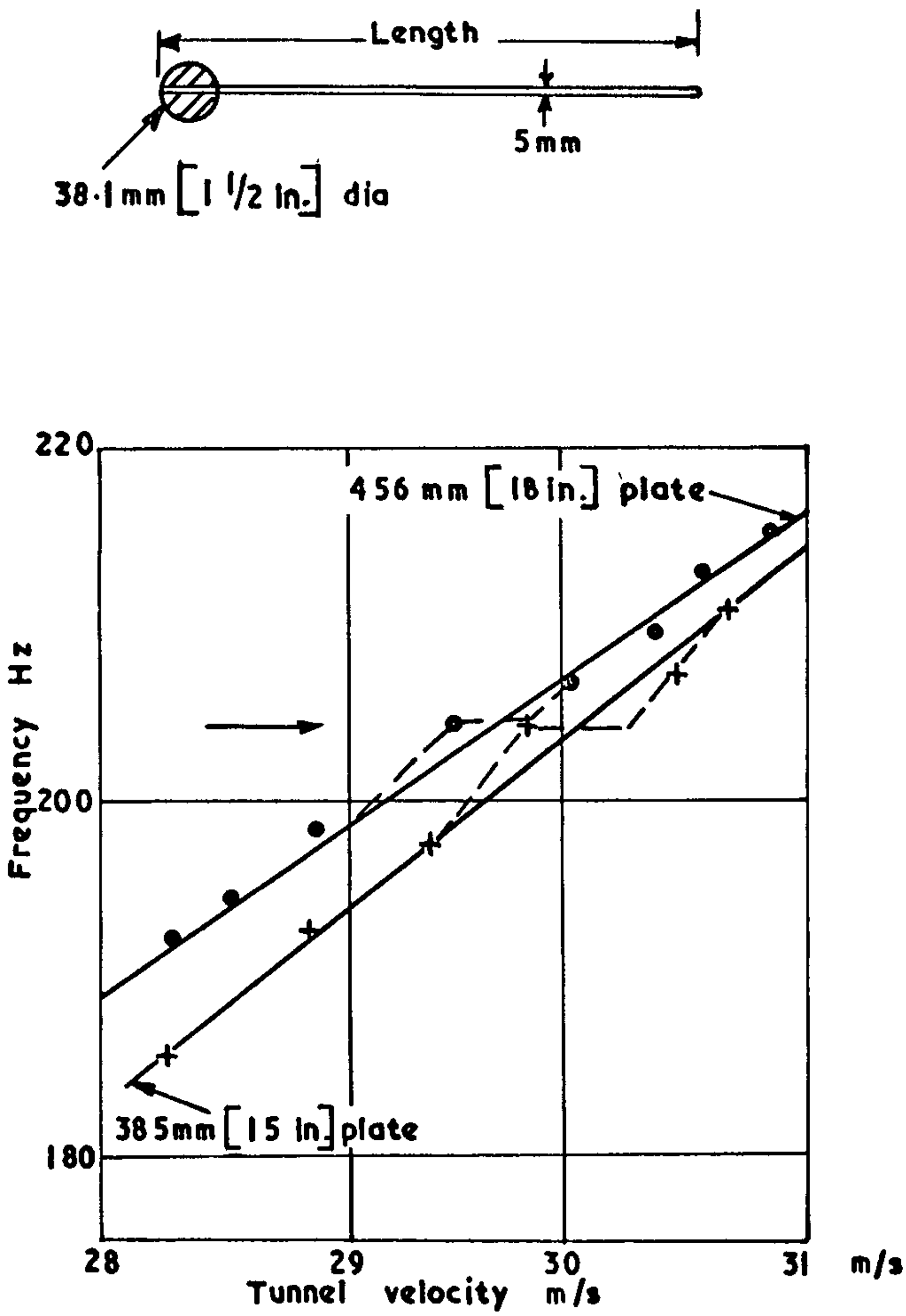
FIG. 1

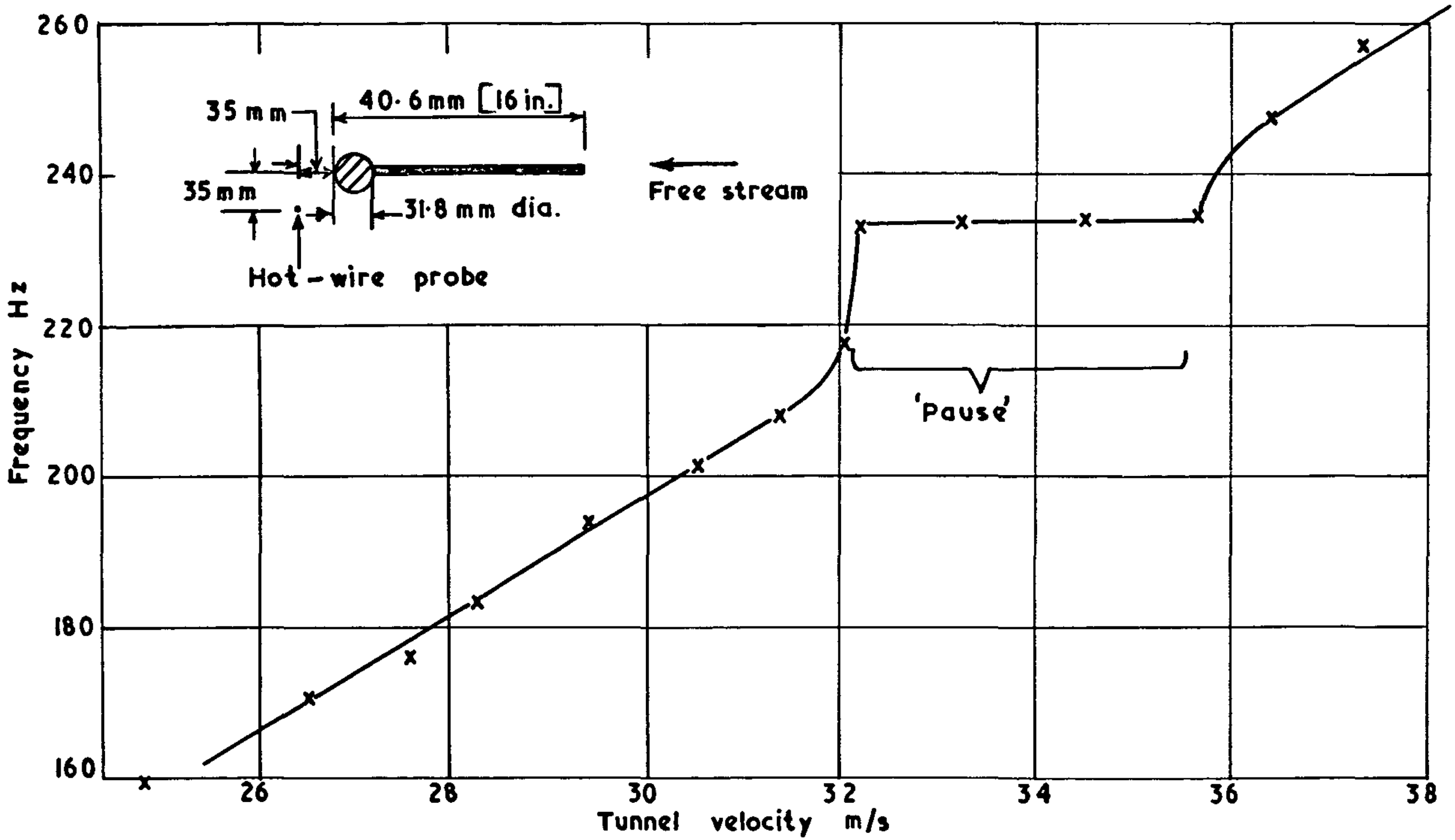


Shedding frequency against tunnel speed for model with smooth elliptic trailing edge

FIG. 2

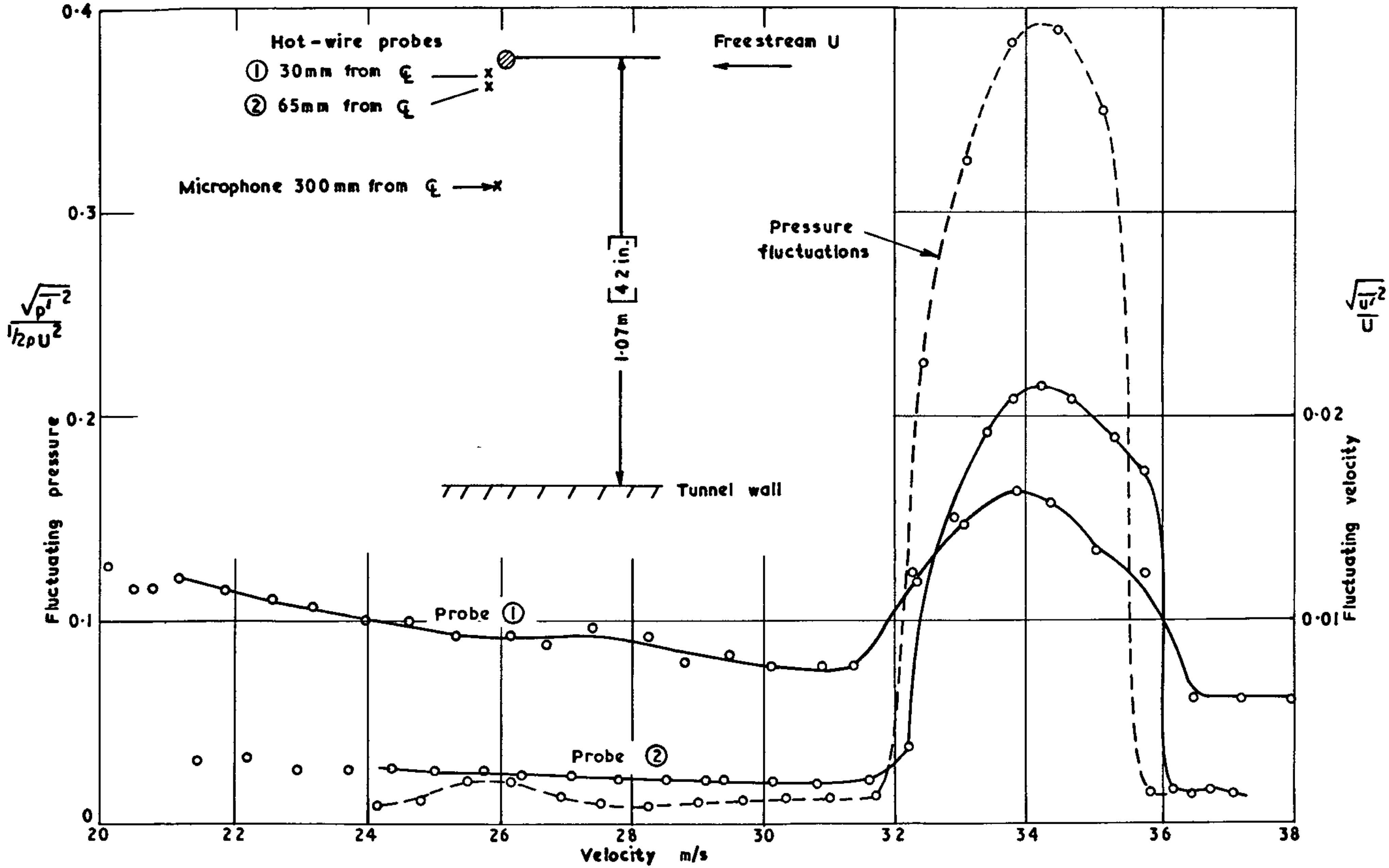


Shedding frequency of models with circular trailing edges



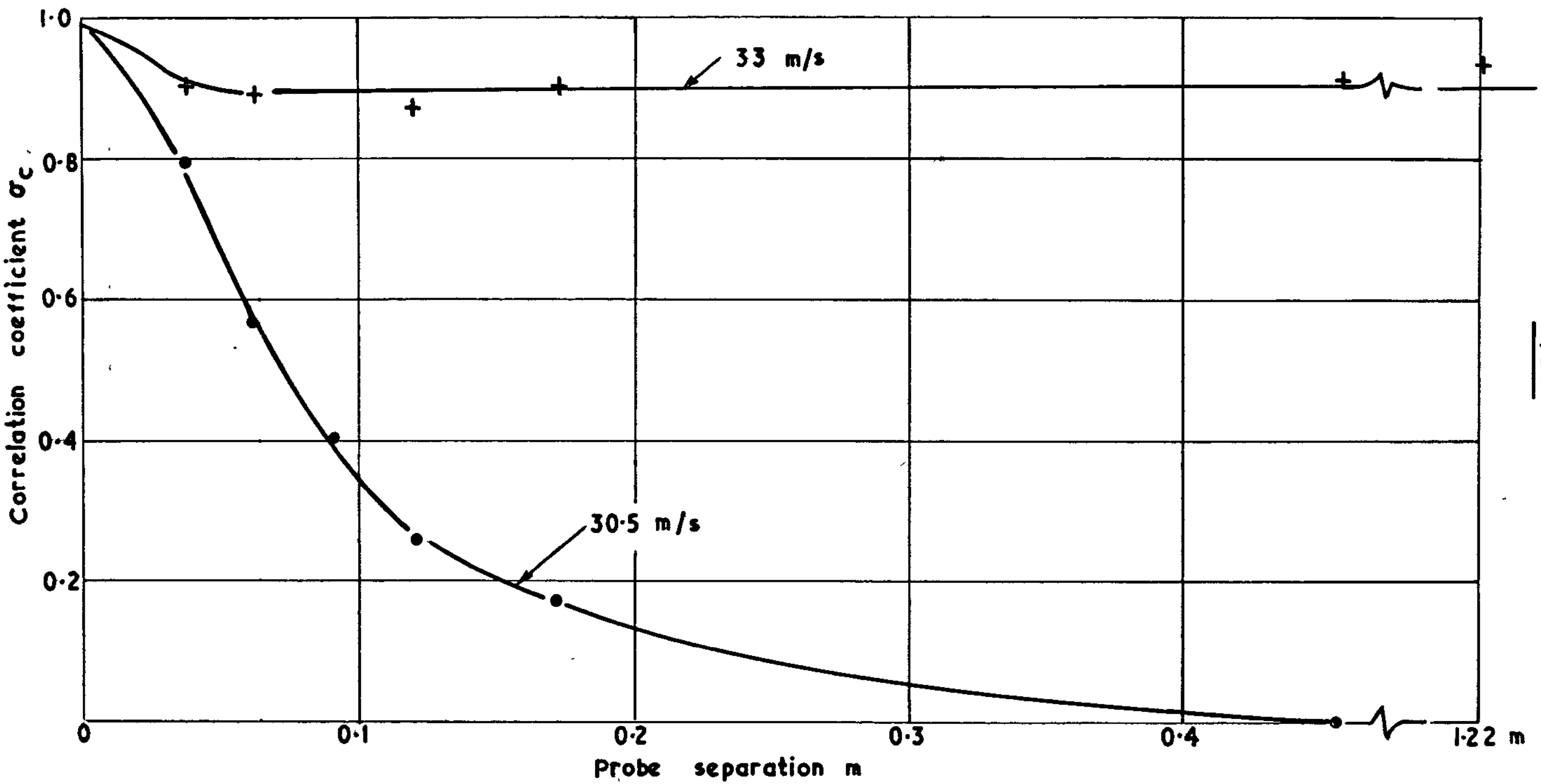
Shedding frequency versus tunnel velocity showing a resonant 'pause'

FIG. 3



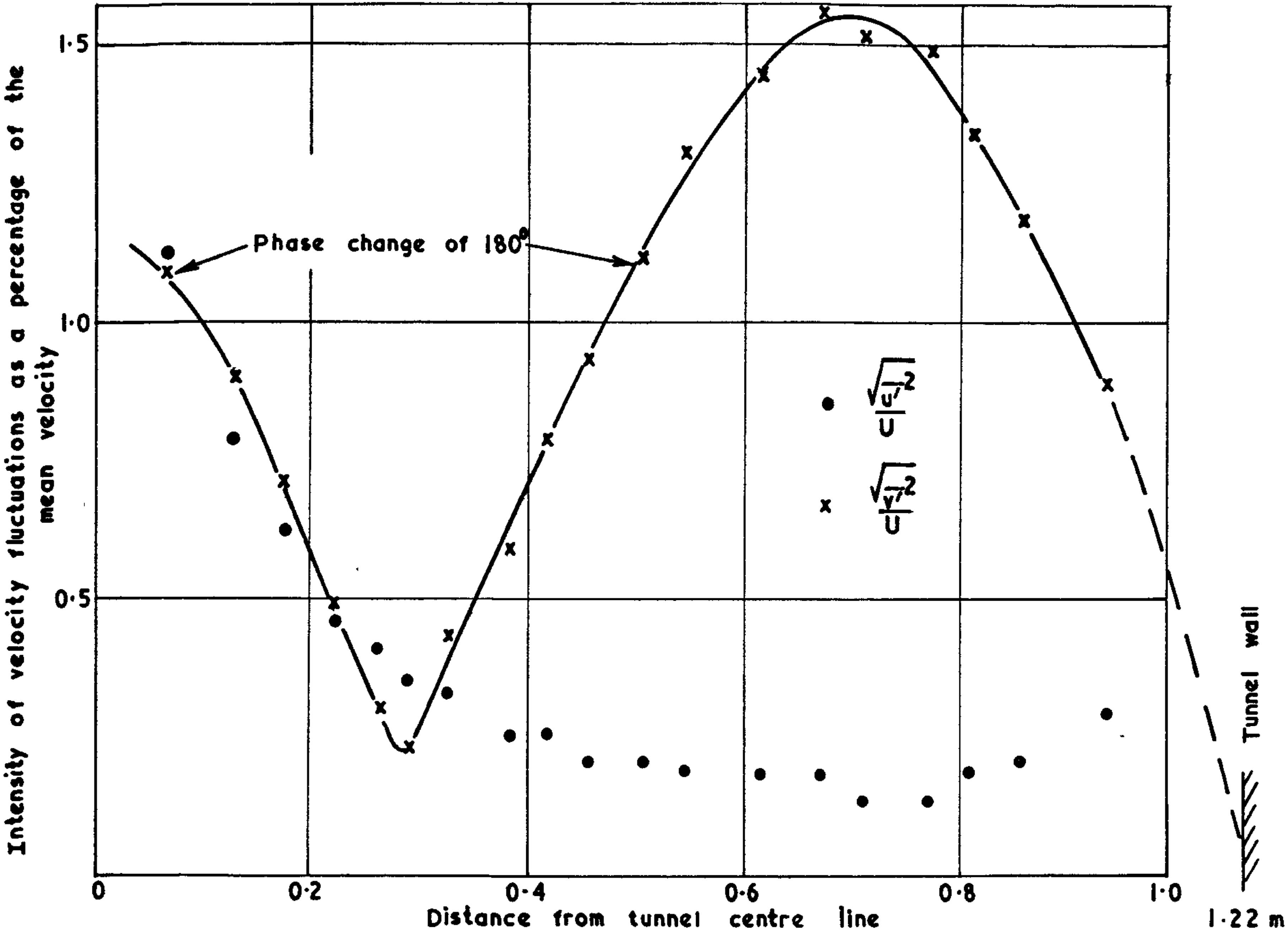
Velocity and pressure fluctuations against flow velocity

FIG. 4



Correlation between signals from a pair of hot-wires with spanwise separation at two speeds showing the effect of resonance

FIG.5



Intensity of the velocity fluctuations across the flow in line with the trailing edge

FIG.6

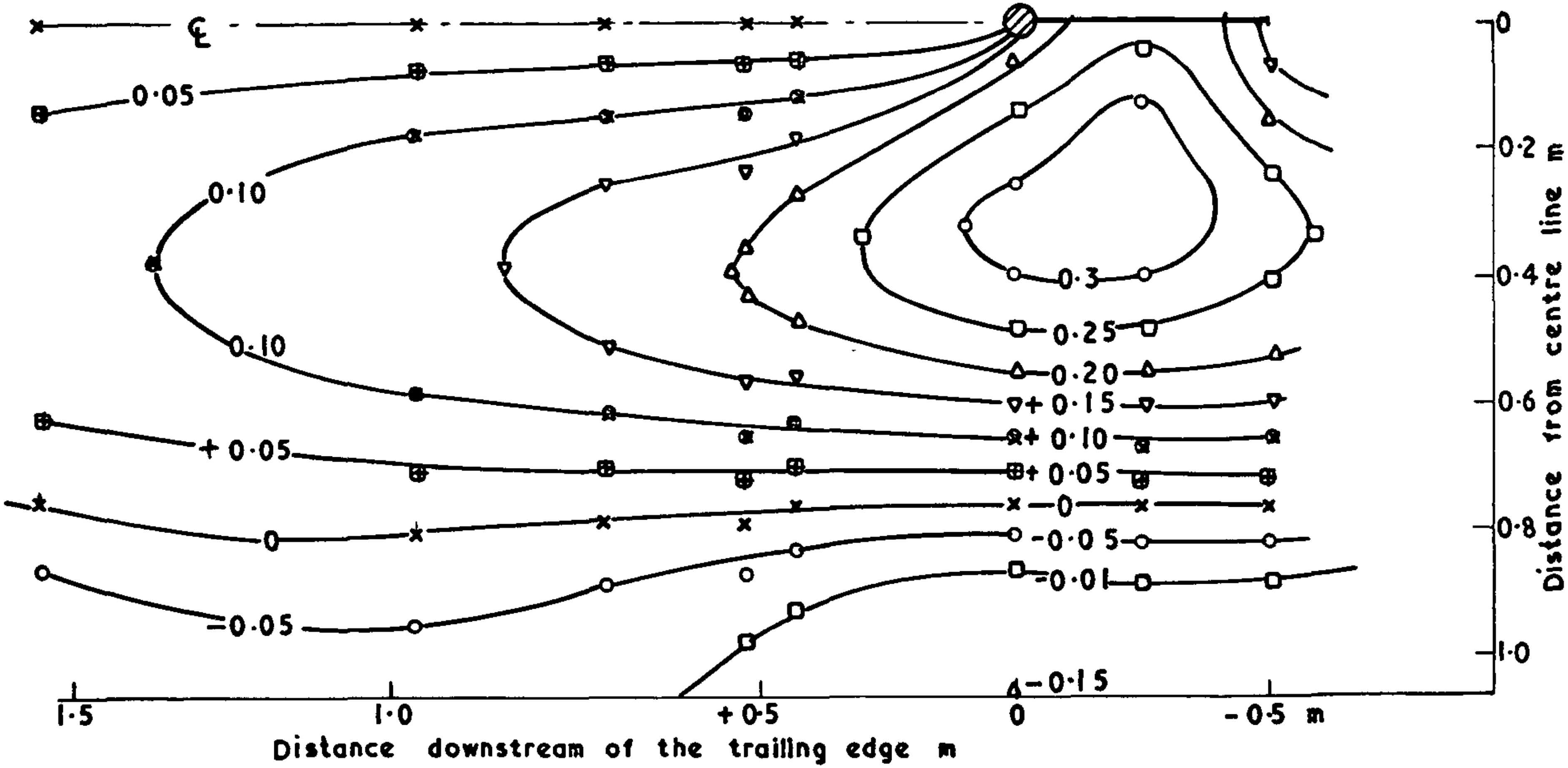
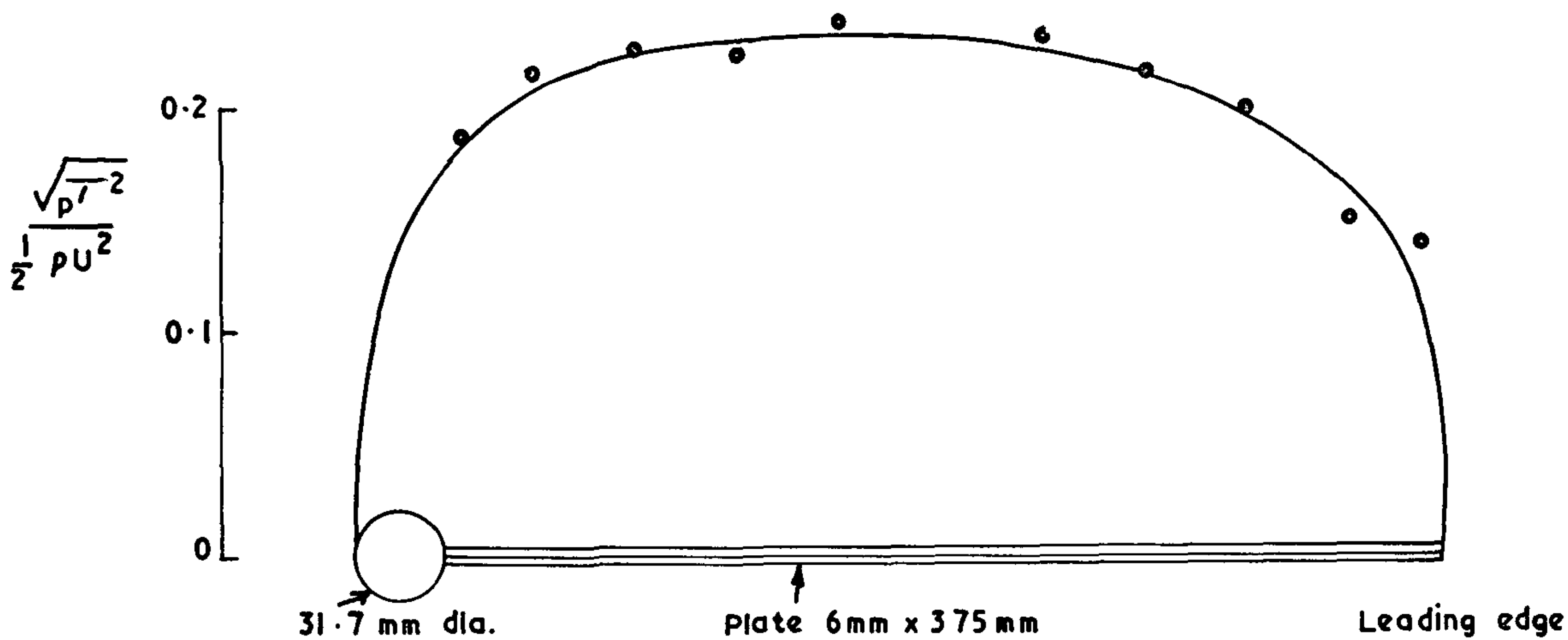


FIG.7

[The numbers refer to the root mean square pressure fluctuation divided by the dynamic head]

Contours of pressure fluctuations in the wind tunnel working section



Cofficient of fluctuating pressure on the plate surface

FIG.8

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