UNSTEADY BASE FLOW -VORTEX SHEDDING AND PRESSURE FLUCTUATIONS-

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Abstract

Fluctuating pressure measurements were recorded along the base of a plain blunt trailing edge aerofoil at half base height intervals along the entire span, with and without end plates. The frequency of vortex shedding was also recorded along the span using hot wire anemometry. These results were used to study the effect of end constraints on the flow and to establish the nature of the flow along the span. They revealed a highly three dimensional near wake structure with end constraint effects apparent for a considerable distance inwards along the span. The hot wire and Fourier Transform analysis of the pressure signals also revealed the different shedding modes that can be experienced along the span. Any correlation or otherwise between the hot wire and the pressure data is also discussed.

Introduction

The present study into blunt trailing edge aerofoils was undertaken for a number of reasons, arising from the need to establish a baseline model of the flow behind such a trailing edge geometry, with particular emphasis on the unsteady nature of the flow.

Previous studies have mostly concentrated on the wake structure of circular cylinders (Williamson and Roshko (1990), Williamson (1989)), and little is known about the unsteady nature of the near wake behind a blunt trailing edge aerofoil. It is only recently that some papers dealing with this problem have started appearing, for example Bearman (1992), Bearman and Tombazis (1992), Petrusma and Gai (1996), and Vassilopoulos and Gai (1995).

Even though previous work has shown that manipulation of end constraints can induce different shedding modes along the span (Gerich and Eckelmann (1982) and Hammache & Gharib(1991)), a full appreciation of the effect of end constraints is still lacking in the literature.

Investigations into different shedding modes in cylinder wakes have been mainly confined to high model aspect ratios, usually more than 100 (Lee & Budwig (1991)), with only a sparse data available for low to moderate aspect ratios ($AR \leq 40$), for example Williamson (1989).

Williamson and Roshko (1990) have shown that the Strouhal number decreases by 10-15% when the model aspect ratio was reduced below some critical value, with a corresponding change in the mean base pressure coefficient. As has been reported in many investigations, such as Maull & Young(1973), Bearman (1965 & 1967), Williamson & Roshko (1990), and Petrusma and Gai (1994), the base pressure does not remain constant across the model span except for a small region around the mid span where the flow could be said to be nominally two dimensional. Bearman (1965) also found that use of end plates reduced the base pressure coefficient by about 2-3%.

Maull and Young (1973) were the first to show that shedding from a blunt trailing edge aerofoil occurred in cells whose boundaries were defined by changes in the slope of the mean base pressure coefficient curve. They also found that large changes in the base pressure coefficient could occur for constant shedding frequency, while changes in shedding frequency directly resulted in changes to the mean base pressure coefficient. Williamson and Roshko (1990) also supported this finding from their experiments on circular cylinders, concluding that changes in one parameter resulted in changes in the other.

This study aims to investigate the unsteady characteristics of the flow in the near wake region of a blunt trailing edge aerofoil, particularly the relationship between the shedding frequency and the fluctuating base pressures.

Experimental Arrangement & Techniques

An open circuit wind tunnel of 460 mm x 460 mm test section was used for the experimental program described below. The wind tunnel free stream turbulence level was 0.2% with a maximum speed of 45 m/s. A modified NACA 0012 aerofoil with a plain blunt trailing edge, spanning the wind tunnel was used, as shown in figure 1.

End plates as specified by Stansby (1974) were also used, reducing the model aspect ratio (span/base height) from 30 without end plates to 20 with end plates, as shown in figure 2.

The Reynold's number based on free stream velocity of 20 m/s and model chord was 1.6 x 10^5. Hot wire measurements of the separating boundary layer just upstream of the trailing edge established that it was laminar (Re_θ = 280). The base height to momentum thickness ratio was 67.75 and with the mean base pressure coefficient of -0.55 (to be discussed later), this is consistent with the results of Petrusma and Gai (1994). In the past, most studies of blunt trailing edge aerofoils have been conducted with a turbulent separating boundary layer, so any comparison of present results with other data needs to be undertaken with care.

Fluctuating base pressures were recorded using ENDEVCO 8507C-2 miniature pressure transducers with a pressure range of 0 - 2 psi, fitted into the base, and vented to the atmosphere. The transducers themselves, were located within brass plugs to facilitate their movement along the model span, and were calibrated in situ before use. Their output was fed into a PC30 A-D board and analysed using a program specifically written for this purpose.

Three pressure transducers were employed with transducer #1 fixed at the centre, and transducers #2 and #3 located on either side along the spanwise axis. When the transducers were closest, this was called position 18, and when they were furthest apart, it was designated as position 1, as shown in figure 3. Due to the placement of the end plates, the furthest position available for measurements was position 4, nine base heights from the centre. Thus the measurements covered 18 base height or 60% of the span between the tunnel walls.

The pressure signals were recorded at a sampling rate of 10 kHz for each position before transducers #2 and #3 were moved progressively outwards away from the centre. This process was repeated for all positions with and without end plates.

The pressure transducers were also connected to an ONI SOKKI Frequency Analyser which gave the Fourier Transform of the fluctuating pressure signals directly, for all positions along the span with and without end plates.

A single axis TSI hot wire anemometer was used to evaluate the state of the boundary layer at the trailing edge as well as to record the shedding frequency along the span. The output from the hot wire was fed through an IFA100 system analyser and the results recorded on a PC for further analysis. An ONI SOKKI Frequency Analyser was also used directly with the hot wire anemometer to determine and record the shedding frequency along the span. Due to limitations in the length of the traverse probe, measurements were only recorded along one half of the model span.

Position of the hot wire to 'catch' the shedding vortex was determined by adjusting the position of the hot wire until a strong sinusoidal signal was displayed on the oscilloscope. This position was found to be one and a half base heights (1.5h) downstream of the trailing edge and just over half a base height (0.54h) above the trailing edge.

In order to measure the shedding frequency along the span, the hot wire probe was rotated through 90° from the vertical, so that it lay in the horizontal plane. An initial reading along the model centreline was taken with the probe in the vertical plane for comparison purposes. A difference of only 5% was found between the shedding frequency measured in the vertical and horizontal planes, which is well within the 10-25% range estimated by Hoole and Calvert (1967).

The shedding frequency results obtained through the horizontal traverse could therefore be said to give a reasonable representation of vortex shedding. Measurements were repeated for all spanwise positions with and without end plates.

Results and Discussion

Fluctuating Pressures:

The data presented here shows the fluctuating pressures normalised with respect to the mean pressure, plotted against time normalised with respect to the Strouhal period. Only two positions are shown for comparison purposes.

Figure 4 shows the output from the three transducers at position 18, when all three are closest. The traces exhibit similar signatures and magnitude of fluctuation although transducers #2 and #3 show a slight asymmetry in the flow.

The transducer signal for position 18 with end plates is given in figure 5. The signatures in all three traces are stronger and the fluctuations larger in magnitude compared to that without end plates and the flow symmetry is more pronounced. The end plates could therefore be seen to have forced a more stable, stronger and perhaps two dimensional vortex shedding.

As the transducers were moved away from the centre, the pressure signals remained fairly constant for a short region before showing any changes in phase or magnitude. With no end plates, this region of nominally two dimensional flow extended for approximately six base heights, while with end plates, this region was extended to approximately ten base heights across the mid span region.

Figure 6 shows the signals at position 4, when transducers #2 and #3 are nine base heights from the centre, that is, transducers #2 and #3 are eighteen base heights apart. The traces from transducers #2 and #3 show a considerable phase drift with a significant reduction in magnitude compared to that of central transducer #1. This would indicate that the vortex shedding is no longer two dimensional, and is also seen to be attenuated.

The transducer signals for position 4 with end plates is shown in figure 7. The signal from transducer #1 is again strong, while it diminishes with spanwise distance for transducers #2 and #3. Here one would also expect maximum end wall effects which is clearly seen by the signal asymmetry and attenuation.

From these fluctuating pressure signals it could be argued that as the spanwise distance is increased, flow symmetry and magnitude of fluctuations diminishes, suggesting that away from the centre, three dimensional effects would dominate the flow and that the flow would no longer exhibit two dimensional like characteristics.

Correlation of Fluctuating Base Pressures:

Further analysis of the fluctuating pressure signals included evaluating the correlation coefficient between the transducers. By taking transducer #1 at the centre as a reference, any spanwise variation could be determined by comparing its signal with those of transducer #2 and #3. Thus the correlation between two pressure signals along the span was calculated as:

$$R_{ij} = \frac{\overline{(P_i' - P_{i\,rms})\,(P_j' - P_{j\,rms})}}{\sqrt{\overline{(P_i' - P_{i\,rms})^2}\;\overline{(P_j' - P_{j\,rms})^2}}} \qquad (1)$$

The variation of the correlation coefficient with spanwise distance, for the conditions of with and without end plates, is shown in figure 8. It is seen that with increasing distance away from the model centre, there is a significant reduction in the correlation coefficient. This reduction is more pronounced for the case without end plates than with end plates, suggesting that three dimensional effects are more evident when the span extends across the tunnel walls. Near the model centre, a higher correlation is evident with end plates than without, suggesting a stronger vortex shedding in this region.

These results seem to be in agreement with Bearman (1992), which are also presented in figure 8 for comparison. It is seen that there is a rapid decrease in the base pressure correlation with increasing spanwise separation, and this is more pronounced without end plates, suggesting that three dimensional effects are more evident for that test condition. This is not surprising because without end plates, the thicker tunnel wall boundary layers would cause stronger interference with the near wake.

The results seem to suggest that different shedding modes are occurring along the span, although the exact mode of shedding -oblique, parallel, or bowed- cannot be determined directly from the correlation data alone.

Base Pressure Coefficient:

The mean base pressure coefficient, as defined below, was also measured across the span, both with and without end plates.

$$\bar{C}_p = \frac{\bar{p} - p_\infty}{\frac{1}{2}\rho U_\infty^2} \qquad (2)$$

Here, $\bar{p}$ is the mean base pressure, p_∞ is the free stream static pressure, and $1/2\rho U_\infty^2$ is the free stream dynamic pressure.

The variation of the base pressure coefficient along the span is shown in figure 9. The results indicate that with increasing spanwise distance from the centre, the base pressure decreases, which in itself shows that the flow is not uniform across the span, but is influenced by spanwise disturbances. This situation existed with and without end plates, although with end plates, the base pressure coefficient at the model centre decreased from -0.53 without end plates to -0.55 with end plates. These results seem to be slightly lower than previously measured values, which may be attributed to the laminar separating boundary layer. This is also consistent with the results of Petrusma and Gai (1994).

Although the results of Bearman (1965), Gai & Sharma (1981), and Petrusma (1990) show that there is little to be gained by using end plates, the above results show that end plates do affect the flow in the mid span region, but perhaps not as strongly.

Frequency Signal Analysis:

The vortex shedding frequency along the span was recorded using a single axis hot wire as well as through the Fourier analysis of the fluctuating pressure signals. These results will be discussed separately as they reveal several interesting features. The shedding frequency will be presented in terms of the Strouhal number which is defined as:

$$S = \frac{fh}{U_\infty} \qquad (3)$$

where h is the model base height, U_∞ is the free stream velocity, and f is the shedding frequency.

The Hot Wire:

As seen in figures 10 (a) and (b), which show the variation of Strouhal number and shedding frequency with spanwise distance, the shedding frequency does not remain constant across the span, either with or without end plates.

Evident from these figures are two dominant shedding frequencies resulting in a change in the Strouhal number at different spanwise positions depending on the end constraints. Without end plates, the Strouhal number changes from 0.26 in the centre to 0.27 at four base heights from the centre, which correspond to shedding frequencies of 344 Hz and 357 Hz respectively. Similarly, with end plates, the Strouhal number changes from 0.27 at the centre to 0.29 at five base heights from the centre, corresponding to shedding frequencies of 357 Hz and 379 Hz respectively.

These results support those of Maull and Young (1973), which are also shown in figure 10 (a), that shedding is occurring in cells and changes in the shedding frequency are not necessarily accompanied by changes in base pressure coefficient. Use of end plates seems to increase the Strouhal number from 0.26 to 0.29.

Higher Strouhal numbers were recorded compared to Maull & Young (1973), Bearman (1992), and Petrusma and Gai (1994), which may be attributed to the laminar separating boundary layer compared to most of the existing data which pertain to turbulent separating boundary layers.

It is interesting to note that with end plates, three dominant shedding frequencies are evident from the Fourier analysis, while only two shedding frequencies are evident when no end plates were used, as shown in figure 10 (b).

At spanwise positions greater then seven base height from the centre (z/h> 7), a double peak in the frequency distribution was experienced when end plates were used. The value of this frequency was 305 Hz corresponding to a Strouhal number of 0.24. It is possible that this frequency is due to the effect of end constraints on such low aspect ratio flows where their influence is felt across the entire span (Williamson (1989), Gerich and Eckelmann (1982)).

Fluctuating Pressures:

The shedding frequency was also extracted from the Fourier transform of the pressure signals, and the results are summarised in figures 11 (a) and (b) for both cases.

The Fourier transforms show a definite peak at 300 Hz for all spanwise positions regardless of the end constraints. Since the hot wire also recorded this frequency close to the end plates, it was concluded that this frequency could be attributed to the end effects, which seems to propagate across the entire span.

The distribution of Strouhal number across the span, as shown in figure 11 (a), is more orderly when end plates are used. As shown in this figure, only one additional dominant shedding frequency of 384 Hz, corresponding to a Strouhal number of 0.29, is evident with end plates, compared to three additional shedding frequencies when no end plates were used. In the latter case, these frequencies are 339 Hz, 384 Hz and 423 Hz , which correspond to Strouhal numbers of 0.26, 0.29, and 0.33 respectively.

Once again, we see that the shedding frequencies and thus Strouhal numbers are higher than previous studies, as discussed earlier.

When comparing the hot wire and fluctuating pressure results, we note that shedding seems to be dominated by this 300 Hz frequency, and even though other shedding frequencies can be evaluated from the Fourier distributions, they would need to be fairly strong, otherwise they would be masked by the wall effects.

It also becomes apparent that although the hot wire is more sensitive when recording the shedding frequency, it's position facilitates the recording of shedding from only one side , while the pressure transducers seem to be influenced by both. The position of the instruments in the flow will therefore play a major role in the measurements recorded.

In his investigation, Bearman (1992) reported that even with the use of end plates, three dimensional disturbances still existed along the span. The disturbances were somewhat suppressed near an end plate, but the main strength of the shedding vortices in this region were attenuated. This can be seen to occur in the results presented here, as the 300 Hz seems to dominate the flow across the entire span when end plates were used, with only one additional dominant frequency evident, and the fluctuating pressure signals were attenuated close to the end plates.

Conclusions

Spanwise flow on the base of a blunt trailing edge aerofoil, is highly three dimensional, regardless of the end constraints used. A nominally two dimensional vortex street was seen to exist up to six base heights without end plates, and was extended to ten base heights with end plates, in the mid span region. Thus, although end plates increase this nominally two dimensional region, care needs to be taken when interpreting the results.

Away from the centre, three dimensional effects dominate the flow regardless of the use of end plates, which were shown to accentuate the end effect.

The influence of confining walls cannot, therefore, be ignored in cases of low to moderate model aspect ratio, as the nature of the shedding vortex street has been shown to be dominated by these end effects.

The results obtained using hot wire anemometry seemed to be more sensitive when measurements of the vortex shedding alone were required, but the pressure results tended to reveal a lot more about the flow. Differences between the pressure and hot wire results can be attributed to their position, that is, the hot wire would only record one half of the shedding vortex street, while the pressure transducers would be affected by both sides.

This investigation has shown that the effect of end constraints cannot be ignored in experiments with models of moderate and low aspect ratio. The vortex shedding seems to be always dominated by these end constraints and to eliminate their effect would require large aspect ratios, perhaps 80 or more (Williamson (1989)). However, when considering the fact that in most of the investigations made with blunt trailing edge aerofoils the aspect ratio has never been more than 30, results must be treated with caution.

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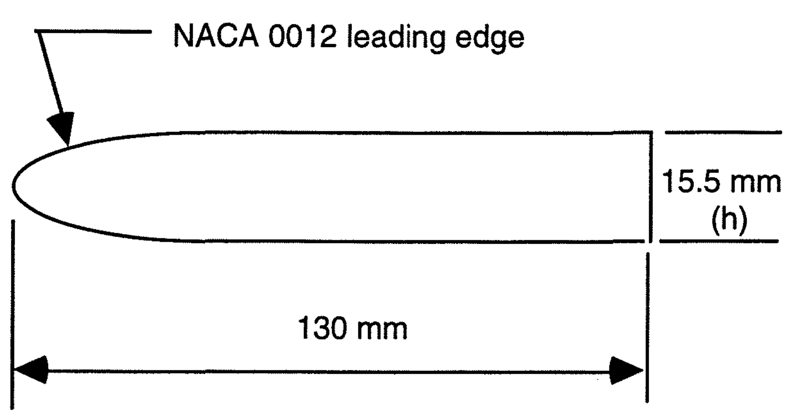


FIGURE 1 - Blunt Trailing Edge Model.

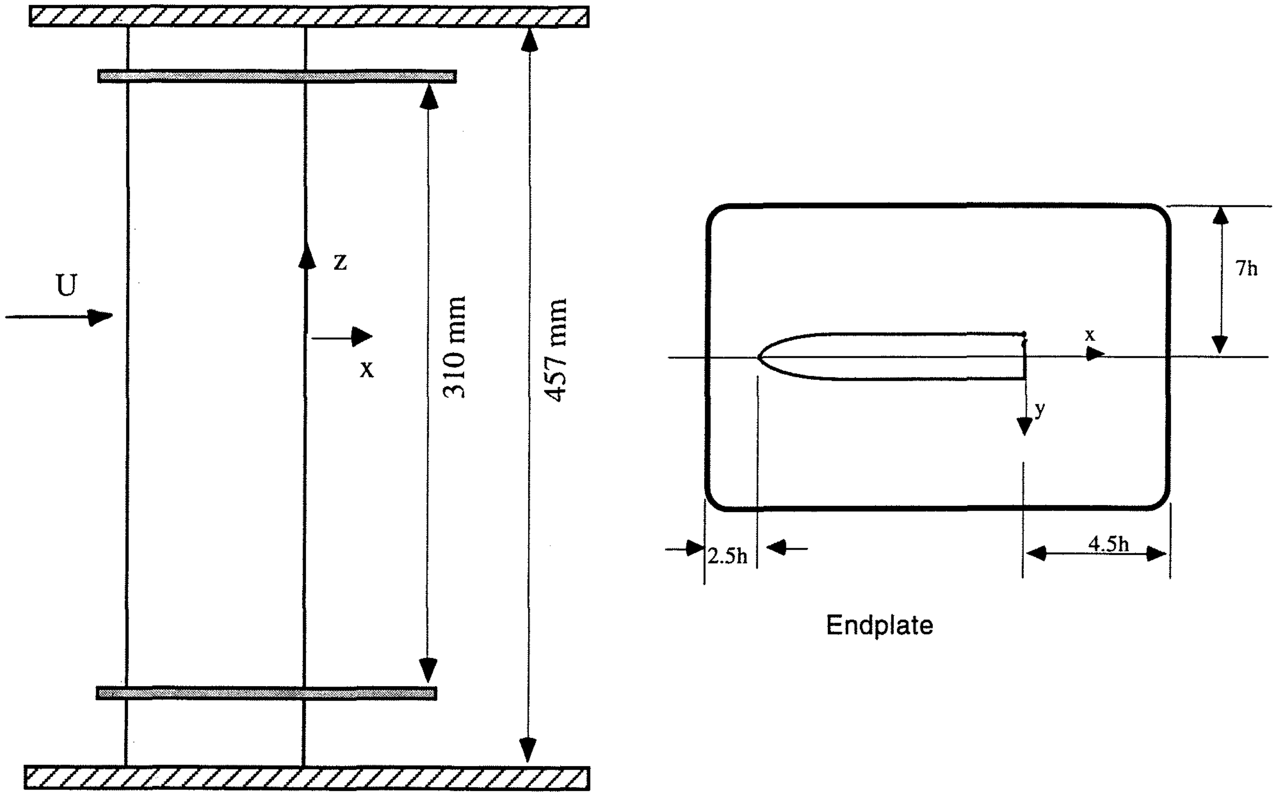


FIGURE 2 - Diagram of Model Fitted with End Plates

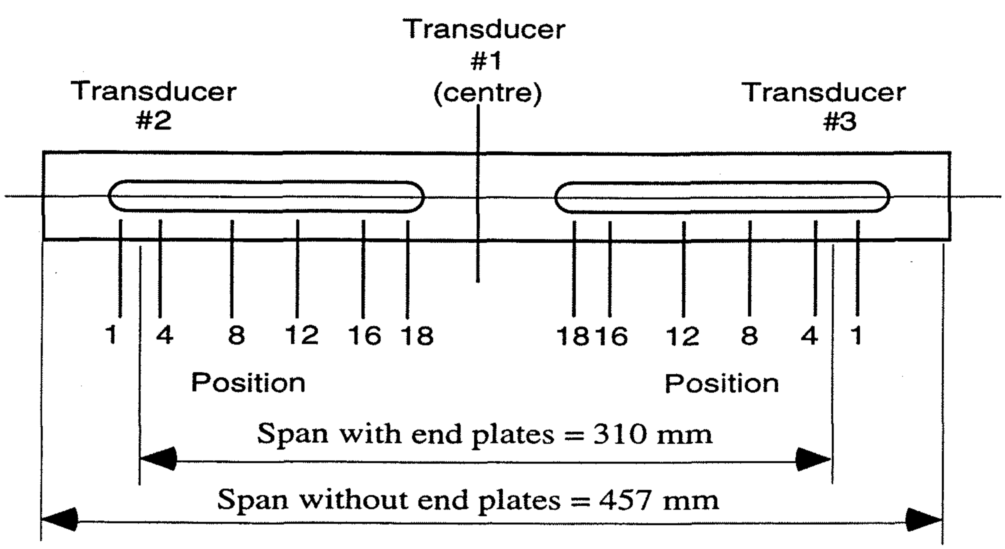


FIGURE 3 - Rear View of Model.

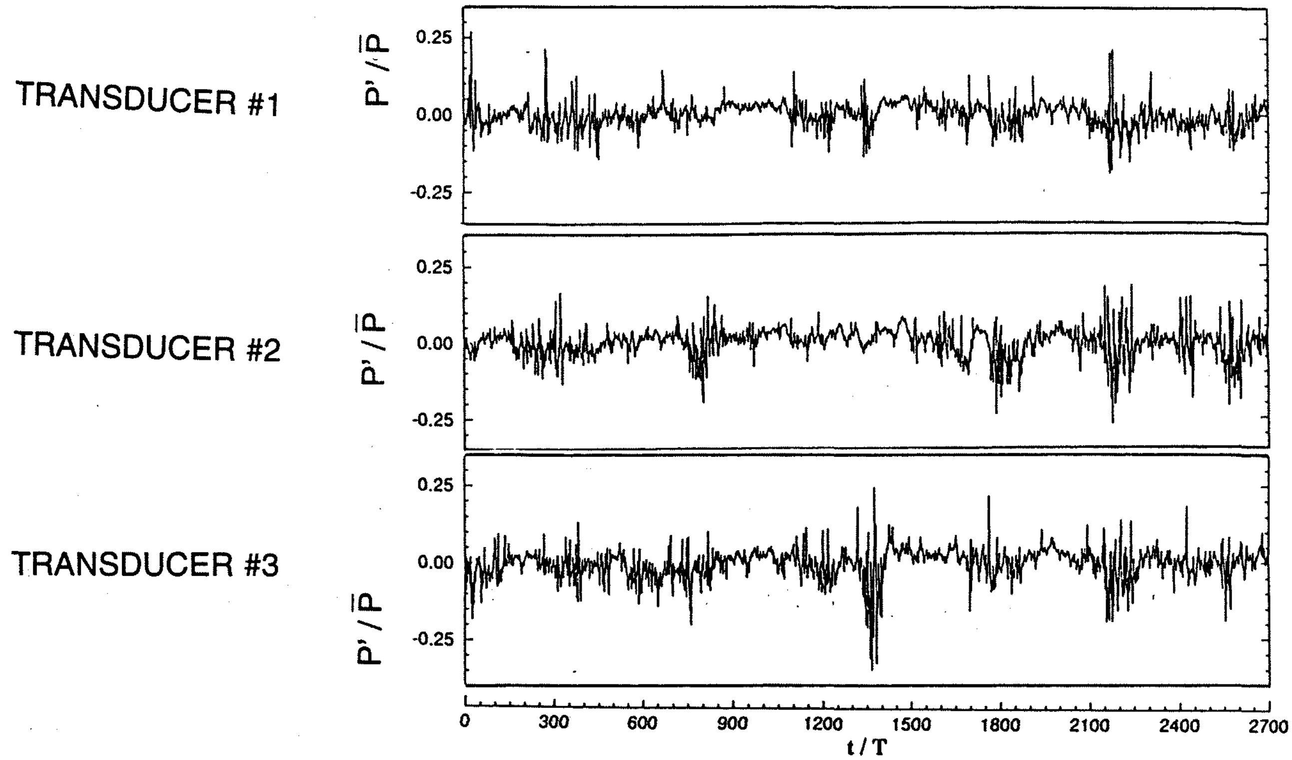


FIGURE 4 - Normalised Pressure Distribution
- Position 18 -
- Without End Plates -

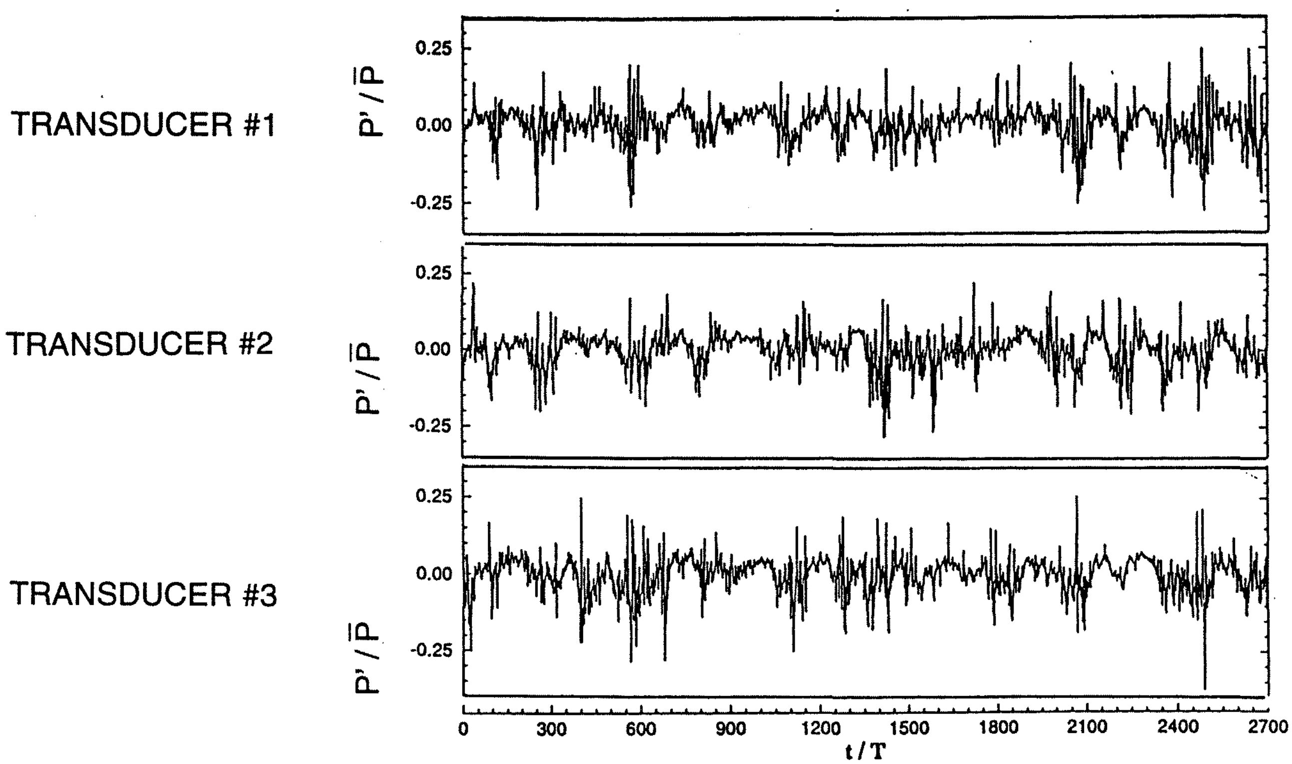


FIGURE 5 - Normalised Pressure Distribution
- Position 18 -
- With End Plates -

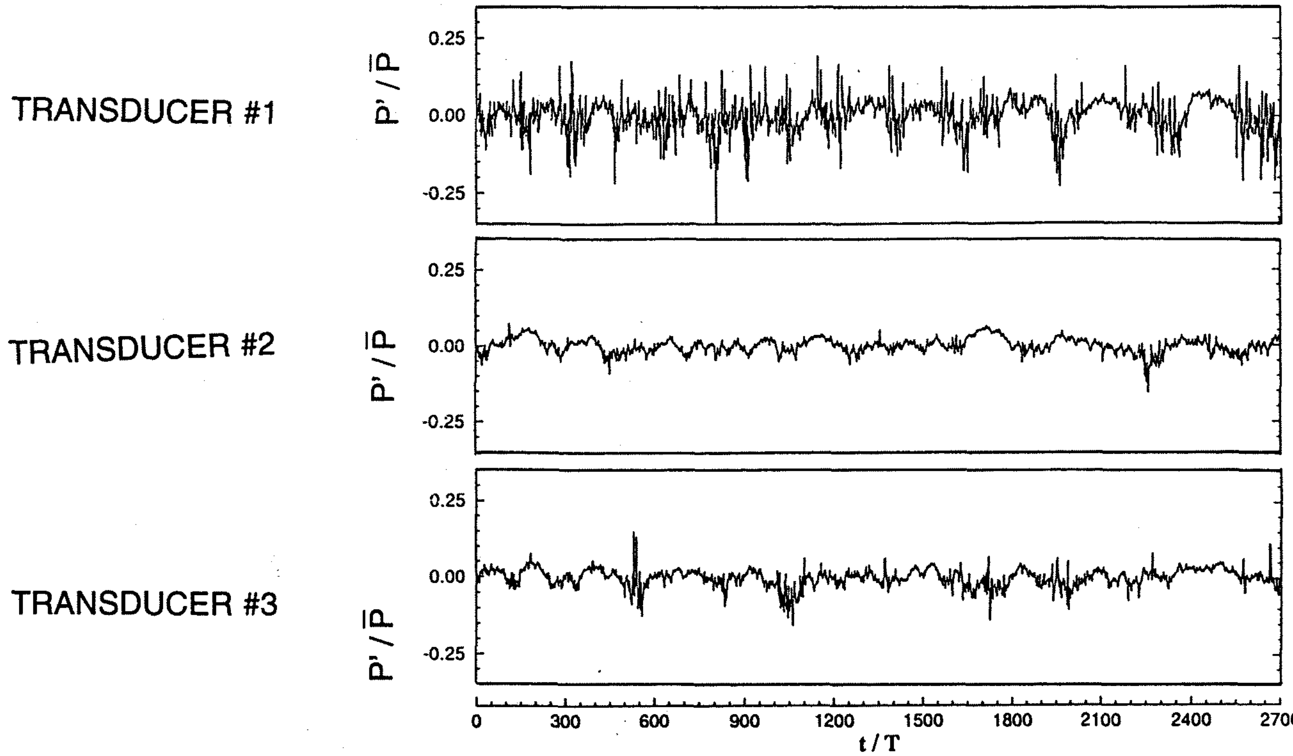


FIGURE 6 - Normalised Pressure Distribution
- Position 4-
- Without End Plates -

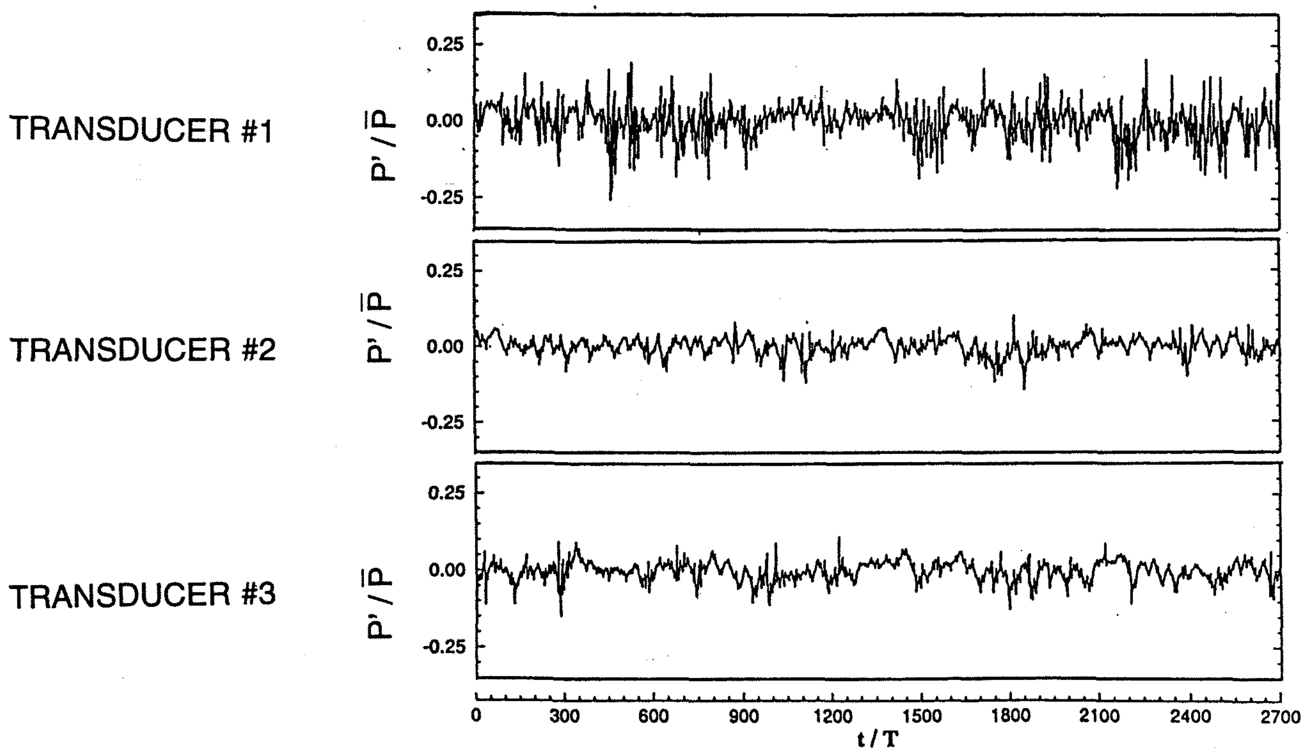


FIGURE 7 - Normalised Pressure Distribution
- Position 4-
- With End Plates -

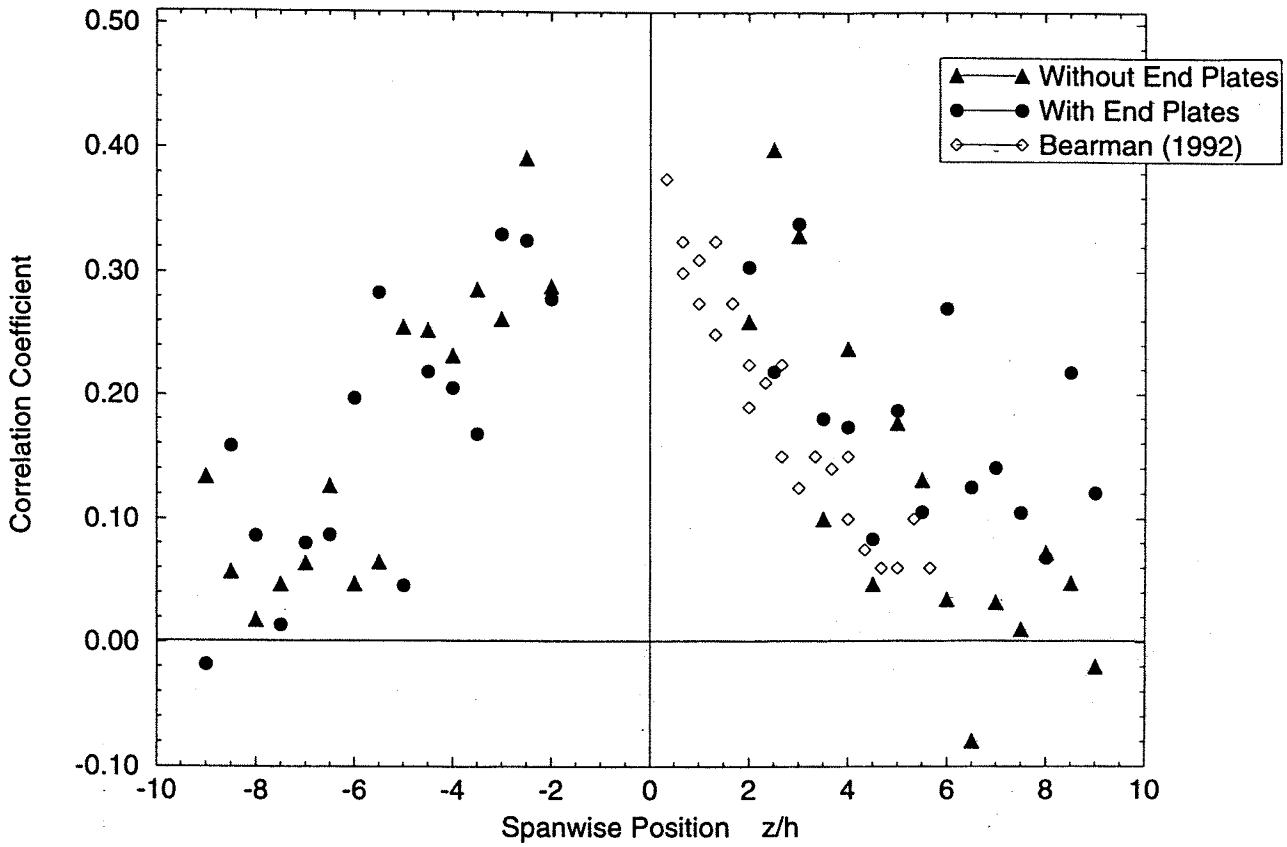


FIGURE 8 - Correlation Coefficient vs Spanwise Position
- With and Without End Plates -

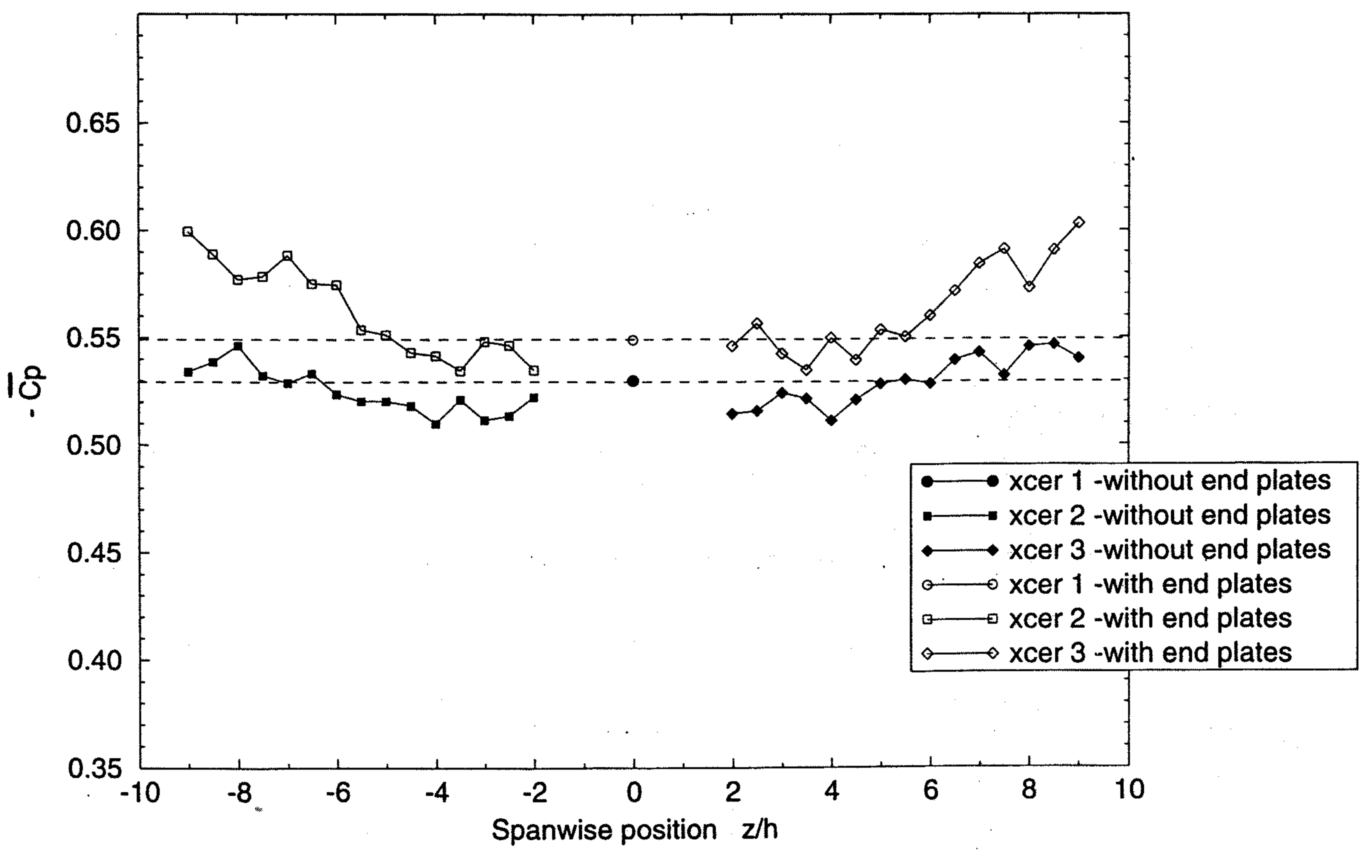


FIGURE 9 - Base Pressure Coefficient Distribution
- With and Without End Plates -

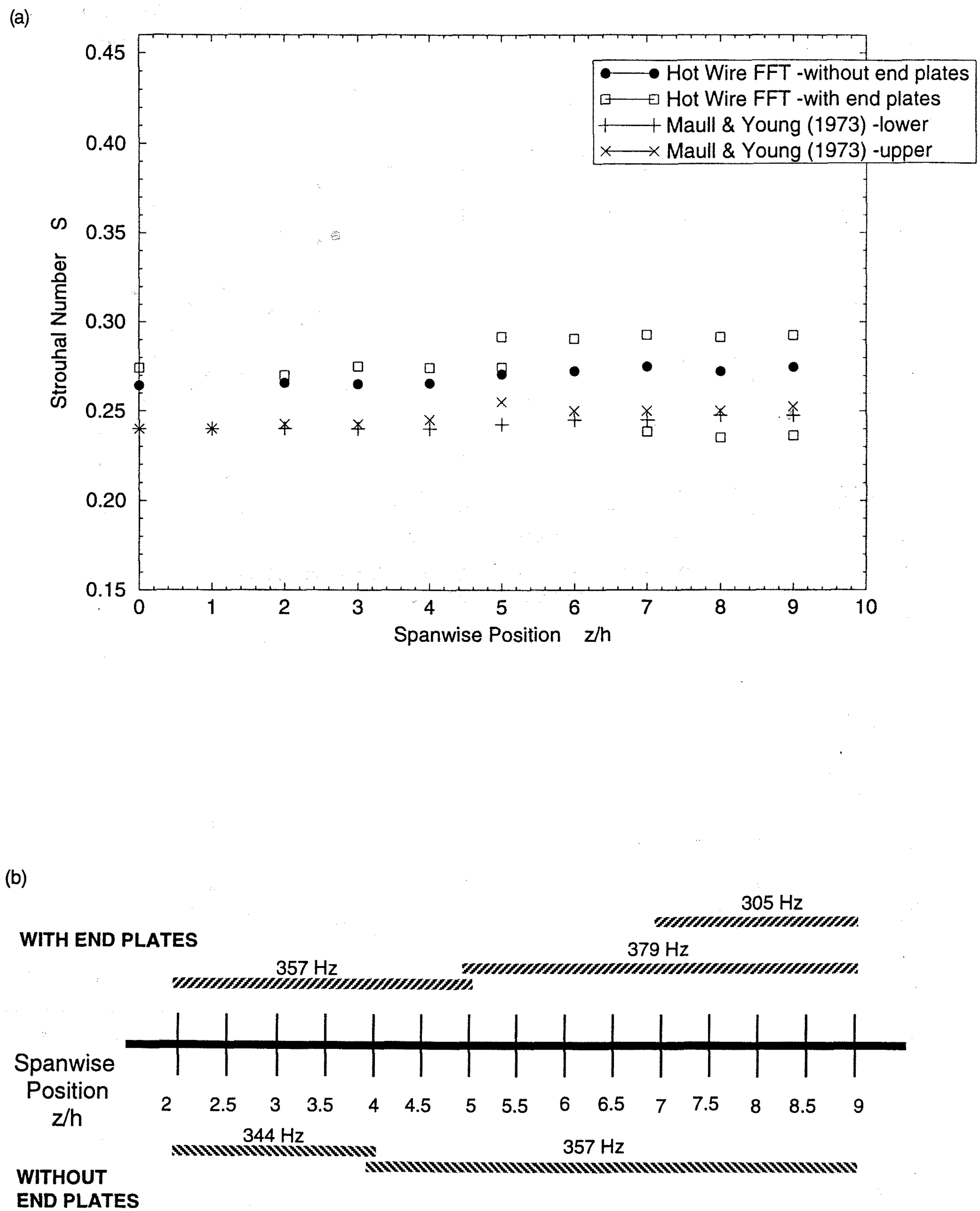
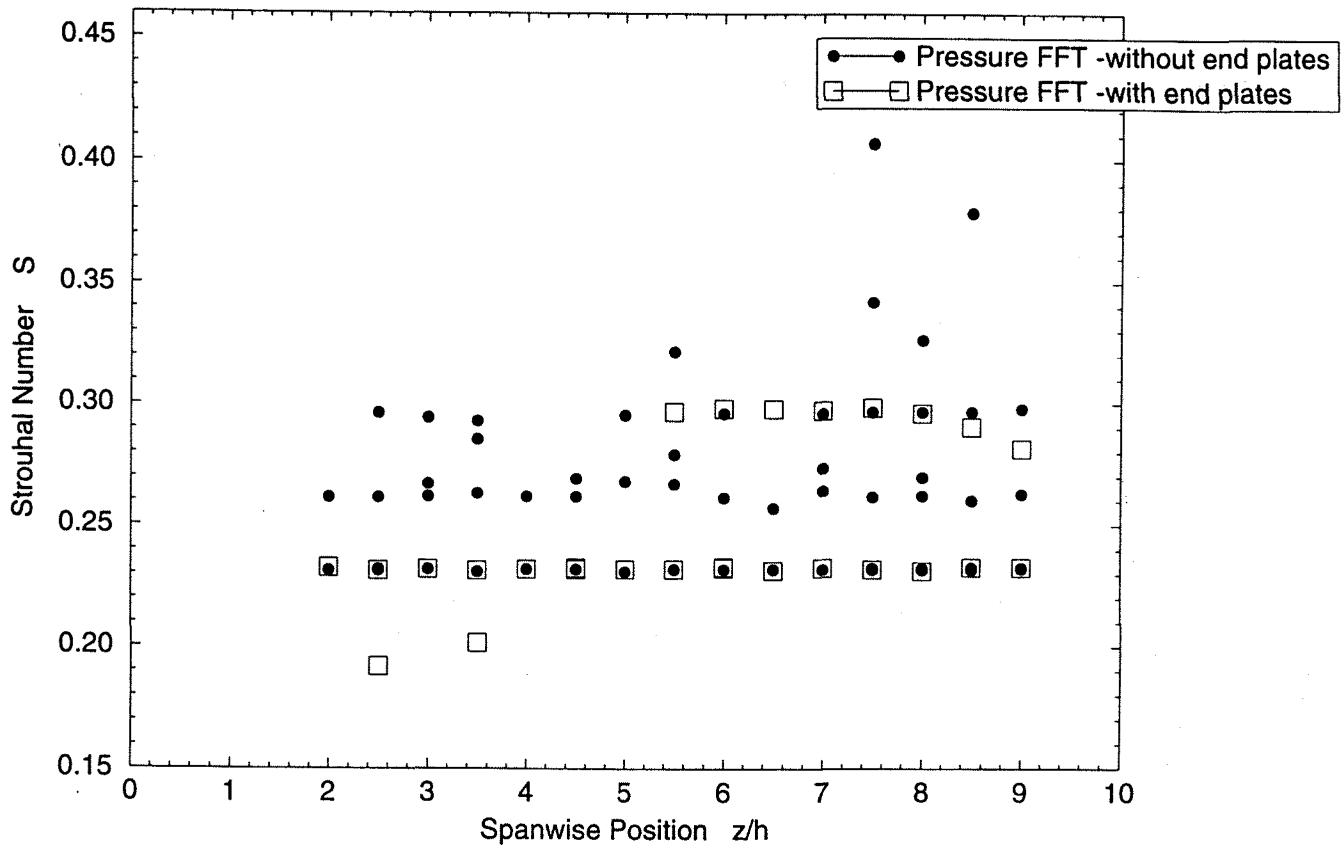


FIGURE 10 (a)- Strouhal Number vs Spanwise Position
(b) Shedding Frequency vs Spanwise Position
- Hot Wire Results-
- With and Without End Plates -

(a)



(b)

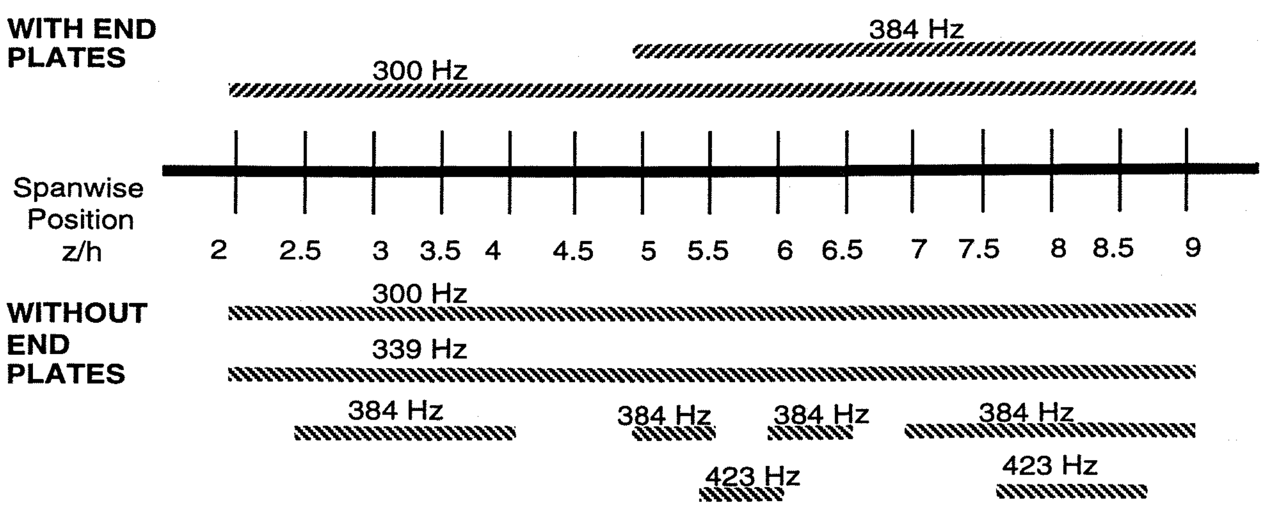


FIGURE 11 (a)- Strouhal Number vs Spanwise Position
(b) -Shedding Frequency vs Spanwise Position
- Pressure Results -
- With and Without End Plates -