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D. A. Lovell and T. B. Owen

Aerodynamics Dept., R.A.E., Farnborough

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LOW-SPEED WIND-TUNNEL MEASUREMENTS OF SURFACE PRESSURE FLUCTUATIONS ON TWO SLENDER-WING MODELS

by

D. A. Lovell
T. B. Owen
Aerodynamics Dept, RAE, Farnborough

SUMMARY

Measurements of the amplitudes and spectra of surface pressure fluctuations have been made on the upper surfaces of two delta wings with 76° leading-edge sweep. The high-frequency portion of each spectrum has been found to conform to a universal scaling law based on twodimensional boundary-layer data. The low-frequency portions of the spectra are not amenable to any such simple scaling but some qualitative conclusions have been drawn from the detailed measurements. Firstly, the high level of low-frequency pressure fluctuations is confined to an area on the upper surface of the wing under and outboard of the core of the leading-edge vortex sheet. Secondly, the amplitudes and spectrum shapes of the low-frequency portions of the spectra are not strongly dependent on the Reynolds number, and the nondimensional magnitude, $\overline{p^2}/q^2$, increases only slowly with increasing angle of incidence. However, the high level of low-frequency fluctuations spreads inboard as the angle of incidence is increased and problems of wing buffet or panel vibration could arise on a large aircraft.

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* Replaces RAE Technical Report 70168 - ARC 32575.

CONTENTS

1 INTRODUCTION

Previous measurements of the surface pressure fluctuations on slender-wing aircraft, at model scale[1,2,3] and in flight[4], have shown that there is a high level of fluctuations under the core of the leading-edge vortices on such aircraft. Whereas on the classical type of aircraft with fully attached flow, high-frequency fluctuations (in the range 500 Hz to 50 kHz) are generated by the boundary layer, it was found that the higher level of fluctuations on slender-wing aircraft designs was occurring at much lower frequencies. Thus, in addition to the transmission of high-frequency boundary-layer noise through the aircraft skin, two other possibilities arise.

Firstly, the pressure fluctuations could cause aircraft buffet by exciting wing bending or torsional modes (typically in the range 1 Hz to 20 Hz). However Mabey[5] and Keating[6] have shown that large surface pressure fluctuations and appreciable buffet in this frequency range occur only when the cores of the leading-edge vortices break-down above the wing surface. The occurrence of vortex break-down above the wing surface at large angles of incidence and/or yaw can, therefore, place limitations on the operating range of slender-wing aircraft.

Secondly, pressure fluctuations (at frequencies in the range 20 Hz to 500 Hz) could excite panel vibration and as rolled-up vortex sheets are normally present at all subsonic speeds this could become an important design consideration.

Earlier tests[1] suggested that there could be an effect of Reynolds number on model pressure-fluctuation measurements and accordingly some of the current set of measurements have been made on a larger model in order to clarify the effect of Reynolds number. In addition instrumentation that gave improved resolution of the fluctuations has been used to obtain a more complete picture of the fluctuations occurring on slender wings. The measurements were all made on delta-wing models in the conical flow region* well removed from the trailing edge.

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* In this region (extending back to approximately 80% of the centre-line chord on a delta wing) the spanwise distributions of both the mean and fluctuating components of the pressure are nearly independent of the distances from the apex, when these quantities are presented in a suitable non-dimensional form; section 3.2.

2 EXPERIMENTAL DETAILS

2.1 Models

Two series of measurements were made in the 13 ft × 9 ft low-speed wind tunnel at RAE Bedford. The first measurements, in December 1964, were made on a delta wing having a root chord of 1.83 m (6 ft), a leading-edge sweep angle of 76° and a rhombic cross section (edge angle 30°). A general arrangement drawing on the model is given in Fig.1 and the model is more fully described by Wyatt and East[7]. Surface pressure fluctuations were measured at 67% of the centre-line chord along a spanwise line.

The second set of measurements, in May 1966, were made on a delta-wing half model having a root chord of 7 m (23 ft), a leading-edge sweep angle of 76° and a flat-plate cross-section with a chamfered lower surface (edge angle 34°). A general arrangement drawing of the model is given in Fig.2 and the model is more fully described by Wyatt and East[8]. Surface pressure fluctuations were measured along a spanwise line at 74% of the centre-line chord.

2.2 Instrumentation

Two systems were used to measure the surface pressure fluctuations on the two models. These systems are described in detail elsewhere[9] but the salient points of the systems are given below:-

System 1. A variable capacitance transducer, designed by RAE instrumentation department (transducer IT 4-6-37), was used, having a flat frequency response from dc to 3 kHz and an orifice diameter of 2.24 mm. The signal was suitably amplified and filtered before being analysed by a Brüel and Kjær 2107 frequency analyser and recorded on a paper trace by a Brüel and Kjær 2305 level recorder. This system was used for all the measurements on the 1.83 m model and for the measurements made by Keating on the 7 m model.

System 2. A modified Muirhead H-112 probe microphone was used having a flat frequency response from 10 Hz to 10 kHz and an orifice diameter of 0.28 mm. The remainder of the system was identical to that of system 1. This system had an overall gain approximately 4 times higher than system 1, and it was possible to make measurements at lower windspeeds without the equipment electronic noise becoming unduly large. As a result of this and the improved high-frequency response of the system, spectra could be obtained up to a higher value of the frequency parameter $n \left(= \frac{fx}{U}\right)$.

The spectra obtained in this manner were corrected for electronic and extraneous noise in the signal and for the finite size of the transducer orifice by the methods detailed in Ref.9.

3 RESULTS

3.1 Mean-flow parameters

In order to aid the discussion of the relation between the measured surface pressure fluctuations and the mean-flow characteristics, a sketch of the flow on the upper surface of a delta wing is included in Fig.3. The spanwise static-pressure and skin-friction distributions for the 1.83 m and 7 m models have been extracted from Refs.7 and 8 and are plotted in Fig.4 and 6 respectively together with the spanwise distribution of the low-frequency part of the mean-square intensity of the surface pressure fluctuations for the two models. The method by which the latter were obtained is explained in a later section (4.2).

3.2 Surface pressure fluctuation spectra

The spectra are plotted as the mean-square pressure-fluctuation level, per unit fractional bandwidth, non-dimensionalised with respect to the dynamic pressure, $\overline{p^2}/q^2\varepsilon$ (= nF(n)), versus the frequency parameter based on the freestream velocity and the chordwise distance from the apex of the model, $\frac{fx}{U}$ (= n). The length parameter x has been chosen as previous work has shown that in the region of the wing surface unaffected by the trailing edge (back to 80% chord approximately) there exists a conical similarity in the spanwise distribution of static pressure, skin friction (e.g. Refs.7 and 8) and fluctuating pressure (e.g. Ref.2 and unpublished work by Keating on a model similar to the delta half-model of the present tests). The local semispan, S_x, would be an equally suitable length parameter to express this similarity and for the two delta models of the present tests $S_x = 0.25x$.

The results for the 1.83 m model are shown in Fig.5 for a range of angle of incidence, [0, 1, 2, 4, 8 and 12 degrees (uncorrected for wind-tunnel wall constraint)] at a windspeed of 76 m/s (250 ft/s) corresponding to a Reynolds number, based on the chordwise distance from the apex (x), of 6.4×10^6. The measurements at an angle of incidence of 8^o have been repeated at a windspeed of 46 m/s (150 ft/s) to see whether any Reynolds number effect is discernible and to assist in identifying any extraneous contribution to the spectrum.

The results for the 7 m model are shown in Fig.7 for a range of angle of incidence, [2, 6 and 10 degrees (uncorrected for wind-tunnel wall constraint)] at windspeeds of 46 m/s and 30 m/s corresponding to Reynolds numbers of 16×10^6 and 11×10^6 respectively. Some measurements were made at 66% span and 6^o incidence for windspeeds of 15, 21, 30, 46 and 61 m/s in order to investigate the effect of Reynolds number variation in more detail and these are shown in Fig.8.

The sets of spectra measured on the two models are similar and change in the same way on moving outboard from the centre line. Near the centre of the wing the spectrum rises continuously from a very low level at low frequencies with no sign of a peak in the spectrum at low frequencies. Further outboard the spectrum changes to a double-humped form* at approximately 60% span. At about 90% span the spectrum changes back to a single peaked form but the peak occurs at a much lower frequency.

4 DISCUSSION OF RESULTS

4.1 The high-frequency part of the spectrum

The scaling of the high-frequency portion of the spectra derived from twodimensional boundary-layer measurements (which is explained in detail in Appendix A) has been applied using the measured values of surface static pressure and skin friction, and the boundary-layer displacement thickness that would exist on a flat plate at the same Reynolds number based on the chordwise distance from the wing apex. As a result, the accuracy of the scaling of the magnitude of the spectra should be good as it is based only on the measured static pressure and skin friction. However, the accuracy of the scaling of the frequency parameter can be poor as the boundary-layer thickness will be considerably different from the flat-plate values in some areas on the models, e.g. at the peak under the core of the rolled-up leading-edge vortex sheet, where the boundary layer is thinned, and also near the secondary and tertiary separations where the boundary layer is very much thickened.

The scaled contributions to the measured spectra are shown in Figs.5 and 7 for the two models. Although much of the spectra clearly lie outside the frequency range of the measuring equipment, there is sufficient general agreement with the measured parts of the upper portions of a number of the spectra

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* The second hump occurring around n = 500 is, in general, outside the frequency range of the measuring equipment; its presence being inferred from generalised boundary-layer results as explained in section 4.1.

to confirm the validity of the scaling method. The large differences between the scaled and measured upper portions of the spectra that do occur in some of the spectra can, in many cases, be accounted for by the inaccuracy of the method used to estimate the boundary-layer displacement thickness.

Inboard of the rolled up vortex sheet, where there is negligible cross flow, the boundary layer may be expected to be similar to a flat-plate boundary layer at the same Reynolds number and this is confirmed by the reasonable agreement of the frequency scaling with the measured spectra.

In the region under the core of the rolled-up vortex sheet, between the attachment line and the inflection line, the pressure gradient is favourable so that the flow is accelerated and the boundary layer will be thinner than the boundary layer that would exist on a flat plate at the same Reynolds number based on the distance from the leading edge. (This has been measured by East[12] for example.) The shift in the frequency scaling if the correct thickness were used would improve the agreement with the measured results.

In the region between the inflection line and secondary separation line the pressure gradient is adverse so that the flow is retarded and the boundary layer is thickened. The shift in the frequency scaling if the correct thickness were used would again improve the agreement with the measured results.

Outboard of the secondary separation line, the frequency scaling of the upper portion of the spectrum is in good agreement with the measured spectra at some spanwise positions. At the other spanwise positions the poor agreement between the measured and scaled spectra is due to the abrupt changes in the boundary-layer thickness outboard of the secondary separation line.

4.2 The low-frequency part of the spectrum

The scaled high-frequency part of the spectrum, determined by the method of section 4.1, has been used to define the upper limit of a low-frequency part of the spectrum. This lower part of the spectrum has been terminated at the top end where it runs into the scaled upper portion and at the bottom end by extrapolating the measured signal to zero level. This extrapolation should omit only a small percentage of the total signal at very low frequencies which was not measured by the instrumentation system. The spectra may be integrated directly in the form in which they are plotted, as:

$$\left(\frac{\overline{p^2}}{q^2}\right)_L = \int_L nF(n)\, d\,(\log n) = \int_L F(n)\, dn \qquad (1)$$

where the suffix L indicates the low-frequency contribution. The spanwise variation of $(\overline{p^2}/q^2)_L$, the mean-square pressure fluctuation from the lower part of the spectrum, is plotted in Figs.4 and 6 for the two models.

The detailed measurements of the surface pressure fluctuations on the two models (Figs.5 and 7) do not suggest any simple method of quantitatively relating the magnitude of the low-frequency part of the spectrum to the mean-flow parameters but some qualitative conclusions may be drawn:-

(a) Inboard of the rolled-up leading-edge vortex sheet there is very little low-frequency pressure fluctuation and it is of the same order of magnitude as the extraneous noise and vibration.

(b) In the region under the rolled-up vortex sheet, between the attachment line and the inflection line, a large, low-frequency peak develops in the spectrum of fluctuations.

(c) In the region between the inflection line and the secondary separation line the low-frequency peak in the spectrum becomes larger. A second low-frequency peak also appears in the spectrum.

(d) Outboard of the secondary separation line the magnitude of the low-frequency part of the spectrum decreases. Although the flow is complicated with further attachment and separation lines in this region, the shape and position of the low-frequency portion in the spectrum does not change abruptly, indicating, in this region at least, the cause is not a local one.

(e) In general the effect of increasing the angle of incidence is a slow increase in the magnitude of the low-frequency portion in the spectrum*. More important from an aircraft design point of view may be the tendency for the high level of fluctuations to move inboard and cover a larger area of the wing surface as the angle of incidence is increased. Depending on the frequency range in which this high level of low-frequency pressure fluctuations occurs at high angles of incidence, this could lead either to the excitation of the low-frequency vibration modes of the larger wing panels inboard from the leading edge with consequent fatigue problems, or to aircraft buffet due to the excitation of wing bending or twisting modes.

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* The only exception to this is the large magnitude of the fluctuations at 2° incidence on the 7 m model. The latter appears to be a consequence of the method of construction of this particular model, which includes rapid camber changes near the apex, resulting in some flow instability in this region at around 2° incidence. This effect has been shown to be absent on symmetrical models, e.g. Fig.4, and on complete aircraft models and is not typical of slender-wing measurements.

(f) The experimental evidence for the variation of the magnitude of the low-frequency part of the spectrum with Reynolds number is at first sight conflicting. Fig.8 shows that on the 7 m delta the spectrum level increases slightly with increasing windspeed but appears to tend to a constant shape at the higher windspeeds. However, comparison of the mean-square pressure fluctuation from the lower part of the spectrum for the two models (Fig.4c and 6c) shows a lower level of fluctuations for the larger model, though there are factors other than Reynolds number which could account for the difference in pressure-fluctuation levels measured on the two models.

Firstly, while the edge angle of the models is similar, there is a considerable difference in cross-sectional shape as can be seen by comparing Figs.1 and 2. This has resulted in a marked difference in the scale of the flow pattern on the upper surface of the models, with the suction peak position at 4° incidence, for example, being at 83% semi-span on the 1.83 m model and 75% semi-span on the 7 m model*; Figs.4 and 6. The position of the core of the leading-edge vortex sheet on the 1.83 m model is in very close agreement with the correlation of Kirkpatrick[13] for slender delta wings of rhombic cross section. It would be surprising if the difference in strength and position relative to the wing surface of the cores of the rolled-up vortex sheet, which these differences in flow pattern imply, did not result in some change in the level of low-frequency pressure fluctuations.

Secondly, there was a much higher extraneous noise level in the tests on the smaller model, and this may not have been fully allowed for by the correction method employed[9].

It is suggested, therefore, that more weight should be placed on the result of varying Reynolds number by varying windspeed on each model (which was shown to produce only a small effect) than on the comparison between the two sizes of model, where factors other than the difference in Reynolds number are also present.

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* The discrepancy in the scale of the flow pattern between the two models occurs because the vortex sheet development is governed, not by the quoted angle of incidence, but by the difference between the angle of incidence and the angle of incidence at which the flow does not separate from the leading edge[14]. At the quoted angle of 4°, this difference is twice as large for the 7 m model as for the 1.83 m model and the scale of the vortex sheet is correspondingly larger.

(g) Two flow mechanisms have been proposed[9] which might explain the presence of the low-frequency part of the spectrum of surface pressure fluctuations.

Firstly, the boundary-layer turbulence structure may be radically changed by the adverse pressure gradient which occurs in the region before the secondary separation line. The work of Bradshaw[10] on equilibrium retarded boundary layers could support this hypothesis, as he found very large pressure-fluctuation levels at low values of the non-dimensional frequency parameter.

Secondly, unsteadiness of the flow field can produce surface pressure fluctuations by inducing changes in the static pressure field. It can be seen from Fig.3 that the secondary and subsequent vortex sheets on a slender wing arise at separation lines which are not located at a fixed edge. Such separation is inherently unsteady and it can be expected that the strengths and positions of the rolled-up vortex sheets will also be unsteady with consequent spanwise and vertical distortions of the flow field. Lambourne has demonstrated[11] that quite small changes in the position of the rolled up vortex sheet on a slender delta wing - produced in his case by forced vertical bending of the forward part of the wing - result in appreciable pressure changes on the wing surface.

The main objection to the first mechanism, which requires a modification to the boundary-layer turbulence structure of the type described and measured by Bradshaw[10], is the long time scale required for the boundary layer to reach a state approaching equilibrium in the adverse pressure gradient. For this reason, the mechanism was not thought to contribute appreciably to the spectrum measured in front of a step mounted normal to the flow on a flat plate[9]. On a slender wing, the adverse pressure gradient may be applied to the boundary layer over a longer distance as the separation line is swept relative to the incident flow. However, some measurements[9] of the surface pressure fluctuations in front of a separation line at a similar angle of sweep (produced by a swept step) showed no increase in the level of low-frequency pressure fluctuations compared with that measured ahead of an unswept step. Therefore, it can be inferred that modifications to the boundary-layer turbulence structure contribute little to the spectra obtained on the slender-wing models.

The second mechanism may produce surface pressure fluctuations in two ways. Either a large spanwise static-pressure gradient or a large variation of static pressure with incidence* can produce surface pressure fluctuations if either a horizontal or vertical oscillation respectively occurs in the flow field. As there is a large static-pressure gradient under the rolled-up leading-edge vortex sheet and also a large variation of the spanwise static-pressure level with the angle of incidence on the outboard part of the wing both directions of oscillation can produce surface pressure fluctuations on slender wings.

In addition to the possibility of these two mechanisms producing low-frequency surface pressure fluctuations, the highly threedimensional nature of the flow in the region of the leading-edge vortex sheet is likely to produce large modifications in the boundary-layer structure, because of the curvature and cross-flow components in the boundary layer, which in turn may lead to the production of low-frequency surface pressure fluctuations.

(h) Comparison of the measurements on the two models used in the present tests with earlier measurements suggests that either there is a large increase in the level of the low-frequency portion of the spectrum with increase in Reynolds number or that there was a very large amount of extraneous noise present in some of the previous measurements. A typical spectrum obtained at or near the inflection line under the core of the rolled-up leading-edge vortex sheet is plotted in Fig.9 from each of the measurements of Owen[1], Wingrove and Gell[2], and Turner and Walker[4]. The models of Owen and Wingrove and Gell were identical and of the same geometry at the 1.83 m model of the present work. The models of Turner and Walker had a slightly lower sweep angle (73.3°) and edge angle (24.4° and 26.8°) and a modified delta planform with curved wing tips. There was known to be a large amount of extraneous noise in the wind tunnel used for the tests of Wingrove and Gell[2]. The high level of the low-frequency pressure fluctuations obtained by Turner and Walker[4] may be attributable to a Mach number effect. The spectrum obtained by Owen[1] agrees very well with the present set of results.

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* A change in the angle of incidence results in changes in the strength and position of the cores of the rolled-up leading-edge vortex sheets. Hence a large variation of surface pressure with the angle of incidence, in a region of low spanwise variation, probably implies that the surface pressure is strongly dependent on the height of the vortex core above the surface as well as on the strength of the vortex core.

5 CONCLUSIONS

Spectral energy distributions of surface pressure fluctuations have been measured on the upper surfaces of two delta-wing models and were found to have two distinct parts over much of the wing area.

The high-frequency part of each spectrum has been compared with the universal scaling proposed in Ref.9 using the measured skin friction and static pressure and a boundary-layer displacement thickness that would exist on a flat plate at the same Reynolds number based on the chordwise distance from the wing apex. The agreement in magnitude is reasonable but, because of the simple method used to estimate the boundary-layer thickness, the frequency scaling is in error in many of the spectra. The errors are consistent with the likely true development of the boundary layer on the wing and, if measurements of the actual boundary-layer thickness were available for inclusion in the scaling formulae, considerable improvement in the agreement between the measured and predicted spectra would be expected.

The low-frequency part of the spectrum is not amenable to such simple scaling but the following qualitative features were noted:-

(a) The low-frequency part of the spectrum only occurs under the rolled-up leading-edge vortex sheet; there being one peak in the lower part of the spectra measured at points between the attachment and inflection lines with a second peak appearing in the spectra measured at points further outboard.

(b) As the angle of incidence is increased the non-dimensional magnitude $(\overline{p^2}/q^2)_L$ of the low-frequency portion increases and spreads slowly inboard to cover a larger part of the wing surface.

(c) The balance of evidence indicates that the magnitude of the low-frequency portion of the spectrum increases slightly with increasing Reynolds Number but appears to tend to a constant level at the highest Reynolds Number tested.

(d) Of the two flow mechanisms suggested as possible causes of the low-frequency portion of the spectrum of surface pressure fluctuations, it seems likely that the first, a major modification of the turbulence structure due to local adverse pressure gradients on the wing, has little chance of contributing to the fluctuations as the gradients do not occur over sufficient lengths for the necessary equilibrium retarded boundary layers to develop. It is much more likely that the second mechanism, unsteadiness of the flow field, will produce a contribution to the surface pressure fluctuations, firstly, by lateral oscillations of the steep pressure gradient under the vortex and, secondly, by vertical oscillations (equivalent to an incidence variation) of the outboard static-pressure field.

Acknowledgments

The authors would like to thank R.F.A. Keating for allowing them to use the results of measurements, made with the first transducer system on the 7 m model, in the preparation of this Report.

Appendix A

THE SCALING OF THE HIGH-FREQUENCY PART OF THE SPECTRUM OF SURFACE PRESSURE FLUCTUATIONS

The upper part of the spectrum of surface pressure fluctuations has been found[9] to conform to a universal scaling dependent on the local skin-friction coefficient c_f, the boundary-layer displacement thickness δ_1, and edge velocity U_1, even when the boundary layer is subject to a large adverse pressure gradient over a short distance. Using this scaling a number of measurements of the spectrum of surface pressure fluctuations under a flat-plate boundary layer, from other sources, have been plotted in Fig.10 (which is reproduced from Ref.9). A standard spectrum was defined from these results as the lowest measured spectrum. (The usual cause of inaccuracy of pressure-fluctuation measurements is the inclusion of an unknown quantity of extraneous noise and/or vibration). Integrating this standard spectrum in the form $\frac{nF(n)}{c_f^2}$ versus log n leads to the result:

$$\frac{1}{c_f}\left[\int nF(n)\ d\ (\log n)\right]^{\frac{1}{2}} = \frac{\sqrt{\overline{p^2}}}{\tau_w} = 2.41 \qquad (2)$$

In order to compare this spectrum with those measured on the slender wing models, the spectrum ordinates, $\frac{nF(n)}{c_f^2}$ were scaled using the local dynamic pressure, $[q\ (1 - c_p)]$, and the local skin-friction coefficient, c_f, measured on the model. The spectrum abscissa, $\frac{f\ \delta_1}{U_1}$, were scaled using:-

(a) the boundary-layer displacement thickness calculated for a flat plate at the same Reynolds number, based on the chordwise distance from the wing apex, using a simple expression derived from a $^1/7$-power velocity distribution:

$$\delta_1 = 0.0463 \times (R_x)^{-1/5} \qquad (3)$$

An approximate measurement[3] of the boundary-layer thickness, made on the upper surface of a slender wing inboard of the primary attachment line, where one might expect the closest approach to a flat-plate type of boundary layer, suggests that the above method of estimating δ_1 is reasonable in this area.

(b) the local velocity calculated from the static pressure coefficients measured on the models:-

$$U_1 = U\,(1 - c_p)^{\frac{1}{2}} \tag{4}$$

As an example consider the scaling of the peak of the upper portion of the spectrum. If $\left[\frac{nF(n)}{c_f^2}\right]_p$ is the magnitude of the peak of the standard spectrum (Fig.10), the magnitude of the scaled high-frequency peak measured on the slender wings will be: $(1 - c_p)^2\, c_f^2 \left[\frac{nF(n)}{c_f^2}\right]_p$. Similarly, if n_p is the frequency-parameter value for the peak of the standard spectrum, the value of the frequency parameter (based on the chordwise distance from the model apex and the freestream velocity) when scaled for the slender wings will be:-

$$\left[\frac{f\,x}{U}\right] = \left[\frac{f\,\delta_1}{U_1}\right]_p \frac{x}{\delta_1}\,\frac{U_1}{U} = n_p\,\frac{x}{\delta_1}\,\frac{U_1}{U} \tag{5}$$

It is worth noting two consequences of this scaling. Firstly, the thinner the boundary layer the higher up the frequency range (based on x) will the peak occur and secondly, the greater the suction under the rolled-up leading-edge vortex sheet the higher up the frequency range will the peak occur.

It should be stressed that this scaling has been derived from measurements made in twodimensional flows and consequently, in areas on a slender wing where the flow is highly threedimensional (under the leading-edge vortex sheet for example), the scaling of the frequency parameter may be considerably in error. In particular, the cross-flow component in the boundary layer in these areas may produce a significant change in the displacement thickness[12], in addition to the effect of a favourable pressure gradient, (which is the only influence in twodimensional boundary layers) so that the displacement thickness δ_1, may not be the correct length for scaling the frequency parameter for the high-frequency pressure fluctuations measured in these areas.

SYMBOLS

c_f	local skin friction coefficient: $= \frac{\tau_w}{q}$
c_p	static pressure coefficient.
f	frequency Hz
Δf	measuring system bandwidth Hz
n	frequency parameter: $= \frac{f\,x}{U}$ for the model results
	$= \frac{f\,\delta_1}{U_1}$ for the universal spectrum
nF(n)	mean-square pressure-fluctuation level per unit fractional bandwidth per unit (dynamic pressure)^2: $= \frac{\overline{p^2}}{q^2\,\varepsilon}$
	(see also Ref.9 for a fuller definition)
p	fluctuating pressure (mean square value $\overline{p^2}$)
q	freestream dynamic pressure
R_x	Reynolds number based on x: $= \frac{U\,x}{\nu}$ where ν is the kinematic viscosity
S_x	wing span at a given chordwise location x
U	freestream velocity
U_1	velocity at the edge of the boundary layer
x	chordwise distance from the wing apex
y	spanwise distance from the wing centreline
α_w	wing incidence (uncorrected for wind-tunnel wall constraint)
δ_1	boundary-layer displacement thickness
ε	fractional bandwidth of the measuring equipment $= \frac{\Delta f}{f}$
τ_w	surface shear stress

Suffices

L	low-frequency contribution to spectrum
P	peak in the high-frequency contribution

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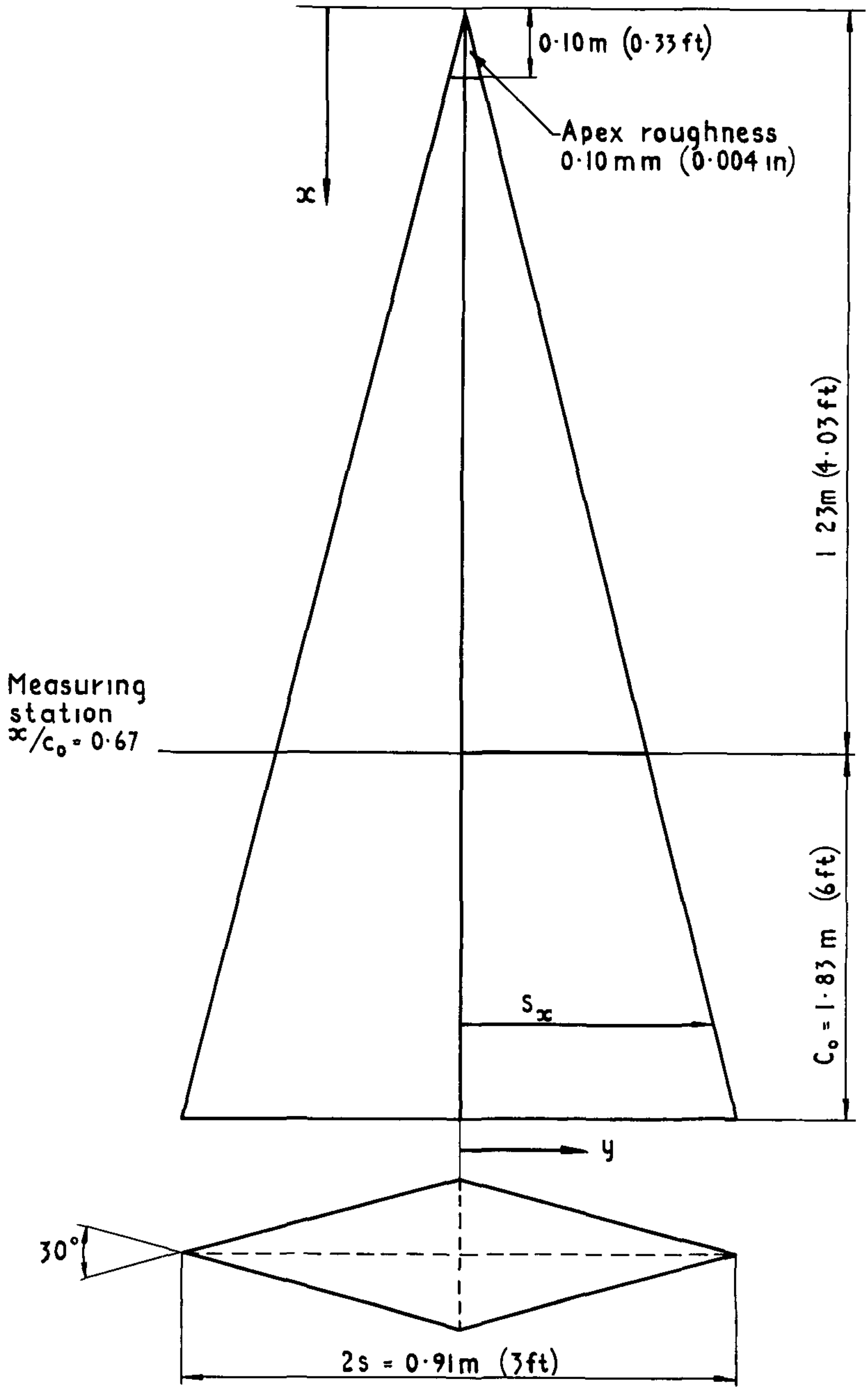


Fig.1 GA of 1 83m model

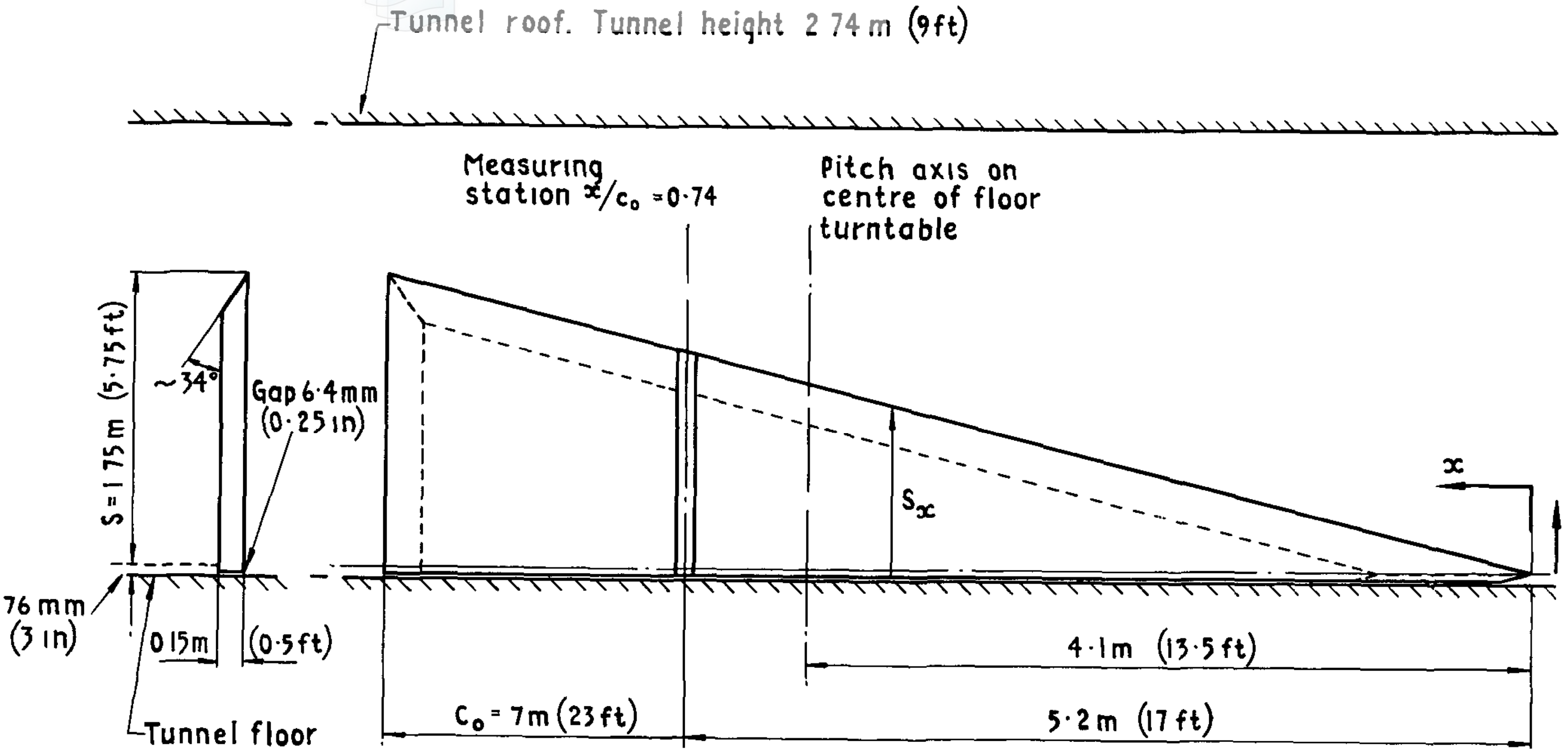
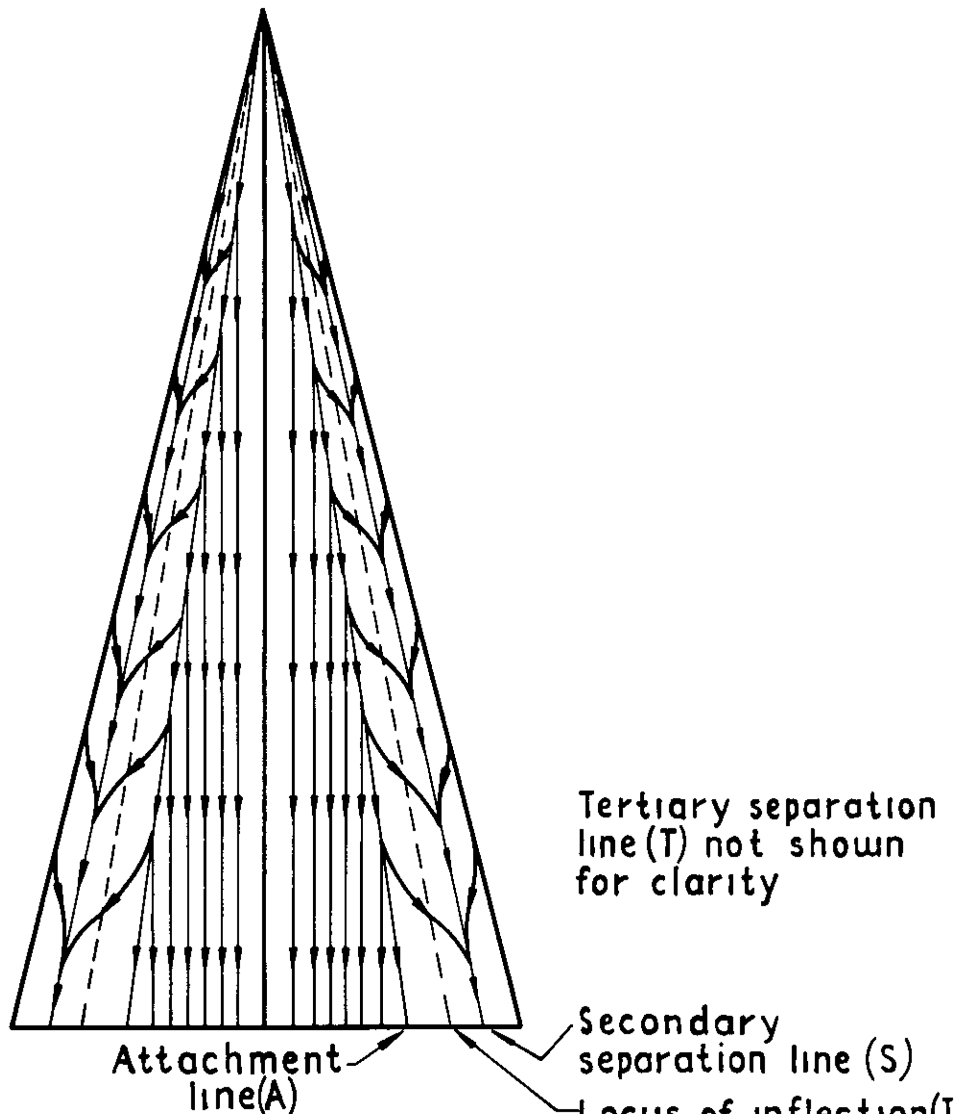
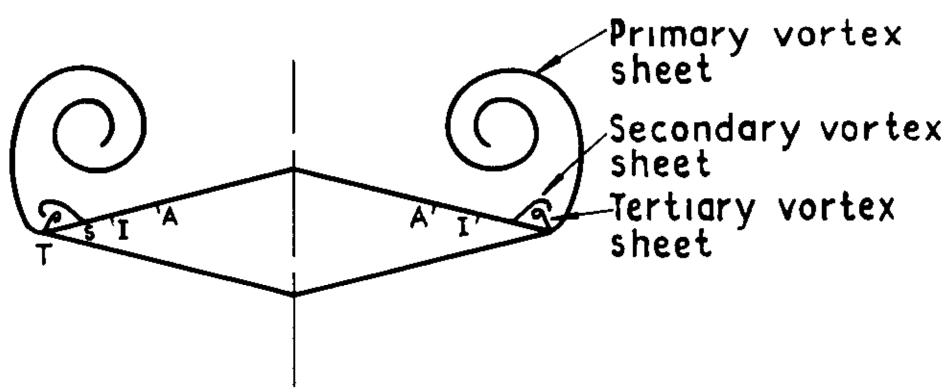


Fig. 2 GA of 7m half model

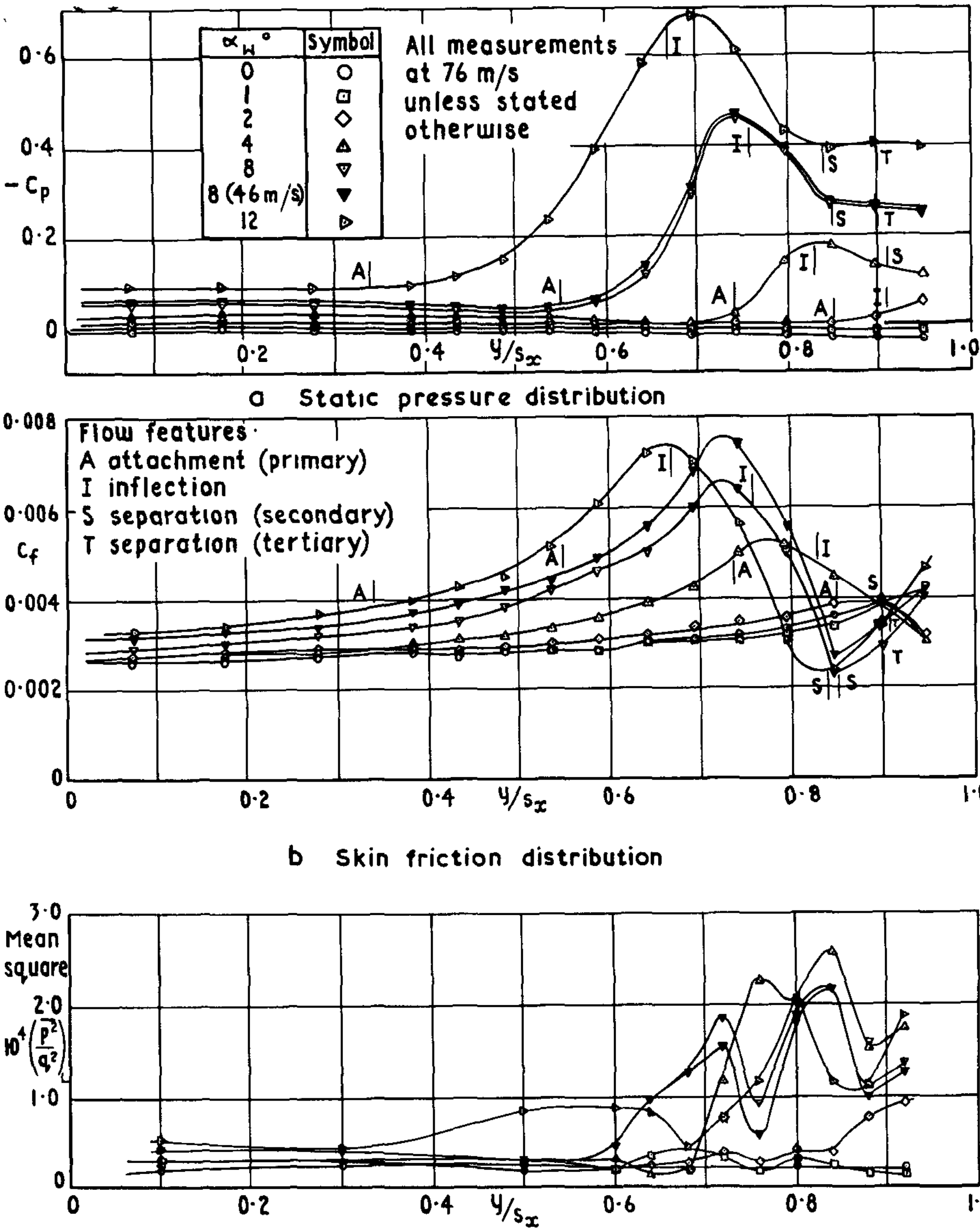


a Surface flow pattern



b Cross-section of flow

Fig 3a & b Flow over the upper surface of a delta wing at incidence



a Static pressure distribution

b Skin friction distribution

c Mean-square pressure fluctuation distribution

NB-does not include the upper part of the spectrum

Fig.4a-c 1·83 m delta. Spanwise variation of static pressure, skin friction, and mean square pressure fluctuation level

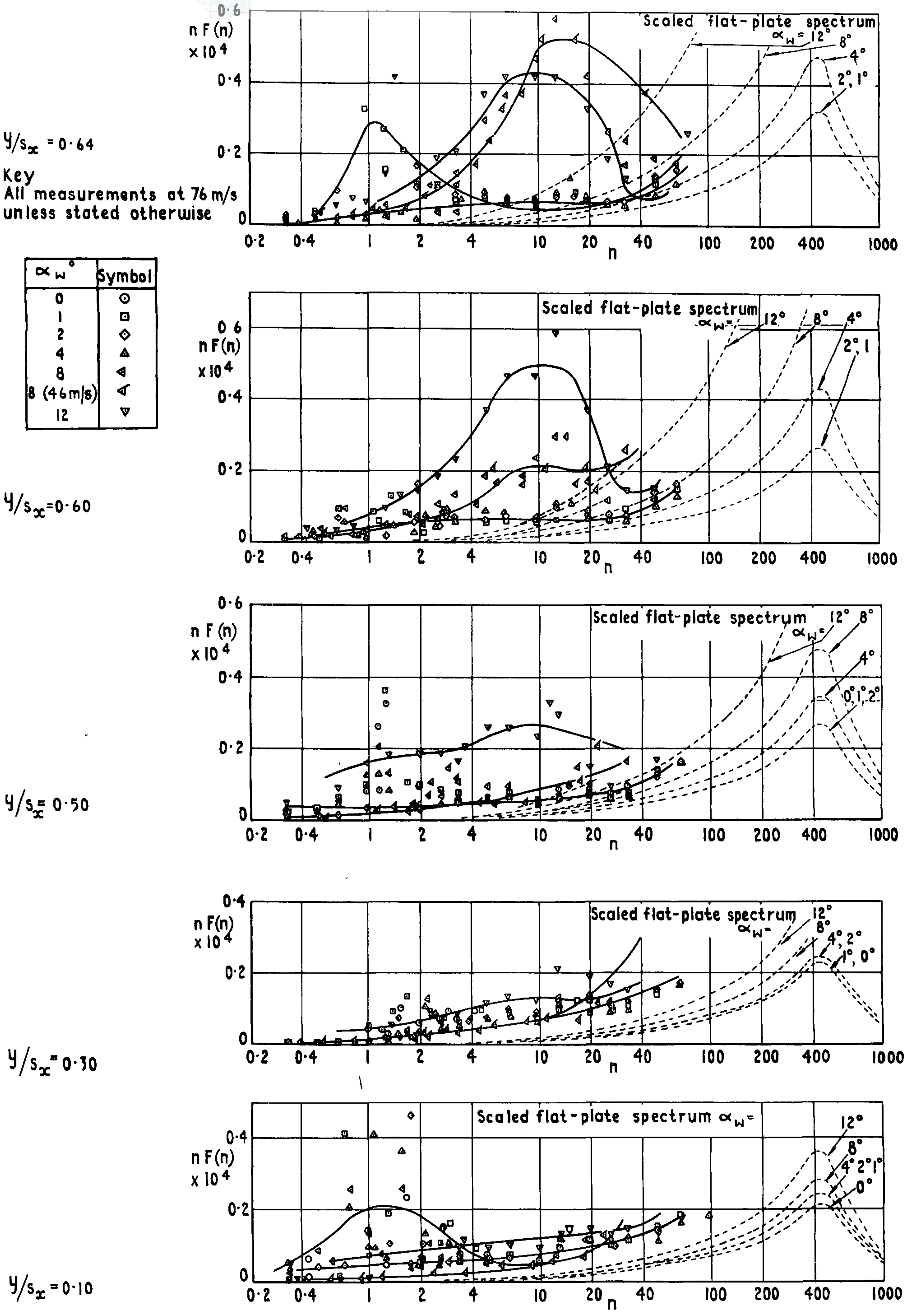


Fig.5 1·83 m delta. Spanwise variation of the spectrum of surface pressure fluctuations (y/s_x=0·10 to 0·64)

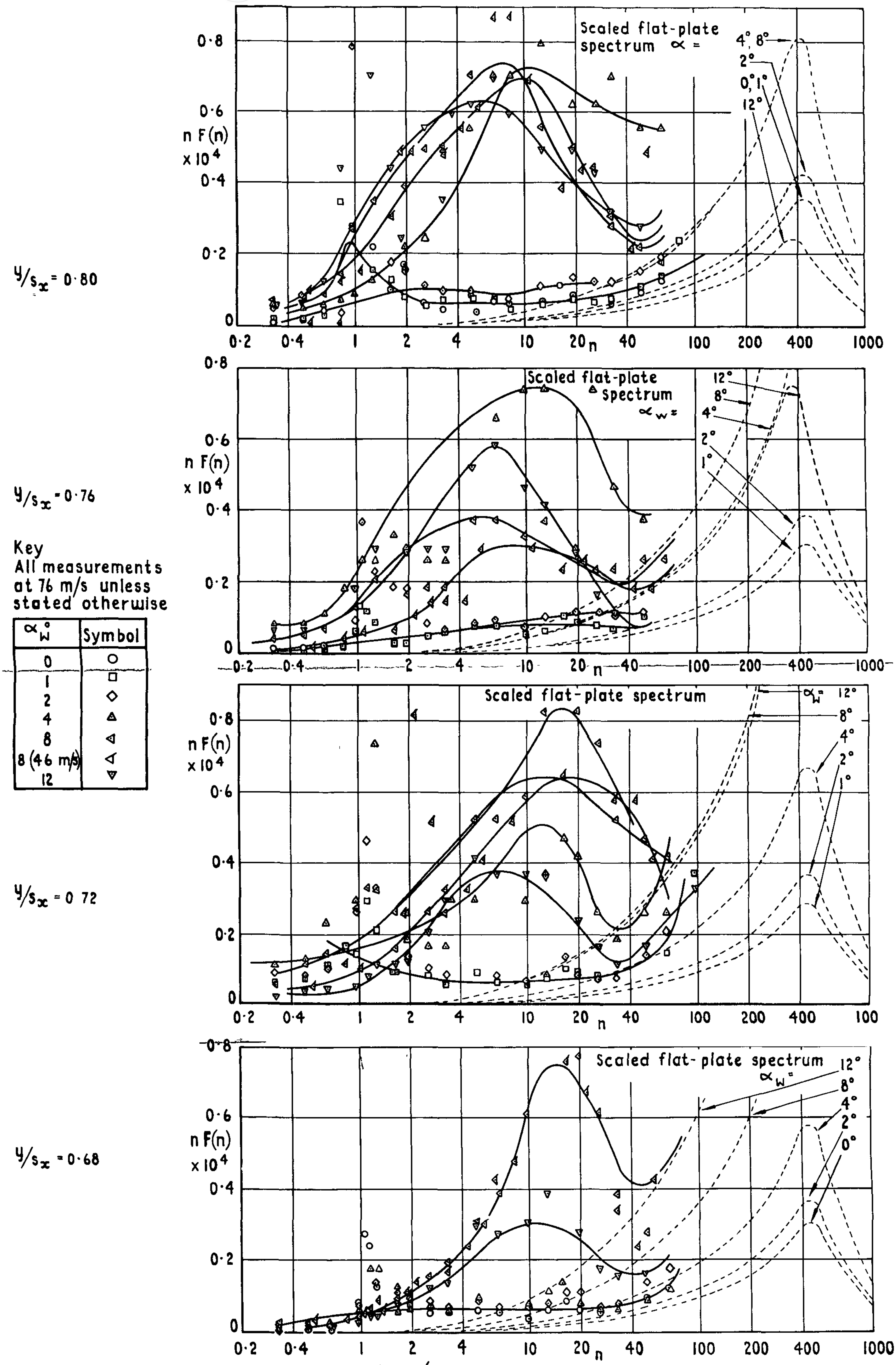


Fig. 5 contd (y/s = 0·68 to 0·80)

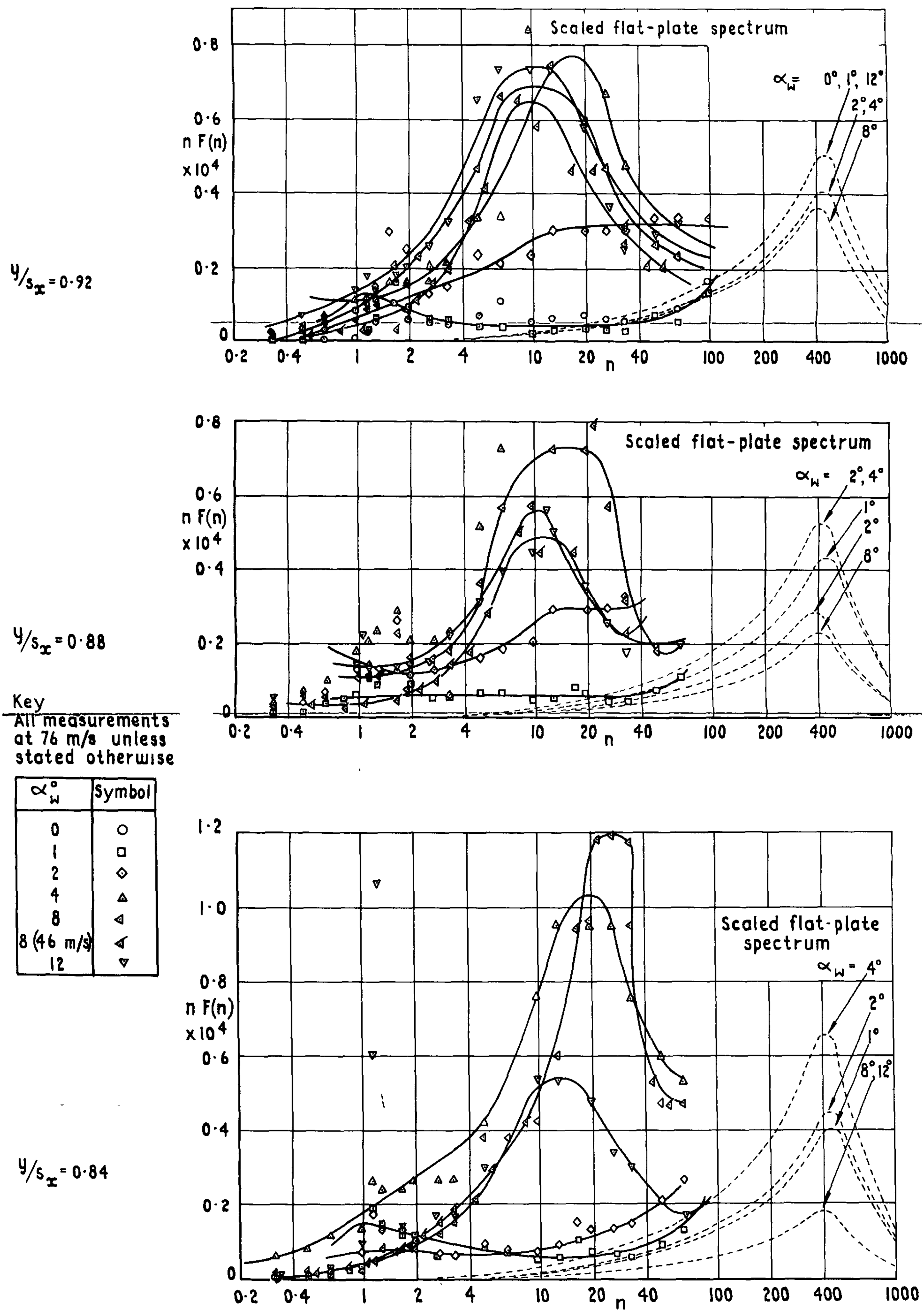


Fig. 5 concld (y/s = 0·84 to 0·92)

Key to symbols

System 1

α_w°	Speed m/s	Symbol
2	46	◇
6	46	▽
10	46	▷

System 2

α_w°	Speed m/s	Symbol
6	46	▼
	30	✓
10	46	▶
	30	◣

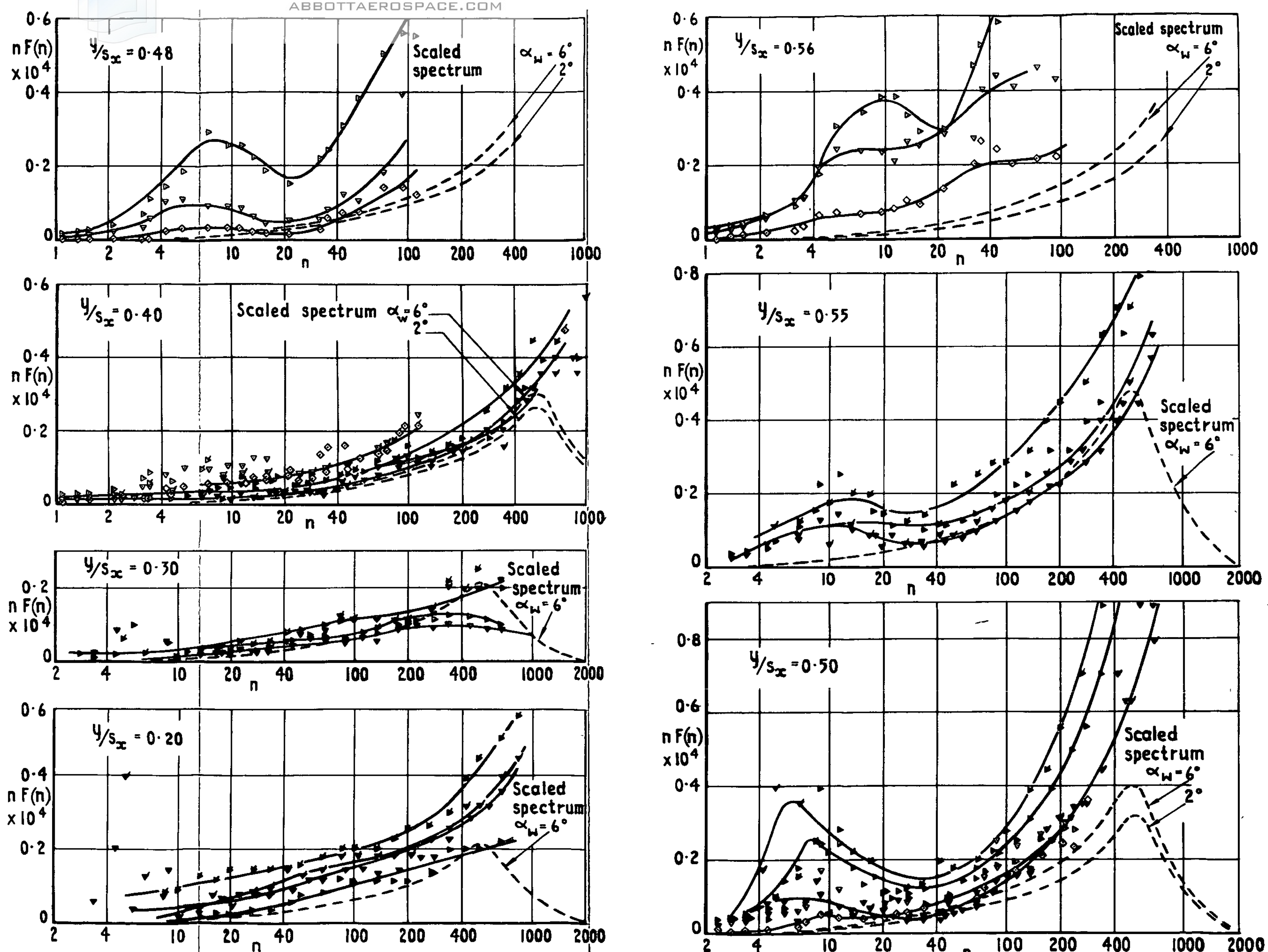


Fig.7 7m delta. Spanwise variation of the spectrum of surface pressure fluctuations (y/s_x = 0·20 to 0·56)

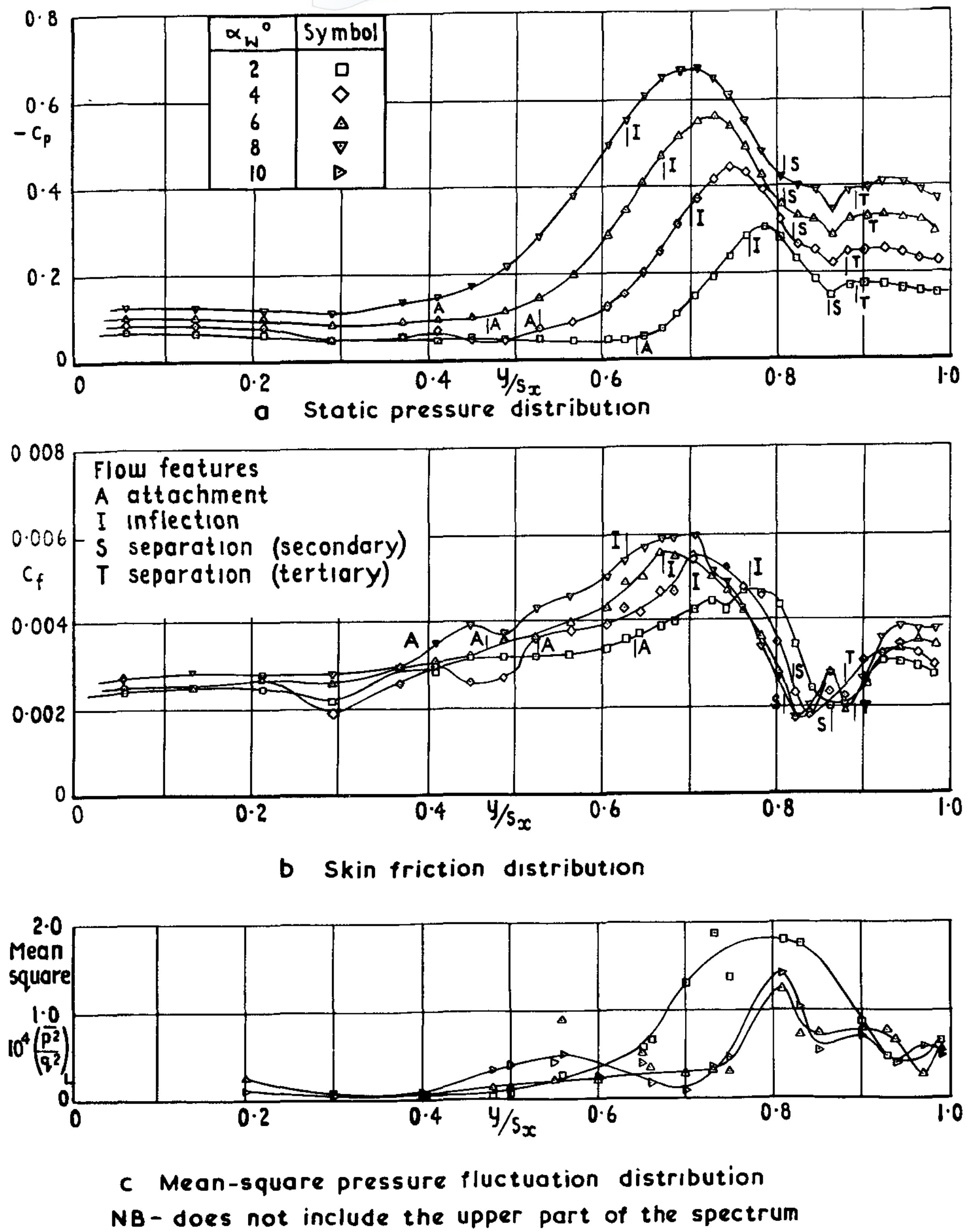


Fig.6 a-c 7 m delta. Spanwise variation of static pressure, skin friction, and mean square pressure fluctuation level

Key to symbols

α_w°	Speed m/s	System	Symbol
2	46	1	◇
6	46	1	▽
	46	2	▼
	30	2	▼
10	46	1	▸
	46	2	▶
	30	2	↙

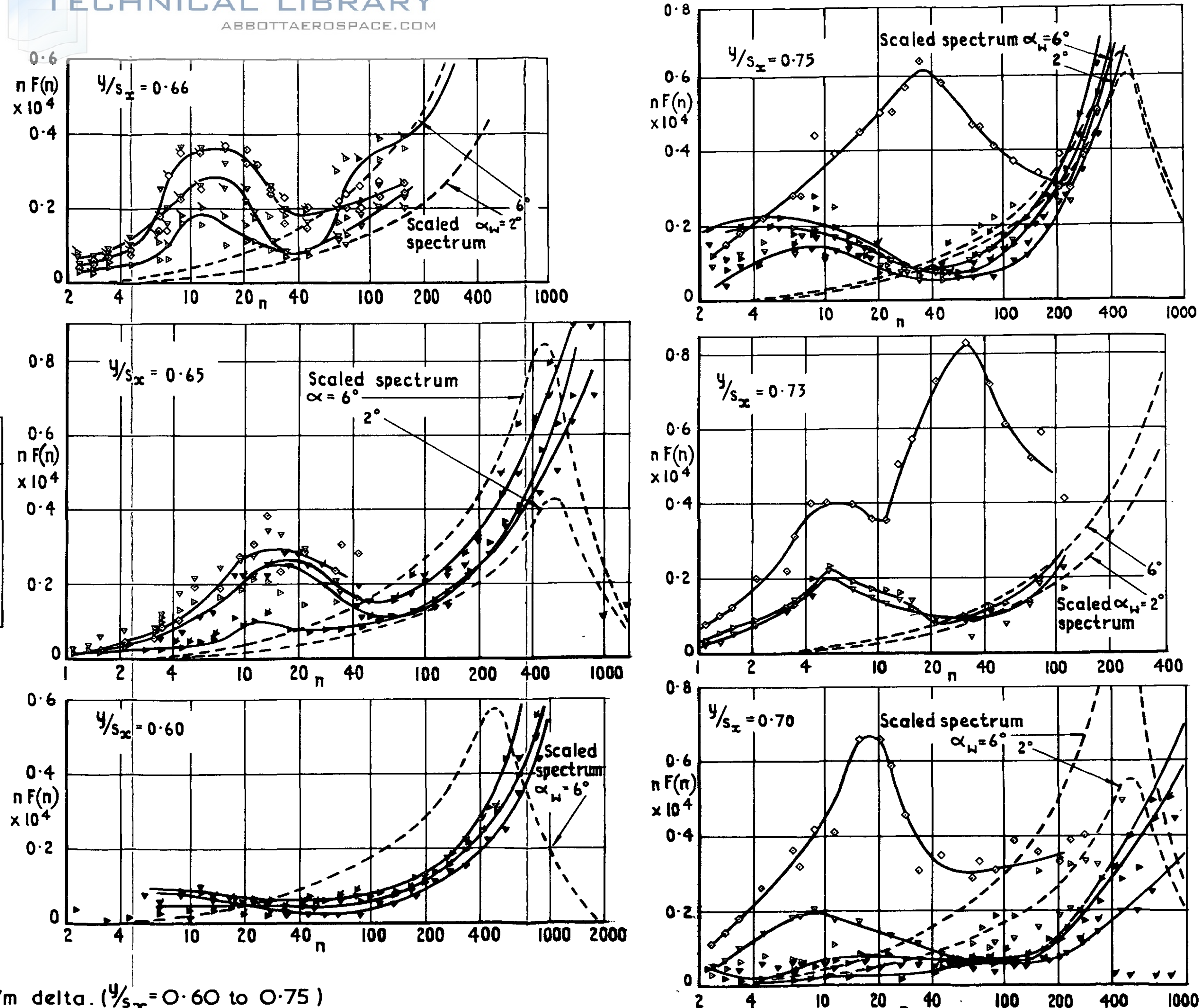


Fig.7 contd 7m delta. (y/s_x = 0·60 to 0·75)

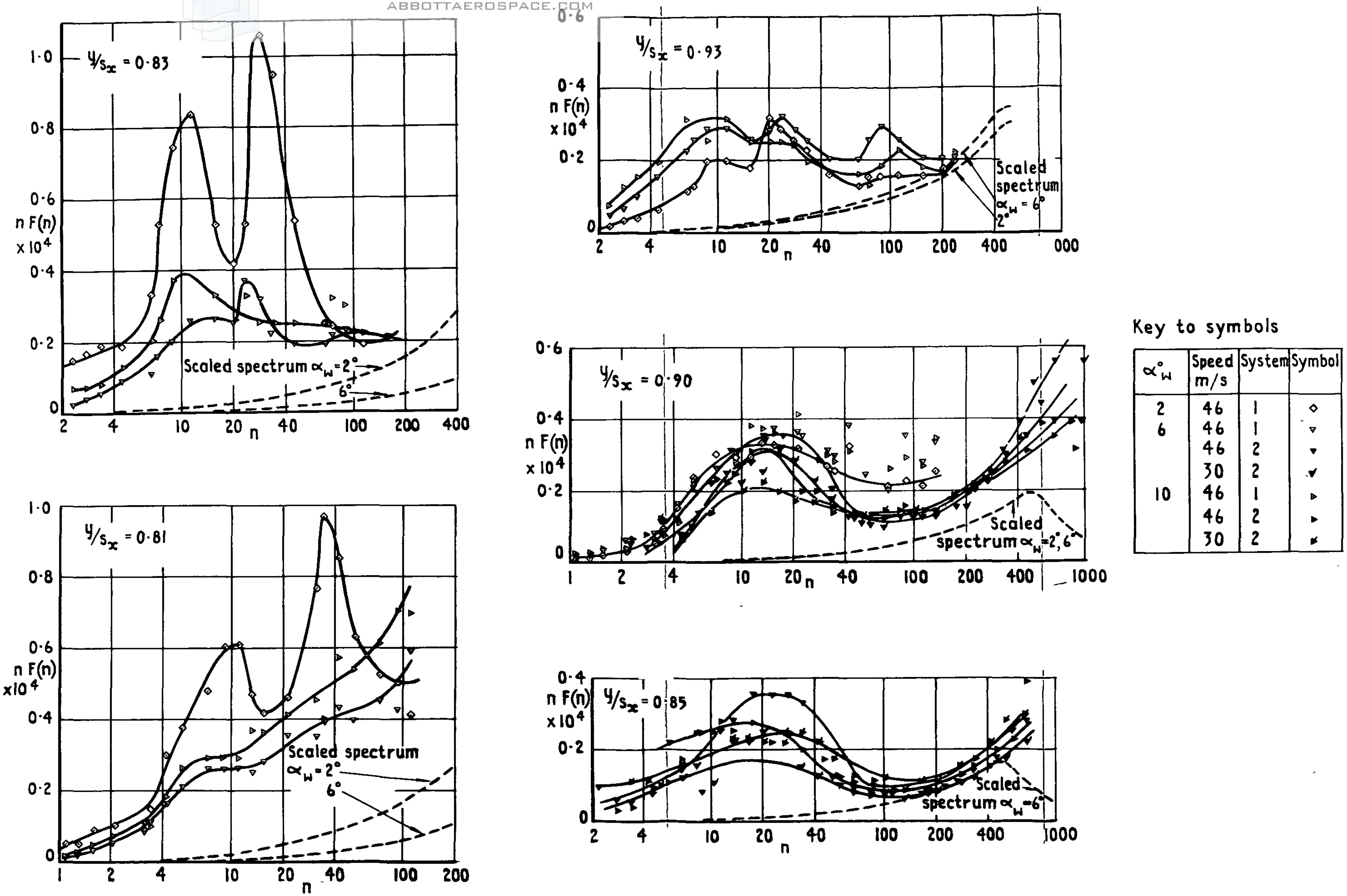


Fig. 7 contd 7m delta. (y/s_x = 0·81 to 0·93)

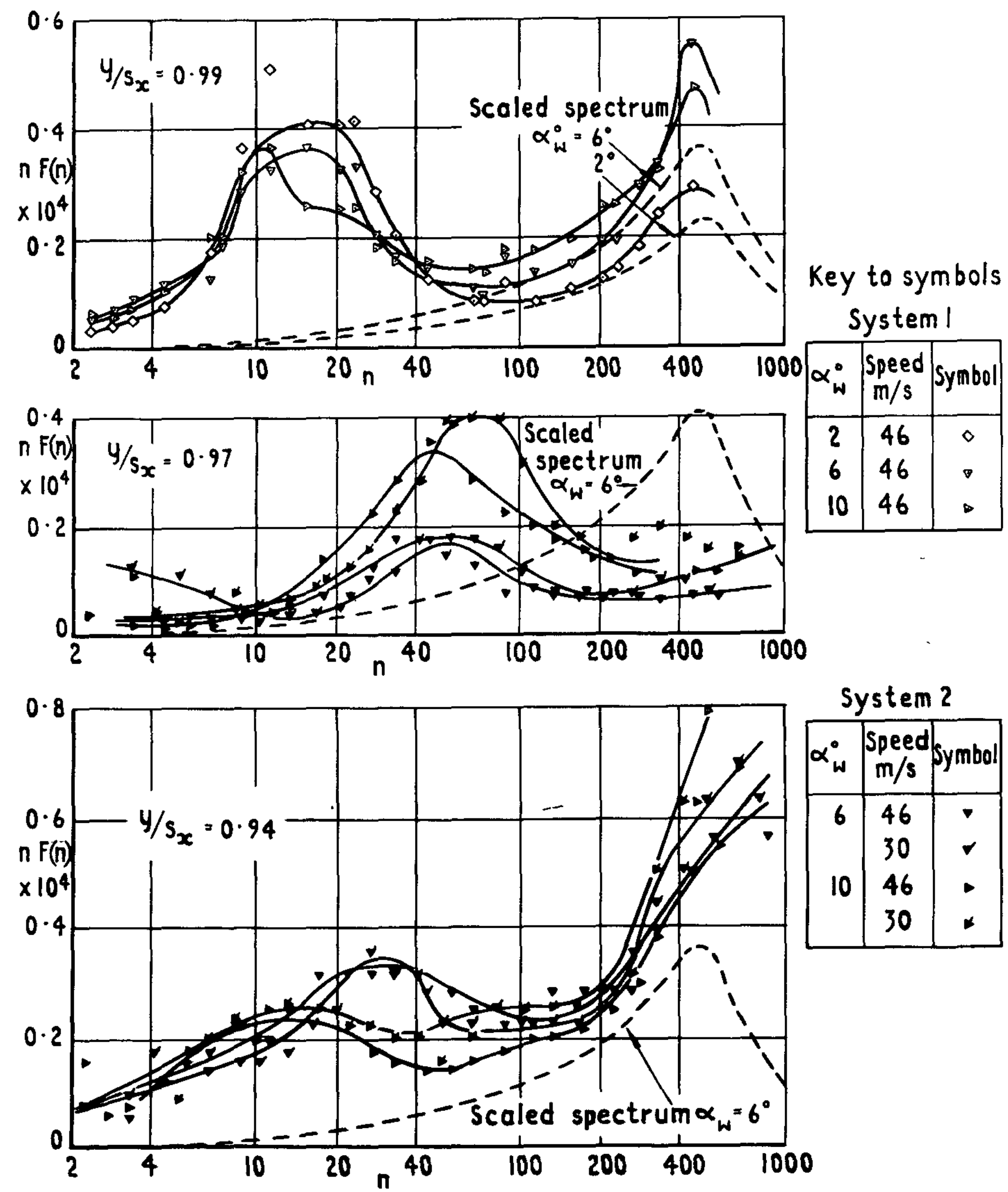
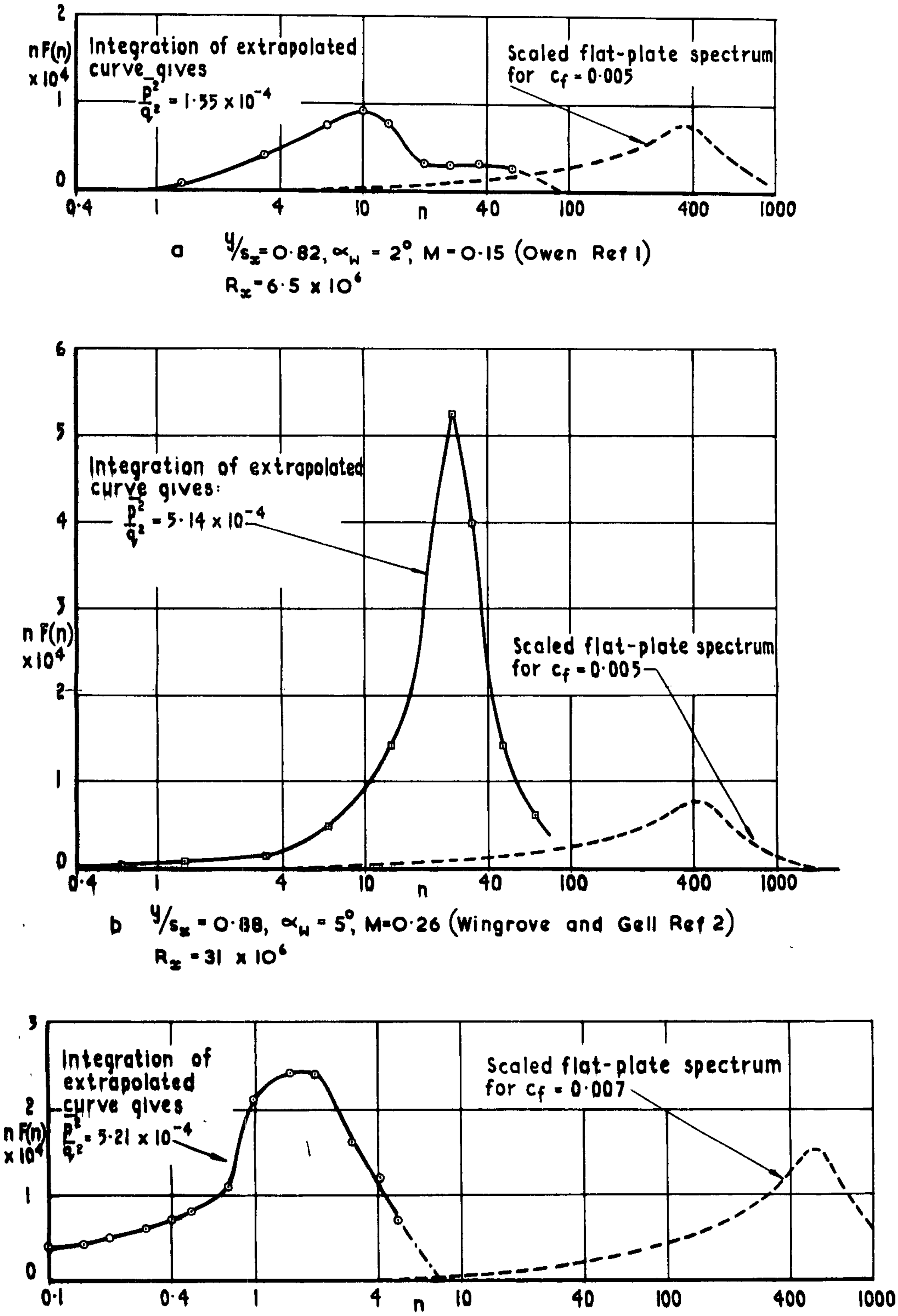


Fig.7concld 7m delta (y/s_x=0·94 to 0·99)



a $y/s_x = 0{\cdot}82$, $\alpha_W = 2°$, $M = 0{\cdot}15$ (Owen Ref 1)
$R_x = 6{\cdot}5 \times 10^6$

b $y/s_x = 0{\cdot}88$, $\alpha_W = 5°$, $M = 0{\cdot}26$ (Wingrove and Gell Ref 2)
$R_x = 31 \times 10^6$

c $y/s_x = 0{\cdot}84$, $\alpha_W \simeq 6°$, $M = 0{\cdot}93$ (Turner and Walker Ref 4)
$R_x = 22 \times 10^6$

Fig.9a-c Surface pressure-fluctuation spectrum measurements under the leading-edge vortex on three delta wings

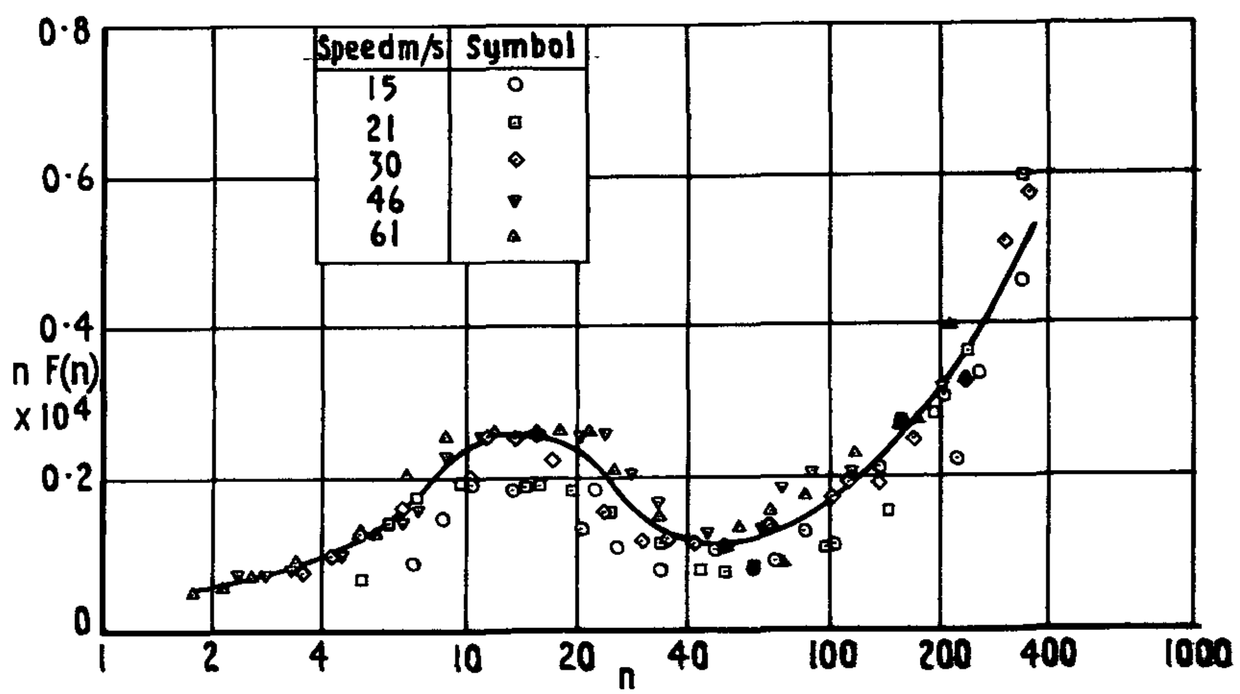


Fig.8 Reynolds number effect: $y/s_x = 0\cdot66$, $\alpha_w = 6^\circ$ (7m delta)

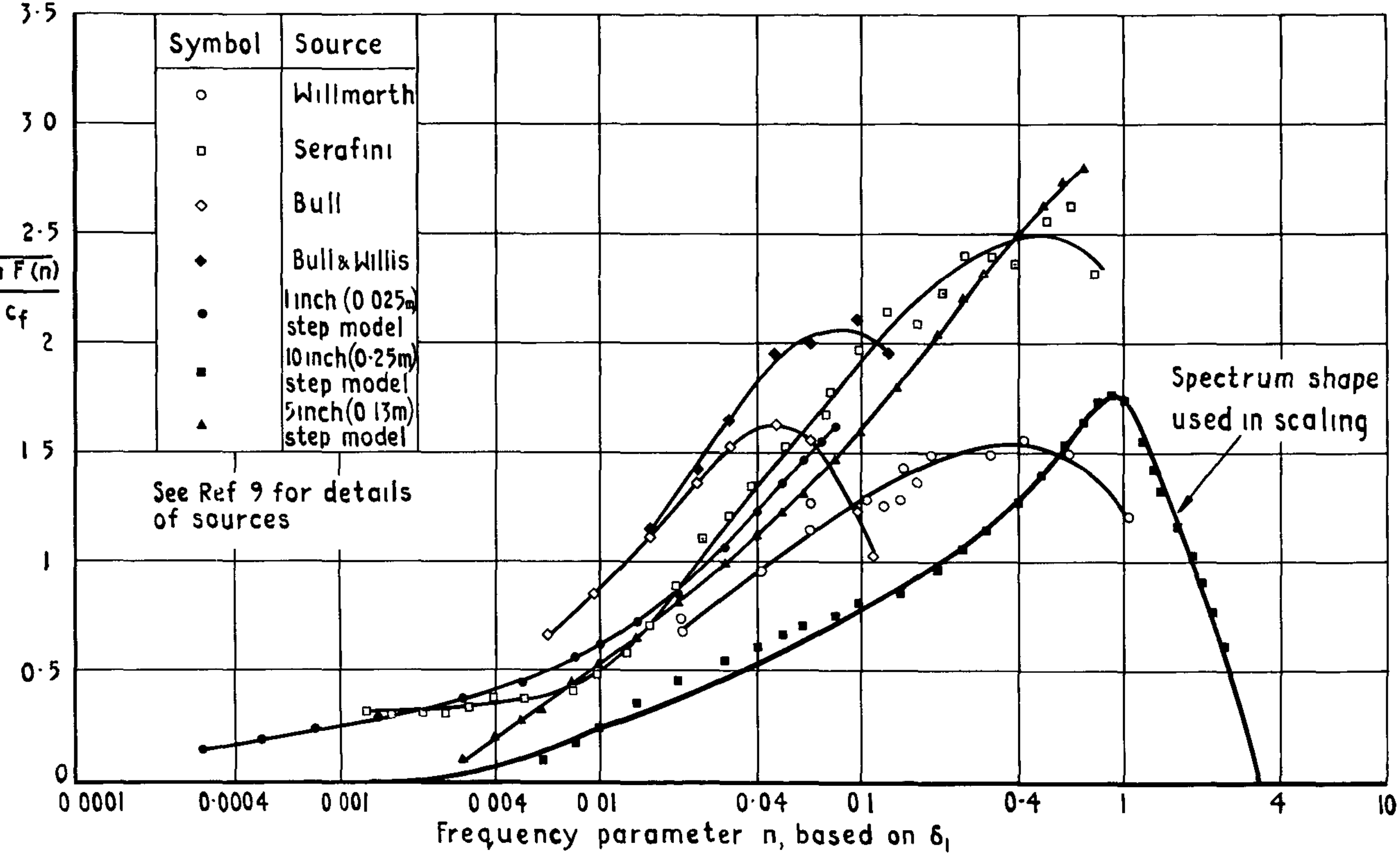


Fig 10 Comparison of pressure-fluctuation frequency spectra measured on a flat plate

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Owen, T.B

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