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The effect of longitudinal stagger on the aerodynamic interference between two axisymmetrical bodies whose centrelines are parallel, at zero pitch and are separated by 1.05 body diameters.

by

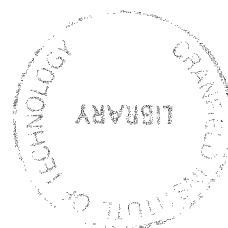
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SUMMARY

The pressure distributions have been measured over an axisymmetrical body of 7.665:1 fineness ratio in the presence of a similar body. The stagger of the second body was varied over the range of -2 to +3 body diameters. The pressures were integrated to obtain the loading distributions and these were then integrated to obtain the overall aerodynamic characteristics.

The interference normal-force loadings are greatest at zero stagger. At other staggers, the loadings over the front body are considerably greater than those on the rear body, but the magnitude of overall normal-force is the same.

The axial-force loading distributions are similar in character at all staggers with the greatest variation occurring at the beginning of the afterbody. The overall axial-force of the pair of bodies, ignoring base effects, is a minimum at zero stagger.

The body pressure distributions have been presented in the form of contour diagrams and isometric plots. These show very clearly the extent of the interference region on the bodies.

Theoretical estimates of the interference effects agreed well with experiment.

SYMBOLS

A	Axial force (due to body pressures only)
C_A	Axial-force coefficient (A/qS)
C_m	Pitching-moment coefficient (M/qSL)
C_N	Normal-force coefficient (N/qS)
C_P	Pressure coefficient ($(p-p_\infty)/q$)
$dC_A/d(x/L)$	Local axial-force loading
$dC_m/d(x/L)$	Local pitching-moment loading
$dC_N/d(x/L)$	Local normal-force loading
D	Maximum body diameter
L	Overall length of the body
M	Pitching moment, (measured about the nose)
N	Normal force
p	Local static pressure
p_∞	Free-stream static pressure
q	Free-stream dynamic pressure
r	Body radius
S	Maximum body cross-sectional area ($\pi D^2/4$)
x	Distance from nose of the body

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1.0 INTRODUCTION

The carriage of stores on aircraft has often led to aerodynamic problems such as high interference drag and poor release characteristics. These problems appear to become more serious when the stores are in close proximity and the mutual interference between them becomes large. Accordingly a research program to investigate the aerodynamic interference between axisymmetrical stores was initiated at the College of Aeronautics with MOD(PE) support.

The object of the programme is to measure the pressure distribution over the surface of an instrumented model of a chosen store shape and then, by successive integration, obtain the local loadings and the overall forces and moments on the store. After this had been done for the store in isolation, then an uninstrumented (dummy) body would be positioned near the instrumented (live) body and the revised pressure distribution obtained and analysed to determine the interference due to the dummy body.

In general, when stores are carried externally on an aircraft they are mounted so that their axes are parallel to each other. The main parameters that then determine the geometric configuration are a) the number of stores in close proximity to each other, b) the distance apart of their centre-lines (separation) and c) the longitudinal spacing relative to each other (stagger). It is planned to investigate initially the effects of separation and stagger on two bodies at zero incidence and then extend the tests to examine the effects of incidence and yaw on chosen configurations that have been shown to have moderate interference at zero incidence. Later three-body configurations will be similarly investigated.

It is also proposed to use computational fluid dynamics techniques to predict these interference effects and establish how well the predictions agree with the experimental results.

Since the theoretical methods considered are unlikely to predict separated flow accurately, a body shape was chosen which would have attached flow over the afterbody but still have significant viscous effects at low incidences.

The shape selected had an ogival nose of 3:1 fineness ratio. The ogive was continued past the maximum thickness until its tangent made an angle of -3 degrees to the horizontal when it blended into a 3 degree semi-angle conical boat-tail which was truncated at a distance of $7.665 D_{max}$ from the nose to form a bluff base of diameter $0.538 D_{max}$ (Fig 1).

References 1 and 2 describe the development of the experimental rig and the measurement of the aerodynamic characteristics of the chosen body shape

Reference 3 reports on the effect of store separation on two unstaggered stores, the separation of the centre-lines varying between 1.025 and 1.40 D_{max} .

The present tests investigate the effect of stagger on the aerodynamic interference at zero incidence at a fixed separation of 1.05 D_{max} .

2.0 EXPERIMENTAL DETAILS

2.1 The models and their support system

The instrumented body was made of aluminium to the shape described above and was 60.56 inches (1538 mm) long with a maximum diameter of 7.906 inches (200.8 mm). It was pressure plotted along one axial generator with 36 pressure tappings located at the body stations shown in Table 1 which also includes the body cross-sectional areas and surface slopes at the pressure plotting stations.

In order to determine the pressure distributions over the whole surface, the model could be rotated about its axis by an internally mounted stepper motor.

The support sting was 2.0 inches (50.8 mm) in diameter, but when the original support rig was modified to minimise the support interference, it was necessary to extend the sting. The sting extension was also of 2.0 inches (50.8 mm) diameter, but it had a socket joint of 2.25 inches (57.2 mm) diameter and 10.5 inches (267 mm) long at its front end. When the model sting was inserted, the front of the socket joint was 2.0 inches (50.8 mm) behind the base of the model. The extension sting was clamped to a pivot joint which in turn was clamped to an unfaired rectangular support tube 2.25 inches (57.2 mm) wide and 4.625 inches (117.5 mm) deep which spanned the tunnel and was attached to channel sections extending from the rear of the top and bottom turntables, Fig 2. The distance of the front of the pivot support behind the base of the model was 37.0 inches (940 mm).

The normal incidence bridle and tension wire was attached to the socket joint at a position 9.5 inches (240 mm), $1.20 D_{\text{model}}$, behind the base of the model. The incidence of the model was set by adjusting the incidence bridle using the tunnel incidence change system which was recalibrated to indicate the incidence of the model.

The dummy body was of the same shape and dimensions as the live body but was designed to be as light as possible for ease of handling and adjustment of its position in the tunnel relative to the live body. It was turned from a block of polystyrene foam glued to a long tube of 2.0 inch (50.8 mm) diameter which extended approximately 63.5 inches (1610 mm) behind the base of the model. No instrumentation was installed, but as it was required to investigate the flow over the body using the oil flow technique, the porous surface of the polystyrene was sealed by a thin skin of epoxy resin before the model was finally turned to shape and sprayed black to provide a suitable background to view the oilflow patterns. The epoxy skin was also necessary to enable the oil to flow easily and to prevent it from interacting with the polystyrene.

The sting was attached to the rectangular tube by a clamp similar to that used for mounting the live body except that the pivot for altering the pitch of the model was not incorporated. The sting was steadied by a single vertical wire from the top turntable to the sting and two wires from the sting to the bottom turntable to form a triangulated support, Fig 2. All three wires incorporated turnbuckles so that, although no pivot was present, the pitch of the dummy model could be set over a small range by tensioning the wires to bend the sting slightly.

The position of the dummy body in the tunnel was set a) by sliding the sting clamp along the vertical support tube to alter the model height, b) by sliding the support sting through the sting clamp to adjust the fore-and-aft position of the model and c) by adjusting the turnbuckles in the steadying wires to adjust the incidence of the model. By cycling round these three adjustments in turn it was possible to set accurately the separation and stagger of the dummy model relative to the live body when it was aligned with the oncoming flow.

2.2 Transition fixing

The test Reynolds number was 500,000 based on body diameter or 3,800,000 based on the length of the body.

In order to ensure that a turbulent boundary was present over the body, a transition wire of 0.014 inches (0.35 mm) diameter encircled the body at 3.7 inches (94 mm) behind its nose, i.e at approximately 0.06L.

2.3 Instrumentation

The individual pressure tapings were connected by plastic tubing to a 48-port Scanivalve pressure switch inside the model. The pressures were then measured by a Setra ± 0.1 psi differential-pressure transducer.

The tunnel dynamic head was obtained from a standard pitot-static probe mounted on the horizontal centreplane of the tunnel at a distance of 12 inches (300 mm) from the side wall and 15.6 inches (400 mm) behind the nose of the model. This pressure was measured by a Setra ± 0.5 psi differential-pressure transducer. The static pressure from the pitot-static was also used as the reference pressure for the Scanivalve pressure transducer and was also connected to the first Scanivalve port to measure the zero reading of the transducer at the beginning of each scan.

A PET microcomputer was used to step the scanivalve and measure the static pressures at the various pressure tapings by means of a 12-bit analogue-digital converter. At each position the pressure at the Scanivalve port was measured as was the tunnel dynamic head obtained from the pitot-static head. The microcomputer then worked out the mean value of the pressure coefficient, C_p , corrected for

instrumentation drift, at each station, printed out the mean pressures and C_p value and stored them on disc.

At the completion of the Scanivalve scan, the microcomputer rolled the model through 18 degrees and repeated the scan. This continued until the model had been rotated through 360 degrees from the datum position which was when the pressure generator was vertically above the model centre-line.

Initially each pressure was sampled 50 times and averaged to obtain the mean pressure. As the time to complete a scan seemed excessive, experiments were made which showed that there was no noticeable loss in accuracy if the number of samples was reduced to 10. Accordingly the reduced number of samples was used over the latter part of the test program.

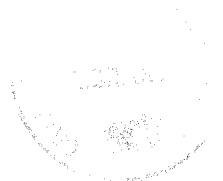
The discrimination of the system was $C_p = 0.003$ approximately, but due to tunnel unsteadiness, noise, etc the overall accuracy was somewhat greater.

2.4 Data reduction

The data was transferred to the CoA VAX 750 computer and an analysis program used to integrate the pressure distribution at each station to obtain the local loadings and then to integrate these loadings along the length of the body to obtain the overall forces and moments acting on the body. Additional programmes were then used to plot the results.

The results are presented about a system of body axes whose origin is at the nose of the live body, Fig 3.

It should be noted that in the previous tests, refs 1 - 3, the reference length used in the calculation of the local loadings was the length of the model plus the length of the base fairing used in the



calculation of the theoretical pressure distributions. As this resulting length has no particular significance, it was decided to change the reference length to one that had a physical significance, i.e. the length of the body. As the body length, L , was 0.8 of the length of the body plus base fairing, the loadings obtained in the present tests will be 0.8 of the loadings obtained previously.

3.0 TEST PROGRAMME

The previous tests on the effects of store separation, ref 3, had shown that the interference loadings increased very rapidly when the separation between the store centre-lines approached $1 D_{max}$. In order to investigate the effects of stagger, it was necessary that the basic separation should be small enough to ensure appreciable interference effects at zero stagger, but not so small that noticeable changes in the interference effects if small variations occurred in the separation of the bodies when the stagger of the dummy body was altered. The basic separation was chosen therefore to be $1.05 D_{max}$.

The instrumented body was mounted in the windtunnel with its axis in the horizontal plane and $0.525 D_{max}$ below the horizontal centre-line of the working section. Brief tests were then made to align the model with the oncoming airstream. From this time onwards, the position of the instrumented model was not altered.

The dummy model was then installed with its axis $0.525 D_{max}$ above the centre plane of the working section and its position adjusted to the required stagger. The stagger was defined as being positive when the dummy body was downstream of the instrumented body.

The pressure distributions were measured at staggers of -2, -1, 0, +1, +2 and +3 D_{max} . Time was not available to test at -3 D_{max} stagger as the accurate adjustment of the model position was found to be very time-consuming especially at negative stagger. This was partly because small pitch adjustments caused appreciable variations in the separation of the models, but mainly because the position of the dummy model had to be determined by measurement from the working-section walls which proved time-consuming to do accurately.

4.0 DISCUSSION OF THE EXPERIMENTAL RESULTS

4.1 Loading distributions

The variation of the normal-force, pitching-moment and axial-force loadings along the body are plotted in Figs 4, 5 and 6 for all separations.

4.1.1 Normal-force loadings

At zero stagger, the loading initially becomes more negative as x/L increases, i.e the induced loading will cause the noses of the bodies to separate. The loading reaches a negative peak at $x/L = 0.15$ and then increases with x/L until it reaches a positive peak at the maximum diameter of the body, $x/L = 0.392$. With further increase in x/L the loading decreases rapidly, becoming zero at about $x/L = 0.58$. Aft of this, the rate of decrease becomes much less resulting in the loadings being small but slightly negative over the remainder of the body.

As stagger becomes positive, i.e. the dummy body moves aft, the position of the peak negative loading moves smoothly aft with increase in stagger, Fig 7, and the magnitude of the peak becomes larger with increase in stagger, Fig 8, up to a stagger of $+2 D_{max}$. However at $+3 D_{max}$ stagger the peak loading has decreased in magnitude to the approximately the same value as it was at $+1 D_{max}$. At negative stagger the position of the peak negative loading moves forward and the peak decreases in magnitude in conformity with the trends established for positive stagger.

The position of the peak positive loading varies with stagger in the same manner as the negative peak loading, Fig 7, with the difference in position of the two peaks remaining approximately constant.

The variation of the magnitude of the positive peak loading with stagger is rather different. The maximum positive loading occurs at zero stagger and decreases with both positive and negative variation of stagger, with the decrease being much greater as the stagger becomes more negative, Fig 8. Although the shape of the loading distribution at a stagger of $-1 D_{max}$ is similar to those obtained at at more positive staggers, the shape of the loading distribution at a stagger of $-2 D_{max}$ is rather different, Fig 4, as the positive peak of the loading distribution is much flatter than at the other staggers and the loadings aft of $x/L = 0.6$ are much more irregular than those at the other staggers in that there are two well-defined peaks in the distribution. The reasons for this change in character of the loading distribution are not obvious. The position and magnitude of the peak are not noticeably at variance with the previously established trends, Figs 7 & 8, and in the absence of any results at a stagger of $-3 D_{max}$, there is no good reason to suspect experimental error.

So far the loadings have been presented as those occurring on the instrumented body due to the presence of the dummy body at various positions relative to it. It should be realised that what is of most interest is the interference loadings on each body of the pair at a given stagger. This can be derived from the results in Fig 4 by plotting the loadings on separate axes staggered by the correct amount and with the sign of the loadings reversed for the upper (dummy) body. These pairs of loadings are presented in Figs 9, 10 & 11 for staggers of 0, 1 and 2 D_{max} .

It is immediately apparent that the corresponding loading peaks occur at approximately the same longitudinal position. The agreement is very good in the case of the first pair of peaks, but, in the case of the second pair, the peak loading of the rearmost body occurs slightly further forward than that of the front body. This is somewhat unexpected as it would be assumed that both positive peaks would occur at the position where the gap between the two bodies was a minimum.

The other main feature of the distributions is that the interference effects on the front body are considerably greater in magnitude than those on the rear body. Whilst the shape of the distributions are similar at a stagger of $1 D_{max}$, at $2 D_{max}$ stagger the shape of the loading distribution over the rear body is significantly different as previously noted. It is unfortunate that the results for a stagger of $3 D_{max}$ were not available so that this feature could be investigated further.

4.1.2 Pitching-moment loadings

As the pitching-moment loadings, Fig 5, are derived directly from the normal-force results, the same general features are present, but as the moments are measured about the nose of the body, the variations in the afterbody loadings are accentuated. The major difference in the shape of the loading distribution for a stagger of $-2 D_{max}$ is again immediately apparent.

4.1.3 Axial-force loadings

The axial-force loadings, Fig 6, show the same general features over the forebody in that there is a positive peak that occurs at approximately $x/L = 0.06$ and a negative peak at $x/L = 0.26$. The magnitudes of the peak values however vary appreciably with stagger, as shown in Fig 12. The variation of the magnitude of the positive peak with stagger takes the form of two straight lines with the break in slope occurring at zero stagger. The slope at negative stagger is positive whilst at positive stagger the slope is negative and much smaller in magnitude. The variation of the magnitude of the negative peak with stagger is much greater than that of the positive peak and while the slope is approximately linear over most of the range of stagger, the peak values at the two extreme staggers, -2 and $+3 D_{max}$, deviate appreciably from the mean line. At $-2 D_{max}$ stagger the shape of the peak is distorted into a well defined double peak, possibly as a result of a local separation caused by the presence of the dummy body

ahead of the instrumented body. The shape of the negative peak at positive staggers also vary from the "sharp" peaks that are the typical shape of the positive peaks and the negative peaks at 0 and -1 D_{max} stagger. The exact reason for these irregularities in shape is not known, but again it may be due to separations on the forebody caused by interference from the dummy body.

Although the afterbody loading distributions show considerable variations in shape at the most positive staggers, the loadings all have a positive peak at $x/L = 0.45$ which is at the beginning of the conical afterbody. The variation of this peak loading at the beginning of the conical afterbody with stagger has also been plotted in Fig 12. The variation is very similar to that of the peak positive loading on the forebody but with the break in the straight line variation occurring at about 1 D_{max} and the negative slope being rather larger than the positive one. All the distributions except those at +2 and +3 D_{max} stagger, fall away rapidly from the afterbody peak value and have negative loadings aft of $x/L = 0.7$. The other two loadings start to diminish aft of the initial peak but then start to rise to a second positive peak which is greater and farther aft at the greater stagger. For these conditions, the maximum diameter of the dummy body is considerably behind that of the instrumented body and so it is likely that the additional axial-force peak is due to interference from the second body.

4.2 Overall aerodynamic coefficients

The variation with stagger of the overall C_N and C_m and the resultant position of the centre of normal-force of the instrumented body is shown in Fig 13.

The C_N variation is symmetrical about zero stagger. However, this was not immediately obvious from the loading distributions, Fig 10 & 11, as the interference loadings on the front body are considerably greater in magnitude than those on the rear body. As the loading distribution consists basically of two large peaks, one positive and the

other negative and the overall normal force is the area under the curve, the magnitude of the peaks is not necessarily significant as far as normal-force is concerned. As the C_N variation is symmetrical with stagger, the interference force on the corresponding pairs of bodies is zero as would be expected.

The variation of C_m with stagger is not symmetrical with stagger as C_m rapidly approaches zero as the stagger becomes more negative whilst not varying greatly at positive staggers. Thus the pitching-moment of a pair of bodies is not zero at other than zero stagger. The net C_m on a pair of bodies can be obtained about a common pitching-moment centre from the measured values of C_m , C_N and C_A . As there was no obvious common position of the moment centre for all staggers, the value of C_m for the pairs of bodies was not obtained.

As the dummy body moves aft from the most forward position tested, $-2 D_{max}$, the centre of normal-force of the instrumented body moves rearwards slowly and linearly until the bodies are at zero stagger. Then, at positive staggers, the normal-force centre moves aft increasingly rapidly as the stagger increases.

The variation of the total and forebody C_A with stagger is shown in Fig 14 as measured on the instrumented body. At staggers of -2 and $-1 D_{max}$, the forebody C_A 's are negative and approximately -0.03 with the total C_A being slightly more positive thus indicating that the afterbody had a small positive axial force. As the stagger becomes more positive, initially both the forebody and total C_A become rapidly more positive, but the rate of increase soon falls off until both values peak at a stagger of $+2 D_{max}$ and then decrease with further increase of stagger. Although the two C_A curves remain approximately parallel up to zero stagger, they diverge rapidly between staggers of 0 and $+1 D_{max}$, and then gradually become closer together with further increase in stagger. This indicates that there is a rapid increase in afterbody C_A between 0 and $+1 D_{max}$ stagger before it gradually reduces with further increase in stagger. The loading curves, Fig 6, show that the rapid

increase is primarily due to the loading peak that occurs at the beginning of the afterbody, (at $x/L = 0.45$), but that above $+1.0 D_{max}$ this well-defined peak collapses and an additional peak develops further aft along the body. This peak increases in magnitude and moves further aft as the stagger is increased and thus results in the afterbody C_A reducing only gradually.

The variation of the total and forebody C_A for pairs of bodies with staggers of 0, 1 and 2 D_{max} is shown in Fig 15. This shows that the total C_A is a maximum for the pair of bodies at a stagger of 1 D_{max} , but the variation with stagger is not large. The variation of the forebody C_A with stagger is much larger, with a minimum value occurring also at 1 D_{max} . Thus the combined afterbody C_A is a minimum at this stagger. However the forebody C_A then increases rapidly with further increase in stagger, but as the afterbody C_A reduces at a greater rate, the overall C_A reduces slightly.

4.3 C_p distributions

Examples of the pressure distributions over the body are plotted in Figs 16 - 21 for each value of the stagger. The axial pressure distributions along the 0 and 180 degree generators are shown together with the radial pressure distributions at the axial positions where the peak C_N loadings occur. Also plotted is the axial pressure distribution for the isolated body as determined in ref 3. As the isolated body is at zero pitch, there will be no variation of C_p around the body at a given station.

Considering first the no-stagger case, Fig 16, it is seen that the axial C_p distribution of the isolated body agrees reasonably well with the axial distribution along the 180 degree generator, i.e. the generator remote from the interfering body, although the pressures for the isolated body are slightly lower over the front part of the ogive and the conical afterbody and slightly higher over the rear part of the ogive. The C_p distribution along the 0/360 degree generator differs

greatly from the isolated body being appreciably more positive over the front part of the forebody and considerably more negative at the maximum diameter position where the peak interference loading occurs. The radial distributions at the positions of the maximum and negative loadings show that there is little variation of C_p for about 45 degrees on each side of the 180 degree (remote) generator and that the bulk of the variation takes place over 90 degrees on either side of the 0 degree generator

As the dummy body moves forward, (negative stagger), Figs 17 & 18, the magnitude of the changes in C_p from those of the isolated body reduce rapidly.

At $-1 D_{max}$ stagger, Fig 17, the difference in the C_p along the 180 degree generator are very similar to those present at zero stagger. The differences from the isolated body along the 0 degree generator are similar to those at zero stagger but the position of the negative peak has moved forward by less than the forward movement of the dummy body. Again the majority of the change in C_p around the body cross-section occurs over the half of the body nearest to the interfering body.

When the stagger between the bodies is $-2 D_{max}$, the changes in C_p due to the presence of the second body are much smaller and the negative peak is considerably flatter. Whilst the general character of the circumferential distribution at the negative peak loading, ($x/L = 0.300$), is similar to that at the previous staggers, the characteristics of the pressure variation at the forward, (positive), loading peak are rather different in that the C_p value at this station for the body in isolation now agrees with the experimental value on the 0 degree generator rather than with that on the 180 degree generator. Looking more critically at the previous results, it can be seen that this change in agreement is part of a general trend. It should also be noted that in spite of the increase in stagger, the axial position of the peak negative value of C_p is approximately in the same position as at $-1 D_{max}$ stagger.

The pressures over the conical afterbody are appreciably more positive than those over the isolated body, and, in particular, the pressures along the 0 degree generator over the last 25% of the length of the body which result in the additional positive loading peak previously noted. However, as the base of the dummy model is located at $0.74 L$, the effect of the diffusing flow behind the base of the dummy model probably is the cause of this additional interference over the rear of the afterbody.

When the dummy body is moved rearwards, Figs 19 - 21, the changes in the axial pressure distributions are rather different to those at negative stagger. Whilst the pressure distribution along the 180 degree generator, i.e. remote from the interfering body, are again similar to that along the isolated body, the agreement is rather worse than previously noted over the nose of the body but agrees closely over the afterbody.

As stagger is increased, the effect of the interfering body on the pressures measured along the 0 degree generator alter. The forward region of interference, where the induced pressures are more positive than those measured over the isolated body, moves aft with increase in stagger but does not alter greatly in magnitude or extent as the stagger increases. The rear interference region likewise moves aft with increase in stagger, but although the peak interference reduces rapidly with increase in stagger, the interference present over the rear of the region increases giving a flatter variation of induced pressure along the body. As at negative staggers, the circumferential pressure distributions at the peak loadings show that the interference region becomes spread more evenly around the body instead of being mainly concentrated in the region of the $0/360$ degree generator as at zero stagger.

The pressure distribution over the body can be visualised better by plotting the results in the form of pressure contours, Figs 22, 23, 25 and 27. It should be noted that as the axes used are the length along the body and the angle around the body, the graphs are a

distortion of the projected body surface. It should be noted that, for all the contourplots and isometric drawings, the datum for the generator angle has been altered so that the position nearest the dummy body is 180 degrees rather than 0/360 degrees as used previously.

In order to help in the interpretation of the contour plots, the following comments may be helpful:-

1) In the case of the isolated body at zero pitch, C_p varies appreciably along the length of the body but will not vary circumferentially at a given axial position. The basic contourplot will consist of a series of vertical lines spaced at intervals determined by the chosen interval in C_p between the contours and the axial pressure distribution.

2) The comparison of the pressure distributions along the isolated body and that obtained along the centre-line of the instrumented body remote from the dummy body are very similar as has been already noted, Figs 16 - 21. Thus the contour spacing at 0 and 360 degree positions represent the contour spacing applicable to that of the isolated body at zero pitch.

3) The positions at which the contours deviate from the vertical will therefore define the boundaries of the interference between the two bodies.

4) Within the interference region, a series of "bumps" in the contours will represent a ridge or valley in the basic pressure surface depending on whether the deflection of the contour is away from or towards the region of high pressure. A closed contour represents a "hill" or "hole" in the pressure surface depending on whether the C_p values are increasing or decreasing towards the centre of the enclosed area.

As a further aid to the interpretation of the pressure distributions over the body, isometric projections of the three-dimensional representation of the pressure distribution over the body surface have been obtained, Figs 22, 24, 26 and 27. As in the case of the pressure contour presentation, the x and y axes are the distance along the body from the nose and the angle around the body. The z axis

is the C_p value. In the isometric projections there are two features that must be borne in mind when interpreting the drawings. Firstly the base is drawn at the minimum C_p value of the surface and secondly the C_p scale is automatically chosen by the computer programme that generates the projection. Thus the C_p scale and its extent may vary for each set of data. In the present case the C_p scales for staggers of $\pm 1 D_{max}$ are the same. The C_p scale for staggers of $\pm 2 D_{max}$ are also the same but differ from those at the other staggers. In the figures, the C_p scales have been removed and thus the projections should be taken as a general impression of the pressure "surface". The regular network of lines that form the surface are drawn through interpolated C_p values to represent the axial and circumferential pressure distributions.

As has been noted, the C_p distributions at the 0 and 360 degree positions are the same and are very similar to the pressure distribution over the isolated body. Thus the distance of these C_p values at the rear of the body above the base give an indication of the relative magnitudes of the minimum C_p values at the position of maximum interference, i.e. at the bottom of the "hollow" in the pressure surface.

Before examining the pictorial representations of the pressure distributions for the various staggers, one general feature in the contourplots can be noticed.

Because the 180 degree radial position corresponds to the position where the pressure tappings are on the plane of symmetry between the two bodies, the contours should be symmetrical about this position. Examination of the graphs shows that although the contours are reasonably symmetrical, the position of symmetry for a given contour is not exactly at the 180 degree radial position and, moreover, the amount of the displacement varies slightly along the length of the body.

This variation is considered to be due to slight misalignments in rigging the model in the windtunnel. If the axes of the two models are not exactly aligned in yaw, the apparent position of the

plane of symmetry will diverge linearly from the nominal position as the axial position varies from the base to the nose of the model. If, however, the roll datum of the model is slightly misaligned relative to the plane containing the centre-lines of the two bodies, the lateral position of the pressure tappings from the plane of symmetry will vary with the body radius and the amount of the roll misalignment. Thus the displacement of the position of symmetry of the pressure contours from the plane of symmetry should increase linearly forward of the base of the model at a rate dependent on the slope of the afterbody until the ogival portion of the body is reached. Forward of the position of the maximum diameter, the apparent displacement will reduce because of the reduction of body radius until the apparent deviation becomes zero at the nose.

Examination of the apparent deviation of the plane of symmetry of the pressure contours from nominal indicates that both alignment errors are present. As the apparent deviation of the plane of symmetry increases linearly up to the position of maximum thickness before reducing as the nose is approached there must be a misalignment of the roll datum. As there is still a misalignment at the nose of the body there must also be a misalignment in yaw.

These errors in misalignment are unimportant in the following analysis, as only the general features of the contourplots are discussed.

4.3.1 Overall C_p distributions at zero stagger.

At zero stagger, Fig 22, the mutual interference between the two bodies can be seen at the most forward station along the body, $x/L = 0.02$, where there is a slight rise in C_p over the half of the body facing the companion body. It is this increase in pressure that results in the local loading that tend to separate the bodies. With increase in distance from the nose this increase in C_p on the 180 degree generator becomes greater but is still confined to the same angular range

resulting in a marked ridge in the pressure surface which is clearly visible in the isometric projection and which attains a peak height at $x/L = 0.2$.

The other main feature of the flow is the marked reduction in C_p that occurs in the region near the position where the two bodies are closest together, $x/L = 0.394$, resulting in a marked "hollow" in the isometric view of the pressure surface. This hollow extends virtually all around the body where the bodies are closest together. Between $x/L = 0.2$ and 0.4 the circumferential C_p distribution is transitional between the "central ridge" type present over the front of the forebody and the "hollow" type present when the passage width is a minimum. The distribution in this region is quite complicated as the ridge gradually becomes less pronounced with increase in distance from the nose while, at the same time, the hollow starts to form outside the ridge with its outer extreme gradually extending around the body. This transitional stage is completed by approximately $x/L = 0.35$.

The pressure contours in the region of the position of minimum C_p are asymmetrical in shape along the length of the body. The pressure gradients aft of the minimum pressure are much greater than those in front of it, with the circumferential pressure gradients being intermediate in value. The shape of the pressure surface in the pressure recovery region is again rather complicated. Soon after the recovery begins a hollow develops along the centre-line. However this soon changes to a ridge which then develops fairly rapidly before spreading circumferentially and becoming virtually unnoticeable in the almost uniform pressure field over the conical afterbody.

The rapid change of shape of the pressure contours leads to some interesting speculations as to the form of the surface-flow patterns that would be present on the body. The flow elements that form a streamline are accelerated normal to the pressure contours, the amount and direction of the resultant deflection depending on the local velocity and the magnitude and direction of the pressure gradient relative to the



streamline. At the base of the boundary layer, i.e at the top of the oil film, the local velocities will be low and thus the flow direction will be approximately normal to the pressure contours. Initially the surface flow will deviate from the centre-line in the region defined by the ridge on the pressure surface whilst the flow over the rest of the body remains axial. At greater distances from the nose, in the transition region, the flow near the 0 and 360 degree generators will start to bend towards the 180 degree generator while there is still an outflow from the 180 degree generator. In the region just in front of the position of minimum gap between the bodies and where the hollow in the pressure distribution occurs, the pressure contours run in an axial direction and so the surface streamlines will be approximately circumferential over most of the body surface with the flow being directed towards the bottom of the hollow. In the region of pressure recovery, it seems likely that much of the flow into the hollow leaves initially through the narrow "gully" in the pressure recovery surface just aft of the minimum pressure position and then spreads out over the conical afterbody.

Due to the extreme changes in flow direction that the above analysis predicts at the base of the boundary layer in the region of maximum interference, it is likely that considerable shear is present in the boundary layer in a circumferential direction as well as normal to the surface. However there does not seem to be any obvious indications of flow separations in this region.

Unfortunately no time had been available to obtain the necessary oilflow patterns when the tests were made and so these speculations cannot be confirmed.

4.3.2 Overall C_p distributions at a stagger of 1 D_{max}

The pressure contours and isometric views of the pressure surfaces of both bodies are shown in Figs 23 and 24.

Considering first the interference effects on the front body, the pressure gradients are smaller in the interference regions than in the no-stagger condition and the depth of the hollow is less. Although the general features of the body pressure distribution are similar to the no-stagger case, there are several changes in detail. These are :-

1) The forward interference region is more prominent and this leads to higher loadings than in the no-stagger case, Fig 4.

2) Although the nose of the rear body isolated at $x/L = 0.131$, the interference effects are noticeable from $x/L = 0.04$.

3) The shape of the hollow region is considerably different being more teardrop shaped with the blunt end facing forward. In addition the "gulley" at the beginning of the pressure recovery surface has almost disappeared.

4) The transition region between the ridge and the hollow shapes is much reduced.

5) The probable direction of the surface streamlines into the hollow now seems to be inclined slightly.

The general shape of the pressure distribution over the rear body is similar to that of the previous cases but again differs in detail as follows:-

a) The forward interference region is noticeable at the nose of the body, but the ridge feature is much less pronounced than that of the front body and extends over a shorter distance.

b) The transition region between the ridge and hollow pressure surface is much larger than that present on the front body and is approximately the same size as that present at zero stagger.

c) The shape of the hollow is much more circular in planform than that of the previous cases and, as for the front body, the "gulley" in the pressure-recovery surface is not very noticeable.

4.3.3 Overall C_p distributions at a stagger of $2 D_{max}$

For this stagger, the interference effects are considerably less than previously as indicated by the increased spacing of the

pressure contours. In addition the character of the pressure distributions over both bodies has changed appreciably, Figs 25 and 26.

The pressure distributions on the front body show that the interference ridge begins about $1 D_{max}$ ahead of the nose of the rear body. Instead of taking the form of a continuous ridge, the forward interference region takes the form of ridge leading to an isolated hilltop whose peak is just aft of the position of the nose of the rear body. A well-defined ridge descends from this peak towards the hollow, but the transition region from the ridge to the hollow does not extend over the whole circumference of the body but is restricted to about half the circumference. There is still a small ridge forming on the centre-line of the pressure recovery surface at the rear of the hollow.

The extent of the forward interference region on the rear body is now appreciable at the nose of the body but the height of the ridge is much less than previously. The transition region between the ridge and the hollow in the pressure surface is also much smaller in both axial and circumferential directions. The ridge on the pressure recovery surface to the rear of the hollow is not now present, but there is an additional slight hollow in the pressure surface beginning at $x/L = 0.5$ whose centre is at about $x/L = 0.7$ and which extends over about ± 90 degrees from the centre-line. As the base of the front body is at $x/L = 0.74$, it is probable that this interference is the result of the expansion of the flow into the base region of the front body.

4.3.4 Overall C_p distribution at a stagger of $3 D_{max}$

The general pattern of the interference effects on the front body, Fig 27, is very similar to that at $2 D_{max}$ stagger except that the front interference peak is now superimposed on the pressure recovery after the maximum diameter position on the body and thus the interference peak and the body pressure recovery region blend into each other instead of being separate entities. The overall extent and

magnitude of the peak and hollow now appear to be very similar, Fig 4, and the transition region between the two now has virtually disappeared.

Owing to lack of time, the windtunnel programme was not completed and so the pressure distribution over the rear body is not available.

4.4 The geometric effects of stagger

It is instructive to examine the effect of stagger on the geometrical variation of the centre-line gap between the two bodies. The variation of the gap between the instrumented and dummy bodies over the length of the instrumented body is shown in Fig 28 a) for the complete range of stagger.

The variation of the corresponding minimum width of the passage between the two bodies is shown in Fig 28 b). The curve is symmetrical about zero stagger as, at a given stagger, the variation of passage width must be the same for both bodies of the pair, e.g for $\pm 1 D_{max}$ etc. Thus the C_p at the minimum width must be the same for both bodies of the pair as must be the pressures on each side of the common channel as the channel has no appreciable curvature. Examination of the relevant pressure distributions along the 0° degree generator shows that this is so.

On the other hand, because of the different profile of the body on either side of the maximum diameter, the position of the minimum passage width with respect to the nose of the relevant body is not symmetrical about zero stagger, Fig 28 c). For these particular bodies, the axial position of the minimum passage width is constant for staggers of -3 to $-1 D_{max}$ and then increases at a steadily increasing rate as the stagger becomes more positive. The position of the minimum measured C_p has been plotted on the same graph and the values agree well with the calculated position of the minimum passage width.

5.0 THEORETICAL ESTIMATES

The Surface Panel And Ring Vortex Method (SPARV) panel method developed by Petrie (B.Ae, Brough), ref 4, was used to estimate the pressure distribution over the bodies and hence to obtain the local loadings. The calculations were done for inviscid flow as it was found that with the recommended transpiration velocities used to represent the boundary-layer, problems were encountered due to lack of convergence of the velocity profiles. This problem did not occur when the bodies were more widely separated or when the calculations were done for one body in isolation.

It was decided to use the same body panelling system for all the various combinations of bodies that it was intended to test in the complete investigation, i.e up to three bodies at staggers of between $\pm 3 D_{max}$. As the present experimental results had shown that the interference loading peaks were liable to occur over a large portion of the length of the body, it was necessary to position the axial panel definition points closely together. This meant that only a relatively wide spacing could be used for the circumferential definition points in order to keep within the program limitations. Some initial computer runs indicated that no great change occurred in the calculated loadings if the circumferential definition of the complete body consisted of 15 or more points.

As the bodies were not yawed in the present tests, each body was represented by a half body with 41 longitudinal stations (40 panels) and 8 radial stations (7 panels). The base closure used ended at $x/L = 1.70$. The front part was a cone of the same (3 degree) taper as the afterbody until $x/L = 1.35$. Aft of this the closure was cylindrical to represent the sting support. Eight circumferential points (7 panels) were used to define the panelling throughout the base closure. The conical part was defined by 3 stations (2 panels) with a further 2 stations (2 panels) defining the sting.

The normal-force loadings obtained for the second body (corresponding to the dummy body) were altered in sign so that they could be compared directly with the corresponding experimental results.

Fig 29 shows that the agreement between the experimental and estimated normal-force loadings is very good at positive staggers when the dummy body is to the rear of the instrumented body. The negative loading peak is predicted well at all staggers, but the positive loading peak is rather overestimated, especially at a stagger of $1 D_{m, \text{max}}$. The loadings over the rear of the body are small and negative, with the estimated loadings being slightly more negative than the experimental results.

At zero stagger, the agreement between theory and experiment is not quite so good over the forward negative loading peak and the positive loading peak is predicted to be slightly farther aft of the experimental position. When the instrumented body is behind the dummy body, i.e. at negative staggers, the agreement between theory and experiment deteriorates further in that theory now over-predicts the magnitude of both the negative and positive loading peaks and the position of the positive peak is now predicted to be slightly farther aft. Previously there had been good agreement between the shapes of the loading distributions over the rear of the afterbody, but the shapes of the curves begin to differ as the stagger becomes more negative. The differences commence at about $x/L = 0.85$ at a stagger of $-1 D_{m, \text{max}}$ and $x/L = 0.70$ for a stagger of $-2 D_{m, \text{max}}$. As these positions coincide with the longitudinal position of the base of the dummy body, it is likely that the cause of the discrepancies is the inadequate representation of the base-cavity flow in the theoretical model.

The axial-force loading distributions are shown in Fig 30. At all staggers the general shape of the curves is similar as discussed previously in the analysis of the experimental results, Section 4.1.3. SPARV predicts the general shape of the distributions quite well, but the predicted loadings are consistently considerably more positive over the

forebody. On the other hand, the predicted afterbody loadings, whilst in closer agreement with the experimental results, are consistently smaller than experiment.

Thus SPARV satisfactorily predicts the general shape of the both the axial-force and normal-force loading distributions at all staggers, but tends to be slightly in error in predicting the magnitude of the peak loadings, especially the peaks that occur at the longitudinal position where the bodies are closest together. At the separation at which the bodies were tested, ($1.05 D_{max}$), this peak loading is varying rapidly with separation, ref 3, and thus the difference between theory and experiment could be due to a small constant error in the setting of the separation of the models. The slight differences that occur in the normal-force loadings over the rear of the afterbody at negative staggers are due to inadequate representation of the shape of the dividing streamline between the base-cavity flow and the general flow.

The predicted pressure distributions have also been plotted in the form of pressure contours and isometric views of the pressure surfaces, Figs 31 - 36. For comparison the corresponding experimental results are plotted adjacent to the theoretical pressure surface representations. The theoretical results were interpolated to the same grid as used in the presentation of the experimental results. This was done for two reasons. Firstly because it made comparisons easier and secondly because the method of defining the panels meant that none of the positions at which the pressures were calculated could be on the vertical centreline of the body, i.e the plane of maximum interference, the nearest being displaced by some 12 degrees from the central plane. In drawing the contours, linear interpolation was used between adjacent points, but in the interpolating procedure used to derive a more closely spaced network of data points, the surface used for interpolation between the original data points was assumed to be a paraboloid and so would give a more accurate representation of the pressure surface in the region of the plane of symmetry.

At zero stagger, Fig 31, the contour patterns and isometric drawings are very similar in character, but the theory predicts that the ridge on the pressure surface is rather more rounded (for the reasons discussed previously) and the "hole" is rather more circular in shape and is also slightly deeper. At staggers of 1, 2 & 3 D_{max} similar comparisons can be made, Figs 32 - 36. However some additional differences are apparent over the afterbody of the rear body due to the effects of the flow round the base of the front body not being predicted. This is not unexpected as the representation of the base flow assumes that it continues unchanged in direction beyond the base of the model while in reality, the base pressure will be less than the pressure at the end of the body and so the flow will deflect into the base region after leaving the rear of the body.

6.0 CONCLUSIONS

The normal-force loading distributions have a consistent character throughout the range of stagger tested. Near the nose the loadings peak negatively (i.e. to separate the bodies). The loading then increases with further movement aft and reaches a positive peak at the position where the gap between the two bodies is a minimum. The loading decreases rapidly to a small negative value aft of this position.

The interference loadings are a maximum at zero stagger. At other staggers, the loadings over the front body are considerably larger than those over the rear body, but the overall normal-force on both bodies are the same but of opposite sign.

The axial-force loading distributions also have consistent characteristics at all staggers, having a positive peak near the nose, a negative peak at just over halfway along the forebody followed by a positive peak at approximately the beginning of the conical afterbody.

Both the overall and forebody axial-force coefficients vary with stagger in a roughly sinusoidal manner, but the difference between them, (the afterbody axial force) is considerably greater for the front body. The overall axial-force (ignoring base pressure effects) of the pair of bodies is a minimum at zero stagger.

The body pressure distributions have been presented in the form of contour diagrams and isometric plots. These show very clearly the extent of the interference region.

Theoretical estimates of the interference effects agreed well with experiment.

6.0 ACKNOWLEDGEMENT

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a) Body co-ordinates and slope at pressure-plotting stations

x/L	r/L	slope (degrees)
0.01875	0.006258	17.987
0.03750	0.012177	17.055
0.05625	0.017763	16.127
0.07500	0.023021	15.203
0.09375	0.027955	14.283
0.11250	0.032570	13.368
0.13125	0.036868	12.455
0.15000	0.040854	11.546
0.16875	0.044530	10.640
0.18750	0.047900	9.736
0.20625	0.050965	8.835
0.22500	0.053729	7.936
0.24375	0.056194	7.039
0.26250	0.058360	6.144
0.28125	0.060231	5.250
0.30000	0.061807	4.358
0.31875	0.063089	3.467
0.33750	0.064079	2.576
0.35625	0.064777	1.686
0.37500	0.065183	0.797
0.39375	0.065298	-0.093
0.41250	0.065122	-0.982
0.45000	0.063897	-2.761
0.48750	0.061941	-3.000
0.52500	0.059975	-3.000
0.56250	0.058010	-3.000
0.60000	0.056045	-3.000
0.65000	0.053424	-3.000
0.68750	0.051459	-3.000
0.72500	0.049494	-3.000
0.77647	0.046796	-3.000
0.80000	0.045563	-3.000
0.83750	0.043598	-3.000
0.87500	0.041633	-3.000
0.91250	0.039667	-3.000
0.95000	0.037702	-3.000

b) General dimensions

Overall length (L)	=	60.56 in.
Maximum diameter (D)	=	7.9091 in. (0.13060L)
L/D ratio	=	0.76645
Forebody length	=	23.7273 in. (0.39280L)
End of ogive	=	27.5562 in. (0.45502L)

TABLE 1. BODY GEOMETRY

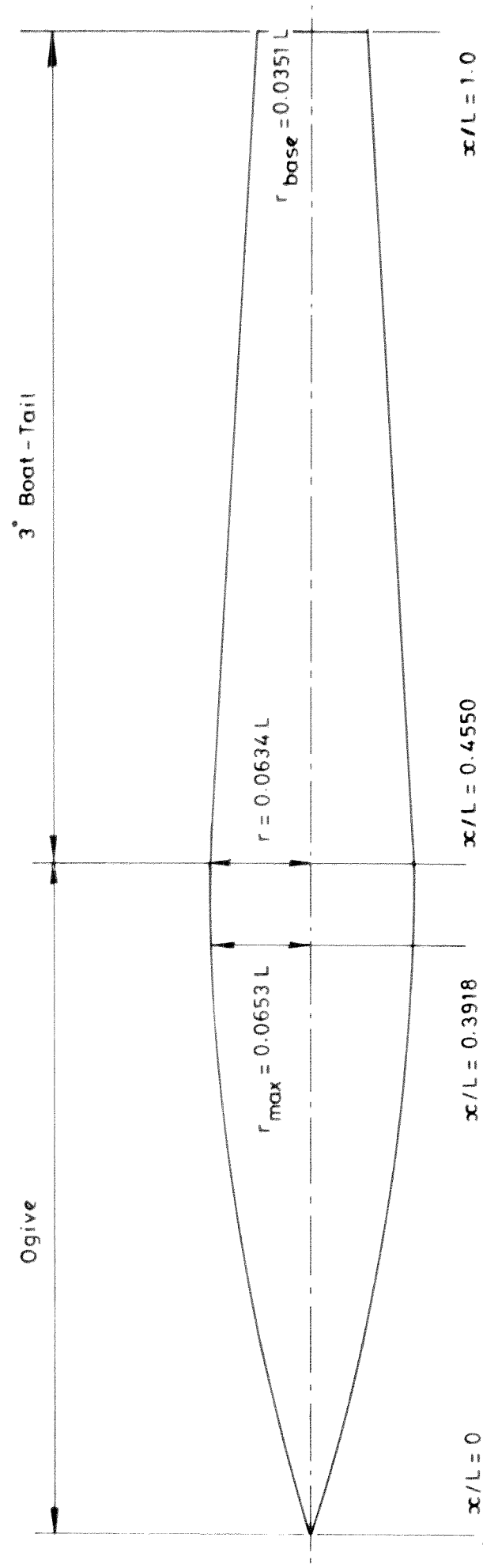


Fig 1. Model Geometry.

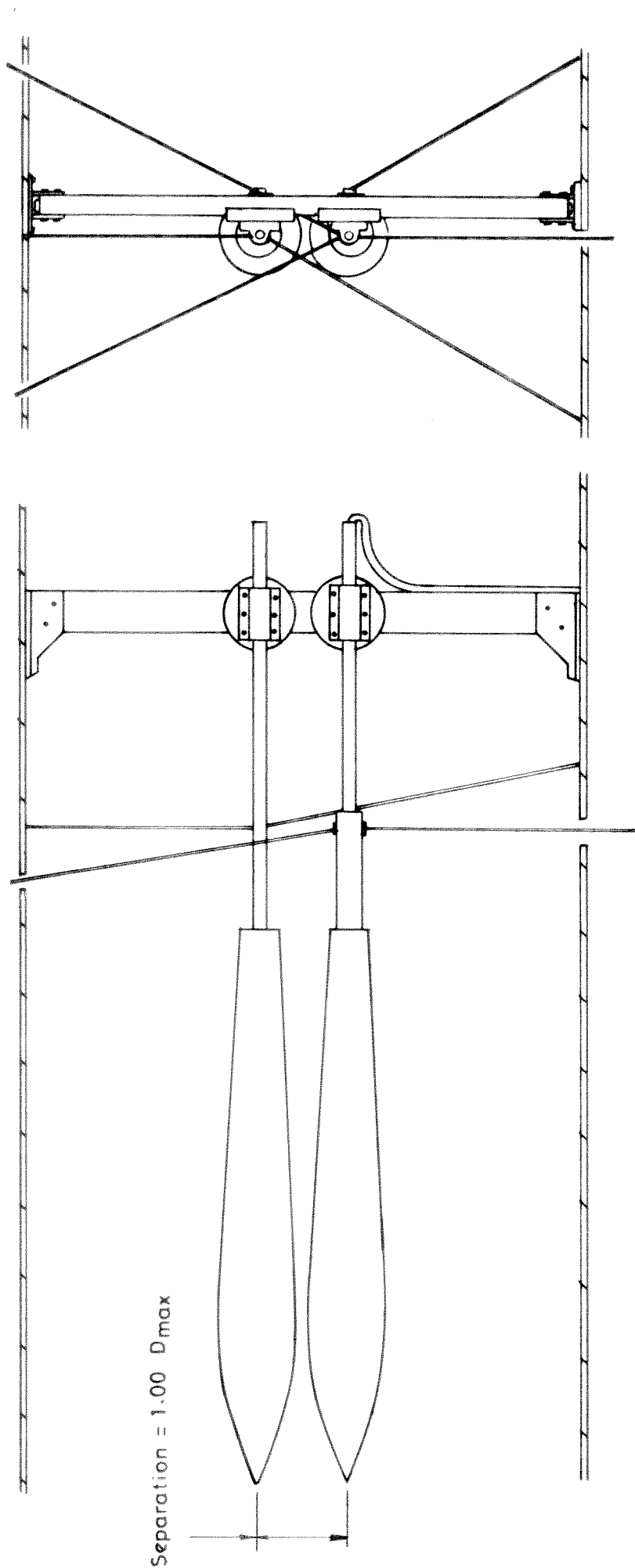


Fig 2 Models Mounted in Tunnel

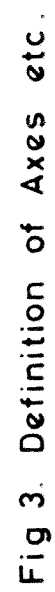


Fig 3. Definition of Axes etc.

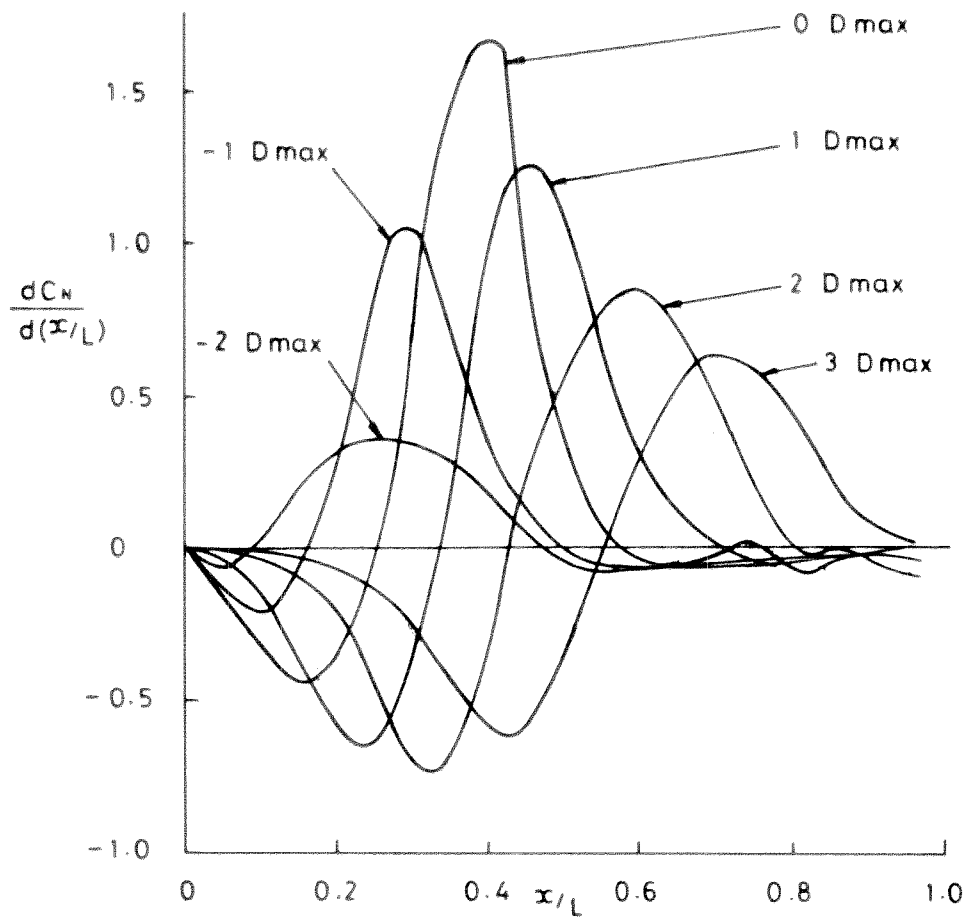


Fig 4. Effect of Stagger on Normal - Force Loadings.

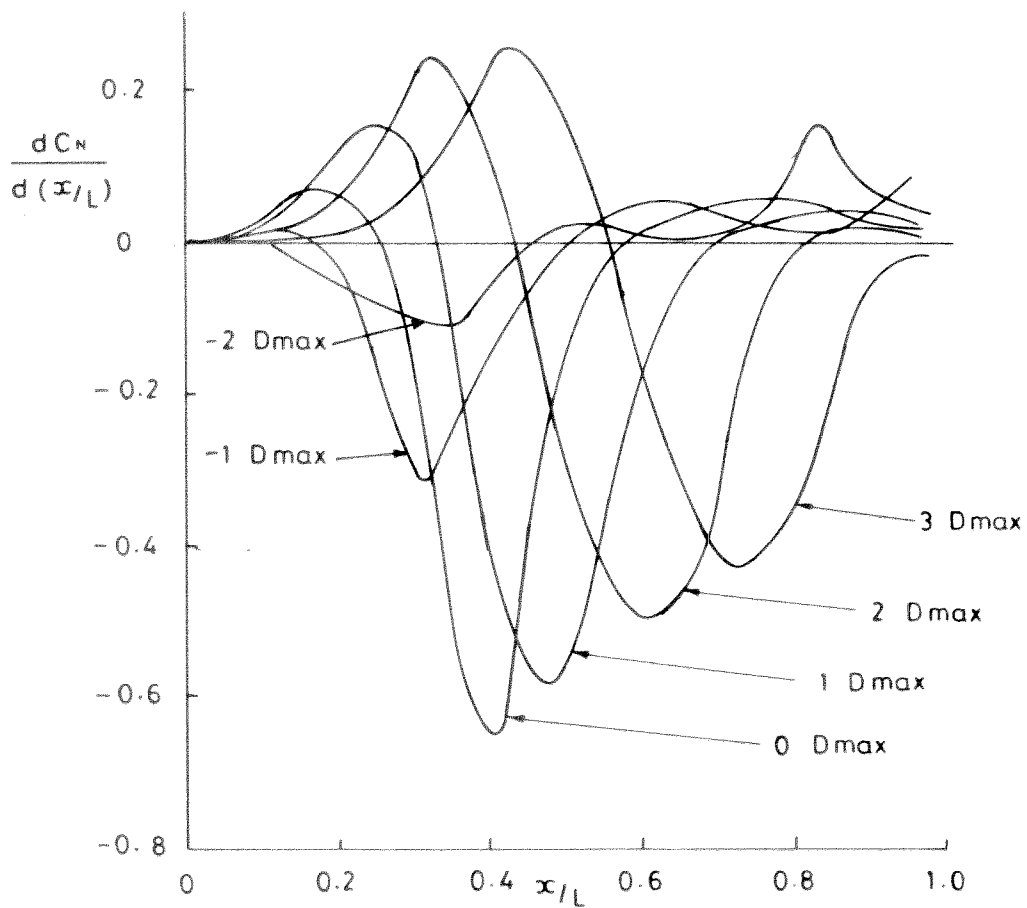


Fig 5. Effect of Stagger on Pitching - Moment Loadings.

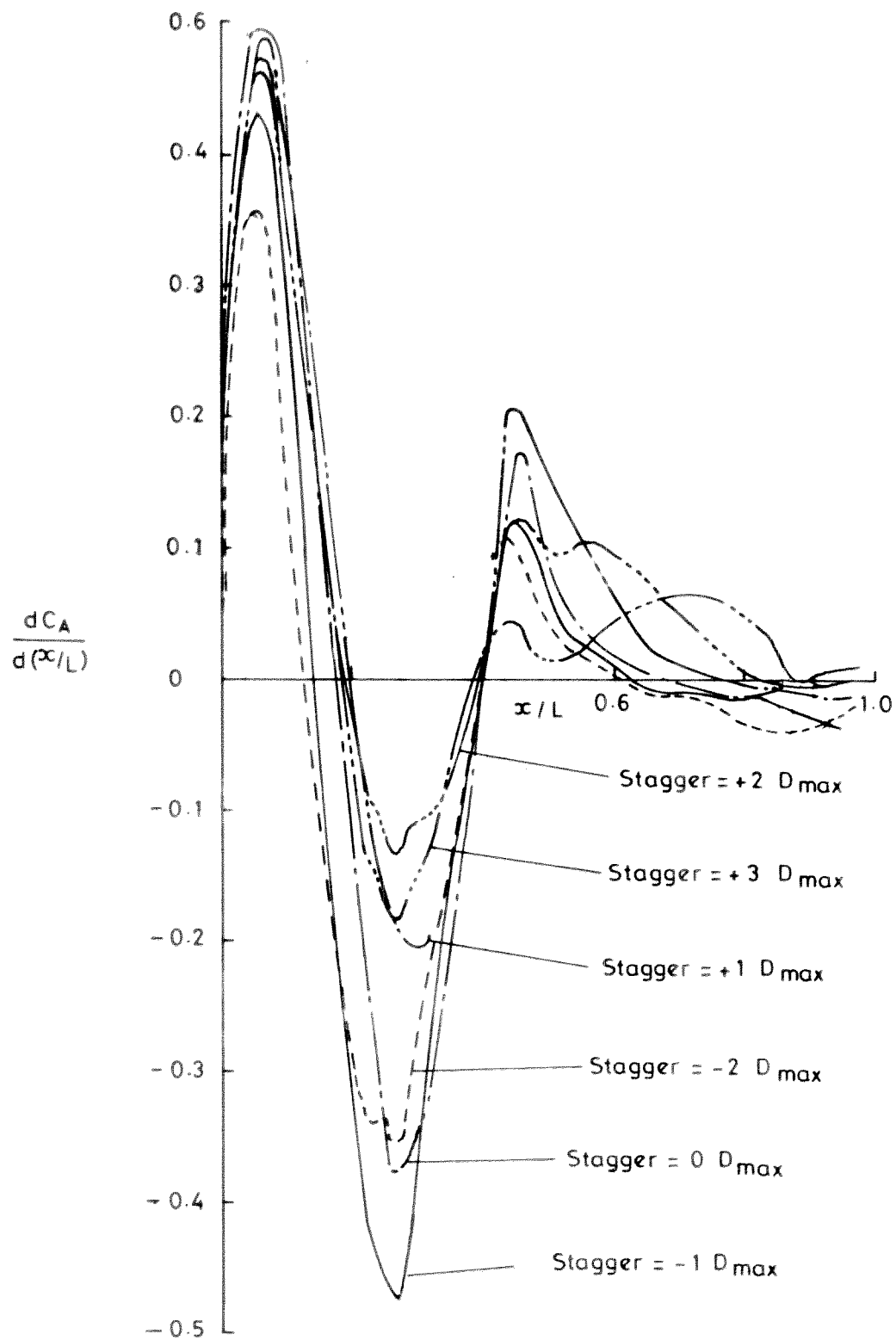


Fig 6. Variation of Axial Force Loading Distribution with Stagger.

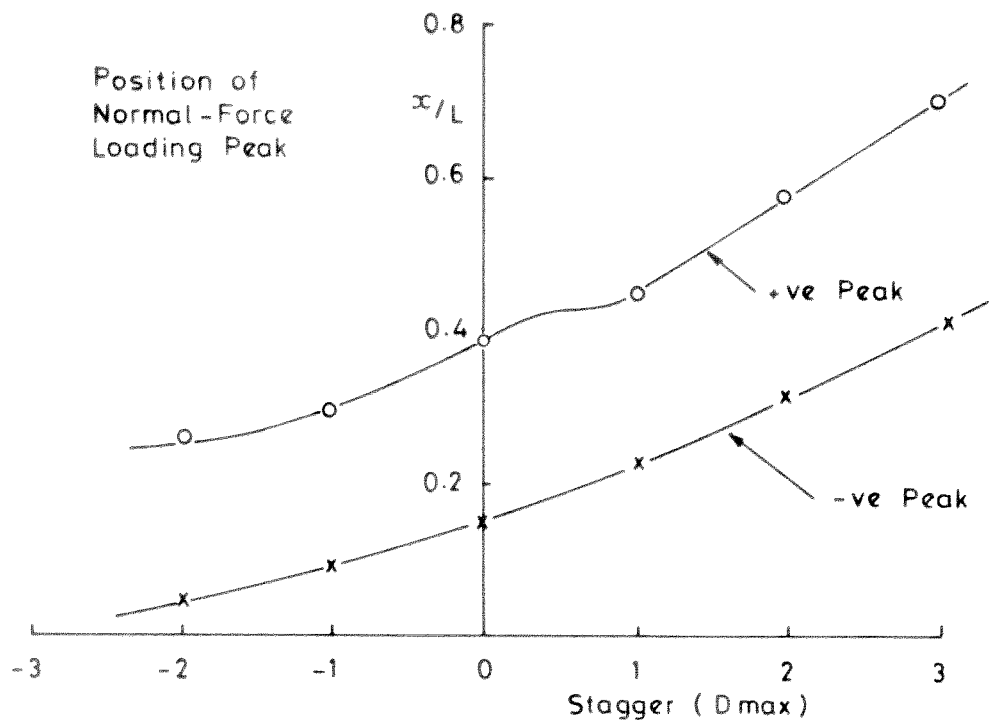


Fig 7. Effect of Stagger on Position of Peak Normal-Force Loading.

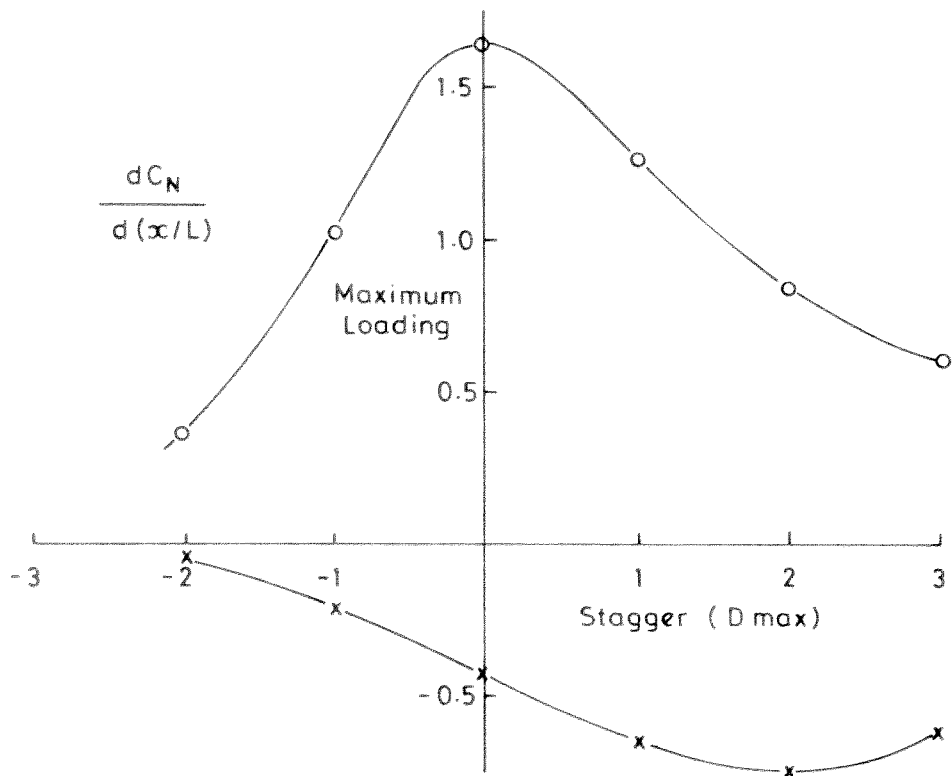


Fig 8. Effect of Stagger on Peak Normal-Force Loading.

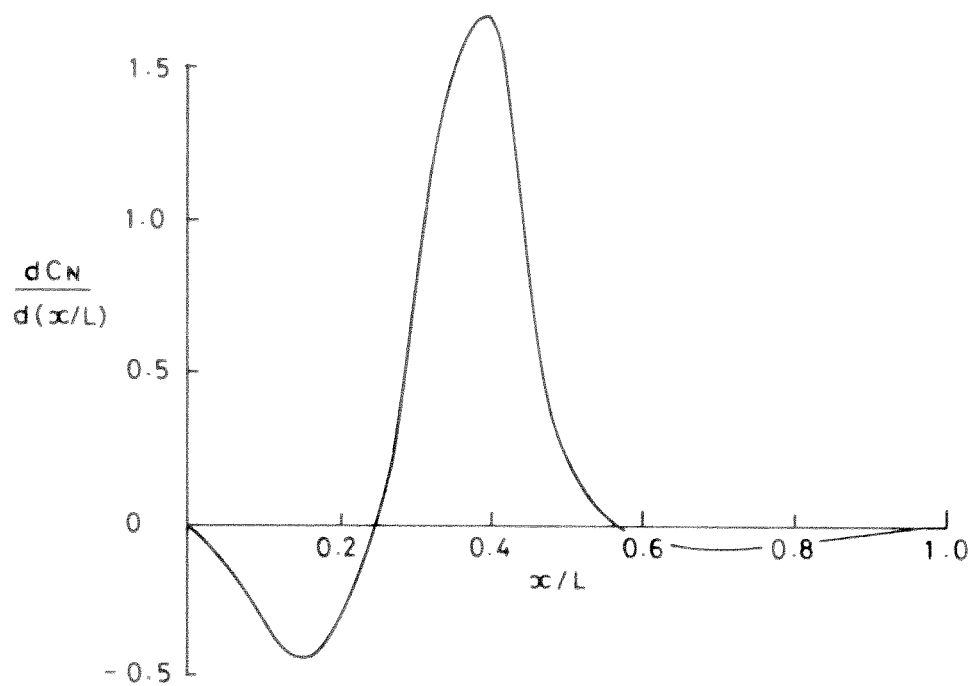
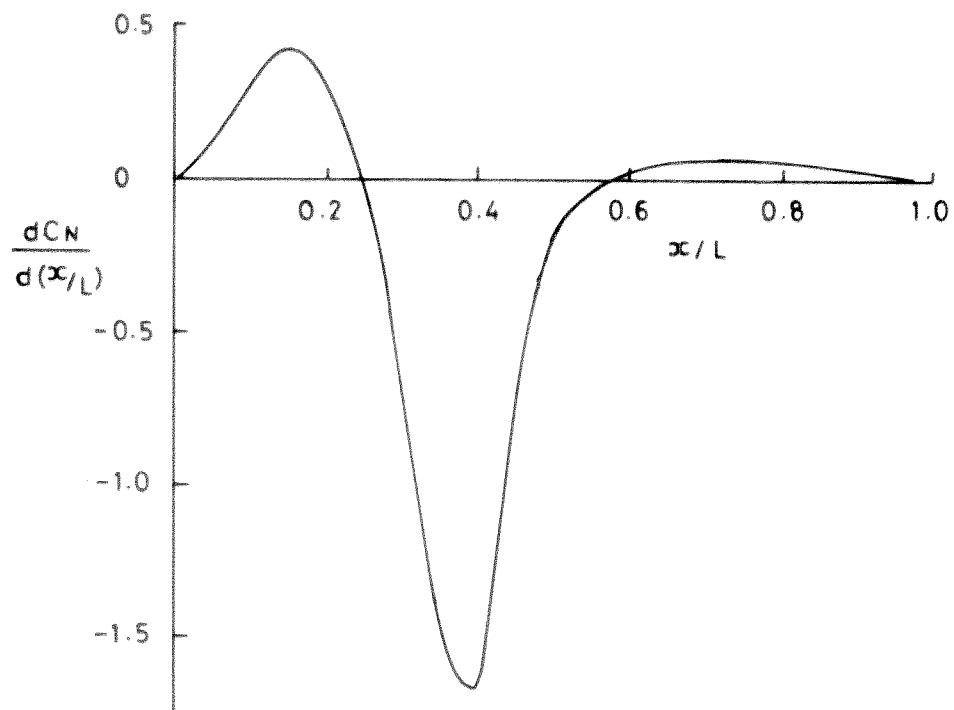


Fig 9. Relative Interference Loadings on the Bodies.
Stagger = $0.0 D_{\max}$

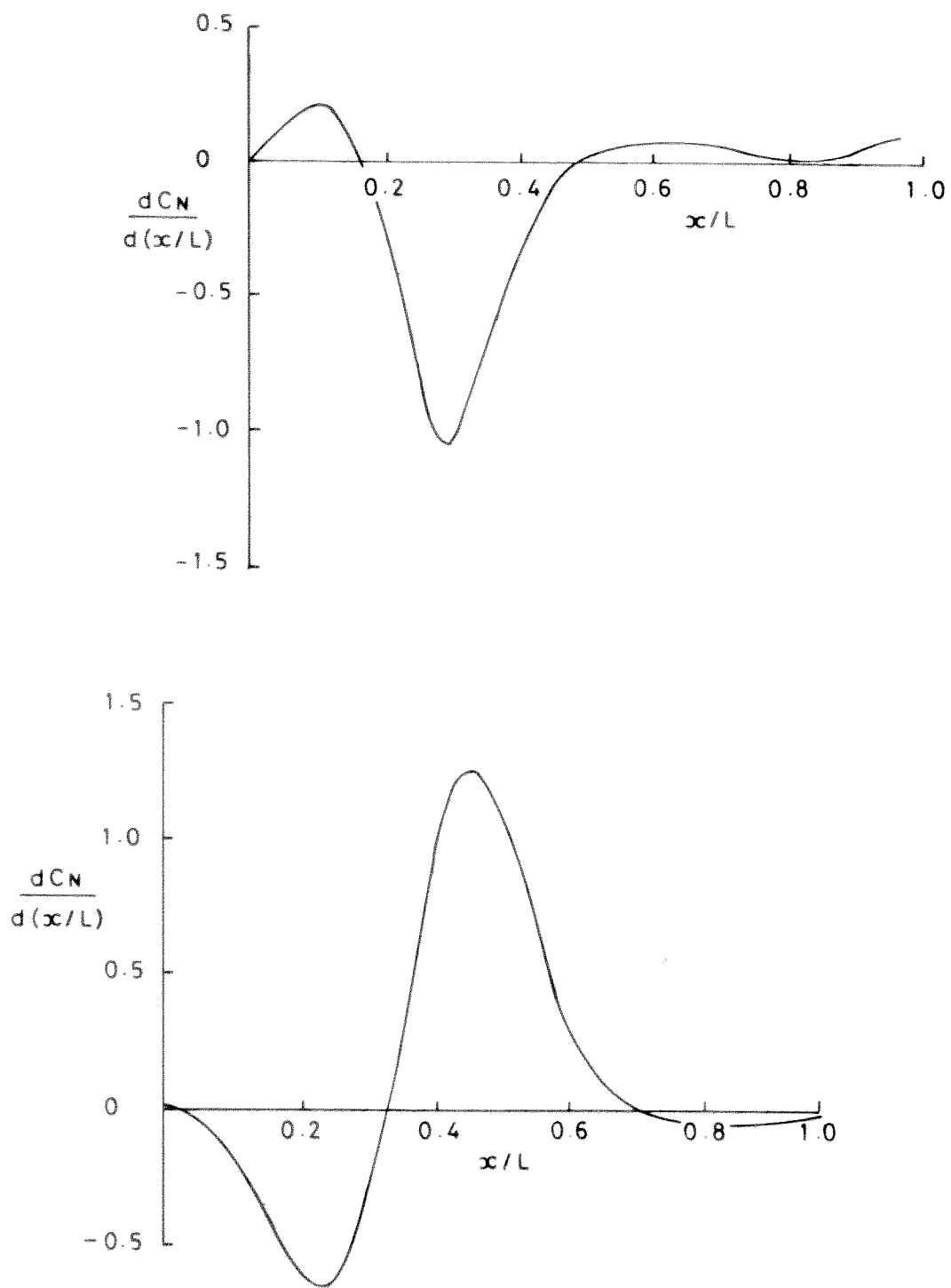


Fig 10. Relative Interference Loadings on the Bodies.
Stagger = $1.0 D_{\max}$

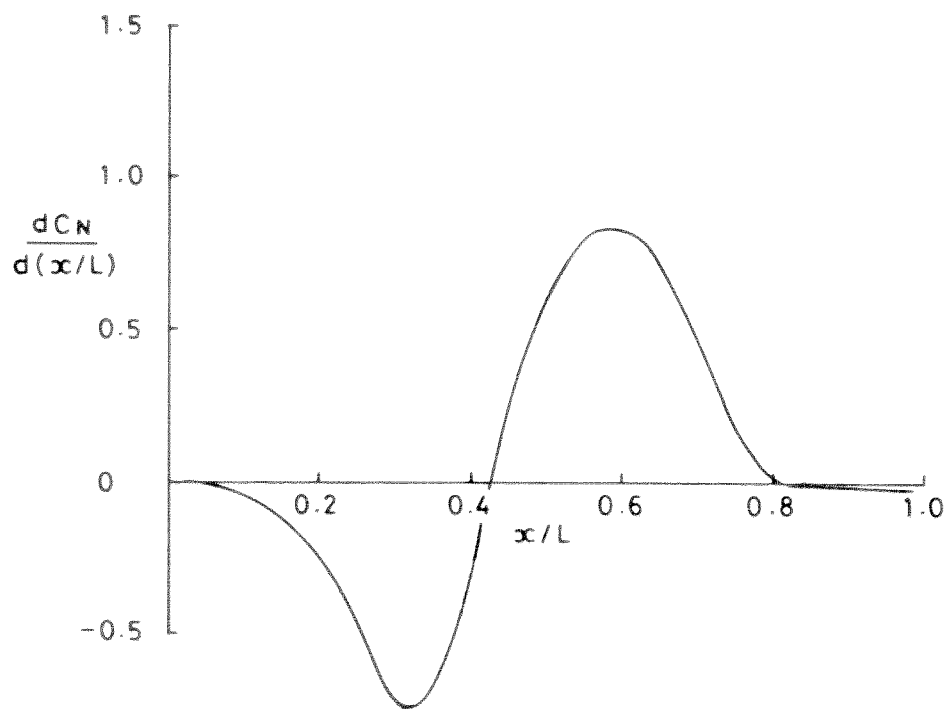
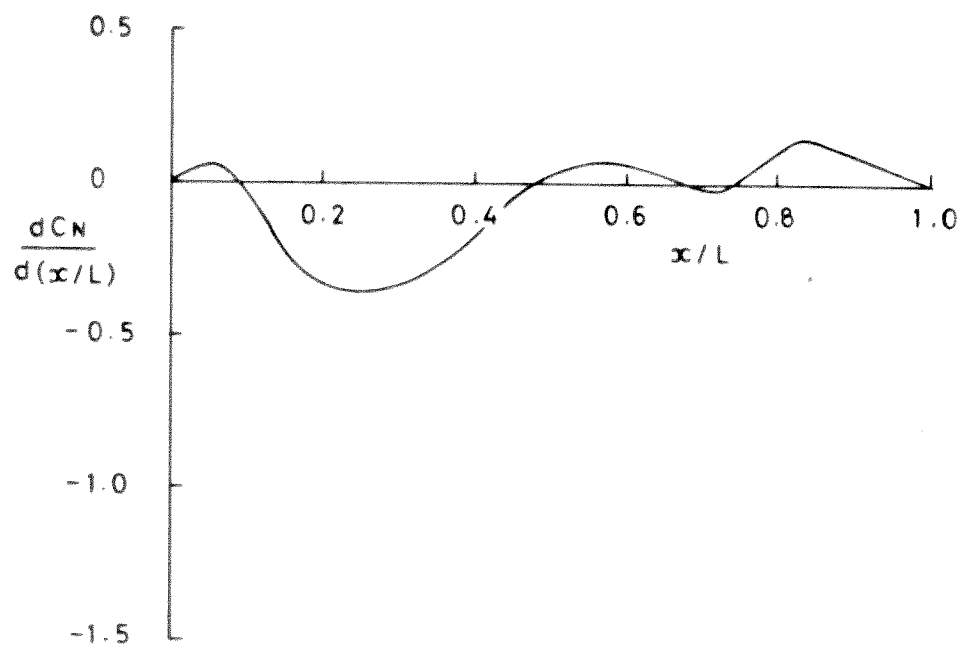


Fig 11. Relative Interference Loadings on the Bodies
 Stagger = $2.0 D_{\max}$

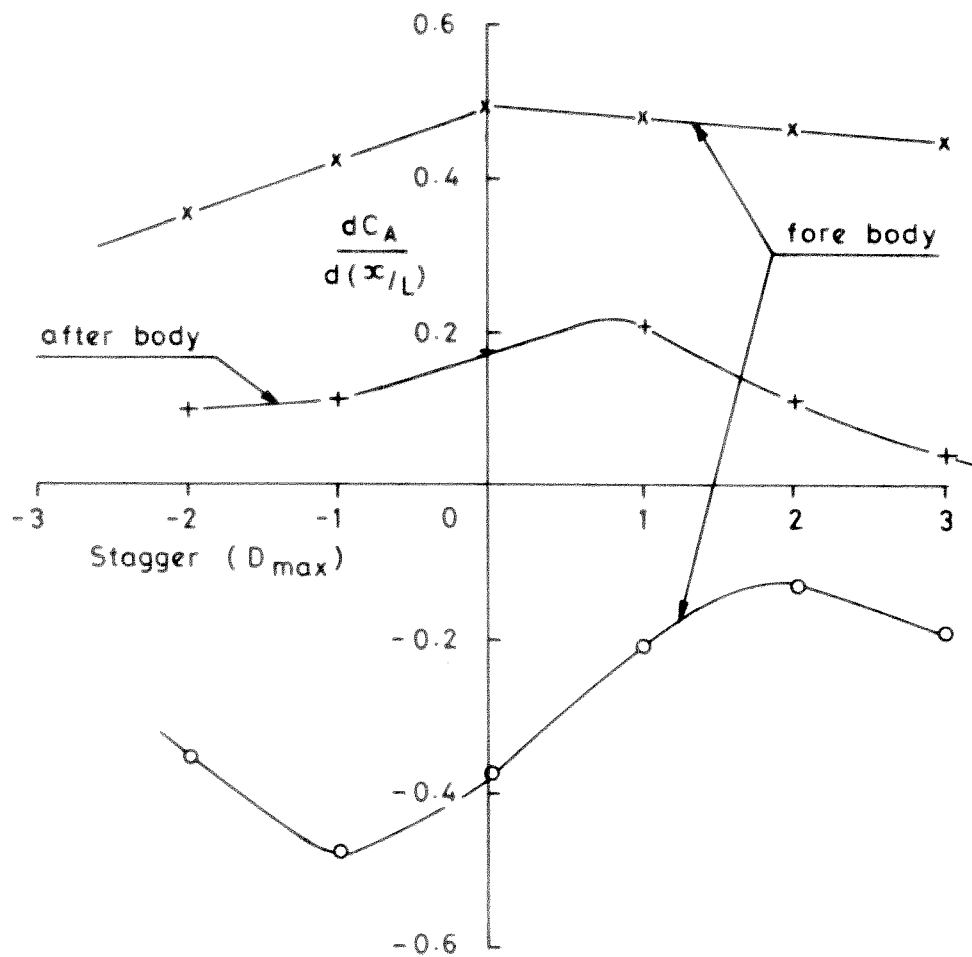


Fig 12. Variation of Peak Values of $dC_A/d(x/L)$ with Stagger.

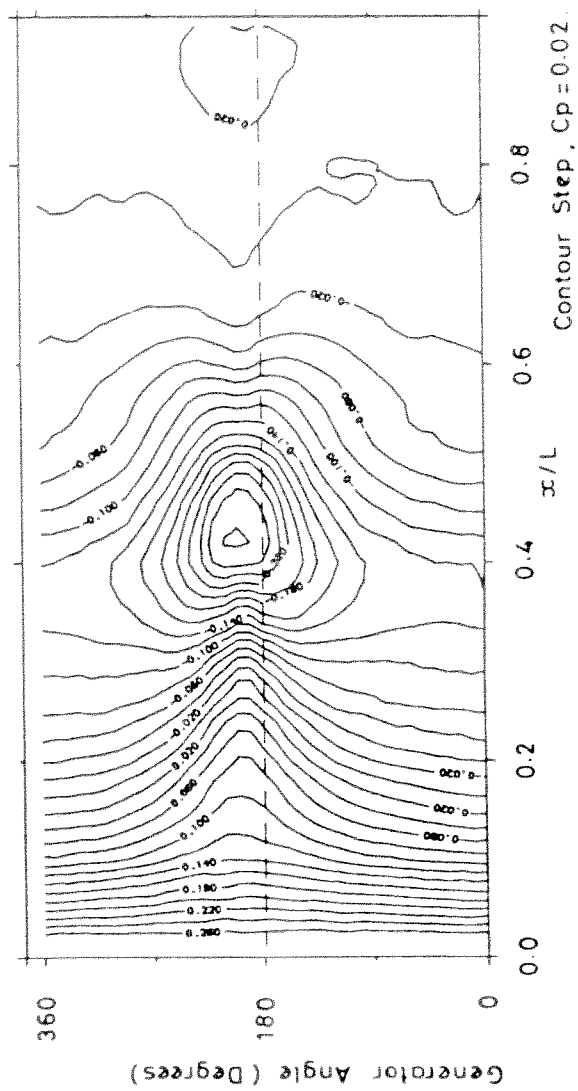
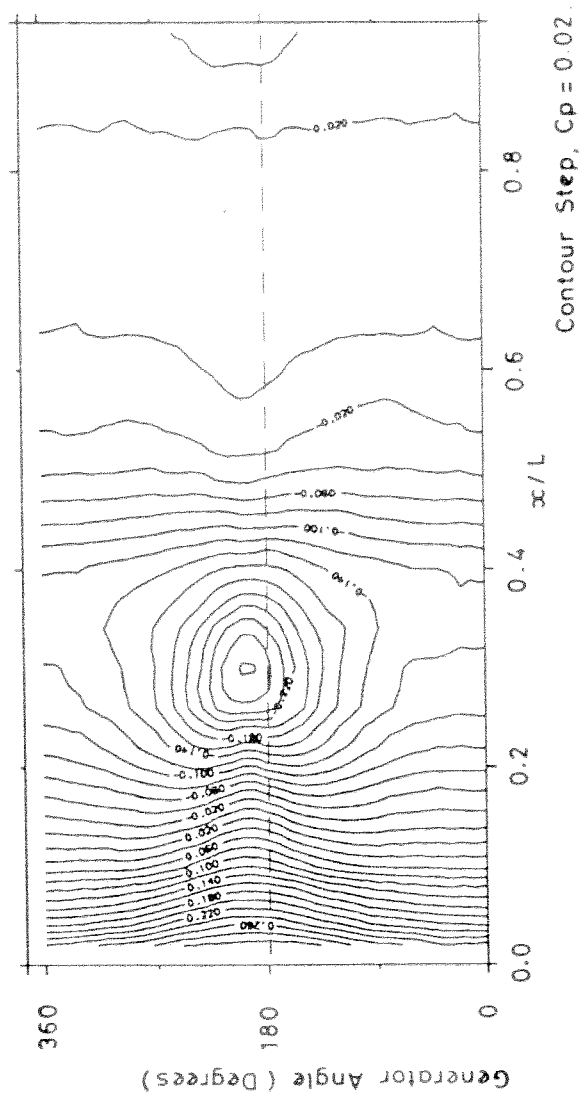


Fig 23. Contour Plots of C_p Variation Over the Bodies - Stagger = $1 D_{max}$.

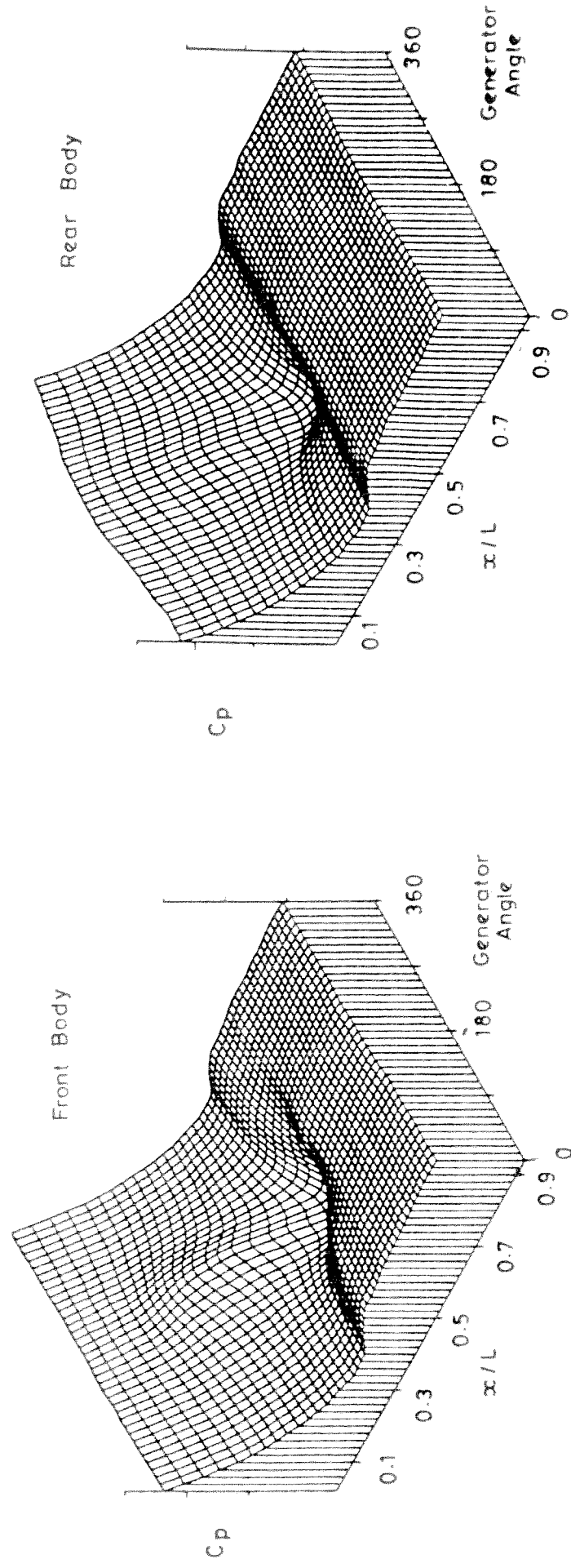


Fig 24 Isometric Plots of C_p Variation Over Bodies - Stagger = 1 D max

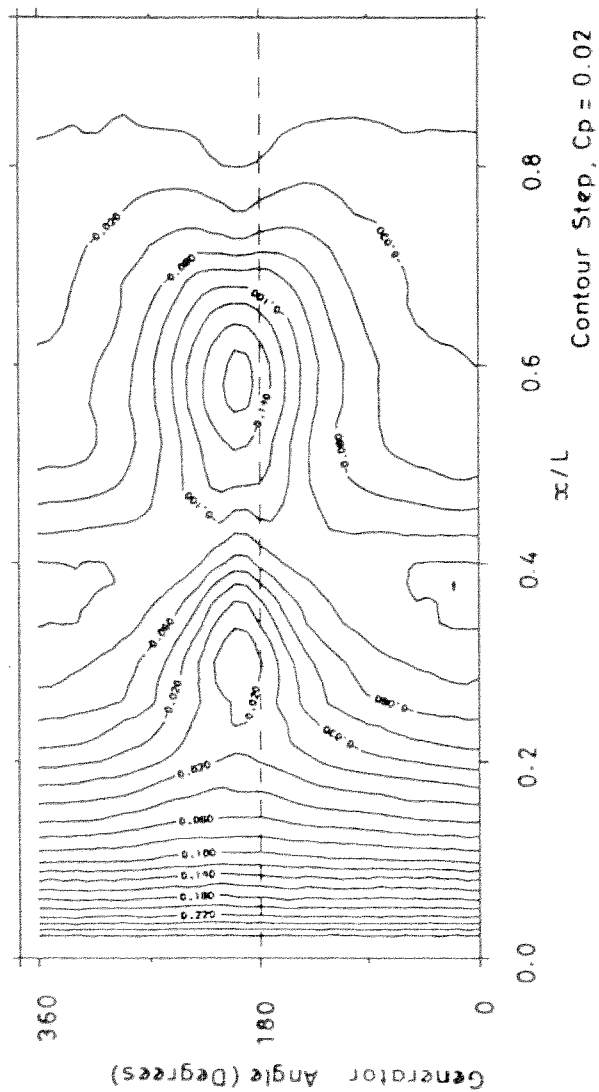
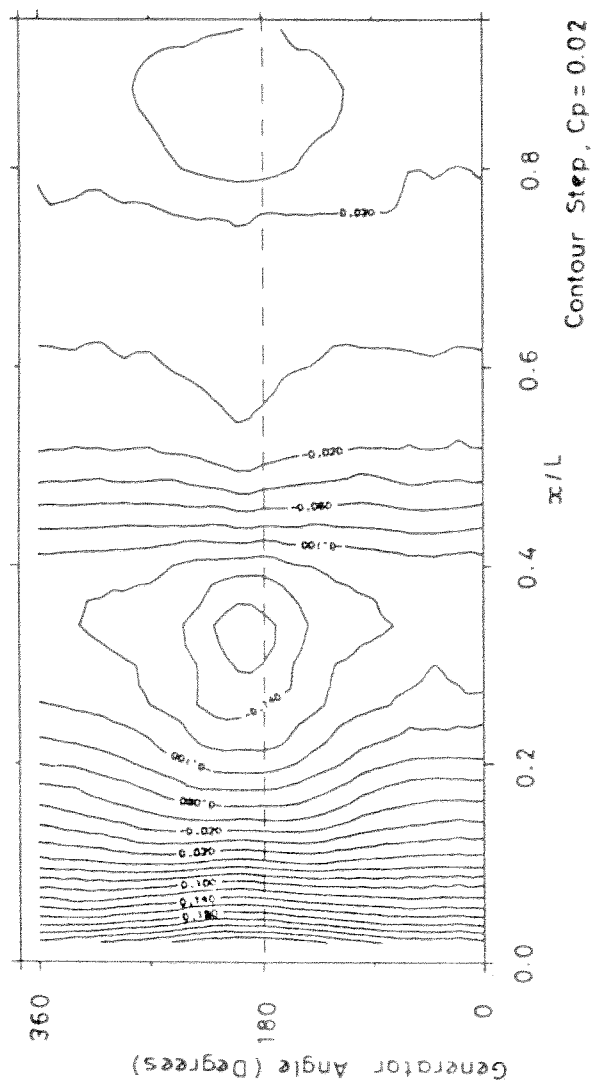


Fig 25. Contour Plots of C_p Variation Over the Bodies - Stagger = $2 D_{max}$

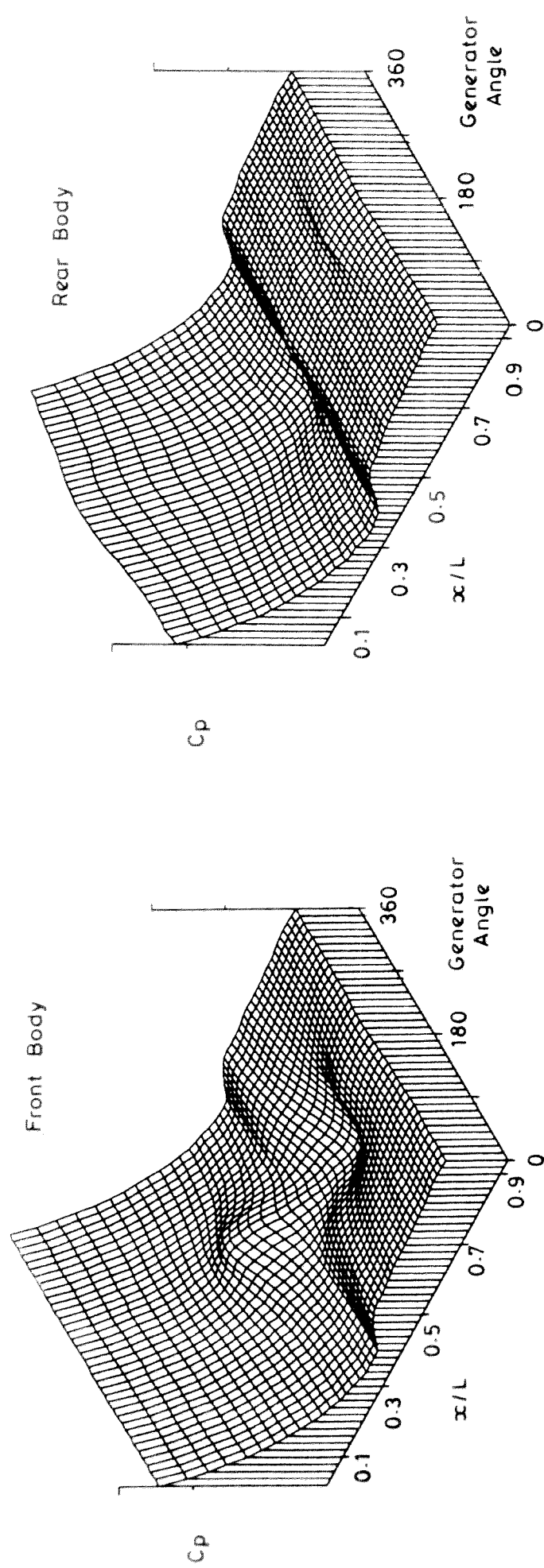


Fig 26 Isometric Plots of C_p Variation Over Bodies - Stagger = 2 D max

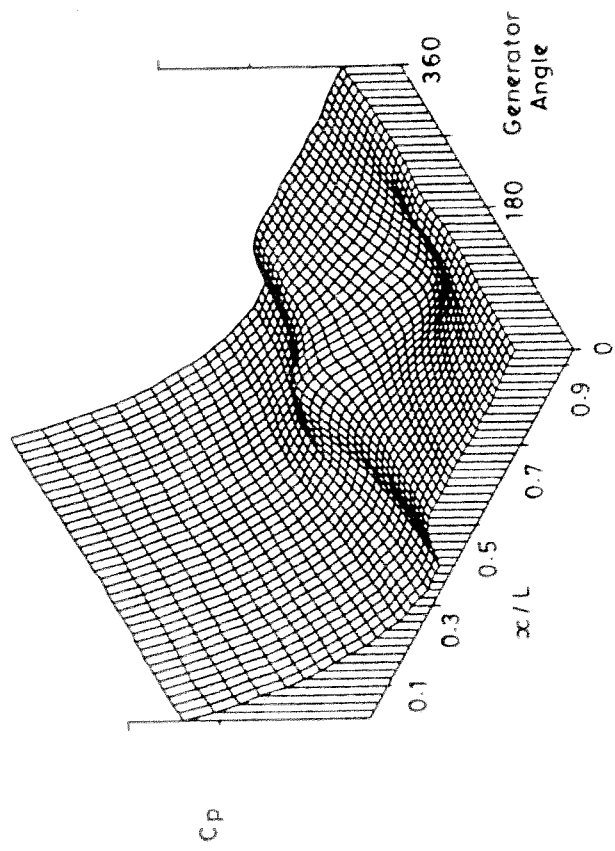
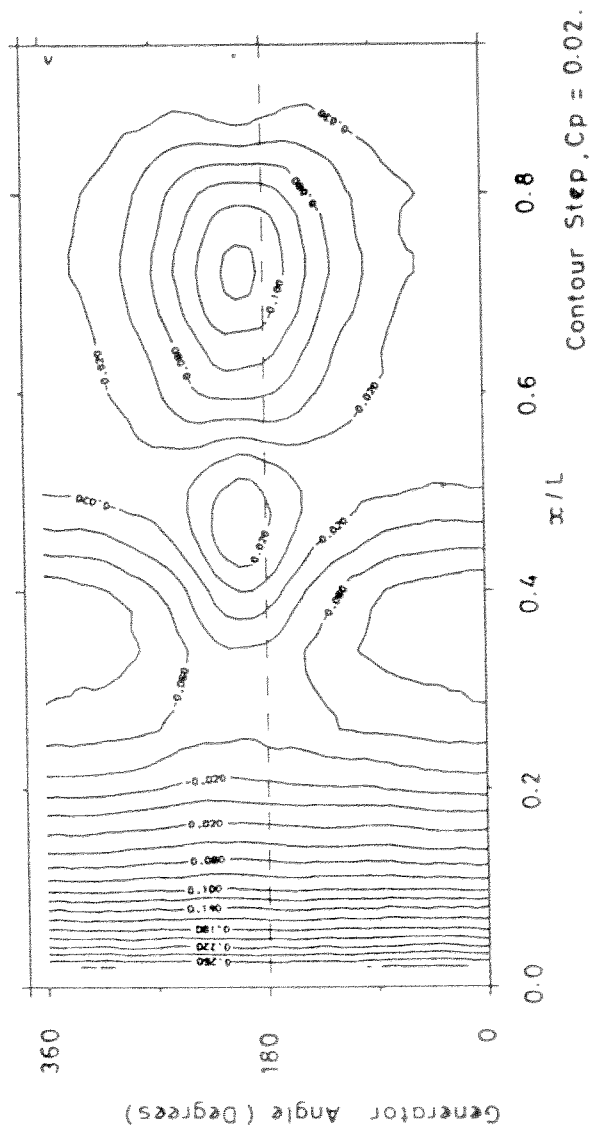
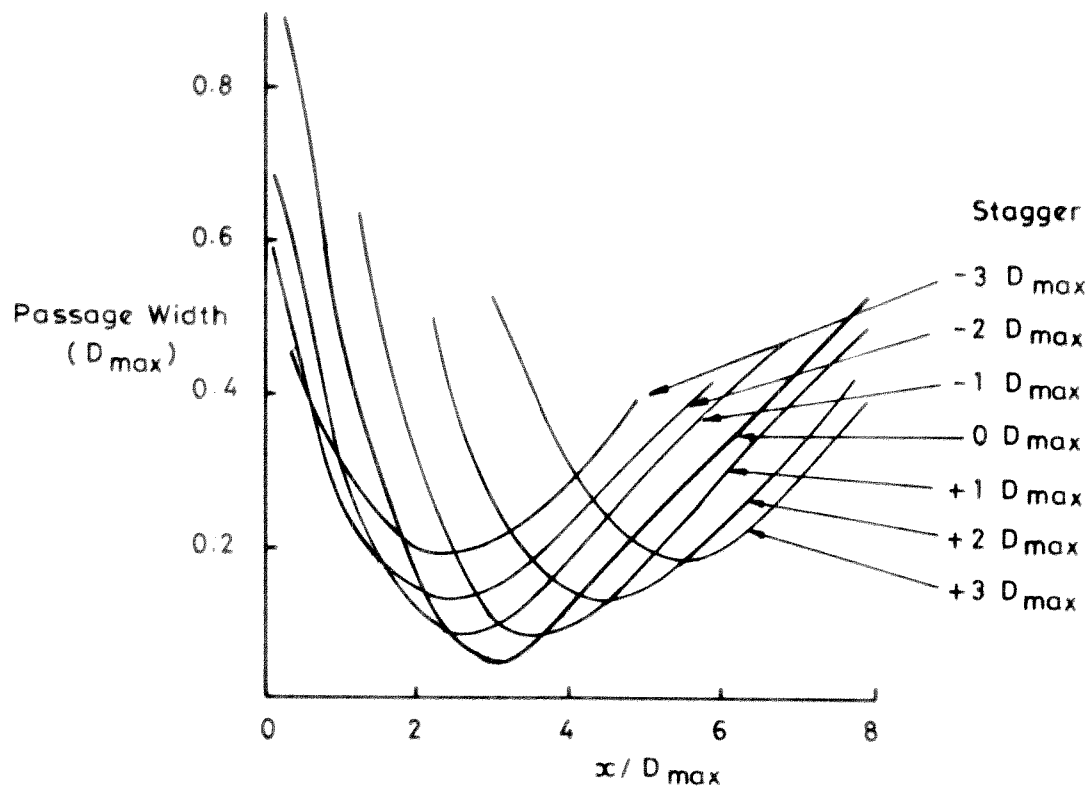
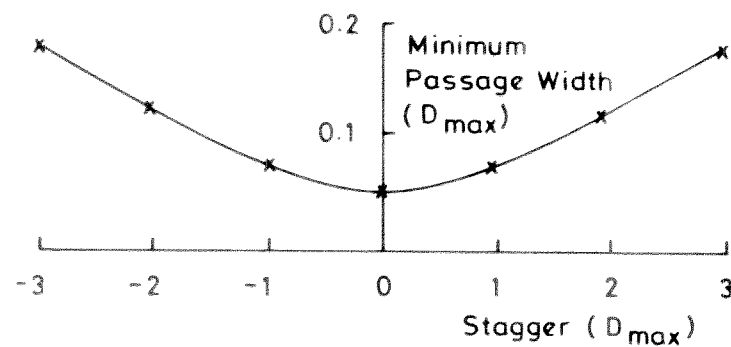


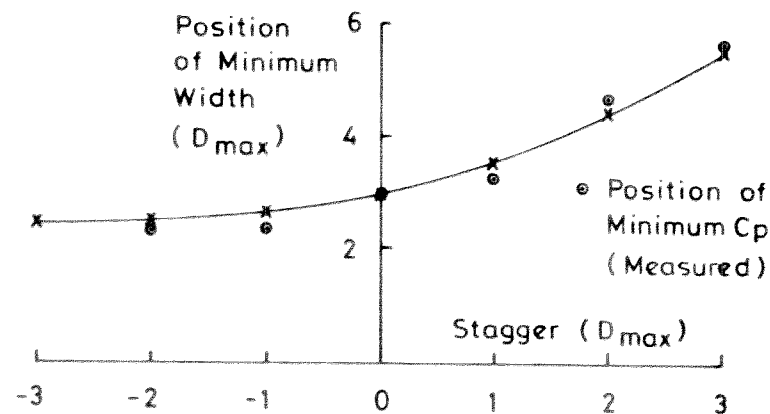
Fig 27 Plots of C_p Variation Over Front Body - Stagger = 3 D max



a) Variation of passage width along the instrumented body



b) Variation of minimum passage width with stagger



c) Variation position of minimum passage width with stagger.

Fig 28. Variation of the Characteristics of the Passage Width between the Bodies with Stagger.

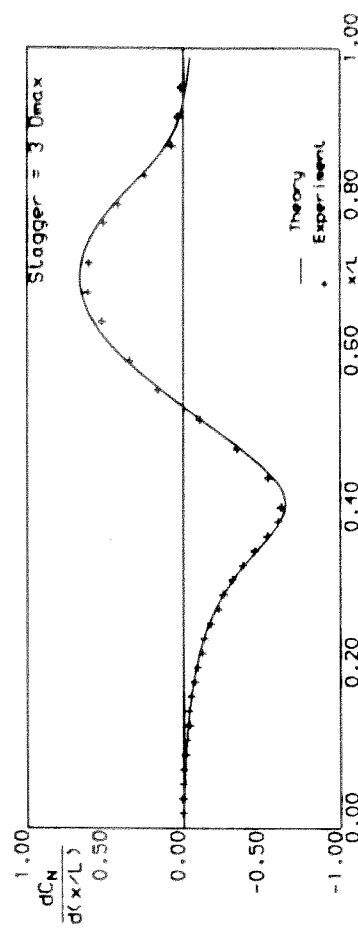
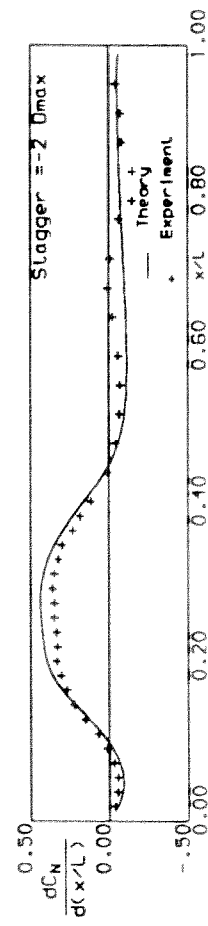
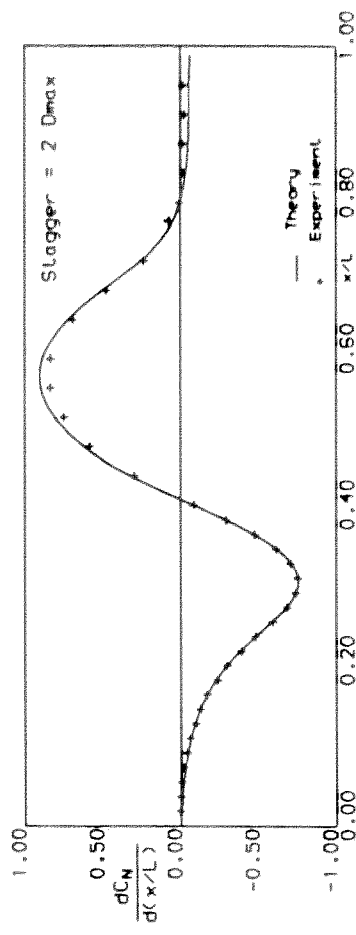
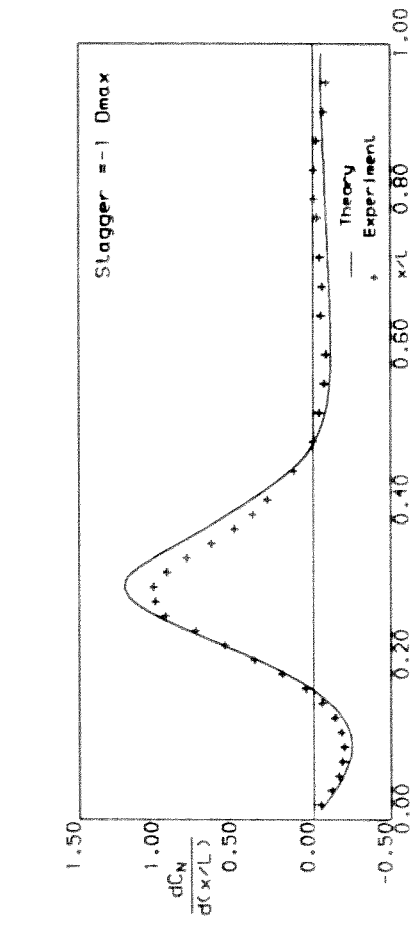
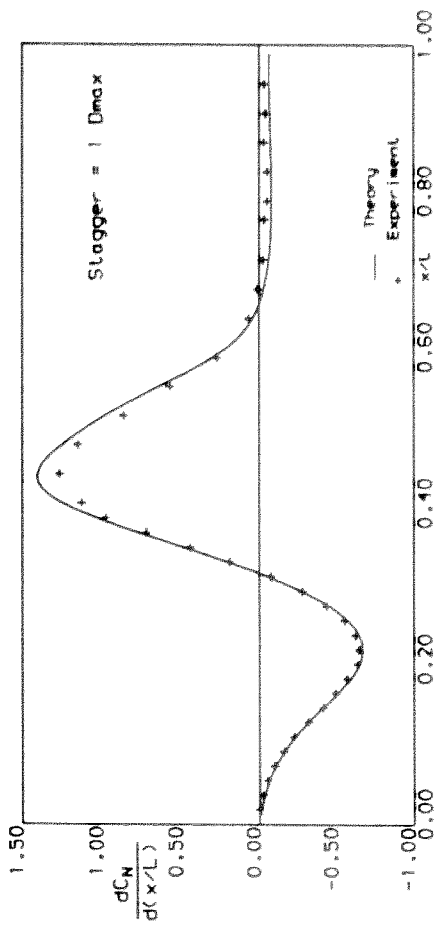
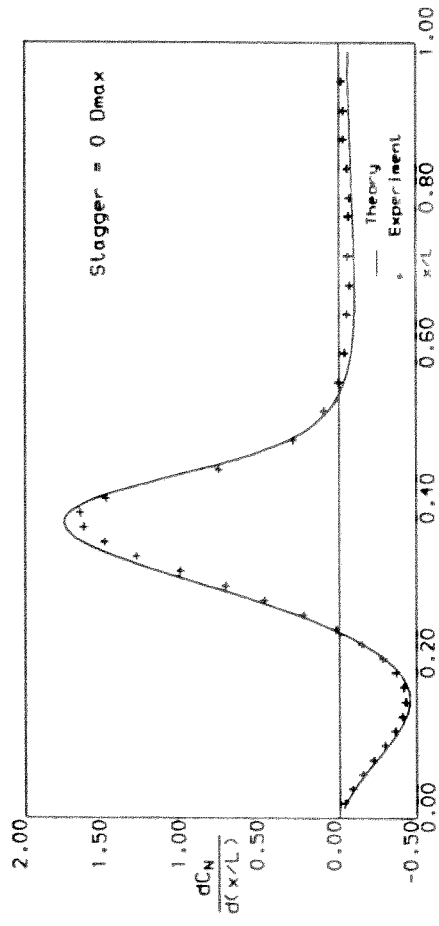


Fig 29 Comparison of Theory and Experiment, Normal - Force Loadings

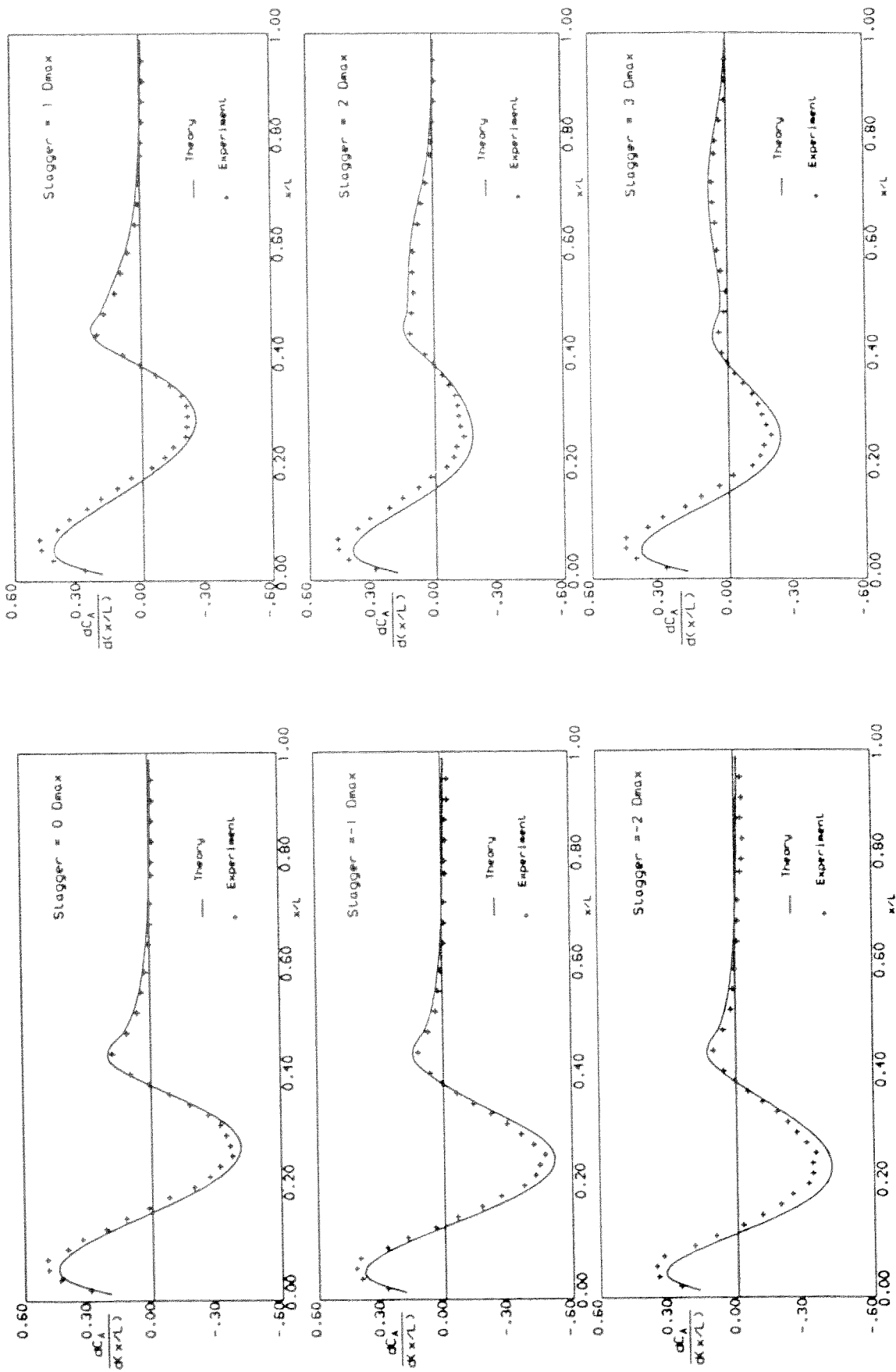


Fig 30 Comparison of Theory and Experiment, Axial-Force Loadings

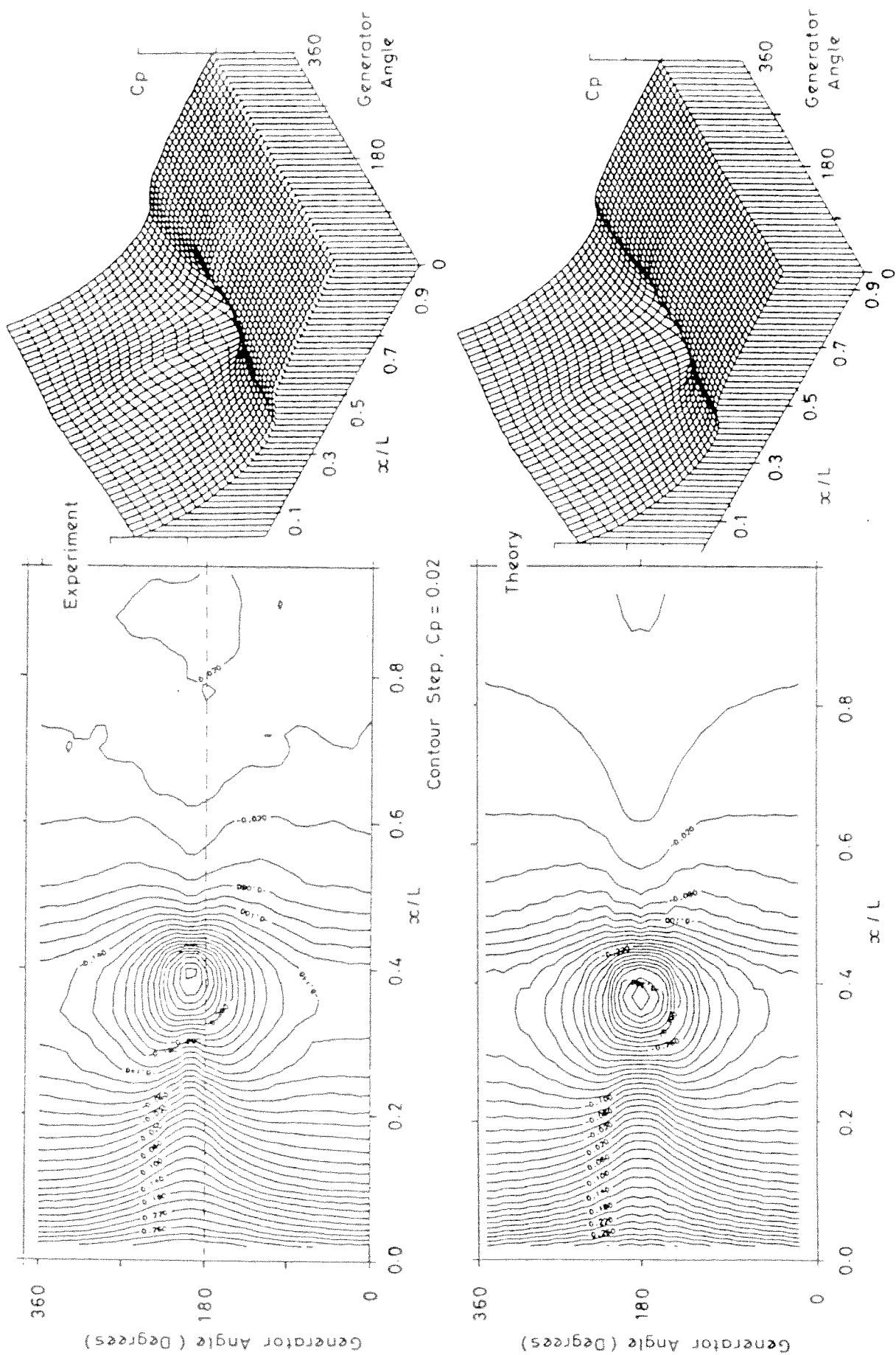


Fig 31 Comparison of Experimental and Theoretical C_p Distributions Stagger = D_{max} .

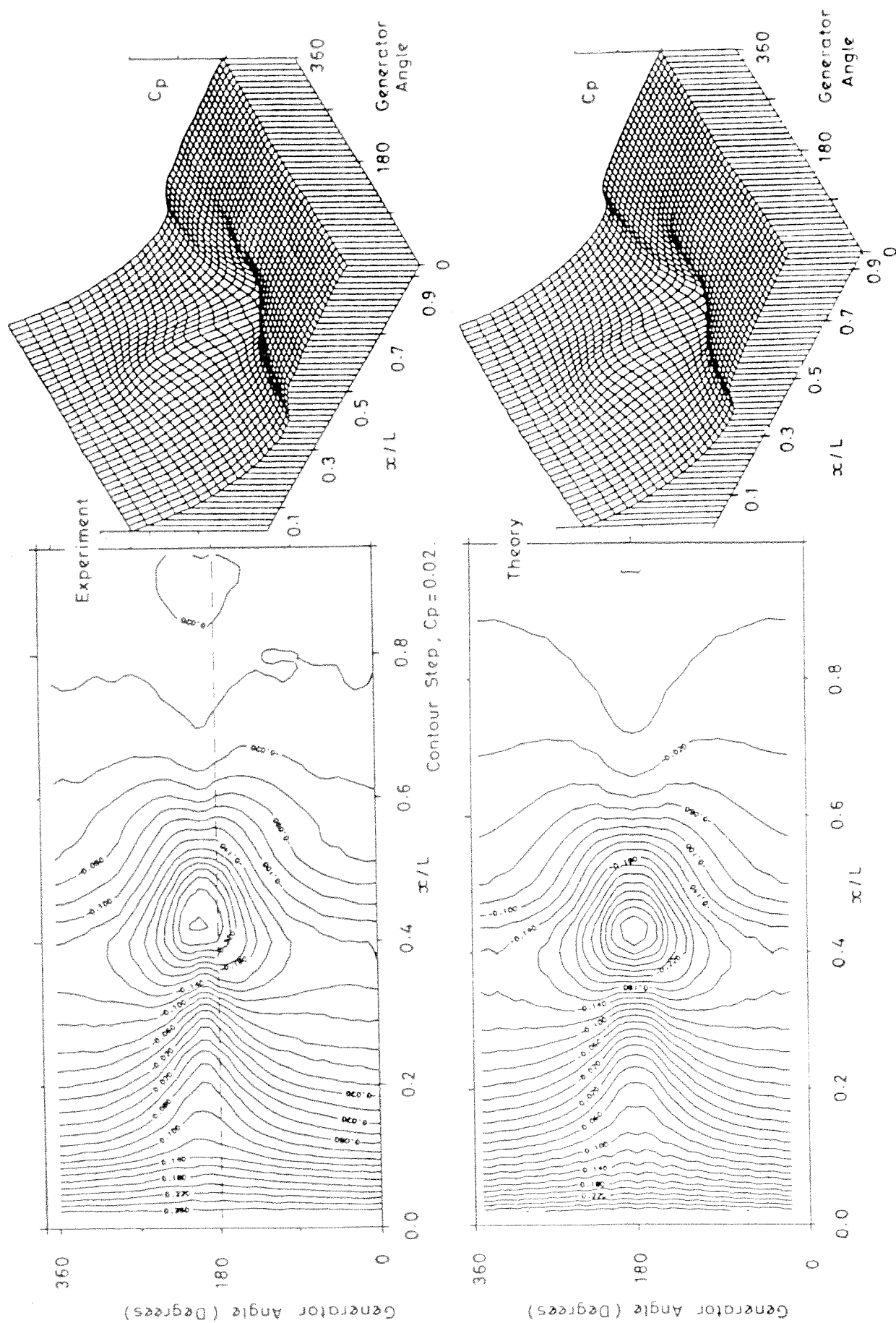


Fig 32 Comparison of Experimental and Theoretical C_p Distributions, Front Body Stagger = 1 D max

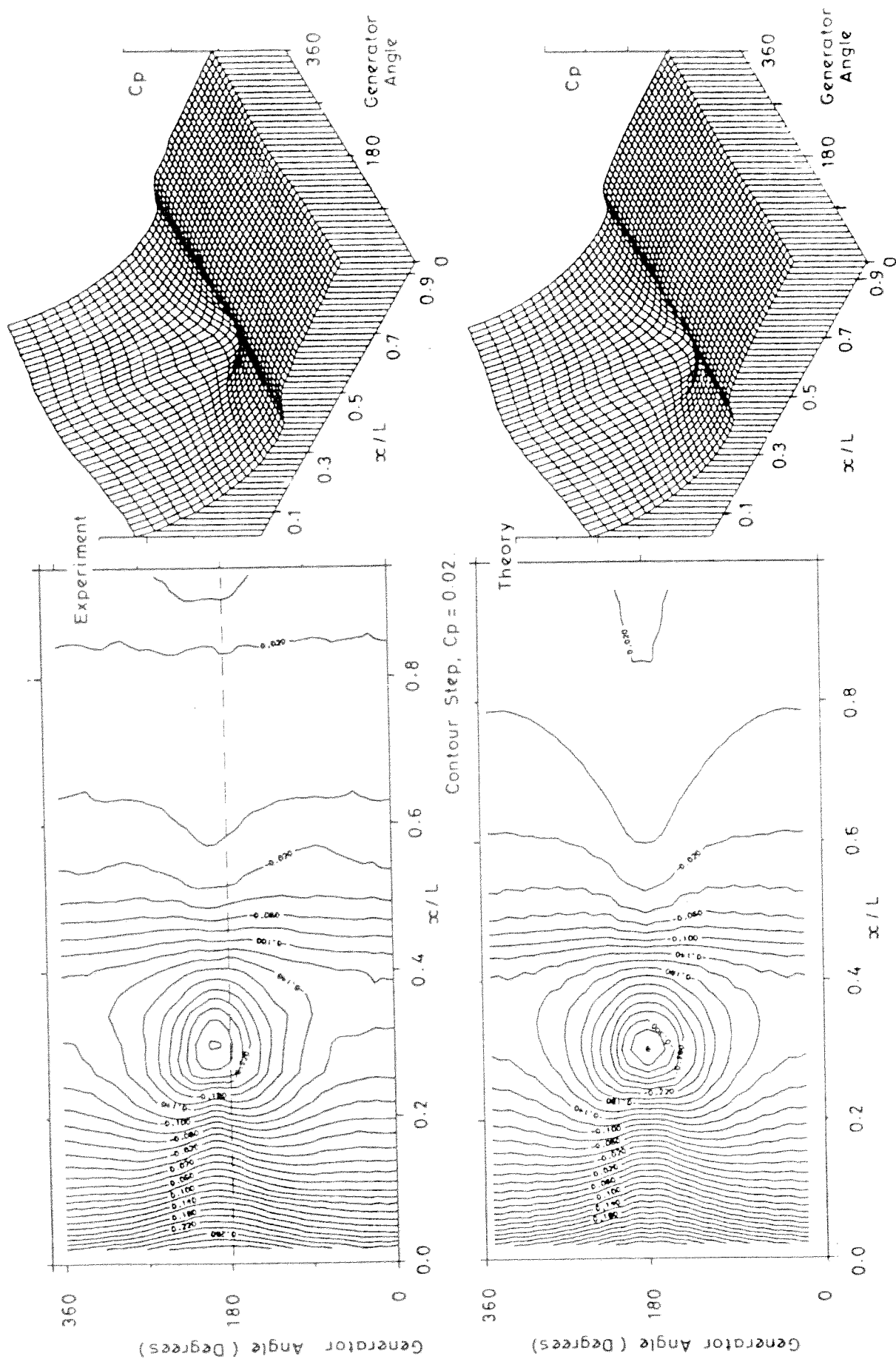


Fig 33 Comparison of Experimental and Theoretical C_p Distributions, Rear Body Stagger = 1 D max

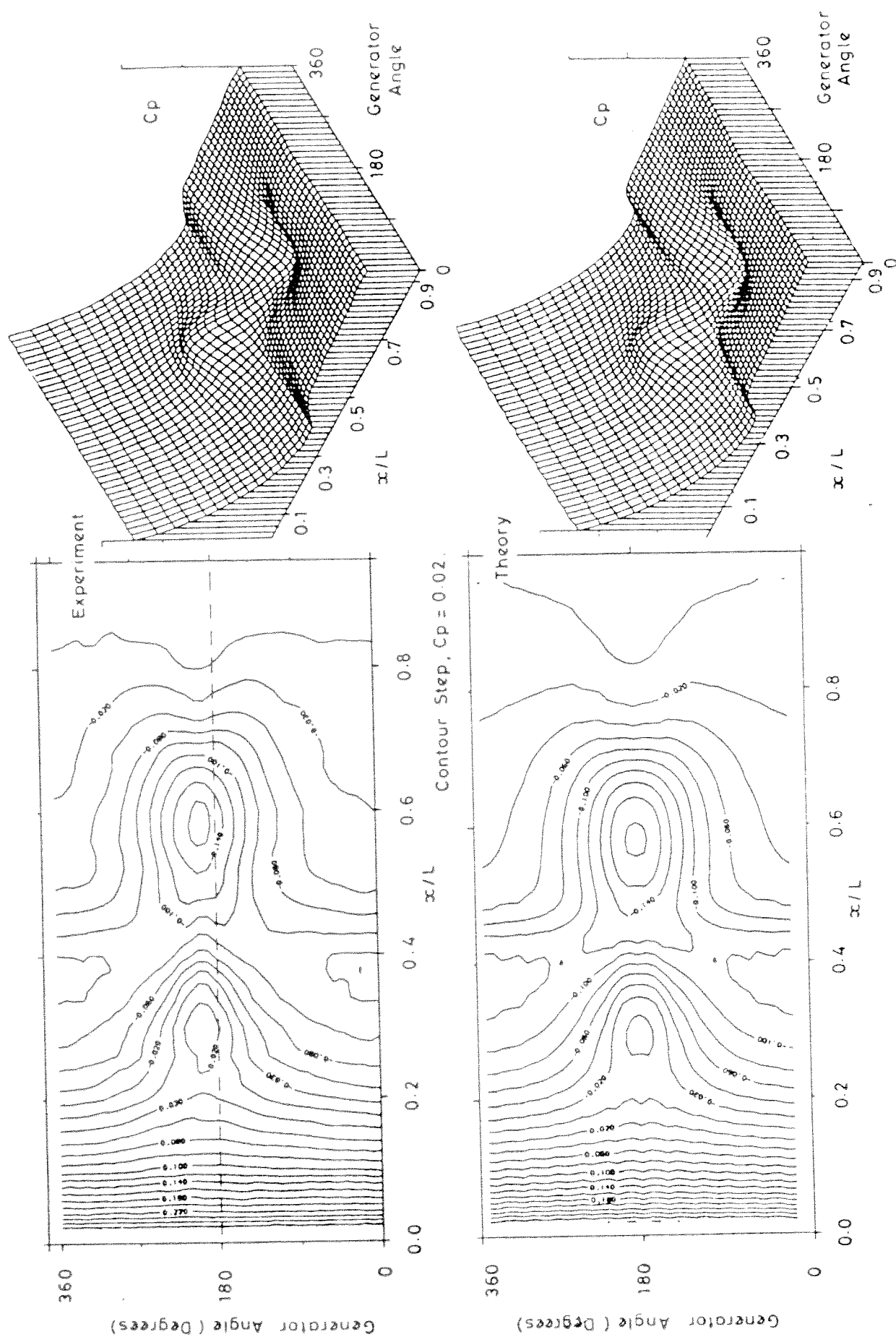


Fig 34 Comparison of Experimental and Theoretical Cp Distributions, Front Body Stagger = 2 D max.

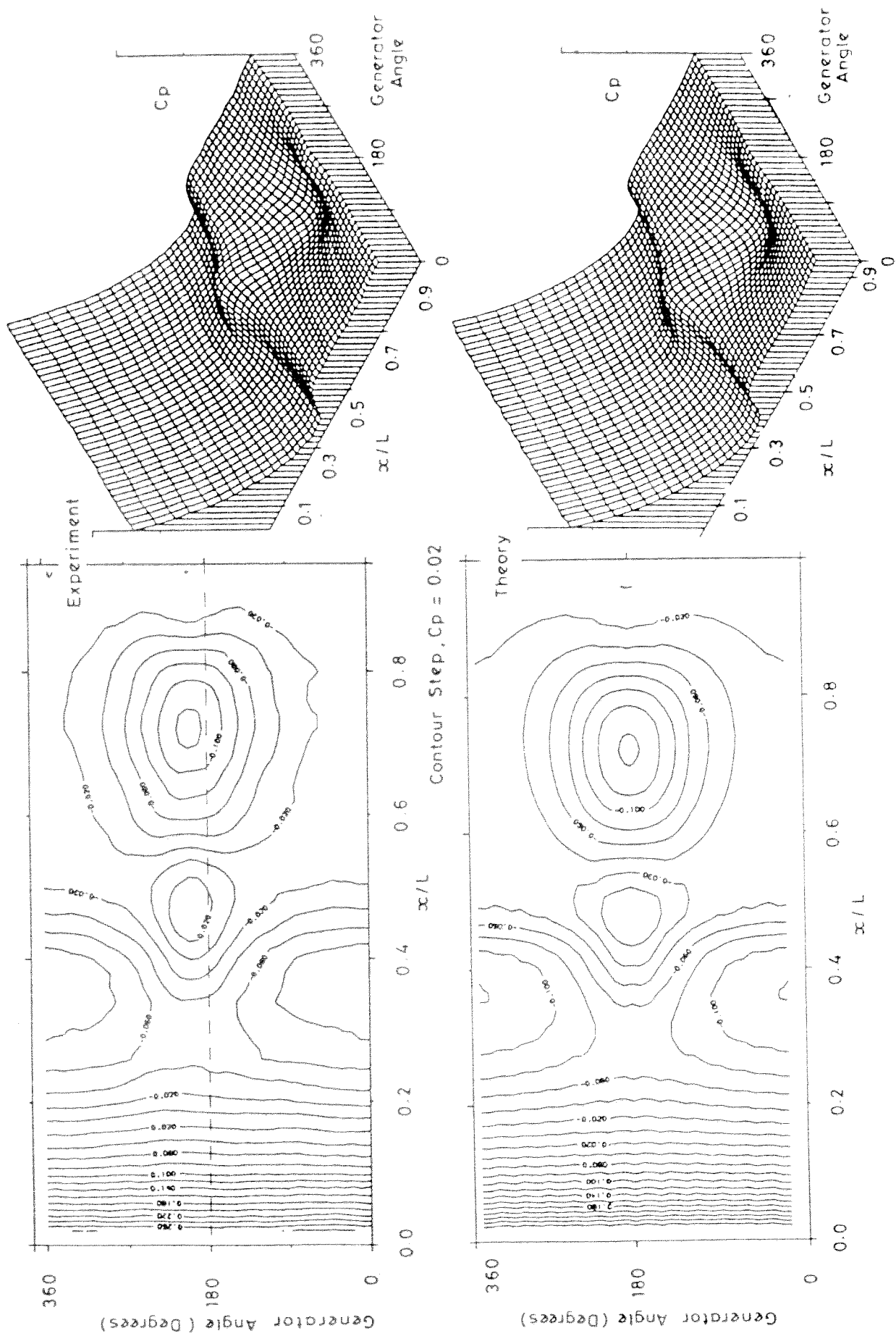


Fig 36 Comparison of Experimental and Theoretical C_p Distributions, Front Body Stagger = 3 D max