

**The effect of pitch and yaw on the aerodynamic interference between
two identical, unstaggered, axisymmetrical bodies whose centrelines are
parallel and separated by 1.11 body diameters**

D.I.T.P. Llewelyn-Davies



**College of Aeronautics
Cranfield Institute of Technology
Cranfield, Bedford MK43 0AL, UK**



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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_n	Yawing-moment coefficient (N'/qSL)
C_p	Pressure coefficient $(p-p_\infty)/q$
C_Y	Side-force coefficient (Y/qS)
D	Maximum body diameter
$dC_A/d(x/L)$	Local axial-force loading
$dC_m/d(x/L)$	Local pitching-moment loading
$dC_N/d(x/L)$	Local Normal-force loading
$dC_n/d(x/L)$	Local yawing-moment loading
$dC_Y/d(x/L)$	Local side-force loading
L	Overall length of the body
M	Pitching-moment (measured about the nose)
N	Normal-force
N'	Yawing-moment
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 the nose of the body
Y	Side-force

SUMMARY

Lowspeed windtunnel tests have been made to measure the pressure distribution over a 7.665:1 fineness ratio body both by itself and in close proximity to a similar, but un-instrumented body. For both configurations, the distributions were measured over a range of pitch from -6 to +6 degrees and a range of yaw from -2 to +6 degrees.

The circumferential pressure distributions at each longitudinal station have been integrated to obtain the local normal-force, pitching-moment, side-force, yawing-moment and axial-force loadings and these have been integrated in turn to obtain the overall forces and moments on the body.

From these results, the aerodynamic characteristics of the body have been obtained over the test range. The interference effects from the second body have also been obtained at zero pitch and yaw, and their variation with change of attitude. The overall forces on the two-body combination have also been determined.

The pressure distributions over the body have been visualised by means of contour plots and isometric diagrams. These give a clear picture of the changes that take place in the pressure distributions due to the presence of the second body and variations of attitude.

The SPARV panel method has been used to predict the corresponding pressure and loading distributions.

Limited oil-flow visualisation tests were made to help in the analysis of the loading and pressure distributions.

1.0 INTRODUCTION

The carriage of stores on an aircraft has often led to aerodynamic problems such as high interference drag and poor release characteristics. These problems become 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 similar axisymmetric bodies was initiated at the College of Aeronautics (CoA) with MOD(PE) support.

The object of the program is to measure the pressure distribution over the surface of an instrumented body first in isolation and then in the presence of a similar, but uninstrumented, body located in close proximity to it. The local loading distribution along the body and the overall forces and moments on the body would then be obtained by successive integration of the measured pressures.

It is also proposed to use computational fluid dynamic techniques to predict the pressure and loading distributions over the instrumented body and the overall forces for comparison 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 would also have significant viscous effects at low incidence.

The body, Fig 1 & Table 1, had a ogival nose of 3:1 fineness ratio. The ogive was continued past the maximum diameter position until its tangent made an angle of 3 degrees to the horizontal when it blended into a 3 degree semi-angle conical boat-tail. This was truncated at a distance of $7.665 D_{max}$ from the nose to form a blunt base of diameter $0.538 D_{max}$, where D_{max} is the maximum diameter of the 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, b) the distance apart of their centre-lines (separation) and c) the longitudinal spacing relative to each other (stagger).

Previous tests in this series have investigated the effect of varying the separation of two unstaggered axisymmetrical bodies at zero pitch angle, ref 1, and the effect of stagger on two axisymmetrical bodies at zero pitch angle whose centrelines have a separation of $1.05 D_{max}$, ref 2.

The present tests investigate the effect of pitch and yaw on two unstaggered bodies. As the bodies were to be mounted one above the other in the pitch plane, variation of the bodies in yaw at zero pitch corresponds to the variation in pitch at zero yaw of two bodies positioned side by side.

It was decided to increase slightly the separation of the bodies for two reasons. In the first place, the interference between the bodies was very large at the separation of $1.05 D_{max}$ used in ref 2, and varied appreciably with change of separation, ref 1. In view of the difficulties found in positioning the bodies accurately relative to each other, a small increase in the basic separation to $1.10 D_{max}$ would still result in appreciable interference between the two bodies, but the effects would not be quite so sensitive to small errors in setting. Secondly, because of the characteristics of the instrumentation system, it was desirable to reduce somewhat the magnitude of the pressures measured in the interference regions.

2.0 EXPERIMENTAL DETAILS.

2.1 Positioning the bodies in the windtunnel

The bodies and their support system, Fig 2, have been described in detail in references 1 & 2. For the present tests, a pivot similar to that used in the support of the instrumented body was incorporated in the support of the dummy model so that it also could be pitched.

In the previous tests, ref 2, the angular position of the dummy model had been determined by direct measurement from the tunnel walls. Not only was the accuracy of this method found to be poor, but it was very time-consuming. As the model was to be moved through a range of pitch angles in the present tests, the position of the dummy model would have to be altered for each change of pitch so as to maintain the correct alignment with respect to the instrumented model. In order to ease the alignment problem, a simple jig was designed which was located on the instrumented body by two semi-circular templates which were located at the position of maximum diameter and at the end of the conical afterbody. The position of the dummy body was defined by two edges at right-angles on each of the location templates which defined the required position of the dummy body at the position of maximum diameter and at the rear of the afterbody, Fig 3.

The rigging procedure was to set the instrumented body at the desired pitch angle using the tunnel incidence change system and with the dummy model well clear. The dummy model was then positioned onto the jig by means of adjusting the turnbuckles on the three rigging wires, Fig 2.

It had been intended to position the dummy body so that it touched all the locating surfaces, but it was found that the sting support was so flexible the slightest contact of the dummy body with the jig was sufficient to deflect the stings. As a result the models

could move appreciably when the jig was removed. Whilst the change in angular position would be negligible, it was considered that the change in the gap between the models was unacceptable because of the considerable change in the normal-force interference with separation at the desired separation. Accordingly, the dummy model was rigged so that it was just clear of the location surfaces. As a result, the separation between the model centre-lines was slightly greater than the desired value of $1.10 D_{max}$. Measurements of the actual gap between the models established that the mean separation was $1.11(4) D_{max}$.

As the support systems for both models were attached to the tunnel turntable, it was not necessary to re-rig the bodies as yaw was altered as rotation of the turntable yawed both bodies without altering their relative position.

2.2 Instrumentation

As in the previous tests, the pressure tappings were connected to a Scanivalve pressure switch where the pressures were measured by a Setra ± 0.1 psi differential transducer.

The windtunnel dynamic head was obtained from a standard pitot-static probe positioned as in the previous tests and was measured by a Setra ± 1 psi pressure transducer. The tunnel static pressure was used as a reference pressure for both transducers and was also connected to the first Scanivalve port to determine the transducer drift by measuring the zero of the transducer at the beginning of each scan.

A PET microcomputer was used to step the pressure switch, measure the output of the transducers by means of a 12-bit analogue/digital converter and roll the model in 9 degree steps after each pressure scan. The computer measured each pressure 5 times, meaned the results, corrected the readings for transducer drift, converted the corrected results to C_p values, printed the results and stored them on disc.

The gain of the analogue/digital converter could only be altered in steps of 10. Thus care had to be taken to ensure that the tunnel speed was chosen so that changes in gain were avoided during the test because of the resultant loss in accuracy.

2.3 Accuracy of pressure measurement

Towards the end of the test programme, the computer programme that controlled the test was modified. In the process of checking its operation, it was discovered that there was a fault in the pressure scanning switch which resulted in a group of tappings giving readings which seemed to be considerably in error. Some brief tests were then made to investigate the matter further and to assess the probable accuracy of the pressure-measuring system.

In these tests, all the connecting tubes leading to the scanning switch and transducer were vented to atmosphere. The tubes leading to the higher range pressure transducer were reconnected so that the tube normally connected to the pitot head was vented to atmosphere and the tube leading to the static source was coupled to a small tank which was sucked down to a pressure of approximately 90 mm H₂O below atmospheric. In this condition the scanning system was cycled through many complete scans to determine the location of the fault in the system.

From these tests it was determined that :-

a) In general, the pressures measured by the scanning switch were within +/- 0.03 mm H₂O of atmospheric pressure.

b) There was a group of ports that were normally connected to the tappings between $x/L = 0.075$ and 0.20625 which were consistently in error by a greater amount. In particular the port normally reading the pressure at $x/L = 0.075$ consistently read a pressure that was higher than atmospheric by about 1mm H₂O and those normally connected to the tappings at $x/L = 0.15$ and 0.16875 read pressures that were also above atmospheric by about 0.8 and 0.6 mm H₂O respectively. The remaining

ports in the group read pressures that were also above atmospheric but generally by less than 0.3mm H₂O.

c) The pressures measured by the higher range pressure transducer varied by no more than ± 0.05 mm over the period of the tests.

d) Using these results, the accuracy of C_p measurement under these controlled conditions was about ± 0.0003 except in the group of ports mentioned where the error could be as much as 0.01. Under typical test conditions, the measurement errors will be increased appreciably due to tunnel unsteadiness etc, but the resultant errors will still be small compared to the errors present in those ports whose readings are affected by the pressure switch fault.

As the measurement errors in the "bad" region tended not to vary greatly during a roll scan, the normal-force loadings would not be too badly effected by the errors in C_p , and as the region of worst interference was in the region of $x/L = 0.4$, it was decided to complete the test programme without curing the pressure switch problem rather than abandoning the test.

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 along the length of the body to obtain the overall forces and moments acting on the body and hence the position of the centres of pressure.

The results are presented about a system of body axes whose origin is at the nose of the body, Fig 4.

2.5 Transition fixing

For these and subsequent tests in the series, the method of fixing transition was altered from that used previously in that a narrow band of distributed roughness was used instead of a trip-wire. The

roughness band was 0.1 inches (2.5 mm) wide and consisted of a sparse distribution of 0.011 - 0.013 inch (0.28 - 0.33 mm) diameter glass spheres (Ballottini) stuck to the body by a thin layer of epoxy adhesive. The front of the band was at the same position as the trip-wire had been i.e. 3.7 inches (94 mm) behind the nose, or at approximately 0.06 L.

This band would ensure that the flow was completely turbulent immediately behind the band at the test Reynolds number of 3,300,000 based on the length of the body, or 430,000 based on the maximum body diameter, ref 3. This reduction in Reynolds number from that of the previous tests in the series, 500,000 based on body diameter, was necessary in order to avoid changing the gain of the analogue/digital converter at the higher pitch angles with the resultant loss in accuracy, section 2.2.

3.0 TEST PROGRAMME

The object of the test programme was to determine the interference between the two bodies in 2-degree steps over a range of 6 degrees in either pitch or yaw.

The instrumented body was first tested in isolation to establish its basic loading distribution and overall characteristics in both the pitch and yaw planes.

The second body was then rigged vertically above the instrumented body with a separation of $1.11(4) D_{max}$ and the pressure distributions over the body were obtained over the desired range of pitch and yaw.

In the pitch plane, the pressure distributions over the upper and lower bodies will differ at other than zero pitch. Thus it was necessary to test the body combination at the corresponding negative pitch angles in order to obtain the pressure distributions appropriate to the dummy body.

In the yaw plane, the pressure distributions over the two bodies will be the same and so it is not necessary to test at negative yaw angles. However tests were made at one negative angle to check on the accuracy of setting zero yaw.

Initially the instrumented body was rigged in the tunnel with its centreline horizontal and $0.55 D_{max}$ below the centre-line of the tunnel. The base of the body was $4.68 D_{max}$ ahead of the front of the sting support. Brief tests were made to align the nose of the model with the oncoming airstream in both pitch and yaw and thus set the correct datum for the pitch and yaw traverse systems.

4.0 EXPERIMENTAL RESULTS FOR THE ISOLATED BODY

4.1 Variation of the loading distributions with change in attitude

The variation of the normal-force, pitching-moment and axial-force loading distributions with pitch are shown in Figure 5 and the variation of the side-force, yawing-moment and axial-force loading distributions with yaw are shown in Figure 6. The variation of the normal-force and pitching-moment loading distributions with yaw and the side-force and yawing-moment loading distributions with pitch are not shown as these loadings are very small in magnitude and vary little with change in attitude.

The general shape of the normal-force and side-force loading distributions are similar. There is a well defined peak in the loadings at about $0.16L$. Aft of this the loadings decrease in magnitude until they are zero at the position of maximum diameter ($0.393L$). Further down the body the loadings again increase in magnitude, but are of opposite sign, to reach a second, much flatter and smaller, peak at about $0.56L$ before decreasing continuously in magnitude with further movement aft until the magnitude at the last measuring station ($0.95L$) is small.

The shapes of the moment loading distributions are similar to the force loadings, but of the opposite sign as would be expected from the sign convention and the fact that the moment is the product of the force loading at the station and the distance of the station from the nose of the body. However this results in the magnitude of the second peak now being very similar to that of the first.

The axial-force loading distributions vary much less with change in attitude and consist of a narrow positive peak at about $0.075L$ followed by a slightly smaller but wider negative peak at about

0.25L before becoming zero at the point of maximum diameter and rising to a small positive peak near $x/L = 0.45$ and then falling to approximately zero over the last 30% of the body. There are considerable differences between the axial-force loadings between the first two peaks, but it is thought that much of this may be due to the uncertainties in pressure measurement in this region as previously discussed.

The position and magnitude of the various peaks in the 'force' loading distributions have been measured and the results have been plotted in Figures 7 and 8. Because the body is symmetrical, the results for both the pitch and yaw scans have been plotted on the same graph, with 'normal-force' being taken to be the force in the plane in which the attitude is varied. It can be seen that the results for changes in attitude in the pitch and yaw planes are in good agreement and the body is closely aligned to the tunnel flow at zero pitch and yaw.

The magnitude of the peaks in the 'normal-force' loading distributions vary linearly with attitude, but the position of the peaks does not vary, Figure 7. There is rather more scatter in the estimated position of the second peak because it is fairly flat and so is difficult to determine accurately.

There appears to be some consistent variation with attitude in the magnitude of the first two peaks in the axial-force loading distributions, but the position of all three peaks does not vary with change in attitude, Figure 8.

4.2 Aerodynamic characteristics of the single body

The loading distributions over the body have been integrated to obtain the variation of C_N , C_m , C_A and the position of the point of action of C_N with change in attitude in the pitch plane and the variation of C_V , C_m , C_A and the point of action of C_V with change in

attitude in the yaw plane. As the body is symmetrical, the aerodynamic characteristics should be the same in the pitch and yaw planes; the results for the variations with pitch and yaw are therefore plotted on the same graphs, Figure 9.

Over the range of attitude tested, the variations of C_N , C_m , C_v and C_h with change in attitude are linear and the results in the pitch and yaw planes are in good agreement, Figures 9 a) and b). It should be noted that, at a given attitude, the sign of moment and force coefficients are the same indicating that the moment contribution from the afterbody is greater than that from the numerically larger forebody normal-force loadings. The positions of the line of action of the forces are plotted in Figure 9 c). The individual points have been obtained by division of the moment and force coefficients and thus show a large scatter at small attitudes. The line drawn through the points is the position obtained from the slopes of the force and moment variation with attitude. The position thus obtained, $0.1785L$ in front of the nose, is a reasonable mean-line through the individual points.

The scatter present in the variation of C_h with attitude is large, especially at ± 2 degrees attitude, and is probably due to the errors present in the measurement in pressure between $0.075L$ and $0.2L$ as previously discussed. It is possible that the large peak that seems to be present at zero attitude may be an illusion in that it depends on accepting the (single) zero-incidence value and the mean of the widely separated measurements made at ± 2 degrees attitude.

5.0 EXPERIMENTAL RESULTS FOR THE TWO-BODY COMBINATION

The variation of the normal-force, pitching-moment and axial-force loading distributions with pitch are presented in Figs 10 and 11. The variation of the side-force, yawing-moment, axial-force and normal-force loading distributions are shown in Figs 12 and 13. The magnitude and position of the various peaks in these loading distributions are plotted in Figures 14 - 18.

5.1 General features of the loading distributions for the two-body configuration, and their variation with pitch

5.1.1 Normal-force loading distributions

The normal-force loading distributions over the instrumented body for the range of pitch tested are shown in Figure 10. It should be remembered that the instrumented body is the lower of the pair and at positive pitch, the nose of the instrumented body moves upwards, i.e. in the direction of the dummy body. Thus for a given pitch angle, the graph shows the loading distribution over the instrumented body and the loading distribution over the dummy body is obtained by inverting the sign of the pitch angle and loading.

The first, and most obvious, comment is that the normal-force loading distribution for the instrumented body of the pair, is completely different from that measured on the isolated body.

At zero pitch, there is now a negative loading over the front of the body, i.e. which would tend to separate the bodies. This falls to a minimum value of -0.45 at approximately the same position ($0.16L$) as the positive peak loading occurs in the case of the isolated body. Further aft the loading rises to zero at approximately $0.25L$ and then rises to a peak value of $+1.3$ at the position of maximum diameter where the bodies are closest together. With further movement aft, the

loading falls, rapidly initially and then more slowly, to reach zero at about $0.6L$ and a minimum value of 0.07 at $0.7L$ before increasing slowly with further movement towards the base of the model.

As pitch becomes negative, little change takes place in the general characteristics of the loading distribution. The magnitude of the first minimum in the distribution varies linearly with pitch, becomes more negative with decrease in pitch and its location moves forward slightly, Fig 14. The magnitude of the second, positive, peak increases slightly between 0 and -2 degrees pitch and then reduces linearly back to its original magnitude by -6 degrees pitch with the position of the peak moving slightly forward as pitch decreases. The position of the second minimum does not alter in position along the afterbody as pitch varies, but its magnitude alters linearly with decrease in pitch and has become slightly positive in value by -6 degrees pitch. The shape of the afterbody loading distribution becomes flatter as pitch decreases and the loading becomes approximately zero aft of $0.6L$ for all negative angles of pitch.

As pitch becomes positive, the initial slope of the forebody loading distribution becomes more positive and is zero by 2 degrees pitch, Fig 10. At this pitch angle, the loading remains zero for a distance of about $0.07L$ aft of the nose and then rapidly reduces to form a minimum in the distribution at a position corresponding to the first minimum in the distribution at negative pitch angles. This minimum increases linearly in value with increase in pitch at the same rate as at negative pitch but its position remains constant instead of moving slowly rearwards with increase in pitch as at negative pitch angles, Fig 14. Because of the change in sign of the slope of the initial distribution there is now an additional maximum in the distribution at pitch angles greater than 2 degrees which moves away from the nose as pitch becomes more positive and increases in value at a slightly slower rate with increase in pitch than that of the first minimum in the distributions. To avoid complication, the changes in position and magnitude of this additional peak have not been further analysed.



As at negative pitch, the changes in position and magnitude of the maximum in the loading distribution near the position of maximum body diameter are relatively small. The magnitude of the peak loading varies in the same way as at negative pitch, but the position of the peak moves slightly forward as pitch increases, Fig 14.

The minimum in the afterbody loading distribution varies linearly in value with increase in pitch at the same rate as at negative pitch, but now moves forward with increase in pitch, Figs 10 and 14. Because the variation of loading is small near the position of the minimum it is difficult to define the position of the minimum very accurately so there is some scatter in the results, Fig 14. However the general trend is clearly defined.

5.1.2 Pitching-moment loading distributions

The pitching-moment loading distributions, Figure 11 a), have the same general features as the normal-force distributions for the instrumented body, but with sign inversion. Because of the contribution from the moment arm, the contribution from the first peak in the normal force distributions is relatively reduced and that of the third peak increased.

5.1.3 Axial-force loading distributions

The general shape of the axial-force loading distributions over the instrumented body, Figure 11 b), is very similar to those over the isolated body, but the peaks are rather greater in magnitude. As the main effects due to variation in pitch occur in the region affected by experimental inaccuracies, no detailed analysis of the changes in the position and magnitude of the forebody loading peaks has been made but the results are presented in Fig 15.

Aft of this region of uncertainty, $x > 0.26L$, there is very little effect of pitch on the loading distributions, Fig 11 b).

5.2 General features of the loading distributions for the two-body configuration and their variation with yaw

When yaw is varied, the main variations will take place in the side-force, yawing-moment and axial-force loadings. However, because there are some considerable normal-force loadings present at zero yaw due to the close proximity of the second body, the normal-force loading distributions were monitored to see if they were effected by changes in yaw. The side-force, yawing-moment, normal-force and axial-force loading distributions over the instrumented and dummy bodies will be the same for both bodies but the sign of the normal-force loadings will be reversed in the case of the dummy body.

5.2.1 Side-force loading distributions

The side-force loading distributions are shown in Figure 12 a). At first sight, the distributions appear to be very similar to the loadings present over the isolated body. However, on closer examination, it can be seen that the results differ appreciably in several ways.

Firstly, there is a significant loading present at zero yaw which would appear to indicate a misalignment at zero yaw of about -0.3 degree. As the position of the instrumented model had not been adjusted when the dummy model was rigged, it is possible that the dummy model was incorrectly positioned and was not truly vertically above the instrumented body.

Secondly, the magnitude of the forebody loading peaks are some 20% greater than that of the isolated body and occur some $0.05L$ farther aft.

The second loading peaks are also considerably greater in magnitude than those of the isolated body and the shape of the distribution is rather different. In the case of the single body, the

forebody distribution blends smoothly into the afterbody loading distribution which is in the form of a long flat curve with an ill-defined peak. In the case of the two-body combination, there is a very well-defined discontinuity in the loading distribution whose position varies slightly with angle of yaw. At small angles of yaw, the maximum afterbody loading occurs at this discontinuity, but at angles greater than +2 degrees the peak afterbody loading occurs rather farther aft and the shape of the loading peak becomes similar to that of the isolated body. The position of the discontinuity in the loading occurs at the same position, ($x/L = 0.4125$) for all positive yaw angles but has moved aft to $x/L = 0.45$ at -2 degrees yaw.

5.2.2 Yawing-moment loading distributions.

As previously, these are similar in shape to the side-force loading distributions but with the magnitude of the forebody and afterbody peaks now being similar, Fig 12 b).

5.2.3 Axial-force loading distributions

The general shape of the axial-force loading distributions, Fig 13 a) is very similar to that of the body in isolation. The first, positive, peak is at the same position but is somewhat greater in magnitude than that present on the isolated body at all angles of yaw. The second, negative, peak is slightly farther aft and greater in magnitude than that of the isolated body. The third, positive, peak is greater in magnitude than in the case of the body in isolation but still occurs at the same position along the body, i.e at the beginning of the conical afterbody. The axial-force loading remains greater than the isolated body until almost the rear of the body.

5.2.4 Normal-force loading distributions

The variation with yaw of the normal-force loading distributions over the instrumented body are shown in Figure 13 b). The

distributions vary little with yaw over the range of ± 2 degrees yaw, but above 2 degrees, the loadings become more positive over most of the length of the body.

5.3 Variation of the position and magnitude of the peaks in the loading distributions with change in yaw.

The variation of the magnitude and position of the side-force, axial-force and normal-force loading peaks with yaw are presented in Figs 16 -18.

The magnitude of both peaks in the variation of the side-force loading distribution with yaw seem to vary linearly with yaw, Fig 16, although the scatter in the results for the second, afterbody, peak is rather large. This scatter is probably due to the discontinuity in the loading distributions that occurred near the beginning of the constant-taper afterbody. There is a discontinuity in body curvature at this point and this can lead to local flow separations in some conditions, ref 4. Again, there is some scatter in the variation of the position of the peaks with yaw, particularly at zero yaw, but it would appear that there is no consistent trend and thus it seems likely that the position of the peaks is probably constant.

When yaw is varied, the first two peaks in the normal-force distributions gradually become more positive as the amount of yaw exceeds 2 degrees, Fig 17, but there is no change in their longitudinal position. There is little change in the value of the third loading peak as yaw is increased, but the position of the peak moves aft with increase in yaw.

There appears to be only minor changes in the variation of size and position of the peaks in the axial-force loading distributions as yaw is varied, Fig 18. The changes that are present are in the regions affected by experimental inaccuracies and so may not be significant.

6.0 ANALYSIS OF THE VARIATION OF THE INTERFERENCE BETWEEN THE TWO BODIES WITH CHANGE OF ATTITUDE

The interference between the two bodies was found by subtracting the loadings obtained in the body-alone tests from those measured on the instrumented body at the same attitude. The changes in interference loading with pitch, (or yaw), was altered was obtained by subtracting the interference loading at zero pitch and yaw from the interference loadings at the other attitudes. Thus the change in loading at the datum position, zero pitch and yaw, is zero by definition. The loadings thus analysed were:-

- a) Normal-force interference with change of pitch and yaw, Fig 19.
- b) Axial-force interference with change in pitch, Fig 20.
- c) Side-force interference with change in yaw, Fig 21.

6.1 Changes in normal-force interference loadings.

The normal-force interference loading at zero pitch and yaw is shown in Fig 19 a). As the normal-force for the single body are very small, the interference loading distribution is virtually the same as the loading distribution described previously, Fig 10.

6.1.1 Changes as pitch is altered

The change in the interference loading as pitch is altered is shown in Fig 19 b). It can be seen that :-

a) the greatest changes take place at approximately $x/L = 0.2$, i.e. slightly aft of the position of the forebody loading peak of the body-alone case and the negative loading peak that occurs on the two-body combination.

b) the change in interference at this position is not symmetrical about zero pitch, the greater interference being present at negative pitch angles.

c) the magnitude of the change in interference at this position is approximately $+0.42$ at -6 degrees pitch . As the interference loading at

this position is -0.38 at zero pitch, there is only a small difference in the peak loading over the forebody from that of the isolated body. As the "additional interference" curve at -6 degrees pitch between $x/L = 0$ and $.2$, Fig 19 b), is very similar in shape to and is the inverse of the forebody loading distribution of the isolated body, it appears that most of the interference effect of the upper body on the lower body normal-force loading distribution up to $x/L = 0.2$ has been eliminated by this pitch angle. The general characteristics of the variation of the interference effect are repeated at the other negative pitch angle with the magnitude of the change varying approximately linearly with pitch. Thus the interference of the top body with the lower body normal-force loading characteristics between $x/L = 0$ and 0.2 gradually reduces as pitch becomes more negative.

d) At positive pitch angles however, the interference effect of the top body on the bottom body actually causes the interference at $x/L = 0.2$ to become more negative. The interference still alters approximately linearly with change of pitch, but at less than half the rate as that observed at negative pitch. Thus at $+6$ degrees pitch the interference loading has altered from -0.38 to -0.55 . The shape of the "additional interference" curves are rather irregular between $x/L = 0$ and 0.2 . This probably is the result of the misbehaviour of the pressure switch.

e) except at one pitch angle, -2 degrees, the change in interference with pitch at the position of maximum interference, (i.e. at $x/L = 0.394$ where gap between the bodies is a minimum), is much smaller than at the first peak, and varies little with change of pitch.

f) immediately aft of the position of maximum diameter there is a rapid positive change in interference followed immediately by a much larger negative change. The magnitude and extent of this feature varies little with change of pitch. As there is no obvious cause for this feature, it is possible that it is due to an error of measurement in the datum case at $x/L = 0.4125$ or 0.45 . This is not unlikely as the interference is changing very rapidly in this region.

g) there are considerable negative interference loadings present at negative pitch angles over the front part of the conical afterbody, the actual magnitude of which seems to be determined largely by the rapid

reduction in loadings immediately after of the maximum diameter position. This negative change in the interference loading varies approximately linearly with pitch and varies only slightly along the body up to $x/L = 0.6L$. Aft of this, the change in interference loading with pitch reduces slowly until it is almost zero by the end of the afterbody. At positive pitch angles, the variation of the interference loading with pitch is similar in character, but much smaller than at negative angles.

6.1.2 Changes as yaw is altered

The change in the interference loading distribution when yaw is altered at zero pitch is shown in Fig 19 c). The changes in interference loading are only appreciable between $x/L = 0.2$ and 0.6 . As with the variation with pitch, there are very rapid changes in the interference loadings immediately aft of the position of maximum diameter. The variation takes the form of a "Vee" at the same three stations and the magnitude of the change is similar at all angles of yaw.

There is close agreement between the changes in interference loadings at $+2$ and -2 degrees yaw which are generally small and restricted to a small positive peak near $x/L = 0.25$ and the marked "Vee" variation at about $x/L = 0.45$ as described previously. Thus it would seem that the change in interference is independent of the sign of the angle of yaw as would be expected.

At both 4 and 6 degrees yaw, the change in interference is approximately the same and much greater than at 2 degrees yaw and there are now appreciable changes in interference over the whole region between $x/L = 0.2$ to 0.6 . It thus appears that the change in interference is not linear with variation in yaw.

6.2 Changes in axial-force interference loading

The axial-force loading distribution over the isolated body at zero pitch and yaw is shown in Fig 20 a). When the dummy body is present, the axial-force loading is altered due to its presence and the interference loading is shown in Fig 20 b). The scatter in the distributions between $x/L = 0.07$ and 0.26 are a result of errors in the pressure measurement in this region.

The interference loading varies in the same way as the basic loading distribution. The magnitude of the first, positive, peak is increased by 15%, that of the second, negative, peak by 60% and that of the third, negative peak by 100%. Although the interference at the respective peak values in percentage terms increases progressively along the body, it should be noted that the maximum change in magnitude takes place at the second peak where the axial-force loading is at its most negative value.

When the two-body combination is pitched, the major changes in the interference loadings take place over the fore-body, particularly near the first loading peak, Fig 20 c). No very clear pattern in the variation of interference with pitch can be discerned due to the scatter in the results, but it is likely that the interference loadings become more positive at positive pitch angles and more negative at negative angles and that the increments are larger at positive angles as had previously been noted for the variation of the normal-force interference loadings with pitch, Fig 19 b). The changes in the axial-force interference loadings are small and show a consistent variation with pitch, becoming more negative as pitch decreases.

6.3 Variation of the side-force interference loadings with yaw

6.3.1 Interference loadings at the datum attitude

The side-force loadings measured at zero yaw for the body-alone case had been found to be very small, (section 4.1). However, when the dummy body was added, appreciable side-force loadings were measured on the instrumented body, Fig 12 a). These, by definition, are the interference loadings at zero yaw.

Although there is a certain amount of scatter in the results, the interference loading gradually increases aft of the nose to reach a maximum value of 0.1 about 0.3L behind the nose, and then reduces gradually to a value of 0.2 at $x/L = 0.45$. The interference loading then behaves rather erratically, falling rapidly to -0.06 at $x/L = 0.48$ and 0.52, increasing to -0.03 at $x/L = 0.56$ and then increasing slowly to near zero at the base of the body.

If the bodies were perfectly aligned, the side-force interference loadings should have been zero at zero yaw. As this was not the case, the dummy body must have been mis-aligned.

In view of the care taken in rigging the model, this conclusion was extremely disappointing. The revised method of rigging the model should have ensured that the model centre-lines were parallel to a high degree of accuracy and that the stagger was zero. However, because of the flexibility of the support stings, it had been found necessary to rig the second model so that it was just clear of the rigging jig instead of touching it as had been intended, (section 2.1). As a result of this the dummy body could have been deflected sideways from the true plane of symmetry. The actual amount was small but unknown because, the setting jig had been allowed to roll slightly so that the nose of the dummy model visually appeared to be directly above that of the instrumented body. The only other source of error is the

alignment of the instrumented body in roll. As this was done by eye, it is possible that the datum plane of the pressure tappings and the plane between the model centrelines did not coincide. It was therefore unlikely that the model was seriously mis-aligned.

6.3.2 Effect of change in yaw

The change in the side-force interference loadings with yaw, relative to that measured at zero yaw, is shown in Fig 21 b). It is immediately obvious that there are several unusual features in the results.

In the first instance, the change in the interference loading at a given position along the ogive shape, increases in magnitude with increase in yaw. The maximum change at a given angle of yaw occurs at about $x/L = 0.3$ as previously noted for the results at zero yaw, Fig 21a).

Secondly, the distributions are not symmetrical with yaw as would be expected, Fig 21b). As the increment between the forebody peaks at -2 and $+2$ degrees is approximately the same as the increment between 2 and 6 degrees yaw, it would seem likely that there is a linear variation of side-force interference with yaw and thus the datum, zero yaw, case would seem to be in error.

Thirdly, all the distributions, other than the one at zero yaw, cross over each other at $x/L = 0.41$. This again suggests that the zero-yaw case differs in some way from the others.

Fourthly, the distributions immediately aft of the $x/L = 0.41$ do not behave in a consistent way. The changes in the distributions over the afterbody at -2 degrees yaw are proportionately larger and also differ in character from those at the other yaw angles. In addition, the distributions at 0 and 2 degrees yaw are very similar whilst those at 4 and 6 degrees are similar to each other but markedly

different from the 0 and 2 degree distributions between $x/L = 0.45$ and 0.65 .

The increase in interference with increase in yaw and the farther aft position of maximum interference are a direct result of the fundamental difference between the side-force loading distributions for the body in isolation and the two-body combination. The initial variation of loading with x/L is very similar, with the slope for the two-body case being slightly greater. However, for the body in isolation, the loading reaches a peak at about $x/L = 0.16$ and then falls away to reach zero near the position of maximum diameter. In the two-body case the loading continues to rise after $x/L = 0.16$ and does not peak until x/L is about 0.21 and then reduces to become zero at about the position of maximum diameter as in the case of the isolated body. As the interference loading at a given x/L and yaw angle is defined as the difference between the loading for the two-body case and the isolated body, the interference distribution will vary slowly at first, but then will increase more rapidly as the isolated-body loading reaches its peak and then starts to fall away at about the same position as the two-body loading approaches its peak. Near the peak loading of the two-body case, the side-force loading varies only slowly with x/L whilst the loading for the isolated-body is reducing rapidly with x/L . Thus the interference loading will continue to increase until the two-body loading peak is passed and the loading starts to reduce at a greater rate than in the isolated-body case. As a result of this, the peak interference loading will occur some distance aft of the position of the peak loading of the two-body case as observed.

The other effects noticed are a direct result of there being a noticeable interference effect on the side-force loadings at zero yaw instead of the "nil-effect" that would be expected for reasons of symmetry. As the zero-yaw distributions are taken as the datum from which the changes in interference are obtained, the somewhat unusual side-force loading distribution at zero yaw will affect the changes in interference with yaw. The large positive interference over the forebody

is the direct cause of the asymmetry of the interference loadings at ± 2 degrees yaw, and the rapid changes of loading between $x/L = 0.4$ and 0.55 , lead to the other unusual features mentioned above with the exception of lack of linearity in the variation of the interference loadings over the first part of the conical afterbody.

6.4 Aerodynamic characteristics of the instrumented body.

The loading distributions along the instrumented body have been integrated to obtain the variation of C_N , C_m , C_A , C_Y , C_n and the positions of the points of action of C_N and C_Y with change of pitch and yaw, Figure 22.

6.4.1 Variation with pitch

The variation of C_N with pitch, Fig 22 a), is very different from that of the body in isolation in that C_N is positive even at -6 degrees pitch and its variation with pitch is no longer linear. The initial slope of curve is rather greater than that for the isolated body, but it decreases steadily with increase of pitch until it is the same as the isolated body at 0 degrees pitch and then decreases at an increasing rate with further increase in pitch.

The variation of C_m with pitch is shown in Fig 22 b). All the values of C_m are considerably negative as the general level is controlled by the contribution from the loadings in the region of maximum interference which alter little in magnitude or position with change in pitch because they are largely controlled by the geometry of the passage between the two bodies. As the large changes in C_m that take place in the front interference region are near the moment centre, the nose, they have a relatively small effect on C_m . This accounts for the gradual increase in value as pitch is varied from 0 to -6 degrees as the afterbody loadings vary little in this range of pitch, Fig 10. As pitch is varied between 0 and $+6$ degrees, the afterbody loadings become more negative and, because of their large moment arm, override the

contribution from the front interference region with the result that C_m becomes more positive with increase in pitch.

As a result of these non-linear characteristics of C_N and C_m , the position of the centre of normal-force varies with pitch, Fig 22 c), and is always behind the nose in contrast to that of a single body whose centre of normal-force does not vary with pitch and is positioned at $0.1875L$ in front of the nose. As pitch decreases from 6 degrees, the position of the centre of normal-force for the instrumented body varies almost linearly from $0.25L$ behind the nose at 6 degrees to $0.6L$ behind the nose at -3 degrees pitch. At more negative angles, the centre of normal-force moves back along the body at an increasing rate to reach a value of $0.8L$ behind the nose by -6 degrees pitch.

The variation of C_A with pitch for the instrumented body is shown in Fig 22 d). The variation of C_A with pitch at positive pitch is not very great, varying little from 0.05 . Below 0 degrees pitch, C_A reduces in value at an increasing rate as pitch becomes more negative to reach a value of -0.008 at -6 degrees pitch.

6.4.2 Variation with yaw.

Although a reasonable straight line can be drawn through the experimental points, Fig 22 e), for reasons explained previously, Section 6.1.2, it is likely that the variation of C_v with yaw is non-linear with the slope at zero yaw being less than that at angles greater than 3 degrees.

The value of C_v at 6 degrees of yaw is 0.168 as compared with a value of 0.106 for the body alone. This very large interference effect was somewhat unexpected as the increase in the magnitude of the forebody loading peak was only about 20%. However, it will be remembered that the interference loadings are very large over the rear part of the forebody due primarily to the aft movement of the loading peak. It is these loadings that are responsible for the large

increase in C_v rather than solely the increase in magnitude of the peak loading.

As in the case of the single-body results, C_n is positive at all positive yaw angles because the contribution from the large positive forebody loadings is less than that from the significantly smaller negative afterbody loadings because of the larger moment arm of the latter, Fig 22 f). However, whilst C_n increases with yaw initially, the rate of increase reduces as yaw increases and becomes negative above 4 degrees yaw.

Because of these characteristics, the point of action of the lateral-force is always in front of the nose. Its position is farthest in front of the nose at zero yaw and moves steadily towards the nose with increase in yaw, Fig 22 g).

The variation of C_A with yaw is shown in Fig 22 d). C_A is a maximum at zero yaw and falls off rapidly with increase in yaw at a rate very similar to the reduction of C_A with pitch at negative pitch angles. The measured value of C_A at -2 degrees yaw indicates that the variation with yaw is symmetrical about zero yaw as would be expected, and not asymmetrical as is its variation with pitch.

There are also some effects of yaw on the components in the pitch plane.

Although C_m increases by 25% between 0 and 6 degrees yaw, Fig 22 a), the actual shape of the variation is difficult to determine as the experimental points exhibit a large amount of apparent scatter. It is difficult to decide whether the variation of C_m with yaw takes the form of a step variation in which C_m is approximately constant between 0 and 2 degrees yaw, followed by a step change somewhere between 2 and 4 degrees yaw, after which it gradually increases with yaw, or whether C_m increases steadily with yaw throughout. As it has already been surmised that the variation of C_v

with yaw could be non-linear, with a change in slope occurring at about 2 degrees yaw, the step-change interpretation of the variation of C_N with yaw may well be correct.

The variation of C_m with yaw, Fig 22 b), shows similar characteristics. In spite of these uncertainties in the variation of C_N and C_m with yaw, the position of the point of action of C_N does not alter with variation in pitch and there is very little scatter in the experimental values. This indicates that the point of action of any sudden additional loading caused by flow changes must be very close to the point of action of C_N , i.e. very close to $0.44L$ behind the nose. This is not only very close to the position at which the conical afterbody begins but is also the position of the discontinuity in the side-force loading distributions as previously noted, Fig 12. In addition it is just to the rear of the main normal-force loading peak. If a small change in the width of the peak on its rearward side was to be caused by flow changes in the interference region, then the additional loading could be large and centred at about the required position.

7.0 THEORETICAL ESTIMATES.

The inviscid Surface Panel And Ring Source (SPARV) panel method originated by Petrie, ref 5, was used to estimate the pressure distribution over the bodies and hence to obtain the local loading distributions.

In the first of the present series of tests, ref 2, a panel definition had been chosen so that the same panelling definition could be used throughout the research programme (which included a 3-body configuration), whilst keeping within the maximum number of panels permissible. Each body was represented by 41 longitudinal stations, (40 panels), and 15 circumferential stations, (14 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 body until $x/L = 1.35$; aft of this the closure was cylindrical in order to represent the sting support. Fifteen circumferential points, (14 panels) were also used to define the half-body throughout the base closure. The conical part was defined by 3 longitudinal stations, (3 panels) with a further 2 stations, (2 panels) to define the sting.

While this panel configuration proved to be satisfactory in general, the tests of ref 2 showed that the flow on the centreline of the body was very complicated in the region of maximum interference, and was concluded that it would be an advantage if the pressure distribution could be more closely defined both experimentally and theoretically.

It was possible to provide increased definition in the experimental tests by reducing the increment in the rotation of the model from 18 degrees to 9 degrees.

A better representation of the theoretical pressure distribution would be obtained if a longitudinal line of panel control points could be located along the centreline surface between the two

bodies together with a more dense circumferential panel distribution. To do this simply would involve an appreciable increase in the number of panels with the result that both bodies could not be panelled identically whilst keeping within the programme limitations. A compromise solution was adopted in which the number of longitudinal panels (40 + 5) remained unaltered, but the number of circumferential panels was increased to 19 for the complete body. This ensured that one line of control points was on the vertical centreline of each body. If the pressure distributions for the pair of bodies was calculated at both positive and negative pitch, then the pressures could be interwoven to give a pressure distribution of approximately the same density as the experimental results. For the yaw cases, the pressures could be interwoven similarly if the pressure distributions were calculated for both bodies instead of reducing the computing demand by making use of the plane of symmetry.

The circumferential panel distribution was more dense than previously and so the basic pressure distribution was more than adequate to determine the local loadings.

7.1 Estimated loading distributions for the body in isolation

The estimated normal-force and axial-force loading distributions for pitch angles of 0, 2, 4, and 6 degrees are shown in Figs 23 & 24 together with the experimental distributions.

The normal-force results show that at 0 degrees pitch, Fig 23 a), the theoretical loadings are zero, but the experimental results show that there is a small positive loading peak over the front part of the forebody, but only very small loadings over the rest of the body. As the first three points show very small loadings with no consistent variation, it is possible that the small loading peak is a result of the experimental inaccuracies previously mentioned which occurred between $x/L = 0.07$ to 0.26 , the region occupied by the peak.

At the other pitch angles, Figs 23 b) - d), the theory underestimates consistently the forebody loading peak with the agreement being worst at 2 degrees pitch where the disagreement is present over the whole of the forebody. At the other pitch angles, the disagreement is confined to the neighbourhood of the peak and the theoretical and experimental loadings agree well over the rest of the forebody.

Conversely, the theoretical and experimental afterbody loadings agree well at zero pitch, but the agreement gets worse with increase in pitch. The maximum negative loading occurs near the beginning of the conical afterbody, ($x/L = 0.455$), and then the loadings gradually becomes more positive with increase in x/L . The theory predicts the minimum loading well, but the estimated afterbody loadings are more positive, with the difference becoming greater with increase in pitch.

The axial-force loadings are shown in Figs 24 a) - d). In general, the agreement between the theoretical and experimental loadings is excellent aft of $x/L = 0.26$, but the agreement forward of this value is poor. The known inaccuracies in the pressure measurements occur between stations 4 and 14, ($x/L = 0.075$ & 0.2625), with the maximum errors occurring near station 4 and appreciable errors occurring near station 9. The sign of the error is consistent and is such that it will increase the axial-force loading. If we re-examine the axial-force loadings bearing this in mind, it would appear possible that the theoretical estimates only slightly over-predict the magnitude of the first peak in the distributions and the agreement between the theoretical predictions and the experimental results is probably good.

7.2 Estimated loading distributions on the two-body combination as pitch is varied

The normal-force and axial-force loading distributions have been obtained for both bodies for pitch angles of 0, 2, 4 and 6

degrees. The theoretical distributions are presented in Figs 25 and 26 together with the corresponding experimental results.

For the cases where the body combination was yawed, the normal-force loading distributions were obtained as well as the side-force and axial-force distributions in order to investigate whether the large normal-force interference loading was affected by yaw. The theoretical loading distributions were obtained for yaw angles of 0, 2, 4, and 6 degrees, and are compared with the experimental loadings in Figs 27 - 29.

7.2.1 Normal-force loading distributions

The presentation of the normal-force loading distributions, Fig 25, is rather different to that used previously, Fig 10. The loading distributions are presented in pairs at each pitch angle, with the upper graph representing the loading distribution over the top, (dummy), body, and the lower graph representing the distribution over the bottom, (instrumented), body. This presentation has the advantage that the differences in the loading distributions between the top and bottom bodies can be compared directly at the different pitch angles. As the pressures had been measured solely on the bottom body, the sign of the measured loadings had to be reversed when used to represent the loadings on the top body.

The shape of the loading distribution at 0 degrees pitch has been described in detail previously. To recapitulate briefly, the loadings over the front half of the forebodies are such as to separate them. The loadings then reverse in sign so as to attract the bodies towards each other with the peak loading occurring at the maximum diameter of the bodies where the gap between the bodies is a minimum. Aft of this position, the loading decreases rapidly and reverses in sign at a short distance down the conical afterbody and then becomes small and almost constant over the rest of the afterbody.

The ratio of the loading peaks is approximately 4:-12:1 starting from the nose of the body.

There is close agreement between the theoretical and experimental distributions at this angle except that, experimentally, the first loading peak is greater in magnitude and occurs slightly farther aft.

Significant changes have taken place in the theoretical loading distributions by 2 degrees pitch.

On the top body, the first loading peak has increased in magnitude and has become more symmetrical in shape. The second peak is unaltered in magnitude and shape, but the general level of the afterbody loadings has diminished.

On the bottom body, the magnitude of the first loading peak is smaller and the initial slope of the distribution has become zero. The second loading peak is also unaltered in size and shape, but the magnitude of the afterbody loadings has increased.

The comparison between experiment and theory is now slightly worse.

On the top body, the agreement between experiment and theory in the magnitude and position of the first loading peak is the same as at 0 degrees pitch, as is the afterbody loading. However, the magnitude of the second loading peak is now greater experimentally.

Experiment and theory agree well as to the magnitude and position of the first peak in the loading distribution on the bottom body, but the agreement in the shape of the distribution is worse near the nose. The magnitude of the second peak is greater experimentally. However, although the agreement between experiment and theory is still good as far as the magnitude of the maximum loading over the rear of

the afterbody is concerned, the experimental loadings decrease in magnitude towards the base instead of remaining constant as predicted theoretically.

At 4 degrees pitch, SPARV predicts that the first peak in the loading distribution along the top body continues to increase in magnitude, Fig 25 c), the second loading peak remains unaltered, but the afterbody loading barely becomes positive before falling slowly and becoming negative aft of $x/L = 0.8$. The initial shape of the loading distribution along the bottom body has now altered so that the initial slope is positive. The slope soon reverses in sign and the loading distribution forms a small negative peak in the same position as the original negative peak. The second peak in the distribution is still unaltered, but the afterbody loadings have become more negative.

The agreement between experimental and theoretical loading distributions over the top body has improved in the region of the first and second peaks in the distribution as compared with the results at 2 degrees pitch while the afterbody loadings still agree well. The agreement between the distributions over the bottom body to the rear of the new positive peak near the nose is not close as the experimental distribution forms a larger peak slightly to the rear of the SPARV prediction. However the agreement is excellent from the position of the negative peak to the beginning of the constant loading over the afterbody. Here the experimental results begin to diverge slightly from the prediction, with the slope of the distribution becoming more positive.

The SPARV prediction of the loading distributions at 6 degrees pitch continues the previous trend. On the top body, the first peak has become more positive, the second peak remains the same, but the afterbody loadings are now completely negative. The magnitude of the new positive loading peak on the bottom body has increased. The minimum in the distribution corresponding to the original negative peak now occurs at a positive loading so that the loadings are now positive over

the first half of the body. The loadings over the remainder of the afterbody are now more negative with the peak loading still occurring at the same position.

The agreement between the experimental and predicted loading distributions along the top body is about the same as at 4 degrees pitch, but the slope of the experimental loading distribution over the rear of the afterbody is more positive. In the case of the bottom body, there are now greater differences in the magnitude and position of the new peak in the forebody distribution, but the agreement over the main loading peak is still very good. This good agreement continues until $x/L = 0.6$. Aft of this point, the experimental results gradually diverge from the theoretical prediction at a greater rate than previously.

7.2.2 Axial-force loading distributions

The SPARV estimates of the axial-force loading distributions for the two-body configuration for pitch angle of -6, -4, -2, 0, 2, 4 and 6 degrees are shown in Fig 26. Although the general shape of the distributions are similar to those calculated for the single body, Fig 24, there are several differences between the two cases. Firstly, if the distributions over the instrumented body of the two-body combination are compared with those over the single body, then it is seen that, at all positive pitch angles, the magnitude of the peaks in the distributions over the instrumented body of the two-body combination are greater in magnitude and occur slightly farther aft along the body. Secondly, if the distributions over the two-body combination at positive and negative pitch are compared, then the distributions are the same at +2 and -2 degrees. At -4 degrees pitch the first peak in the distribution is smaller and occurs at the same position as the +4 degree case. The second peak is larger in magnitude and occurs farther forward than at + 4 degrees whilst the loadings over the afterbody do not differ. The distributions at +6 and -6 degrees pitch differ in a similar way to those at +/- 4 degrees.

As in the case of the single body, the experimental and theoretical distributions aft of the second peak are almost identical at all pitch angles. Forward of this peak, the experimental loadings are consistently the more positive and the first peak is considerably greater in magnitude. Because of the increased experimental error between $x/L = 0.07$ and 0.26 , the true differences in loading will be rather less in this region.

7.3 Estimated loading distribution for the two-body combination when yaw is varied.

The estimated side-force, axial-force and normal-force loading distributions at zero pitch for yaw angles of 0 , 2 , 4 and 6 degrees yaw are presented in Figs 27 - 29 together with the corresponding experimental results.

7.3.1 Variation of side-force loading with yaw

The variation of the side-force loading distributions with yaw is shown in Fig 27.

At zero yaw, the calculated loadings are zero but, experimentally, there is a small positive loading between $x/L = 0.2$ and 0.4 and small negative loading over the afterbody aft of $x/L = 0.45$, indicating that the body is not perfectly aligned with the oncoming flow.

The agreement between the calculated and experimental forebody loadings improves as yaw increases until the loadings agree exactly at 6 degrees yaw.

The comparison between the calculated and experimental afterbody loadings is not as good. At 2 degrees yaw, the side-force loading distributions begin to diverge aft of $x/L = 0.41$ with the experimental loadings becoming more positive and tending to zero at

the base of the body. As the angle of yaw increases so the divergence becomes greater. The negative peak in the experimental loading distribution occurs at about $x/L = 0.41$ at all yaw angles, but the SPARV calculations predict that the peak loading moves farther aft as yaw increases. The combination of these two effects results in the considerable differences in the afterbody loadings that are present at 6 degrees yaw.

7.3.2 Variation of axial-force loading with yaw

The theoretical and experimental axial-force loadings are shown in Fig 28.

The agreement between the experimental and calculated distributions aft of $x/L = 0.3$ is good at all angles of yaw.

At 6 degrees yaw this close agreement is also present over most of the forebody except for a small region near $x/L = 0.075$ where the experimental loadings are considerably greater.

At all other yaw angles, the experimental loadings at the first two stations, $x/L < 0.04$, agree reasonably with the theoretical estimates but aft of this, the experimental loadings are considerably greater. The maximum difference occurs at $x/L = 0.075$ and then gradually diminishes with increase in x/L until the difference becomes very small at about $x/L = 0.25$. These differences are probably the result of the experimental errors known to occur in this region as previously noted. However, as the loadings at the third station, $x/L = 0.0375$, were not expected to be in error, it is likely that the first axial-force loading peak was rather greater than predicted.

7.3.3 Variation of normal-force loading with yaw

The variation of the theoretical and experimental normal-force loading distributions with yaw are presented in Fig 29.

It is seen that the agreement between theory and experiment is very good at all yaw angles, and is closest at 4 degrees.

In the experimental results, as yaw decreases below 4 degrees, the first loading peak becomes progressively more negative than predicted and occurs farther aft. As the magnitude and position of the main interference peak is well predicted, this results in the experimental forebody loadings being slightly less than predicted at $0.15 < x/L < 0.3$. In addition, the experimental afterbody loadings gradually become more positive than predicted as yaw decreases below 4 degrees.

At 6 degrees yaw, the experimental forebody loadings are closely predicted, but the afterbody loadings become increasingly more negative than predicted for $x/L > 0.45$.

7.4 Variation of C_N and C_A with pitch and yaw.

The SPARV normal-force and axial-force loadings have been numerically integrated to obtain C_N and C_A for both the single body and the instrumented body of the two-body combination. The results are included in Figs 9 and 22 to enable direct comparisons to be made with the experimental results.

7.4.1 Single body

The predicted variation of C_N with pitch for the single body is linear with a slope of only 58% of the experimental value, Fig 9 a). Looking at the comparable loading distributions, Fig 23, it can be seen that there are two regions of disagreement. These are:-

- a) the experimental loadings have a larger positive forebody loading peak
- b) although the peak negative afterbody loadings agree well, the magnitude of the experimental loadings reduce much more rapidly towards the base of the body.

Thus both of these differences will result in an increase in the experimental value of C_N . At 0 and 2 degrees pitch, the larger forebody loading peak is the main reason for the increase in C_N as the predicted and experimental afterbody loading distributions are very similar. However the differences in the afterbody loading distributions at the higher pitch are sufficiently large to account for the major part of the difference in C_N .

The predicted values of C_A are considerably less than the experimental values. This is because the experimental axial-force loadings between $x/L = 0.07$ and 0.26 are liable to have large positive errors as previously mentioned and as these loadings determine the large positive peak in the loading distribution, it would be expected that the experimental values of C_A would be more positive than the true values and the scatter could be considerable.

7.4.2 The instrumented (bottom) body of the two-body combination

Both the predicted and experimental variation of C_N with pitch is smooth, Fig 22 a), except for the experimental value at zero pitch which seems to be slightly off the smooth curve through the remainder of the data. Although the shape of the variation is similar, the variation of the experimental results with pitch is much greater. The experimental value of C_N is 0.019 less than predicted at -6 degrees pitch, approximately the same at -2 degrees and then the difference increases steadily with increase in pitch until the experimental value is 0.06 greater than predicted at $+6$ degrees pitch.

The predicted values of C_A vary linearly with pitch from -0.025 at -6 degrees to 0.035 at $+6$ degrees thus giving a value of 0.008 at zero pitch. The variation of C_A with yaw is completely different. C_A has a maximum value of 0.008 at zero yaw and decreases, slowly at first, to a value of 0.004 at 6 degrees yaw. Although the variation is only shown for positive yaw, the variation will be

symmetrical about zero yaw for reasons of geometry. The predicted C_A values are considerably less than experiment as was expected. However the shape of the experimental variation was different. The variation with pitch is now appreciably non-linear. Although there appears to be appreciable scatter at 2 and 4 degrees pitch, a smooth curve can be drawn through the remainder of the data. Whilst much of the difference in magnitude between the predicted and experimental data can be attributed to experimental error, it is unlikely that this will account for the nonlinearity of the variation. In the same way, it is likely that the experimental variation with yaw is considerably greater than predicted.

The predicted variation of C_v with yaw is linear and is very much less than experiment. Not only is the experimental variation much greater but it appears to be nonlinear. The data at 2 degrees and above varies very linearly with yaw while the variation of the data between + and - 2 degrees yaw can be approximated by another straight line of much smaller slope. However, even this reduced slope is nearly double that predicted.

8.0 BODY PRESSURE DISTRIBUTIONS

It had been found in ref 2 that the C_p distributions over the instrumented body could be visualised effectively by using the GINO plotting package to plot the C_p contours over the surface of the body and also to produce an isometric representation of the C_p distribution over the body.

In order to produce the diagrams, it was necessary for the C_p data to be presented as heights at defined points over a rectangular area. The x-axis was taken as the body axis, the y-axis as the angle of the line of pressure tappings from the datum position and the z-axis as the C_p value. Because the restrictions in the choice of axes, the rectangular format of the graphs is a distorted representation of the surface of the body and so this presentation is mainly useful in visualisation of the general features of the pressure distribution.

As the main interest is in the neighbourhood of the region of maximum interference, i.e. the position of minimum gap between the bodies, the bottom centreline on the bottom body and the top centreline on the top body were chosen to be the datum, 0 degree, generator for the respective diagrams so that the region of maximum interference was in the centre of the diagrams.

For the "single-body" case the datum position of the body generator was chosen to be the top centreline of the body, i.e the same datum as the top body, so that the changes in distribution near the bottom centreline would be most prominent.

Some problems were encountered with the experimental results owing to the experimental inaccuracies present at $0.075 > x/L > 0.26$. Basically the problems were :-

a) the position of the points did not have to be on a regular grid. However, if they were not (as in our case), the program interpolated the data to produce a regular rectangular grid before producing the

diagrams. In some cases, this interpolation tended to exaggerate any inaccuracies in the data.

b) the errors could be greater than the contour intervals necessary to visualise the pressure distribution adequately. When this occurred, the contours tended to degenerate into "islands" or "ridges" over the affected region.

The best way of dealing with this problem was found to be to remove all the data at the affected stations and use the interpolation routines to reconstruct the data. However, in several cases the resultant change in density of distribution of the grid caused additional problems which also gave faulty contour diagrams. It was found possible to produce sufficient acceptable diagrams so that the pressure distributions at the datum position and the extremes of pitch and yaw could be compared with the predicted distributions.

Because of this, the predicted pressure distributions will be examined first.

8.1 Predicted C_p distributions

8.1.1 Single-body - variation with pitch

The pressure contours and the isometric representation of the pressure distribution over the surface of the body are presented in Fig 30 a) - d).

At zero pitch, Fig 30 a), the circumferential pressure distribution is uniform at all stations. C_p falls steadily from the nose of the body and reaches a minimum value at the position of maximum diameter. There is then a rapid recovery in C_p over the ogival part of the afterbody followed by a slight rise in pressure over the remainder of the (conical) afterbody.

As pitch increases, the pressure distributions change gradually with the main changes taking place in the circumferential distribution.

Along the forebody, the pressures at any station increase over the bottom of the body and reduce over the top of the body. This is represented by the pronounced ridge that can be seen on the diagrams. This ridge is most marked at the nose of the body and gradually fades out until the circumferential pressure distribution becomes almost uniform over the ogival part of the afterbody.

Along the conical afterbody, the pressure along the bottom centre-line becomes rather less than that along the top centre-line, but with the minimum pressure occurring near the horizontal centre-line. As pitch increases, these "hollows" in the pressure distribution become more pronounced. As the longitudinal pressure gradients over the afterbody are small, the general features of the pressure distribution likewise alter little along the afterbody but the "hollows" are more pronounced at the front of the conical afterbody due to the changes taking place in the transition region where the circumferential pressure distribution changes from the forebody, "ridge" type, distribution to the "twin-hollow", type of distribution which varies little over the length of the conical afterbody.

In the transition region, considerable changes take place in the character of the pressure distributions as pitch increases. At 2 degrees pitch, Fig 30 b), there is still a region of uniform circumferential pressure separating the two regimes. By 4 degrees pitch, Fig 30 c), this region of uniform circumferential pressure is being affected by two additional "hollows" are beginning to form in the pressure distributions over the top half of the body just forward of the position of maximum diameter and thus leading to the "dual-valley" type of pressure distribution present over the afterbody. At 6 degrees pitch, Fig 30 d), the general features of the pressure distribution are very

similar to those at 4 degrees, but are more pronounced especially the "hollows" in the pressure distribution at the rear of the forebody.

8.1.2 Two-body combination - variation with pitch at zero yaw

The pressure contours and the isometric representation of the pressure distribution over the surface of both bodies at pitch angles of 0, 2, 4 and 6 degrees pitch are shown in Fig 31 a) - d).

At zero pitch, Fig 31 a), the mutual interference between the two bodies can be seen at the most forward station along the body as a slight rise in C_p over the half of the body facing the other body. It is this increase in pressure that results in the local loading that tends 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 around the body. As a result there is a marked "ridge" in the pressure surface which is clearly visible in both the isometric and contour plots and reaches a peak height above the pressures present outside the interference region at about $x/L = 0.2$.

The other main feature in the pressure representations is the marked reduction in C_p that occurs in the region near the position where the two bodies are closest together, $x/L = 0.394$. Here the C_p values become extremely negative resulting in a marked "hollow" in the pressure surface which is clearly visible in both the contour and isometric representations of the pressure surface. Here, at the position of maximum interference, the interference region extends over most of the circumference of the body. Between $x/L = 0.2$ and 0.4 the circumferential distribution is transitional between the "central ridge" type present over the front of the forebody and the "hollow" type present where the passage width is a minimum. The distribution in this transition region is quite complicated as the "ridge" gradually becomes less pronounced with increase of distance from the nose while the "hollow" starts to

form outside the "ridge" with its outer extreme gradually extending around the body and the inner part extending towards the centreline and absorbing the "ridge". This transition stage is completed slightly in front of the position of minimum gap between the bodies.

The pressure surface near the position of minimum C_p is asymmetrical along the length of the body. The pressure gradient aft of the position of minimum pressure are much greater than that in front of it, with the circumferential gradients being intermediate in value. The pressure gradients along the conical afterbody, $x/L > 0.45$, are small, but a small "ridge" develops rapidly at the beginning of the afterbody which gradually diffuses into an almost uniform circumferential distribution by the base of the body.

The effects of increasing pitch are shown in Figs 31 b) - d).

It is seen that, for both bodies, the position and magnitude of the minimum pressure in the "hollow" alters very little with change in pitch, as does the shape of the "hollow" near the region of maximum interference. Away from this region considerable changes take place in the pressure distributions over the bodies. This is because the interference between the two bodies is superimposed on the pressure distribution over the bottom surface of the lifting body in the case of the top body and the upper surface in the case of the bottom body. The interference effects on the two bodies will therefore be considered separately.

Considering the top body first, although the forebody pressure "ridge" becomes more prominent with increase in pitch, it blends into the "hollow" in the same place on the 180 degree (bottom centre-line) generator, and the circumferential extent of the "ridge" remains constant. Major changes occur in the extent of the transitional flow region on the forebody. As pitch is increased, this region extends

circumferentially and towards the nose thus affecting more of the upper surface of the body. The variation of the pressure distribution over the afterbody with pitch is small, particularly between 0 and 4 degrees pitch. Between 4 and 6 degrees pitch, more noticeable changes take place. Although little change takes place along the 180 degree generator, small "valleys" appear in the afterbody pressure distributions centred on the horizontal centre-line of the body and thus affect an increasing amount of the surface of the afterbody. These "valleys" begin to form at about $x/L = 0.5$, i.e. slightly aft of the beginning of the conical afterbody.

The pressure surface over the bottom body varies in rather a different way with change in pitch because the interference region is on the top surface of the body. Because of this, the pressure on the 180 degree generator near the front of the body reduces appreciably with increase in pitch and that at the 0/360 degree generators increase with increase in pitch. As the magnitude of these changes with pitch is considerably greater than those due to the interference effect at zero pitch, the extent of the forebody "ridge" diminishes with increase in pitch, Figs 31 b) - d). Although the general shape of the afterbody pressure surface is similar to that of the top body, the magnitude of the "ridge" feature is greater on the bottom body.

8.1.3 Two-body combination - variation with yaw at zero pitch

The effect of yaw on the pressure distributions over the bottom body is shown in Figure 32 a) - d).

The changes in the pressure surfaces as shown by the contour and isometric plots are much greater and more complicated than when pitch is varied.

At zero yaw, Fig 32 a), the pressure surface has been described in detail previously, but can be loosely described as

consisting of a "ridge" feature over the forebody blending smoothly into a deep "hollow" of approximately circular planform located at the position of minimum passage width between the bodies. The pressure surface over the afterbody from the rear of the "hollow" is mainly flat, but a small central "ridge" can be detected immediately to the rear of the "hollow". These features are all symmetrical about the top centre-line of the body.

When the body is yawed by 2 degrees, Fig 32 b), the centre of the "hollow" feature is still on the centre-line plane of the body but the bottom of the "hollow" has become somewhat deeper and slightly oval in shape with its major axis inclined to the centre line plane of the body in the opposite sense to the oncoming flow. The "ridge" features have become more pronounced and their centre-lines are also inclined to the centre-plane of the bodies so that the position of the "ridge" peak rotates around the body, the amount varying with the distance from the centre of the "hollow". The forebody "ridge" is on the windward side of the body and the afterbody "ridge" on the leeward side.

At 4 degrees yaw, the forebody "ridge" has become more prominent and its inclination to the centre-line has increased. The "hollow" has deepened, become appreciably more oval, is inclined to the body centre-line at approximately the same angle as at 2 degrees yaw and its major axis is still inclined in the opposite direction to the "ridge". The afterbody pressure surface has altered completely. The single "ridge" surface has become a "two-ridge" surface with a marked "valley" between the "ridges". One "ridge" is an extension of the forebody "ridge" as previously described, but there is now a companion "ridge" running parallel to it and separated from it by a well-defined valley which is an extension of the "hollow" but is inclined to the body axis at a smaller angle than the "hollow" but still in the opposite direction to the "ridges".

At 6 degrees yaw, the inclination of the forebody "ridge" has increased slightly and the "ridge" is slightly more

prominent. The pressure distribution near the position of maximum interference has the same general features as previously, but rather more pronounced. The pressure at the base of the "hollow" is slightly more negative and the area of the base is much greater, but the inclination of the major axis has not changed. The "valley" coming away from the rear of the "hollow" likewise has not altered in inclination or width, but its "walls" have become much steeper. The pressure surface over the afterbody has altered further in that the inclination of the afterbody "ridges" is now considerably less than the forebody "ridge" and neither "ridge" is an extension of the forebody "ridge". In addition, the "ridges" have become more noticeable, especially that on the lee side of the afterbody.

8.2 Experimental pressure distributions

The experimental pressure distributions over the bottom body are shown in Fig 33 for a), the datum attitude and b), 6 degrees yaw. The pressure distributions over the top and bottom bodies are shown in Fig 34 for an attitude of 6 degrees pitch.

Comparing the contour and isometric representations of the measured and estimated pressure distributions over the instrumented body at zero pitch and yaw, Figs 32 a) and 33 a), the general features are very similar after ignoring the effects of the instrumentation errors on the forebody "ridge". The only major difference between the two cases is the pronounced "valley" that is present in the experimental results along the centre-line of the pressure recovery surface at the rear of the "hollow". This "valley" is confined to the steep pressure recovery surface and does not extend past $x/L = 0.5$, i.e aft of the beginning of the conical afterbody. This difference had been observed previously in the tests investigating the effect of staggering the bodies, ref 2. In that case the number of circumferential panels used to represent the body was only 14 and their distribution was such that the pressures were not calculated in the plane of the centrelines of the bodies although the pressures were measured in that plane. As 39

circumferential pressures were calculated at each station in this investigation including the pressures on the centre-line, the lack of the "valley" in the calculated distributions cannot be due to lack of data on the centre-line of the body. It is probable that the "valley" is due to viscous effects triggered by abrupt changes in the flow direction when the air that has flowed semi-circumferentially towards the centreline from both sides of the body, "collides" with the air coming from the other side and is forced to flow towards the base of the body along the plane of symmetry. It seems unusual that this local region of very rapid pressure recovery at the beginning of the conical afterbody does not effect the flow over the rest of the afterbody as the discontinuity in curvature at the beginning of the conical afterbody might be expected to magnify any flow peculiarities.

When the body combination is at 6 degrees yaw, the calculated and measured pressure distributions over the bottom body are again very similar and even include similar representations of the "valley" in the pressure recovery surface at the rear of the "hollow" that is now present in the contour representation of both the experimental and predicted pressure distributions, Figs 32 d) and 33 b). However, there are two differences in the pressure distributions in the experimental results that are not predicted. Firstly, there is a small additional "valley" in the afterbody distribution on the opposite side of the centre-line from the above mentioned "valley" and, secondly, the circumferential variation in the afterbody pressure differences is rather less than predicted and becomes almost negligible at the base of the body.

The additional "valley" comes from the lee side of the "hollow" but it does not become really prominent until the beginning of the conical afterbody. As the "valley" coming from the rear of the "hollow" is predicted by the inviscid calculations whilst the additional "valley" is not, it is likely that the additional "valley" comes from viscous interactions in the region near the maximum width of the "hollow" where the pressure gradients in a streamwise direction are now

much greater due to the increased size of the base of the "hollow" and the inclination of its axis.

The increasing uniformity in the circumferential pressure distribution over the afterbody as the base is approached explains the reason for the large differences between the experimental and predicted loadings that have been noted previously. As the uniformity in the circumferential distribution has been achieved by reducing the pressures on the lee side of the afterbody, it is likely that the additional "valley" which discharges into this region, is responsible for this major change in the afterbody pressure distribution.

The experimental pressure distributions over both bodies at a pitch of 6 degrees are shown in Fig 34. The general features of the pressure distributions, Figs 31 d) and 34, agree quite well with prediction. However there are several differences, which are :-

a) On both bodies, the "hollow" of the region of maximum interference is slightly farther aft than predicted although the minimum pressure is as predicted.

b) The "valley" in the pressure-recovery surface at the rear of the "hollow" is still present in the experimental pressure distributions on both bodies although not predicted. Although there is some slight indication, on the top body, of the "valley" extending aft of the steep part of the pressure-recovery surface to the "hollow", $x/L = 0.5$, this does not occur on the bottom body.

c) The circumferential variation of pressure over the afterbody is much more uniform than predicted. In the case of the top body this is because the pressures near the top of the body are smaller than predicted. On the other hand, the central "ridge" on the top of the bottom body is much flatter than predicted. As the "valley" in the pressure-recovery is directly upstream of the ridge, it is possible that it contributes in some way to the flattening of the ridge although there is no indication on the contour plots of the "valley" extending aft of $x/L = 0.5$.

9.0 FLOW VISUALISATION

A short time was available, after the experimental data had been acquired, to do some flow visualisation tests using the oil-flow technique. Flow visualisation tests were made on the two-body combination at the following attitudes:-

- 0 degrees pitch, 0 degrees yaw
- 0 degrees pitch, 6 degrees yaw
- 6 degrees pitch, 0 degrees yaw

For all the tests, the oilflow patterns were only obtained over the top (dummy) model, so as to avoid the possibility of the oilflow mixture interfering with the pressure holes and instrumentation on the bottom (instrumented) body. For the tests at zero pitch, the flow patterns are directly applicable to both bodies. At 6 degrees pitch, oilflow patterns should have been obtained at both +6 and -6 degrees pitch to get the flow patterns over both bodies. Unfortunately time was only available to obtain the flow pattern at -6 degrees pitch.

In order to record the flow patterns, the model was photographed in the test attitude from the same position on the port side to show the side, top and bottom views as required. This was done by rolling the model clockwise (from the rear) in 90 degree increments. Unfortunately the pattern definition was not good enough for direct reproduction. A selection of the streamlines on the photographs were enhanced and the resultant patterns traced and reproduced in Fig 35 - 37 to show the main features of the flow over the bodies.

9.1 Flow pattern at 0 degrees pitch, 0 degrees yaw

The side view of the oilflow patterns, Fig 35, show that there is an outflow near the nose of the body followed by a pronounced inflow into the region of maximum interference, i.e. the "hollow" in the contour and isometric diagrams, Figs 31 a) and 34, with

the streamlines being at a large angle to the body axis near the position of maximum diameter. Most of the flow going into the interference region appears to come from the lower half of the forebody. The flow from the top part of the forebody is also deflected towards the position of minimum passage width but does not actually reach it as the streamlines bend back to flow in an axial direction aft of the position of maximum diameter with many flowing along the bottom part of the body.

When the body was rotated through 90 degrees to show a plan view of the region of maximum interference, much of the flow can be seen converging on a region on the centre-line of the body near the position of maximum diameter. In this region the flow velocities were so high that all the oil had been removed from a small oval region on the axis, corresponding to the "hollow" in the contour diagrams. The flow out of the "hollow" seemed to be confined to a narrow, constant width band centred on the bottom centreline which was separated from the flow converging on it from outside the "hollow" by a rather wider flowline.

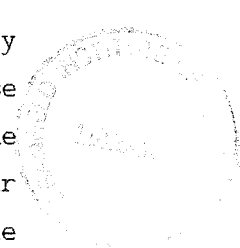
Looking at the isometric diagram of the pressure distribution over the afterbody, it can be seen that, at the stations at the beginning of the afterbody, the pressures at the 180 degree generator are rather higher than those on either side of it. Continuing around the circumference the pressures reach a minimum at about the 135/225 degree generators before rising as the 0/360 degree generator is approached. As the flow streamlines will tend to flow along "valleys" of low pressure, it is interesting to see that the "valley" coincides with the position where the flow from the top of the body that does not enter the "hollow", turns to flow down the body along the direction of the "valley". With increase in distance down the afterbody, the circumferential pressure distributions become flatter until the distribution is almost completely uniform at the base of the body.

9.2 Flow pattern at 0 degrees pitch, 6 degrees yaw

In the diagram of the oilflow patterns at 0 degrees roll, Fig 36, we are looking at the windward side of the model. The oil did not flow very well in the nose region, so the outflow is not very obvious but streamlines are deflected to the bottom of the model nearer to the nose than in the datum attitude diagrams and the S-bend in the streamlines near the position of maximum diameter is less pronounced.

The planview of the region of maximum interference, 90 degrees rotation, shows the flow from both sides of the body going into the region of lowest pressure, the "hollow" in the contour diagrams, and shows that the axis of the hollow is inclined to the axis of the body in the opposite sense to the oncoming flow as shown in the contour diagrams, Figs 32 and 33 and shows the dividing streamline between the flows coming downwards over the two sides of the body is inclined in a similar direction.

In looking at the oilflow pattern for the lee side of the body, it must be remembered that the body has been rotated through 180 degrees so that the region of maximum interference, which actually is at the bottom of the body, is now shown at the top of the body. The flow pattern is very different to that on the windward side. The flowlines over most of the ogive section come over the top of the body at a very large angle to the axis of the body. Those from near the nose disappear into the interference "hollow", but those from the rest of the ogive behave in a rather different manner. The lines start in a similar manner to those nearer the nose, but at an even greater angle to the axis of the body. Soon after reaching the horizontal centreline of the body, the flow lines change direction abruptly, continue in an axial direction for some way and then sweep to the bottom of the body. The flow lines that appear at the top of the conical afterbody behave in yet another way. They go diagonally across the body from top to bottom at a fairly acute angle with a brief transition region between the two types of flow located on the ogival part of the afterbody.



As the difference between the oilflow patterns over the windward and leeward sides of the body were so marked, the corresponding isometric and contour diagrams, Figs 32 and 33, were examined to see if the pressure distributions could help in the interpretation of the oilflow patterns and the pressure distributions. Whilst the main feature in both the pressure distribution over the body and the oilflow pattern is still the low pressure "hollow", there are significant differences in the pressure distribution compared with the unyawed condition. These are:-

a) the forebody pressure "ridge" has shifted around the body near the nose to be centred near the 90 degree generator and leads to the interference "hollow" which is still on the 180 degree generator. The centre of the "hollow" is unaltered in position because this is controlled by geometric considerations and is at the position of minimum passage width where the velocity is a maximum and the pressure a minimum.

b) the afterbody pressure distribution has altered completely in character from that at zero yaw. Instead of a central "ridge" with a slight "valley" on either side which gradually fade into an uniform distribution by the base of the body, the pressure distribution is now in the form of a central "valley" with a "ridge" on either side.

Because of the offset "ridge" feature near the nose, there is a pronounced circumferential pressure gradient from the peak of the "ridge", near the 90 degree generator, to the minimum pressure in the "valley" which is near the 270 degree generator. As the pressure gradient over the top of the body is much greater than that round the bottom, the oilflow lines going over the top of the body to the leeward side are much more circumferentially inclined than those going round the bottom of the body.

The two "ridges" in the afterbody pressure distribution run along body generators but are not symmetrical. The one on the lee side of the body starts nearer the nose of the body, is wider circumferentially and the pressures are larger than that on the windward

side. The effect of this would be to make the oilflow lines coming over the top of the body on the lee side to become increasingly circumferential as the position of maximum diameter is approached as the flow is channelled towards the "valley" between the "ridges" which is slightly offset to the windward side of the body. This flow towards the "valley" accounts for the sudden change in direction towards the base of the body of the lee-side flowlines coming over the top of the body.

Similar reasoning to the above explains the course of the flowlines on the windward side of the body and the differences in the flow patterns on the leeward and windward sides of the body due to the asymmetries in the pressure distribution.

9.3 Flow pattern at -6 degrees pitch, 0 degrees yaw

Due to lack of time, it was only possible to obtain the flow pattern over the dummy body at -6 degrees pitch, Fig 37. This pattern must be compared with the corresponding pressure distribution, namely that over the bottom body at +6 degrees pitch, Figs 32 d) and 34.

Because the bodies are pitched at -6 degrees, care must be taken in the definition of top and bottom. In the description that follows, the top body is the one used for obtaining the oilflow patterns and the top of this body is the side remote from the other body, i.e. exactly as it is presented in the diagrams.

The flow patterns are very similar to those at zero pitch. The differences being that, in side view, the flowlines start sloping towards the interference "hollow" from immediately behind the nose instead of from about half way along the forebody and that the flowlines over the afterbody, because they are still aligned with the oncoming flow, sweep downwards towards the gap between the bodies.

In the bottom view, rotation 90 degrees, the interference "hollow" is still clearly seen with the flow going towards it from the top of the body. The flowlines along the body centreline aft of the position of maximum diameter are made up from two separate groups, one flowing axially from the rear of the region of maximum interference and the other flowing from the top of the body due to the effect of pitch. These join together about halfway along the afterbody to flow towards the base in a well defined stream which, however, is rather wider than that at zero pitch.

The view of the top of the body, rotation = 270 degrees, shows the flow downwards from the top centre-line dividing into two parts, one going towards the interference "hollow" and the other going towards the bottom of the body at a more acute angle, as would be normal for a body at incidence.

The pressure contours and isometric representation of the pressure distribution of the corresponding condition, the bottom body in Figs 32 d) and 34, show that the maximum pressure near the nose of the body is on the top, (0/360 degree), generator and the minimum pressure is on the 180 degree generator. The interference "ridge" that extended to the nose at zero pitch, is still present over the middle of the forebody, but is absorbed into the general pressure distribution of a pitched body at a position slightly behind the nose. The pressure gradients in the pressure distribution will tend to direct the flow that affects the oil, along the "valleys" in the distributions. Thus, at the nose, the oilflow lines from the top of the body will start immediately to slope downwards in the direction of the "hollow". On the other hand the oilflow lines that start at the bottom of the body near the nose will soon sweep upwards slightly to avoid the forebody "ridge", before likewise sloping downwards towards the "hollow". In a similar way, the flow that does not enter the "hollow" will tend to flow along the afterbody along the two "valleys" on either side of the central "ridge". It will be seen that the oilflow patterns confirm these observations.

10.0 THE AERODYNAMIC CHARACTERISTICS OF THE COMPLETE TWO-BODY COMBINATION

Previously only the aerodynamic characteristics of the instrumented body in the presence of a second similar body have been discussed.

Because the bodies are symmetrical about the x-y plane, the variation of C_V and C_A with yaw for the 2-body combination are the same as those measured by the instrumented body if the reference area for the single-body results is its maximum cross-sectional area and that used for the two-body configuration is the maximum cross-sectional area of the two bodies. However, for reasons of symmetry, C_N is zero for all angles of yaw.

When the bodies are pitched in the x-z plane, the loads on the two bodies differ and thus the body combination must be tested at both positive and negative pitch so that the loadings etc. on both bodies of the combination can be obtained from the measurements made on the instrumented body. Fig 22 a) shows the variation of C_N with pitch for the instrumented, (bottom), body between -6 and +6 degrees pitch. However, if the sign of the normal-force is reversed, the variation between 0 and -6 degrees pitch represents the variation between 0 and +6 degrees for the top body.

Because of the effect of the region of maximum interference, the bottom body has a large positive normal-force, $C_N = 0.154$, at zero pitch. As pitch increases, this normal-force increases primarily due to the change in pitch, but modified due to changes in the interference between the bodies, Fig 19 b). As pitch becomes more positive, it can be seen that the interference contribution diminishes, particularly between 4 and 6 degrees, and so the increase in normal-force with pitch will become non-linear.

In the case of the top body, this will have a large, negative normal-force at zero pitch, $C_N = -0.154$, and this will become more positive with increase in pitch for the same reasons as above. However, because the variation of the interference effect on the top body with increase in pitch is larger and also more linear than that on the bottom body, the variation of normal-force with pitch will be greater than that of the bottom body.

C_N for the two-body combination is half the sum of the C_N values for the top and bottom bodies, (allowing for doubling the reference area.

In obtaining C_A for the top body, the same procedure is followed but with no reversal of sign. C_A for the two-body combination is again half the sum of the C_A values for the two bodies.

The variations of both the experimental and predicted values of C_N and C_A with pitch are shown in Fig 38 a) and, for completeness, the variation of C_V and C_A with yaw in Fig 38 b). For ease of comparison, the predicted and experimental values of the same coefficients for the single body are also shown.

10.1 Variation of C_N and C_A with pitch

The variation of C_N with pitch is linear in the case of the single body but is slightly nonlinear in the case of the two-body combination. There is considerable difference between the experimental and predicted results for both the single-body and two-body configurations with the predicted mean slopes being approximately 55% of the experimental ones for both configurations.

Examination of the loading and pressure distributions shows that they are in good agreement in region where the most obvious interference effects are present, i.e. the front half of the body. However, in most cases, there are appreciable differences over the rear

half of the body as the experimental loadings become more positive towards the base of the body with the effect becoming more noticeable with increase in pitch. The reason for this is that the circumferential distribution of pressure is more uniform experimentally and the local "downs" that are eliminated in the pressure distributions are the ones that cause the normal-force loadings to be more negative. The conditions under which these differences occur are when the loadings at the beginning of the conical afterbody are large and negative. When the loadings at that position are small, i.e near zero pitch in the case of the single body or at negative pitch in the case of the top body in the two-body combination, the agreement is good, presumably because the circumferential pressure distributions are nearly uniform in any case.

There is also a considerable difference in the variation of C_N with pitch between the single and two-body configurations in both the predicted and experimental results. In both cases, the predicted slope of the two-body configuration is approximately 80% of the experimental value. This is not unexpected as the slope of the C_N v pitch curve for the top body is approximately the same as that for the single body and appreciably greater than that of the bottom body.

The agreement between the predicted and experimental variation of C_A with pitch is poor as expected because of the known experimental errors. However both the experimental and predicted results agree that C_A reduces as pitch increases and that C_A for the two-body configuration is larger than that of the body alone.

10.2 Variation of C_Y and C_A with yaw

The effect of yaw on C_Y and C_A is shown in Fig 38 b). The predicted and experimental variations are shown for both the single-body and two-body configurations.

Considering the predicted results first, although the variation of C_Y with yaw is linear for the single-body configuration,

the variation for the two-body configuration is slightly non-linear with the slope near zero pitch being slightly greater than at the higher angles. Also the mean slope for the two-body configuration is some 12% greater than that for the single-body due to the alteration of in size and position of the forebody loading peak as previously described, Section 5.2. The variation of C_A with yaw is virtually the same as the variation with pitch

Although the experimental variation of C_V with yaw is much greater than predicted as in the case of the variation of C_M with pitch, the experimental results for the two-body configuration have some unusual features in that the variation of C_V with yaw is no longer linear but is best approximated by two straight lines with a break in slope at 2 degrees yaw. The initial slope is 17% greater than that of the single-body configuration, but above 2 degrees yaw the slope increases to become approximately 53% greater than that of the single body. This increase in slope must be caused by some flow change that occurs near 2 degrees yaw, although exactly what it is or what is the cause of the change has not been discovered.

If the loading distributions in Fig 12 a) are examined again, it can be seen that the distributions at ± 2 degrees are very different as previously remarked. Although the forebody and afterbody loadings at -2 degrees yaw are much greater in magnitude than those at +2 degrees yaw, the magnitude of C_V , obtained by integrating the loading distribution, is virtually the same, Fig 22 e). The interference loading distributions, i.e, the loading distribution measured over the two-body configuration minus that over the single body, show approximately the features as the loading distribution, but emphasize the loading discontinuities and irregularities that occur at the beginning of the afterbody and, in particular, near the junction between the ogival and conical sections. It would therefore seem that this is the critical region.

In spite of the completely different variations of loadings in the pitch and yaw planes, the variation of C_{m} with yaw is virtually indistinguishable from that with pitch presumably because the main differences occur where the surface slopes are small.

11.0 CONCLUSIONS

11.1 Single-body characteristics

At positive pitch the normal-force loading increases with distance from the nose of the body until it reaches a peak value at a distance of $0.16L$ behind the nose. The loading decreases with further increase in distance from the nose to become zero at the position of maximum body diameter, $0.39L$, and reaches a maximum negative value at about $0.52L$ aft of the nose, i.e. $0.07L$ aft of the position where the ogival shape blends into the conical part of the afterbody. With further increase in distance aft, the loading becomes less negative and tends to zero at the base of the body.

The magnitude of these loading peaks vary linearly with increase in pitch. The position of the positive, (forebody), loading peak does not vary with pitch. The position of the afterbody, (negative), loading peak is rather more difficult to determine accurately, but it also seems to vary little with pitch.

The theoretical predictions of the loading distributions estimate the position of the forebody loading peak accurately, but slightly underestimate its magnitude. The position and magnitude of the afterbody loading peak is well predicted, but the variation of the predicted loadings over the afterbody is much less than that measured experimentally.

Although the negative loadings over the afterbody are smaller in magnitude than the positive loadings over the forebody, they vary less and act over a larger proportion of the length of the body. When the loadings are integrated to give the overall normal-force and pitching moment on the body, this distribution has two main effects:-

a) The contribution to the overall pitching moment about the nose from the negative afterbody loadings is greater than that from the positive forebody loadings, thus the overall pitching moment is negative,

(nose-down), at positive pitch and the pitch centre is in front of the nose.

b) The contribution of the negative afterbody loadings to the overall normal-force acting on the body, although smaller than the contribution of the positive forebody loadings, is comparable in magnitude with the result that the overall normal-force is the medium-size difference of two large quantities. Thus the difference in the predicted and experimental afterbody loadings has a large effect on the overall normal-force on the body and accounts for the bulk of the 60% increase in the variation of C_N with pitch that is measured experimentally as compared with prediction.

The distribution of axial-force loading along the body is rather different. Initially the loading increases rapidly with distance along the body until it reaches a positive peak at about $0.05L$. The loading then decreases to become zero at about $0.15L$ and reaches a negative peak at $0.26L$ before rising again to zero at the position of maximum diameter, $0.39L$, to reach a second positive peak at the beginning of the conical afterbody, $0.45L$. The loading then reduces, rapidly at first, to reach a small value by about $0.65L$ which alters little over the remainder of the length.

This distribution varies little with change of pitch. At the highest pitch angle, 6 degrees, the first two peaks have become slightly more negative but little change has taken place in the afterbody loading distributions.

There are considerable differences between the predicted and experimental axial-force loading distributions between the nose of the body and the position of the second loading peak. These differences were expected and are mainly due to experimental error. However the loadings up to $0.05L$ were thought to be free of error and indicate that the magnitude of the first loading peak was rather greater than predicted. Aft of the second loading peak, the agreement between the predicted and experimental loadings is very good.

When the loading distributions are integrated, it is found that the predicted C_A is small and reduces slightly with increase in pitch. Because of the experimental errors the experimental variation of C_A with pitch shows considerable scatter and although C_A is much larger than predicted at zero pitch, it reduces much more rapidly with increase in pitch.

11.2 Two-body combination

At zero pitch, the main feature of the normal-force loading distribution on the instrumented body is the positive loadings that are present between $0.26L$ and $0.56L$ and which reach very high values near the position of the maximum body diameter where the passage between the bodies is very small. Here high velocities, and therefore low pressures, are present as a result of the airstream having to flow through the restricted space between the bodies. The resulting interference region consists of a small circular area of very low pressure centred on the position of minimum gap between the bodies whose effect extends around most of the circumference of the body. The sense of the loadings is such that the instrumented body is attracted towards the second body.

Initially, however, the normal-force loading becomes more negative with distance aft of the nose and reaches a minimum value at about $0.16L$ aft of the nose, i.e at the same position that the forebody peak loading occurs on the isolated body, before returning to zero at $0.26L$. The interference pressure field in this region is restricted to the half of the body circumference that faces the second body and the peak interference loading is only about $1/3$ the magnitude of the peak loading at the position of maximum diameter. As the pressures in the interference region are greater than those on the other side of the body, the sense of the loadings is such that nose of the instrumented body is repelled from the second body.

Aft of $0.56L$, the loadings again become negative and reach a peak at about $0.7L$, and then reduce slowly in magnitude as the

rear of the body is approached. The magnitude of this peak is only about 1/12 of the main interference peak. As in the nose region, the interference pressure field is restricted to the half of the circumference facing the second body, but the increase in pressure over this region is very small.

These interference effects agree quite closely with prediction, the only differences being that the front interference peak is slightly larger and farther aft than predicted and the loadings over the rear of the afterbody are slightly more negative.

The axial-force loading distribution over the instrumented body is very similar to that of the body in isolation except that the peaks are all greater in magnitude, the first, positive, peak by 20%, the second, negative, peak by 45% and the third, positive peak by nearly 100%. These changes in the loading distribution result in an increase in the overall C_A of about 1/3 as compared with the single-body results.

11.2.1 Effect of pitching the bodies.

The pressure and loading distributions at zero pitch define the basic interference between the bodies. When the bodies are pitched or yawed, the appropriate pressure distribution will be added to that due to the mutual interference between the bodies. The pressure and loading distributions on the top and bottom bodies will now differ because, as the major interference effects are restricted to the half of the circumference facing the other body, the interference pressure distribution will be modified mainly by the pressure distribution over the top (suction) surface of the body in the case of the bottom body and the bottom (pressure) in the case of the top body.

Because of the pressure variations due to the interference effects are much greater than those due to pitch in the region near the position of minimum passage width, the loadings in this

region do not vary greatly with variation in pitch. Thus the main changes in loading distribution take place near the nose of the body and over the conical afterbody.

If the change in the interference loading with pitch is obtained by subtracting the pitch loading distribution measured on the single-body and the basic interference loading at zero pitch from the measured loading distribution, then it is found that the change in the interference loading on the instrumented body is very different at positive and negative pitch.

The change in interference loading with pitch is much greater at negative pitch with large positive changes taking place over the forebody and large negative changes taking place over the afterbody. As the net area under the distribution is small, the variation in C_N with pitch at negative pitch will not differ greatly from that of the single-body. At positive pitch, the change of interference loadings with pitch is much smaller. The change in the forebody interference loadings with pitch is now negative, is less than half that at negative pitch and, in addition, the shape of the distribution is now much flatter. The change in the afterbody interference loadings is now positive and small in comparison with the changes in the forebody loadings. Thus the variation of C_N with pitch at positive pitch will be less than that of the single body.

Interpreting these conclusions to apply to the two-body configuration, the variation of C_N with pitch for the top body is about the same as that of the single body, but that for the bottom body will be rather less. Thus the overall C_N for the two-body combination will be rather less than that of two widely separated bodies.

The predicted loading and pressure distributions agree closely with experiment as far as $x/L \approx 0.6$. If the loading at this position is appreciable, as when the bottom body is pitched, then the experimental loadings diminish almost linearly with distance to be

almost zero at the base of the body, but the predicted loadings vary little over this region. This is the result of the predicted circumferential pressure distributions altering little over the afterbody whilst the experimental distributions gradually become more uniform as the base is approached.

11.2.2 Effect of yawing the bodies

The effect of yawing the body is rather different as the interference distributions due to the proximity of the bodies in the pitch plane has to be combined with lifting effects in the yaw plane.

When the body combination is yawed, the side-force loading distribution is different from that of the single-body. Although the initial slope of the loading distributions are similar, that of the two-body combination peaks some distance to the rear of that of the single body, thus generating more side-force. In addition, above about 2 degrees yaw, the side-force flow field interacts with the interference flow field to increase the side-force loadings still further and also to increase the normal-force loadings between 0.1 and $0.6L$. These changes are sufficient to increase the value of C_v at 6 degrees yaw by about 70% as compared with the single-body and to increase the interference C_N on the body by about 20%.

These changes in the loading distributions are well predicted as far aft as $x/L = 0.45$. Beyond this the experimental loadings reduce in magnitude much more rapidly than predicted as the base is approached.

Although the pressure distributions are very complicated, they are well predicted except for what look like relatively small differences over the afterbody where the experimental circumferential pressure distributions become more uniform towards the base instead of retaining the same characteristics as that at the beginning of the conical afterbody. Unfortunately these apparently small

differences in the experimental pressure distributions reduce the negative loadings over most of the afterbody and this leads to appreciable gain in the overall force on the body.

11.3 Possible improvements in the prediction methods

In general the inviscid SPARV method predicts the complicated pressure and loading distributions very well, even in the regions of greatest complexity. The position at which the predictions start to diverge are aft of $0.5L$ in the pitch results for both the single-body and two-body combination and aft of about $0.45L$ for the yawed two-body combination. There is an abrupt change of curvature at the beginning of the conical afterbody, $x/L = 0.45$, which could trigger viscous effects, i.e. boundary-layer thickening or separation, in the yaw case, but, in the pitch cases, the loadings start to diverge too far aft of the junction for this to be the sole cause of the differences. In these circumstances it is possible that using the viscous version of SPARV might improve the accuracy in predicting the afterbody distributions at least in the yaw case.

The other possible improvement is in the method chosen to model the base cavity flow. In the present investigation, the base conditions were modelled by extending the 3-degree semi-angle cone past the base of the body until it met a cylinder representing the support sting. A previous investigation has shown that, in the case of a body with a cylindrical afterbody, large changes could be made over a large part of the afterbody by representing the base cavity by conical or ogival fairings of various fineness ratios. It is intended to alter the present body by installing additional pressure taps at the extreme rear of the afterbody and in the base region and then trying to match the experimental afterbody pressure distributions by changes in the modelling of the base cavity.

12.0 ACKNOWLEDGEMENTS

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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	=	7.6645
Forebody length	=	23.7273 in. (0.39280L)
End of ogive	=	27.5562 in. (0.45502L)

TABLE 1. BODY GEOMETRY

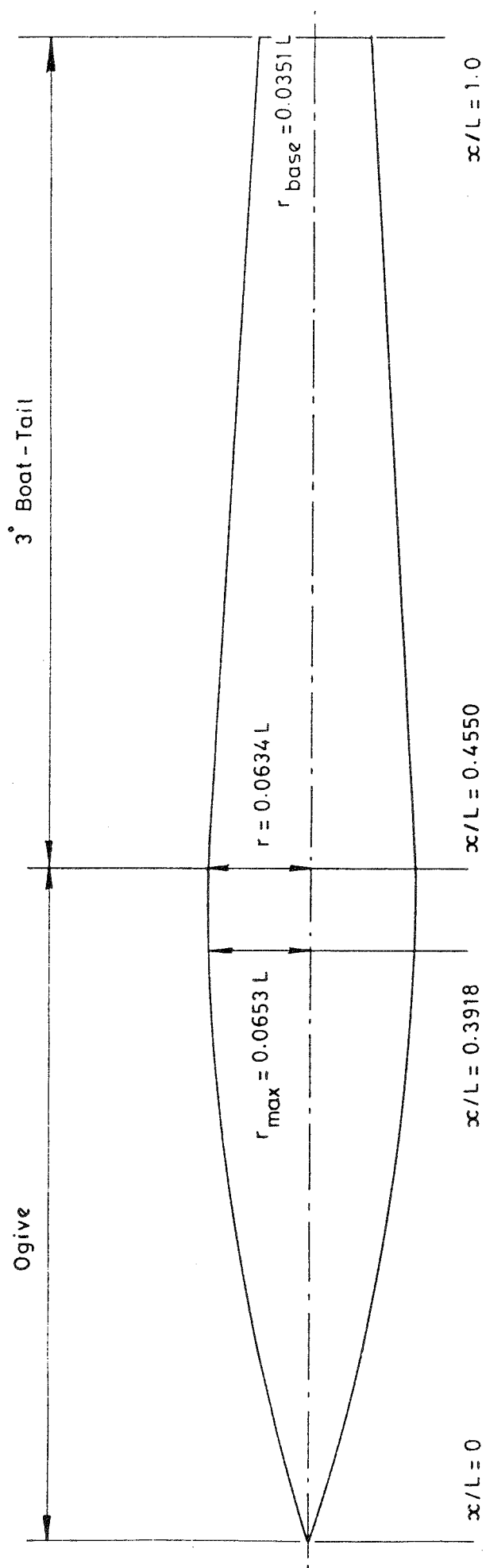


Fig 1. Model Geometry.

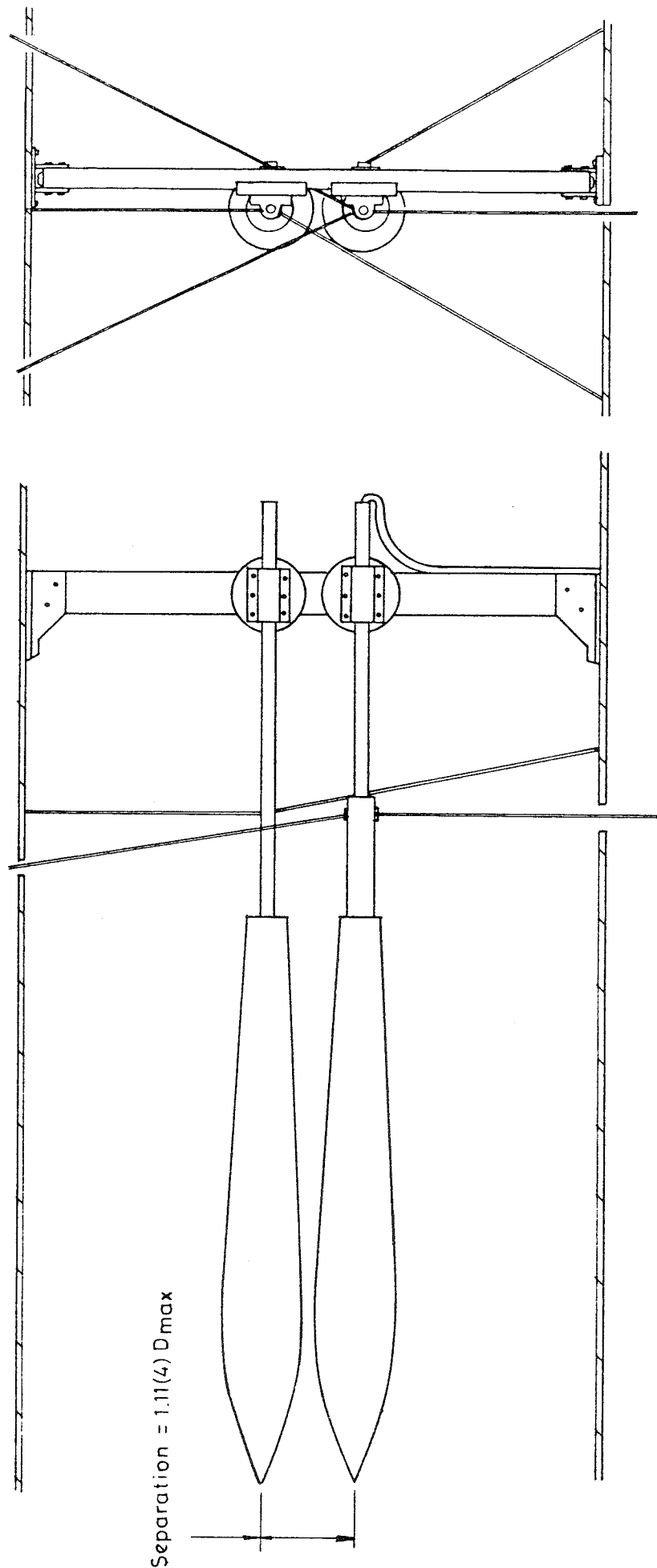


Fig 2 Models Mounted in Tunnel

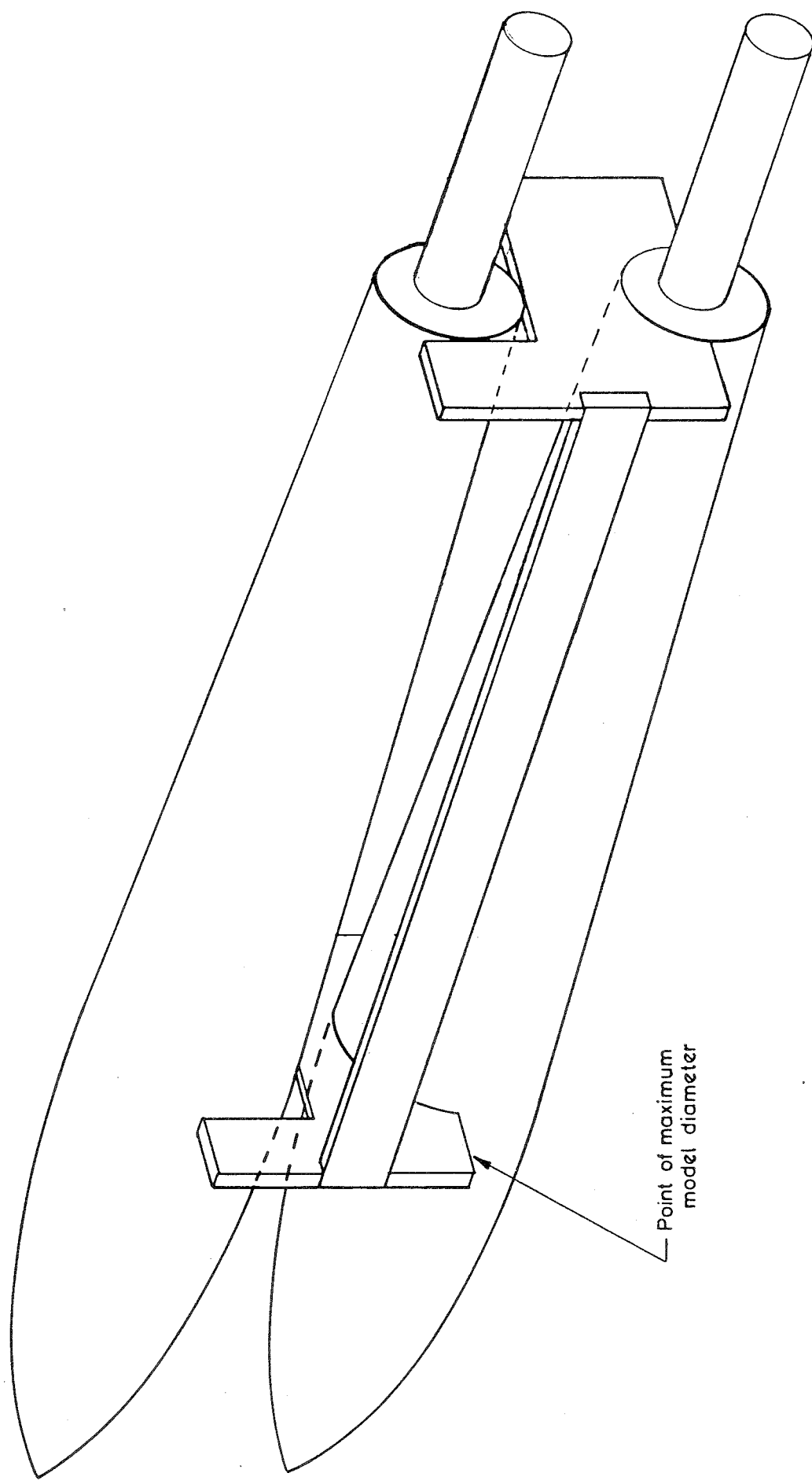
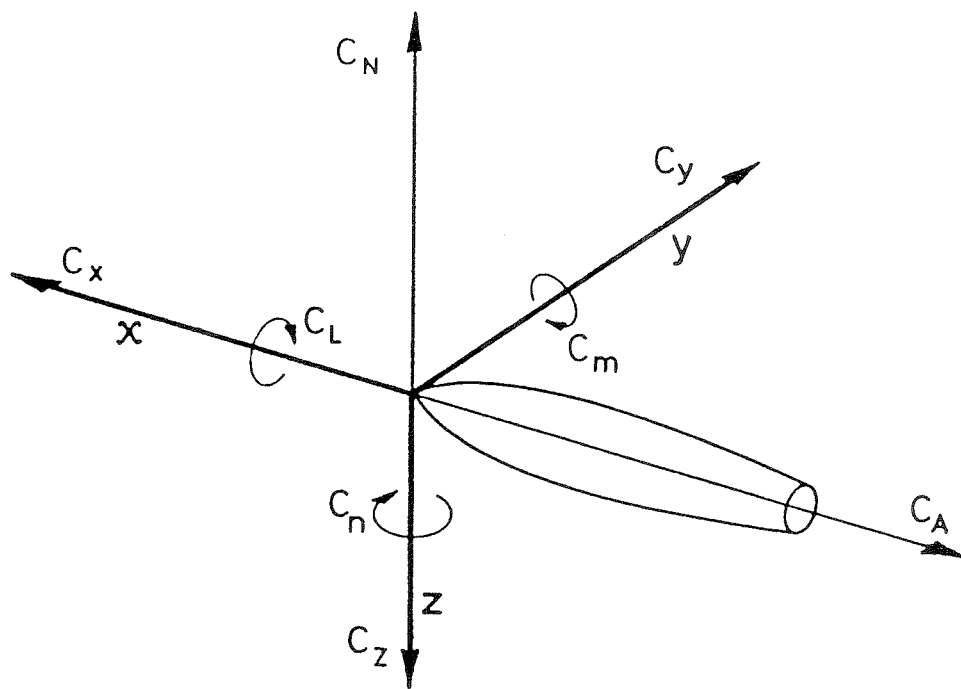
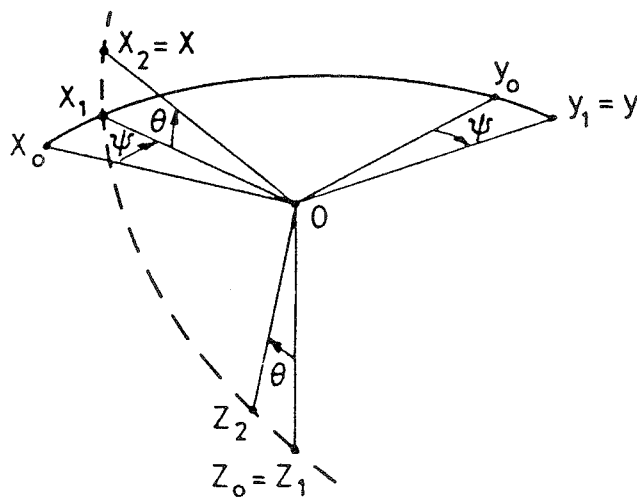


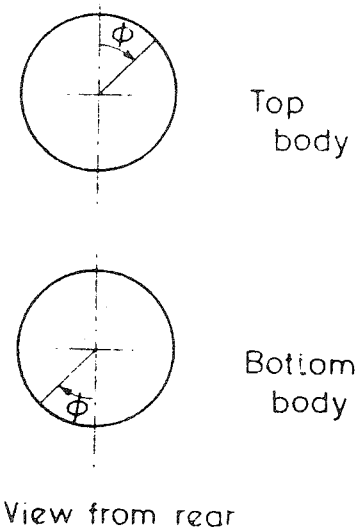
Fig 3. Model Rigging Jig.



(a) Body axis system of forces and moments.



(b) Definition of incidence (θ) and yaw (ψ) in non-rolling body axes.



(c) Definition of generator angle.

Figure 4. Definition of axis system.

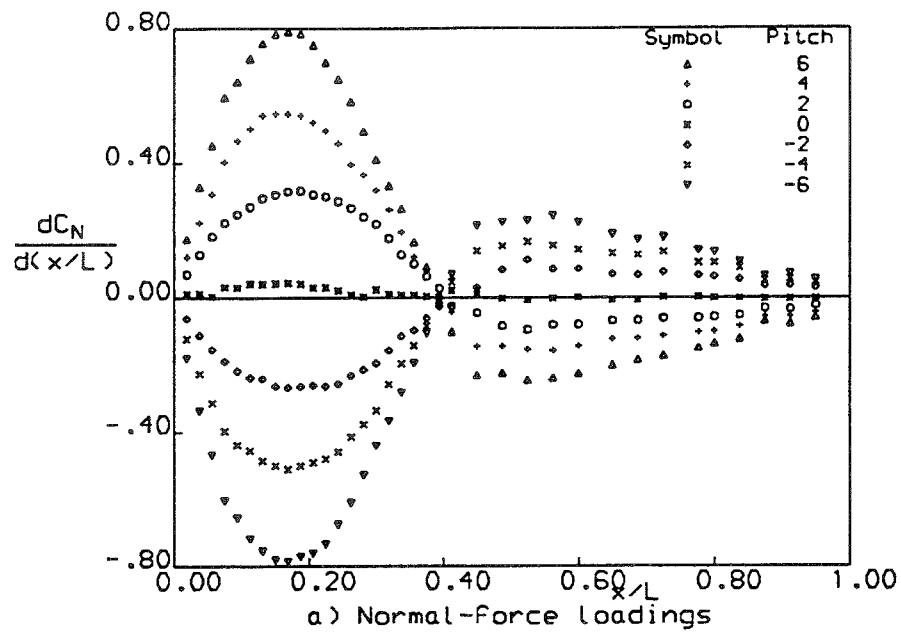
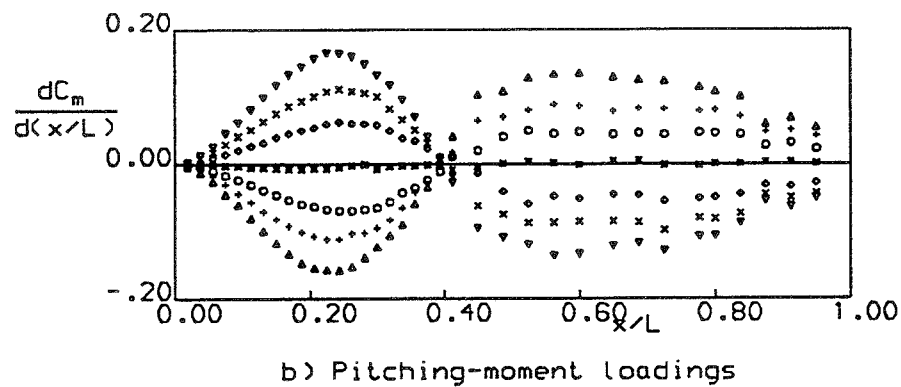
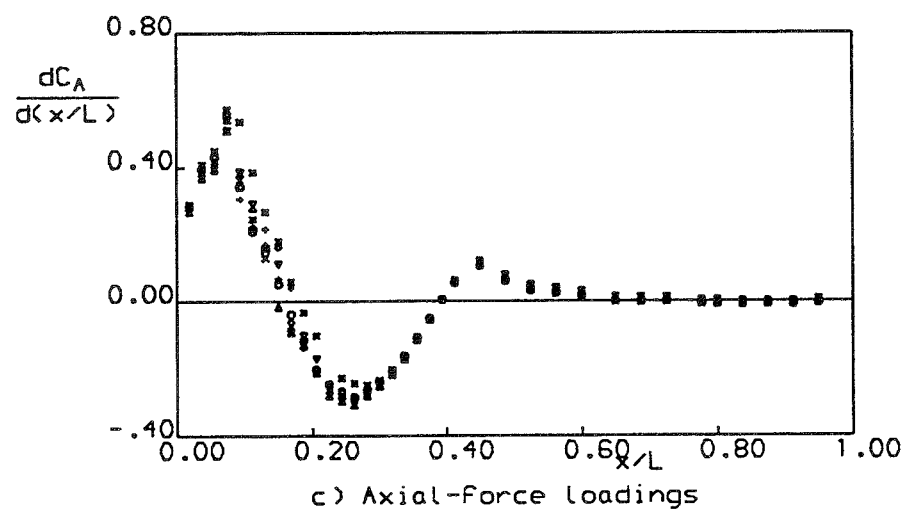


Figure 5. Single body. Variation of aerodynamic loading distributions with pitch

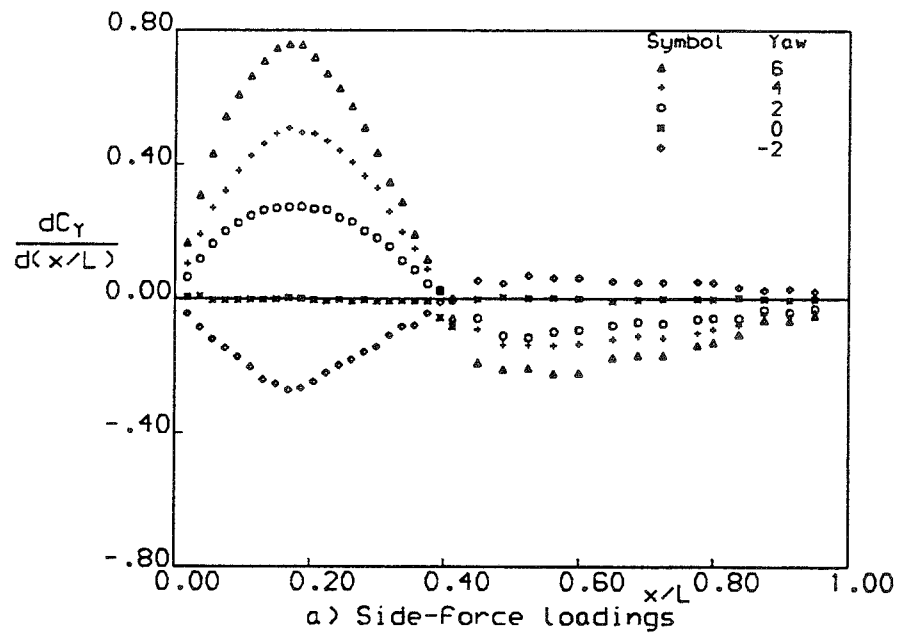
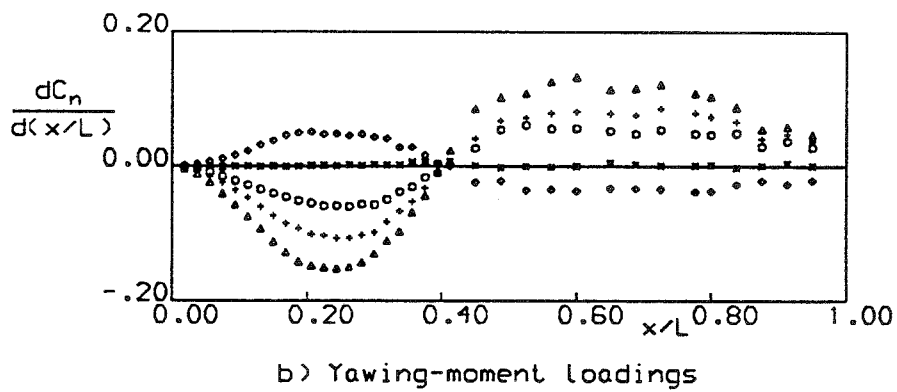
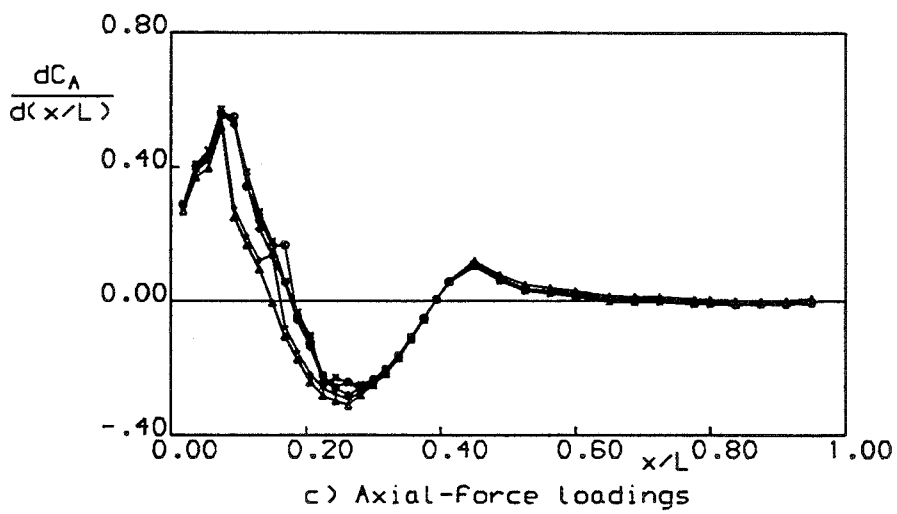
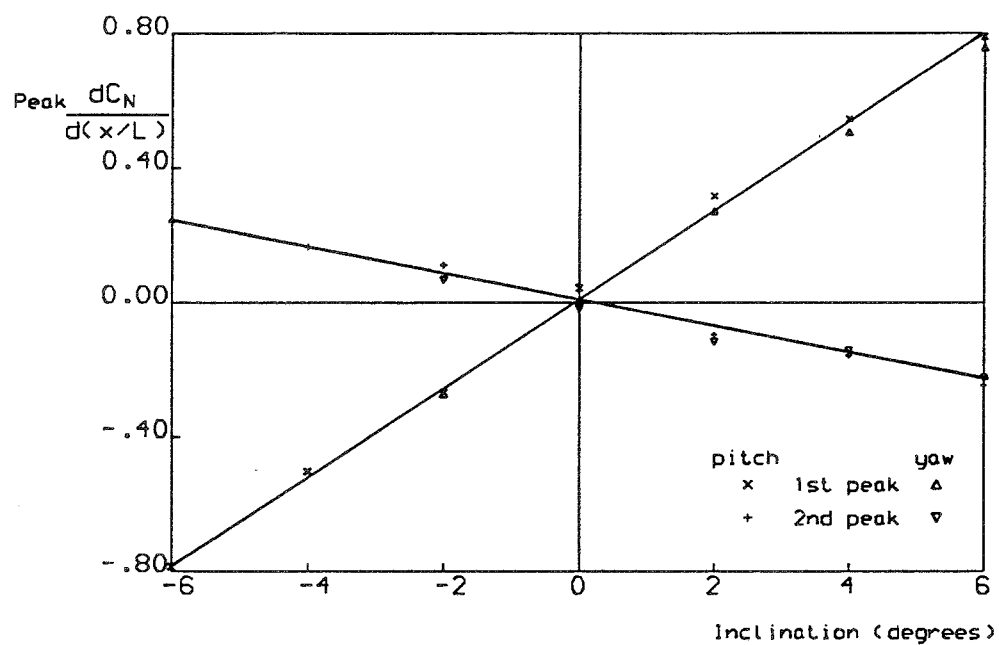
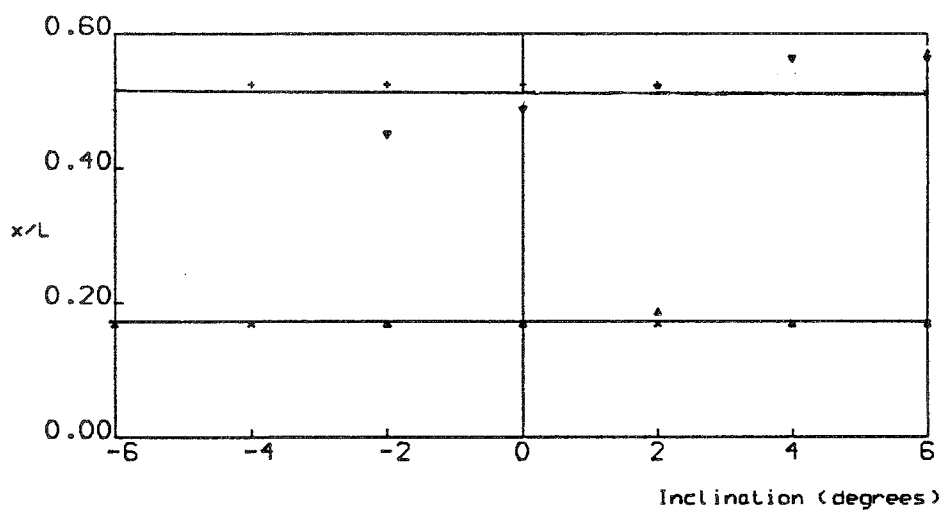


Figure 6. Single body. Variation of aerodynamic loading distributions with yaw

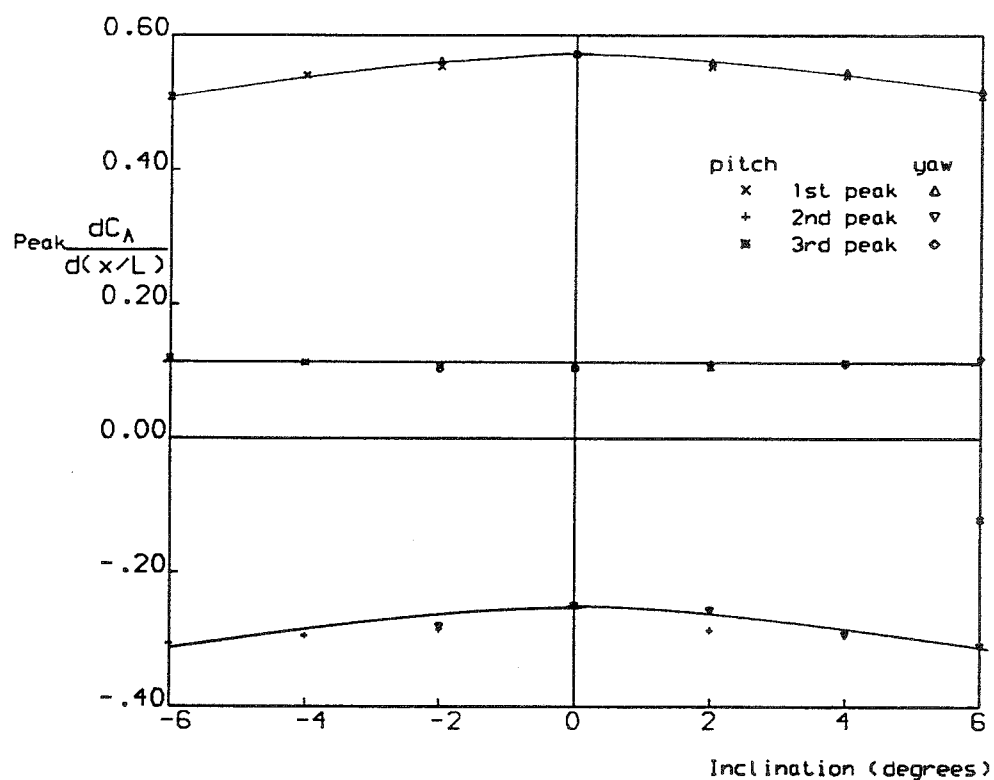


a) Variation of maximum loading with attitude

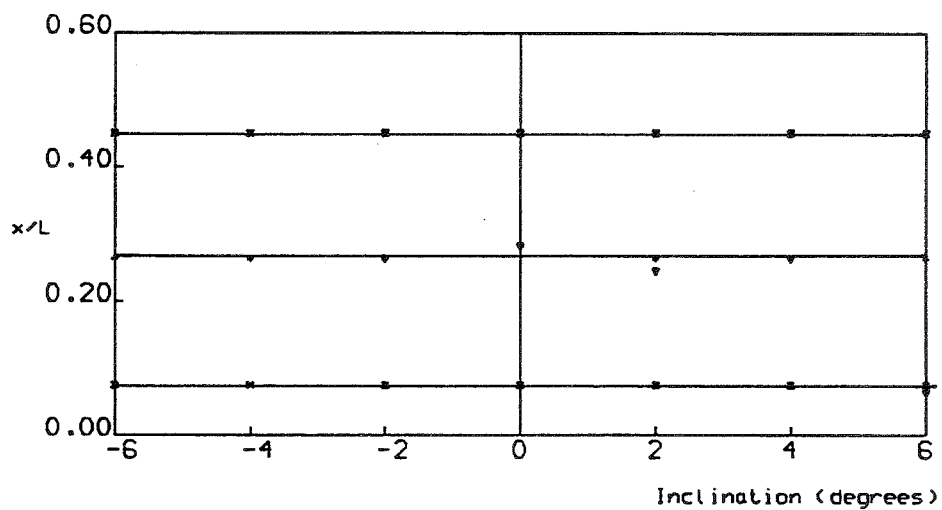


b) Variation of position of maximum loading with attitude

Figure 7. Single body. Variation of magnitude and position of the normal-force loading peaks with attitude



a) Variation of peak loadings with attitude



b) Variation of position of loading peaks with attitude

Figure 8. Single body. Variation of magnitude and position of the axial-force loading peaks with attitude

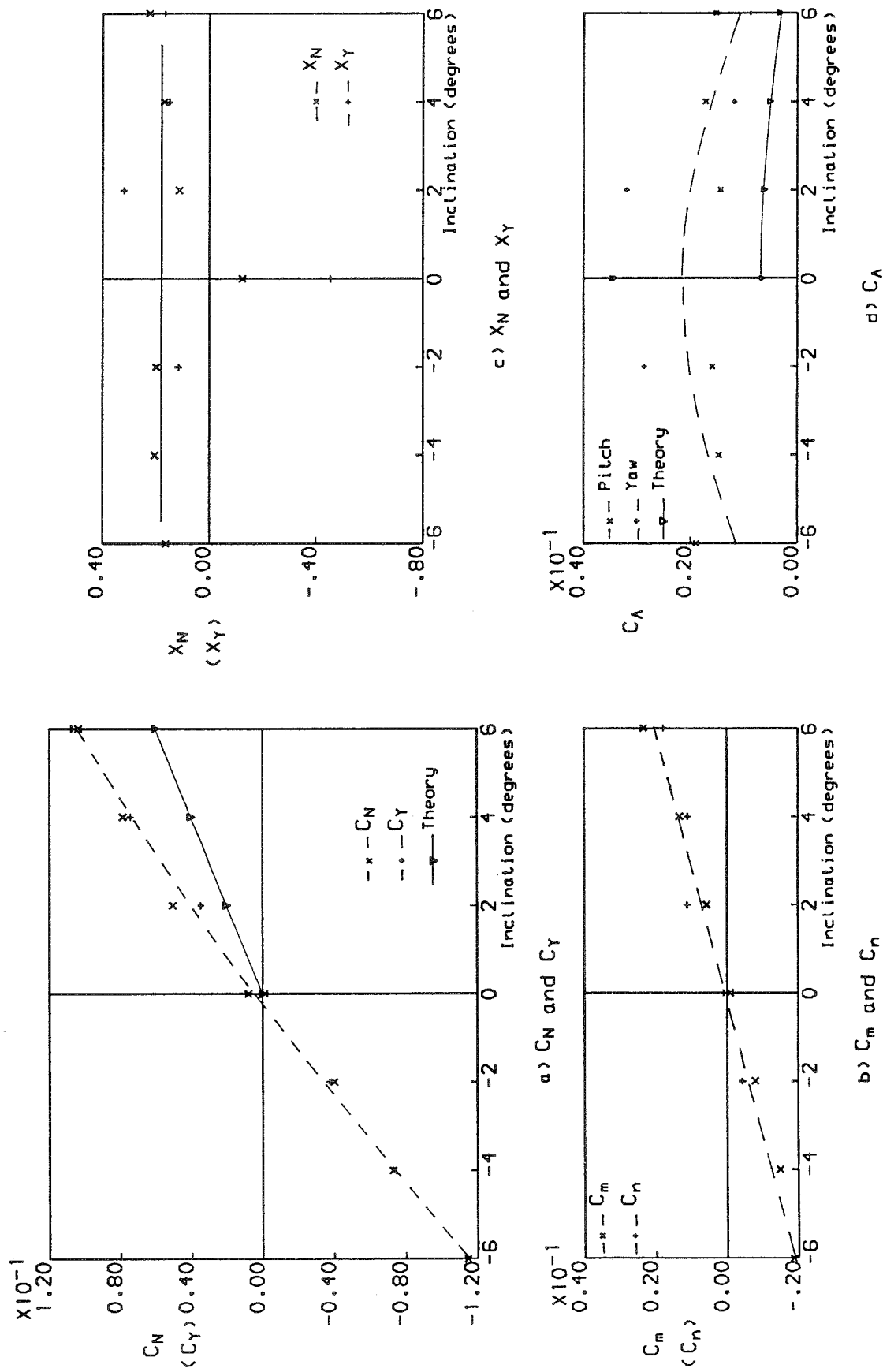
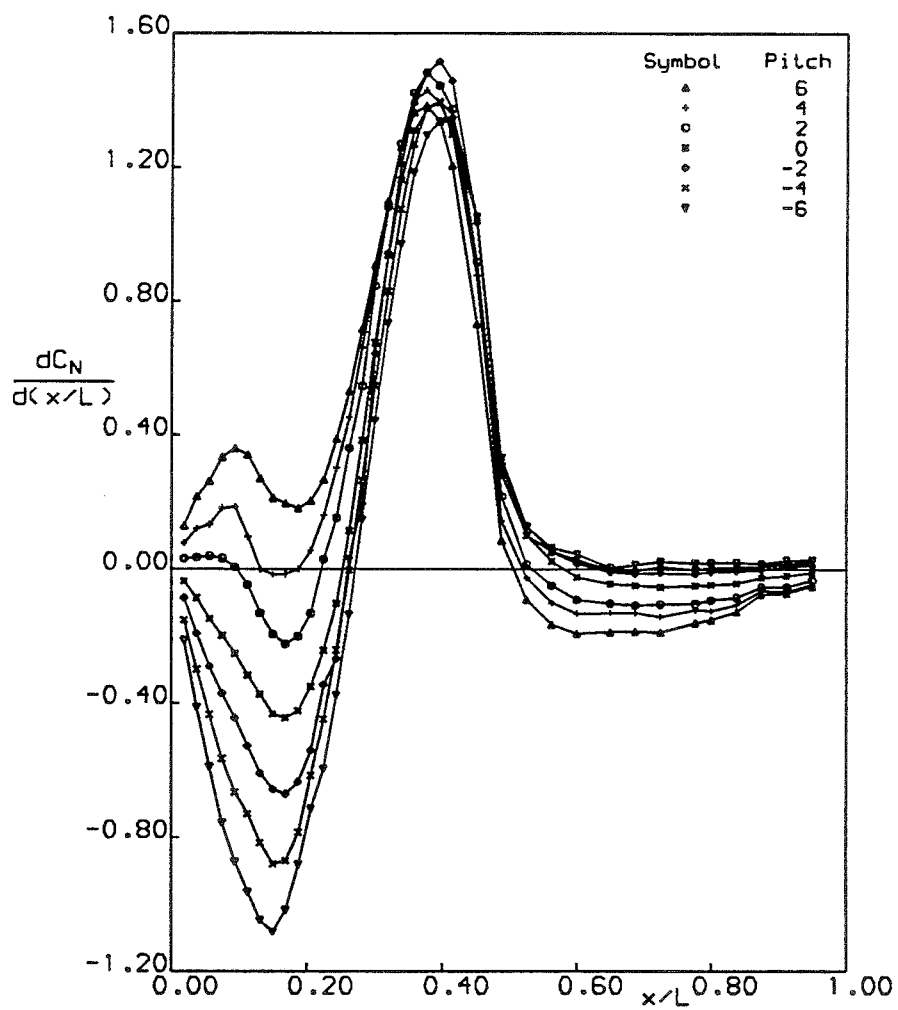
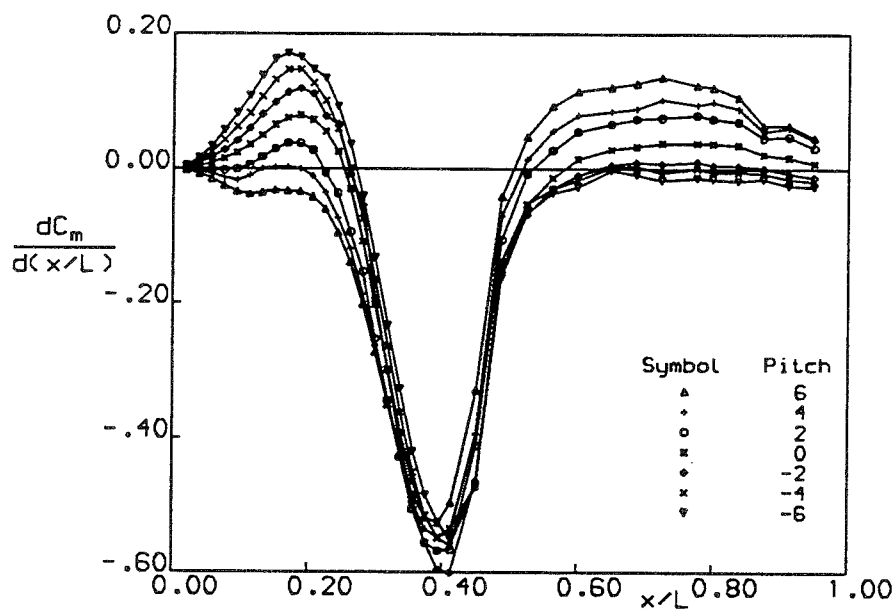


Figure 9. Single body. Overall aerodynamical characteristics

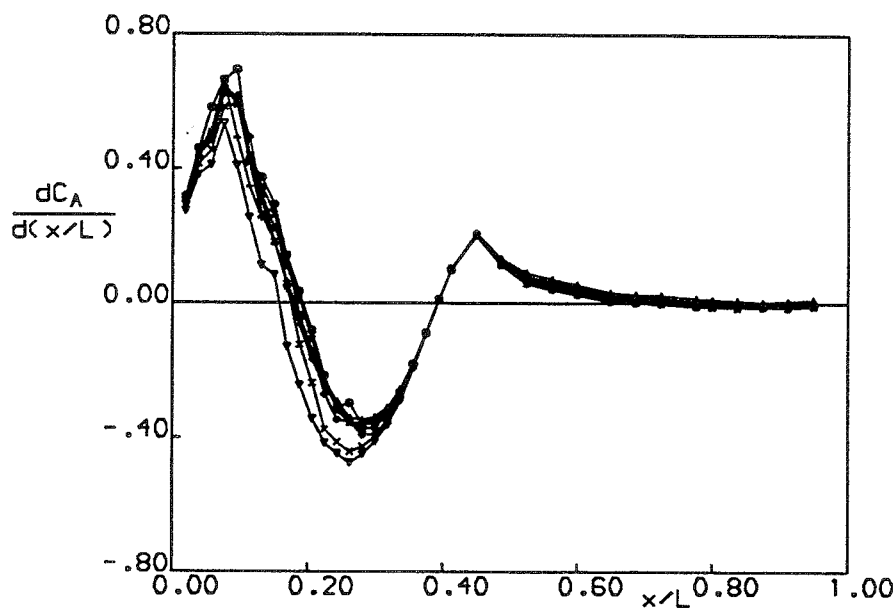


Stagger = 0.00Dmax Separation = 1.11Dmax

Figure 10. Two-body combination. Variation with pitch of the normal-force loading distribution over the instrumented body



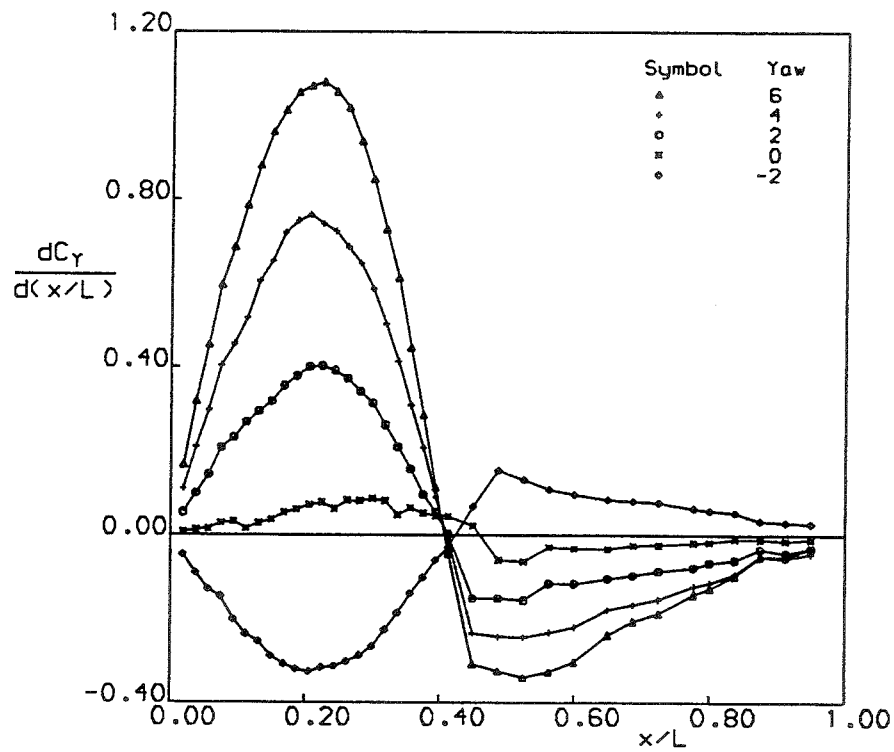
a) Pitching-moment loadings



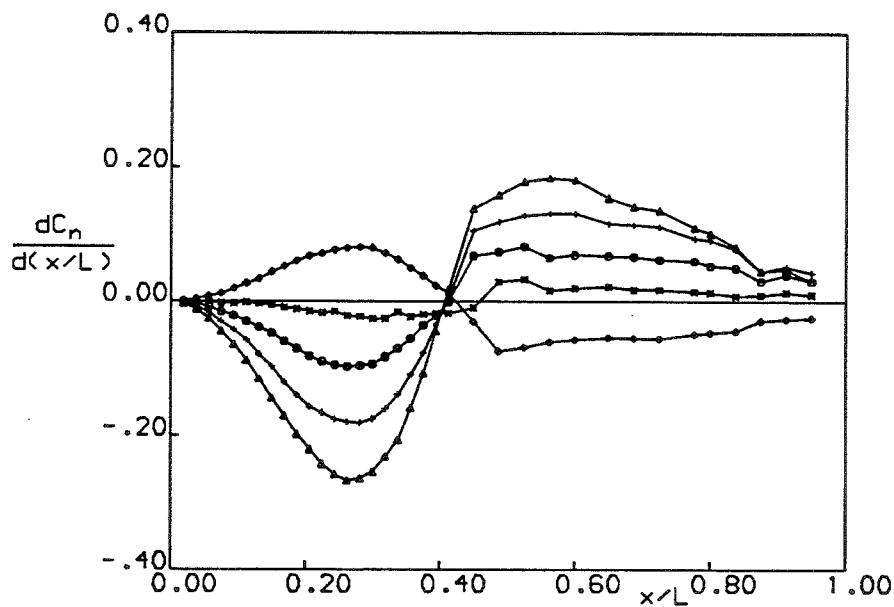
b) Axial-Force loadings

Stagger = 0.00D_{max} Separation = 1.11D_{max}

Figure 11. Two-body combination. Variation with pitch of the pitching-moment and axial-force loading distributions over the instrumented body



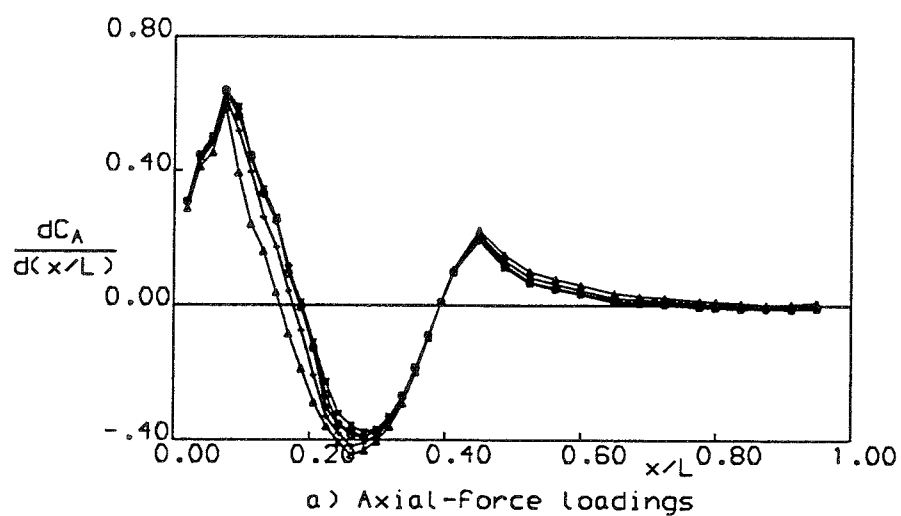
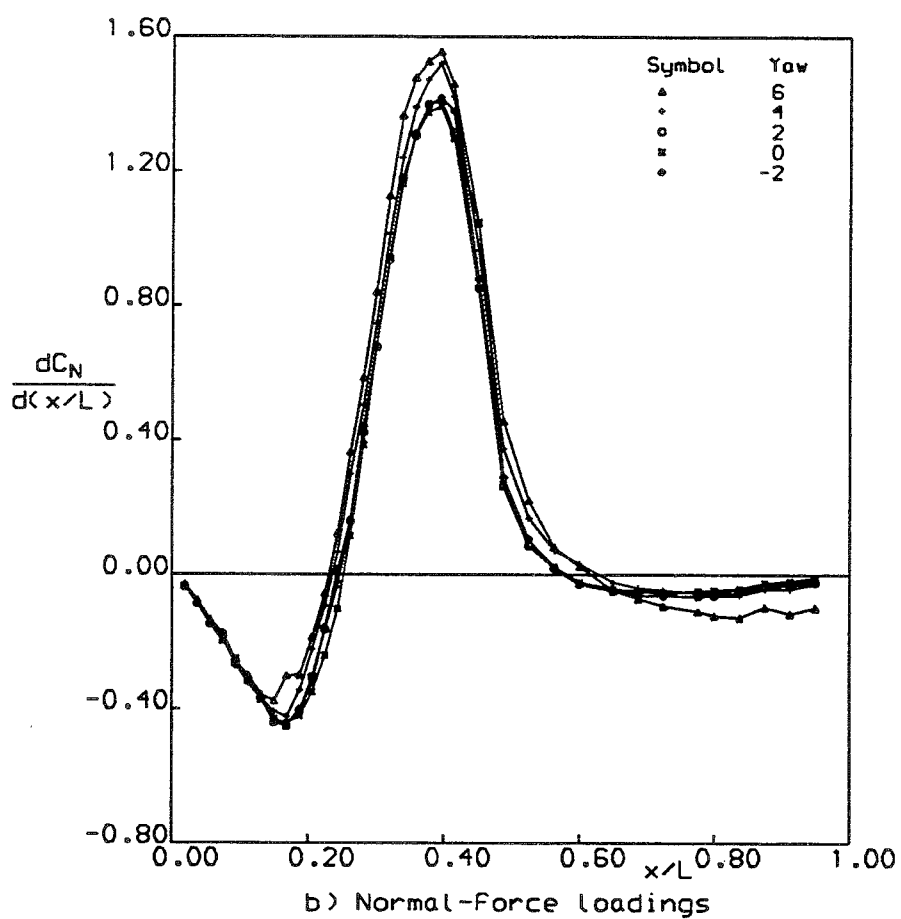
a) Side-force loadings



b) Yawing-moment loadings

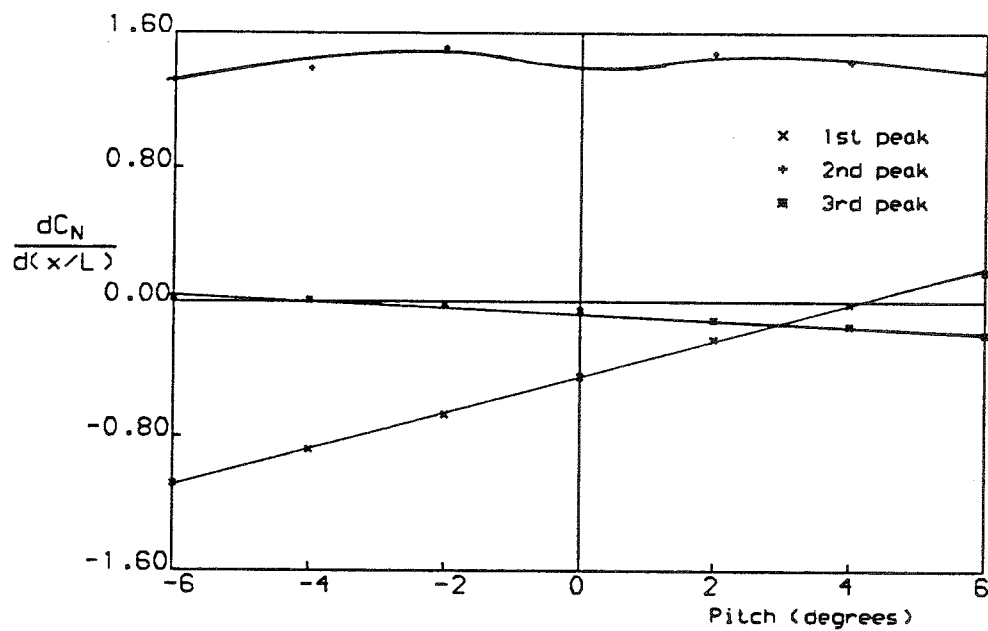
Stagger = 0.00Dmax Separation = 1.11Dmax

Figure 12. Two-body combination. Variation with yaw of the side-force and yawing-moment loading distributions over the instrumented body

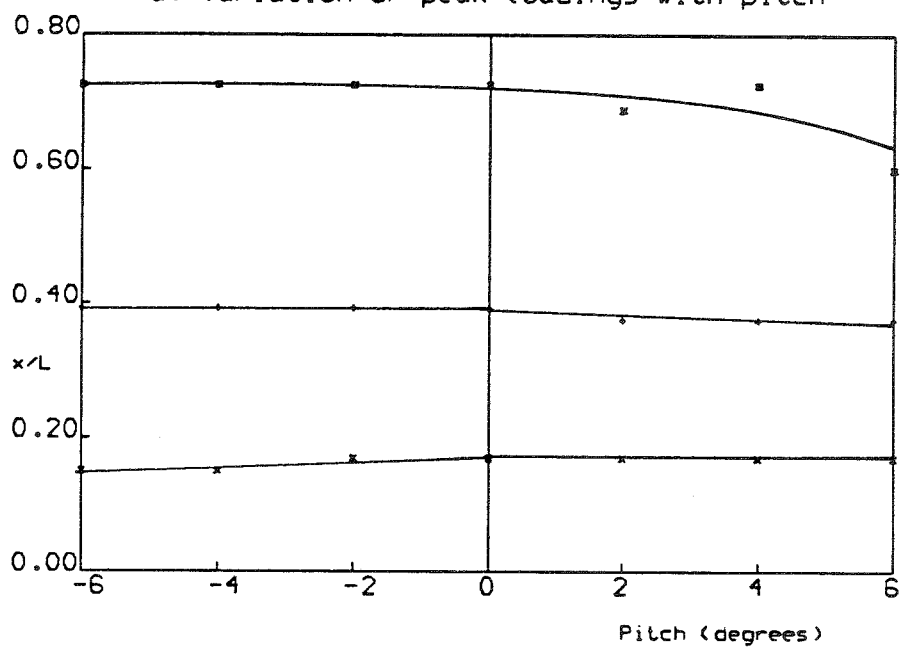


Stagger = 0.00Dmax Separation = 1.11Dmax

Figure 13. Two-body combination. Variation with yaw of the axial-force and normal-force loading distributions over the instrumented body

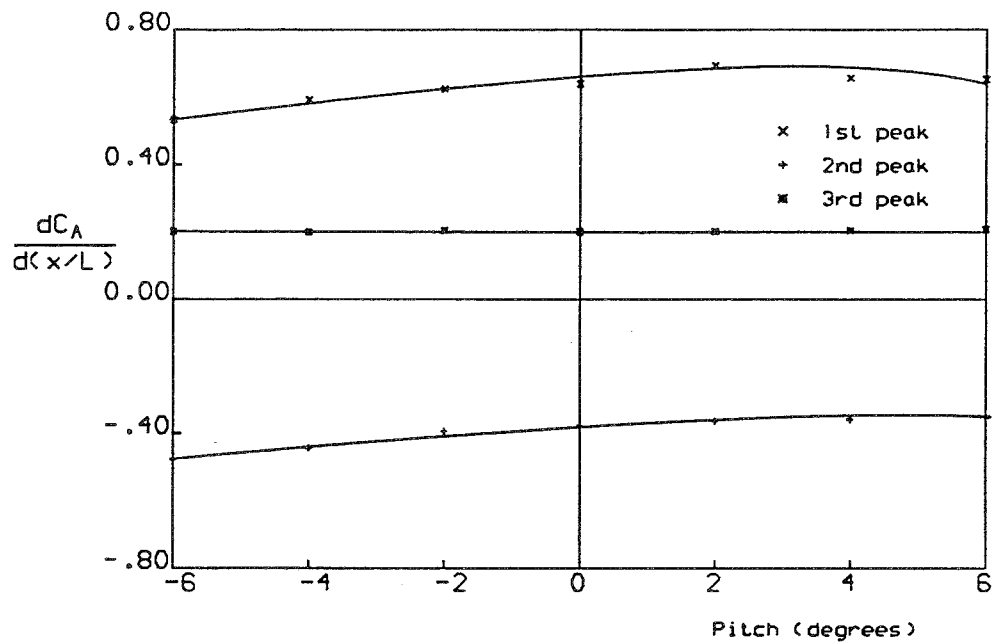


a) Variation of peak loadings with pitch

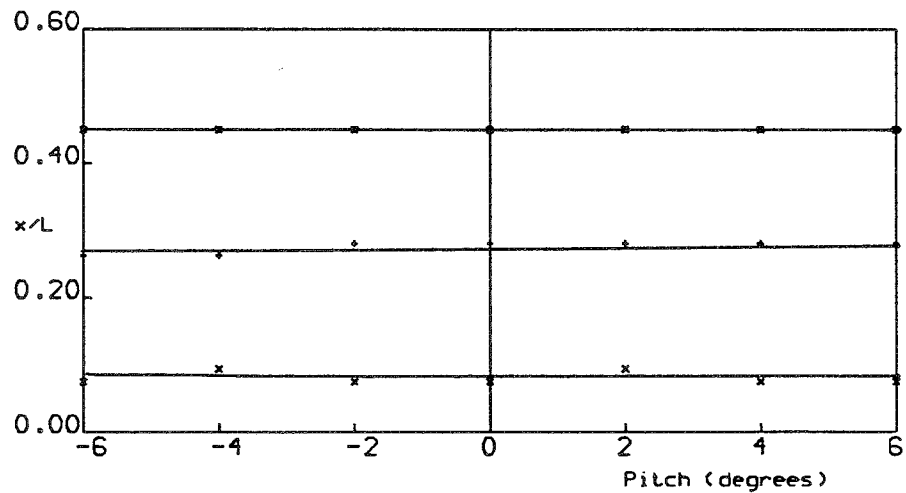


b) Variation of position of loading peaks with pitch

Figure 14. Two-body combination. Variation with pitch of the magnitude and position of the normal-force loading peaks

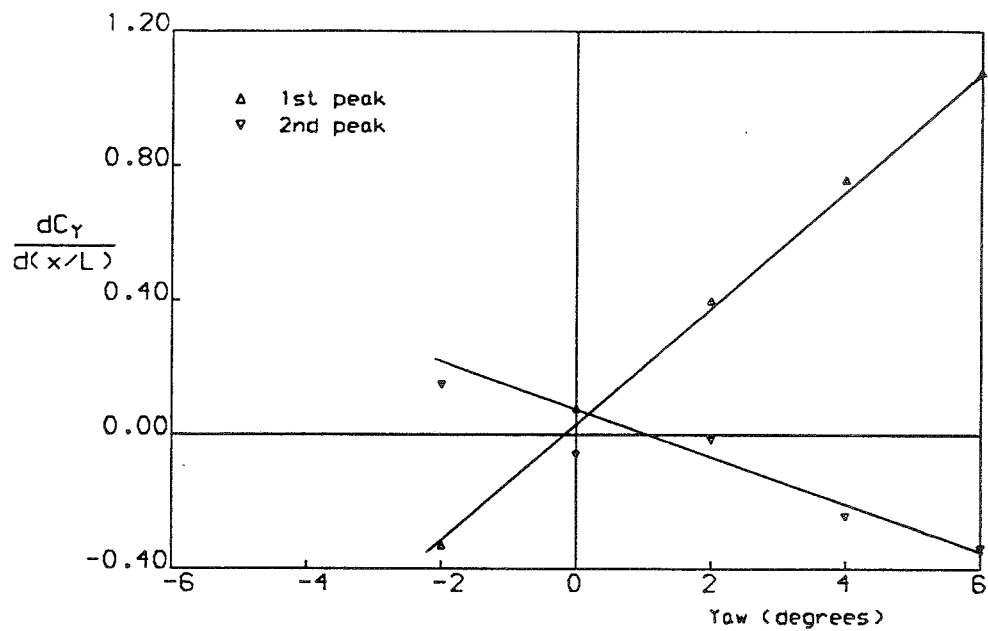


a) Variation of peak loadings with pitch

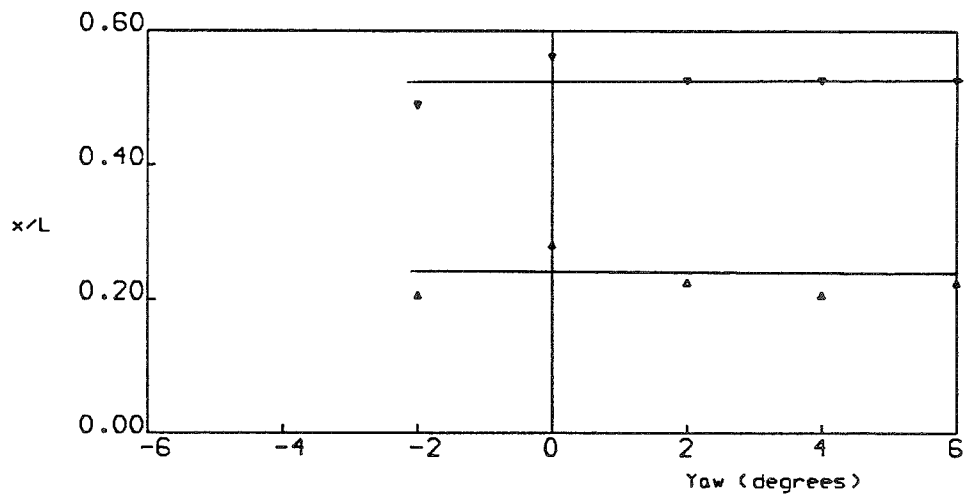


b) Variation of position of loading peaks with pitch

Figure 15. Two-body combination. Variation with pitch of the magnitude and position of the axial-force peak loadings

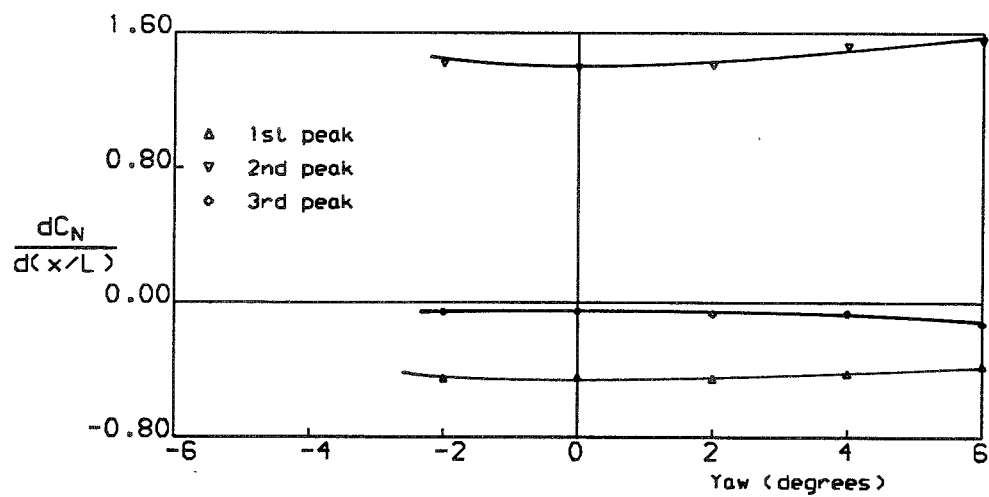


a) Variation of peak loadings with yaw

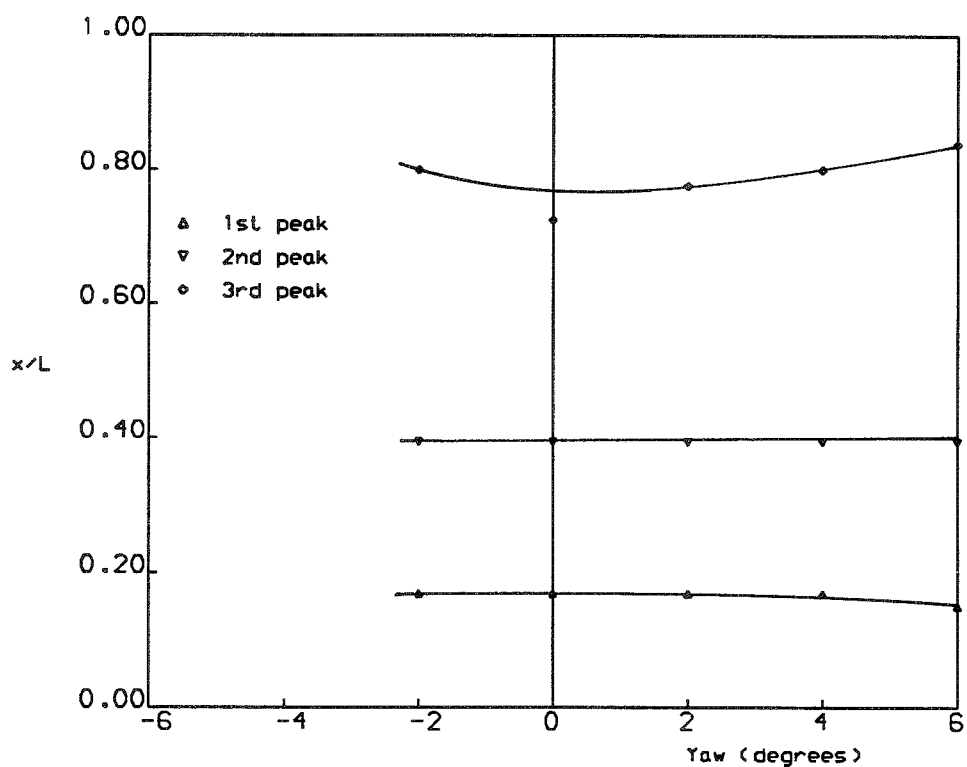


b) Variation of position of loading peaks with yaw

Figure 16. Two-body combination. Variation with yaw of the magnitude and position of the side-force loading peaks

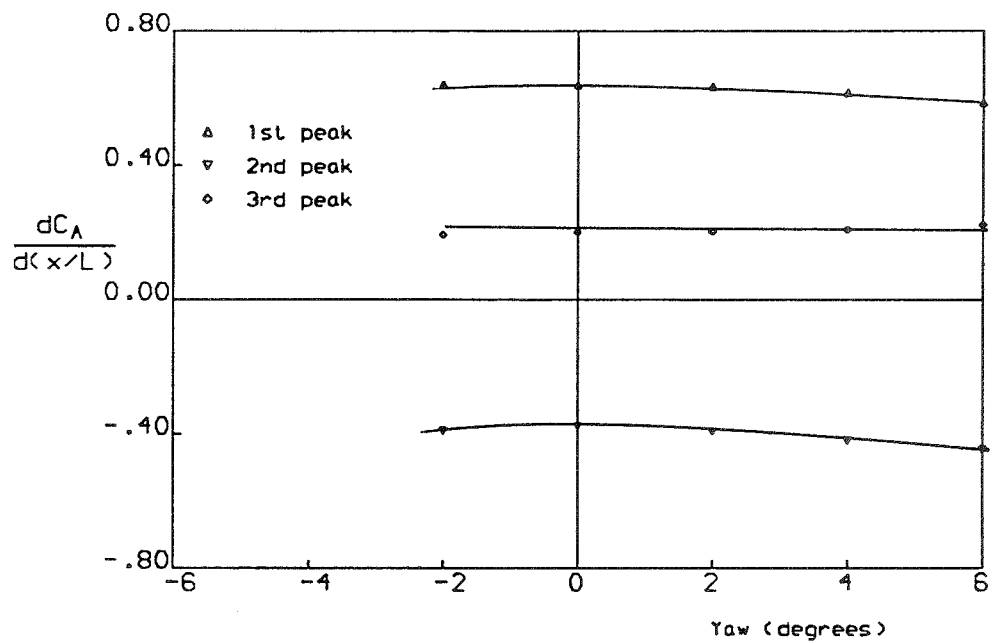


a) Variation of peak loadings with yaw

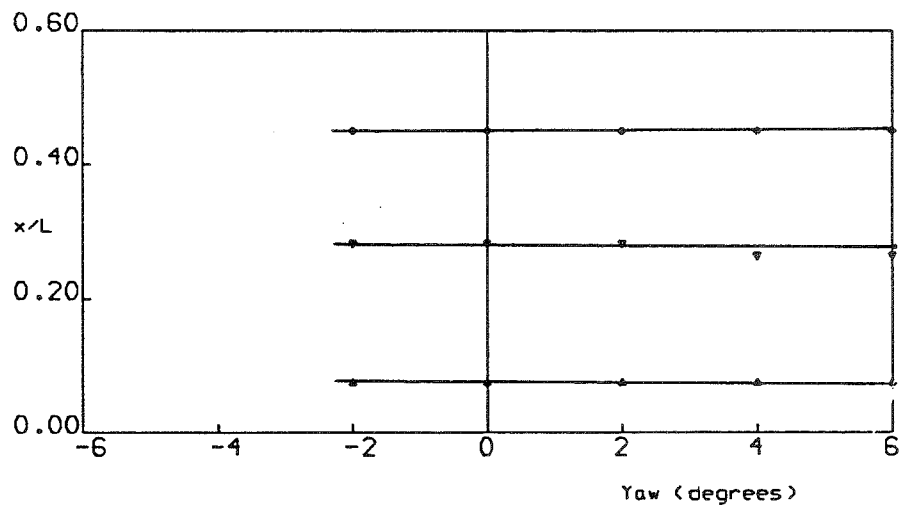


b) Variation of position of loading peaks with yaw

Figure 17. Two-body combination. Variation with yaw of the magnitude and position of the normal-force loading peaks



a) Variation of peak loadings with yaw



b) Variation of position of loading peaks with pitch

Figure 18. Two-body combination. Variation with yaw of the magnitude and position of the axial-force peak loadings

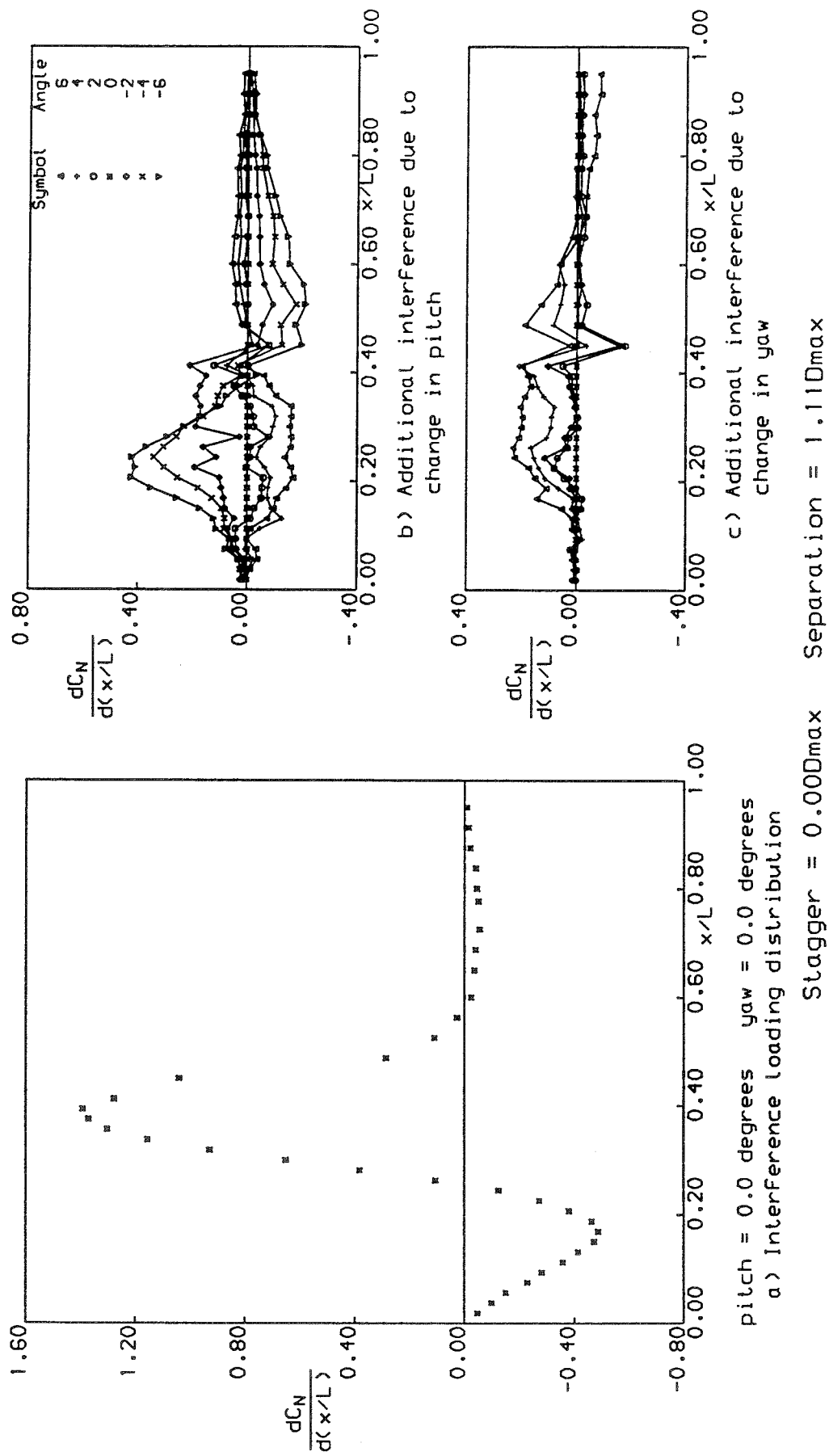


Figure 19. Variation of the interference normal-force loading with pitch and yaw

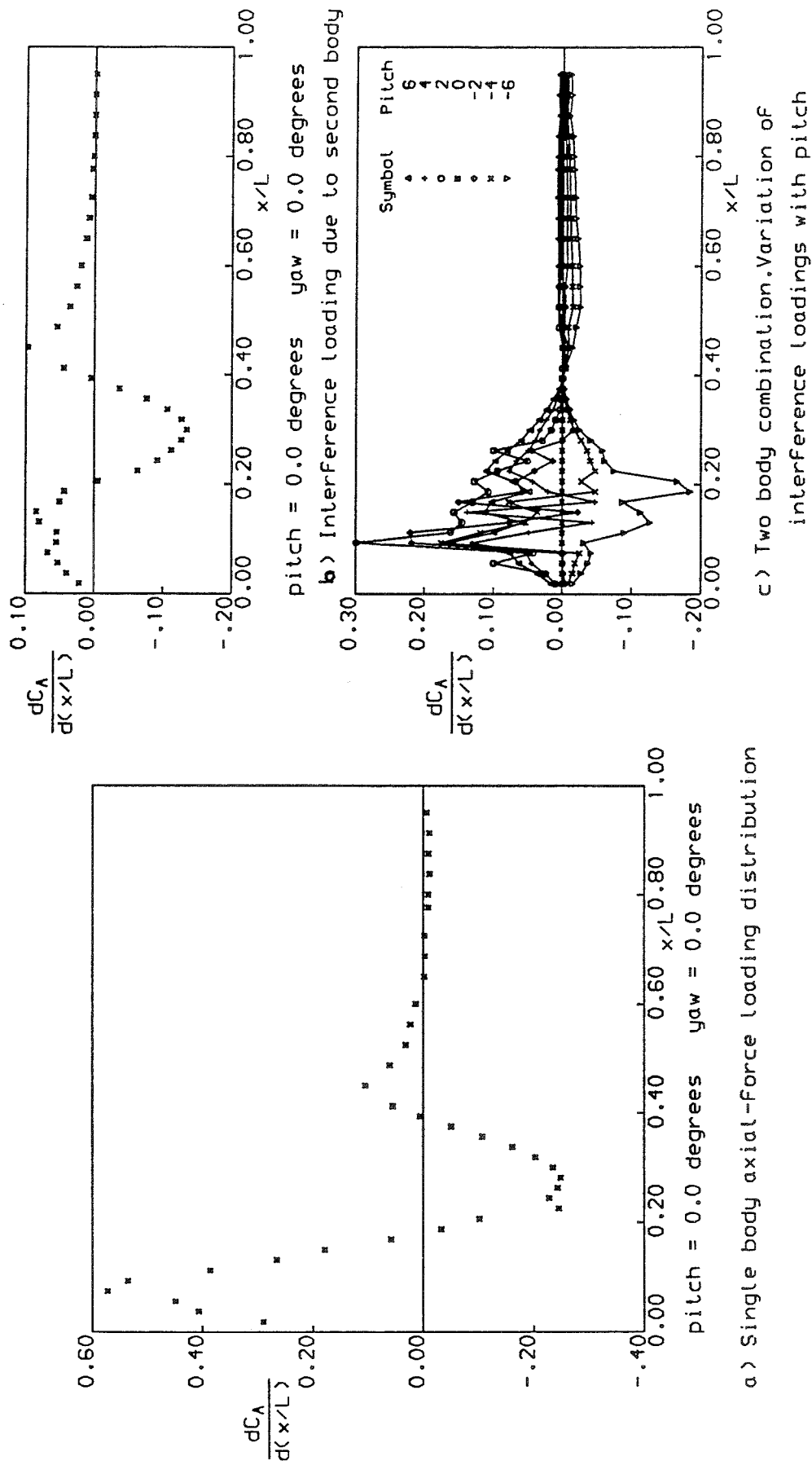
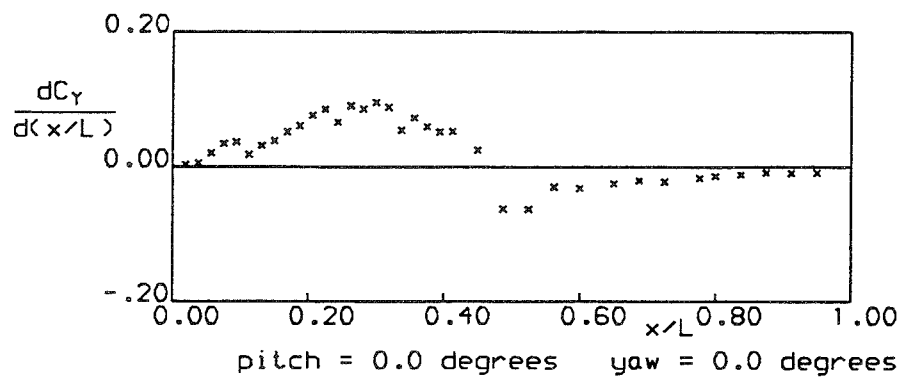
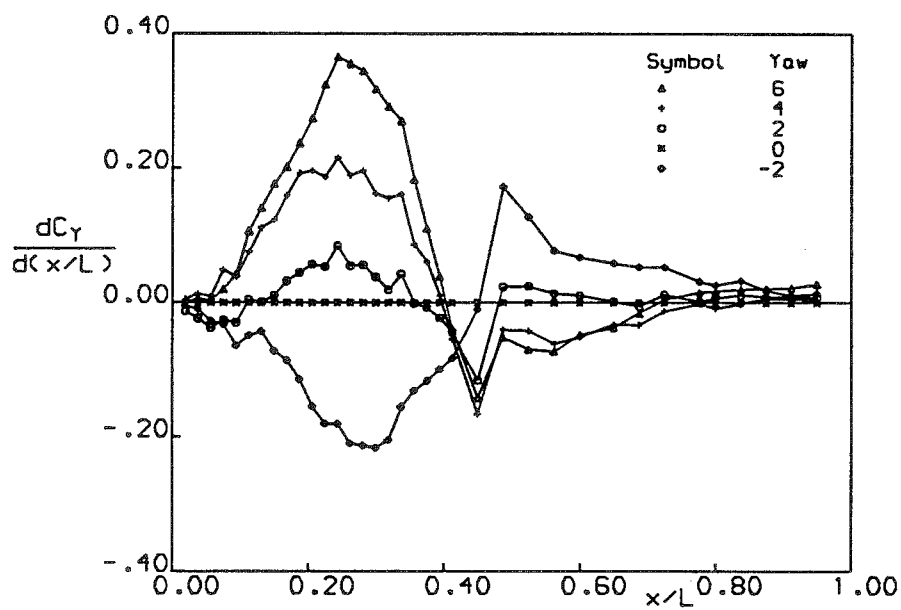


Figure 20. Changes in the axial-force loading on the instrumented body due to the second body and changes in pitch



a) Interference due to second body



b) Two body combination. Variation in interference loading with change in yaw

Figure 21. Variation in side-force loading due to the presence of the second body and change in yaw

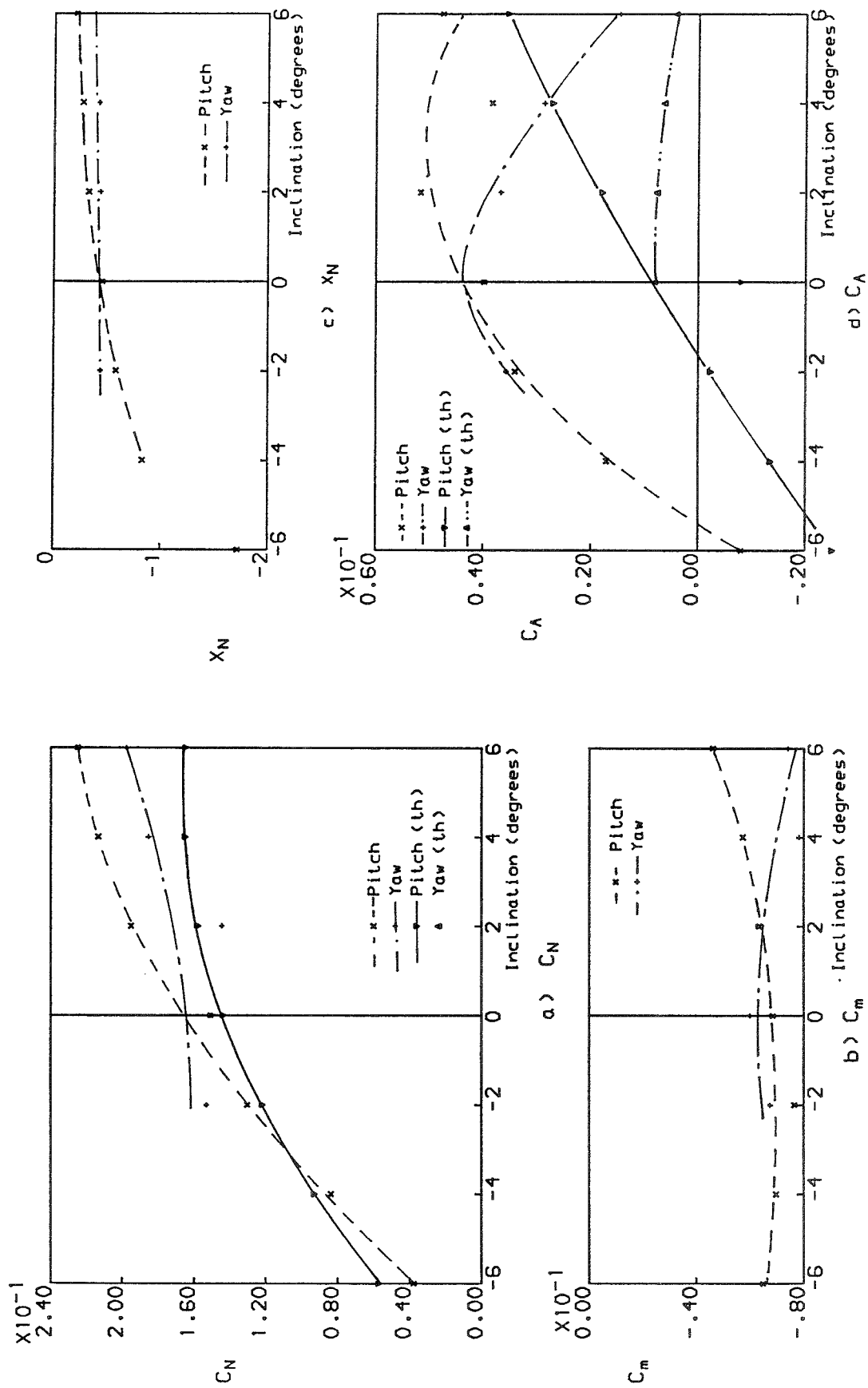


Figure 22. Two-body combination. Overall aerodynamic characteristics of the instrumented body

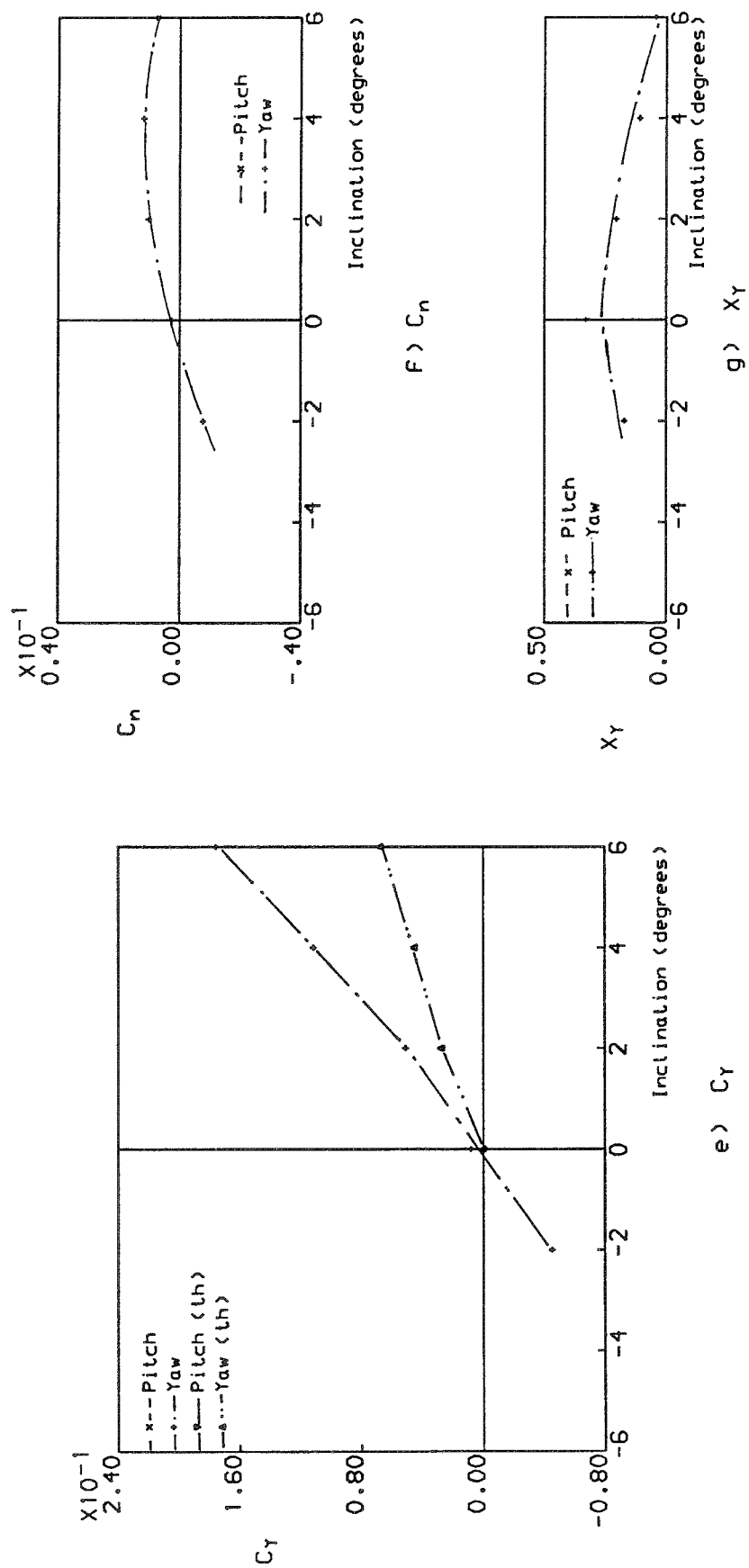


Figure 22 continued

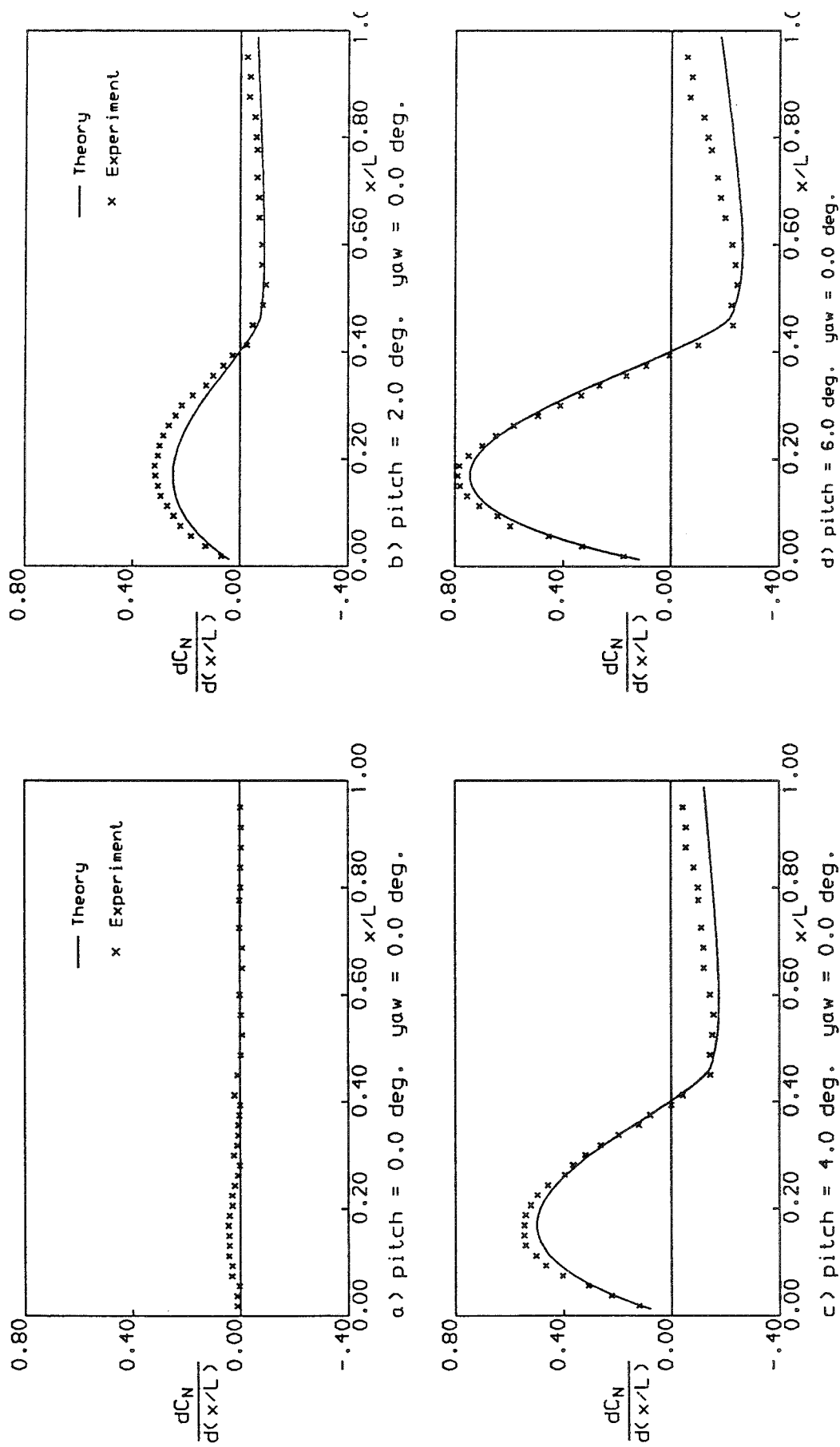


Figure 23. Single body. Comparison of experimental and theoretical normal-force loading distributions as pitch is varied

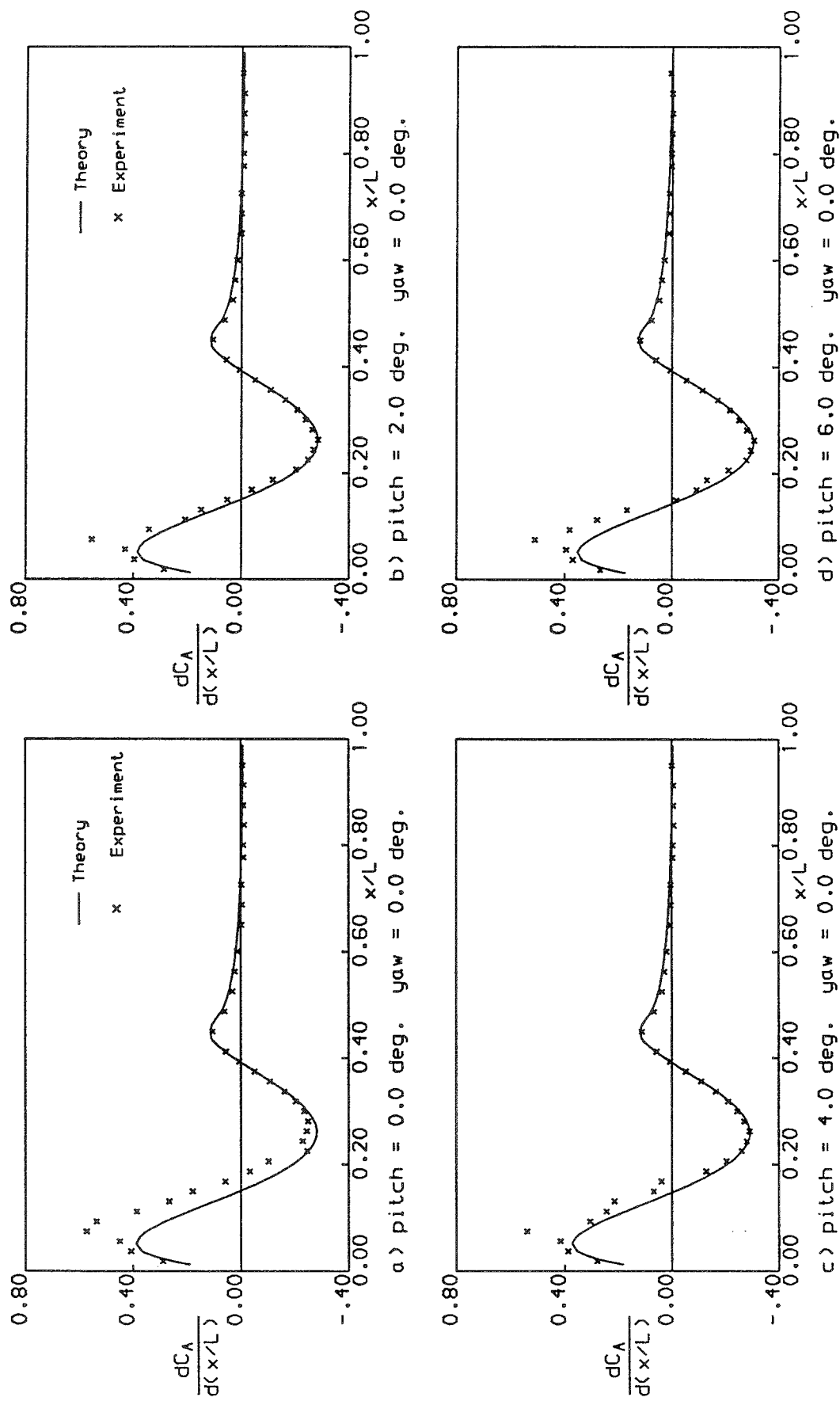


Figure 24. Single body. Comparison of experimental and theoretical axial-force loading distributions as pitch is varied

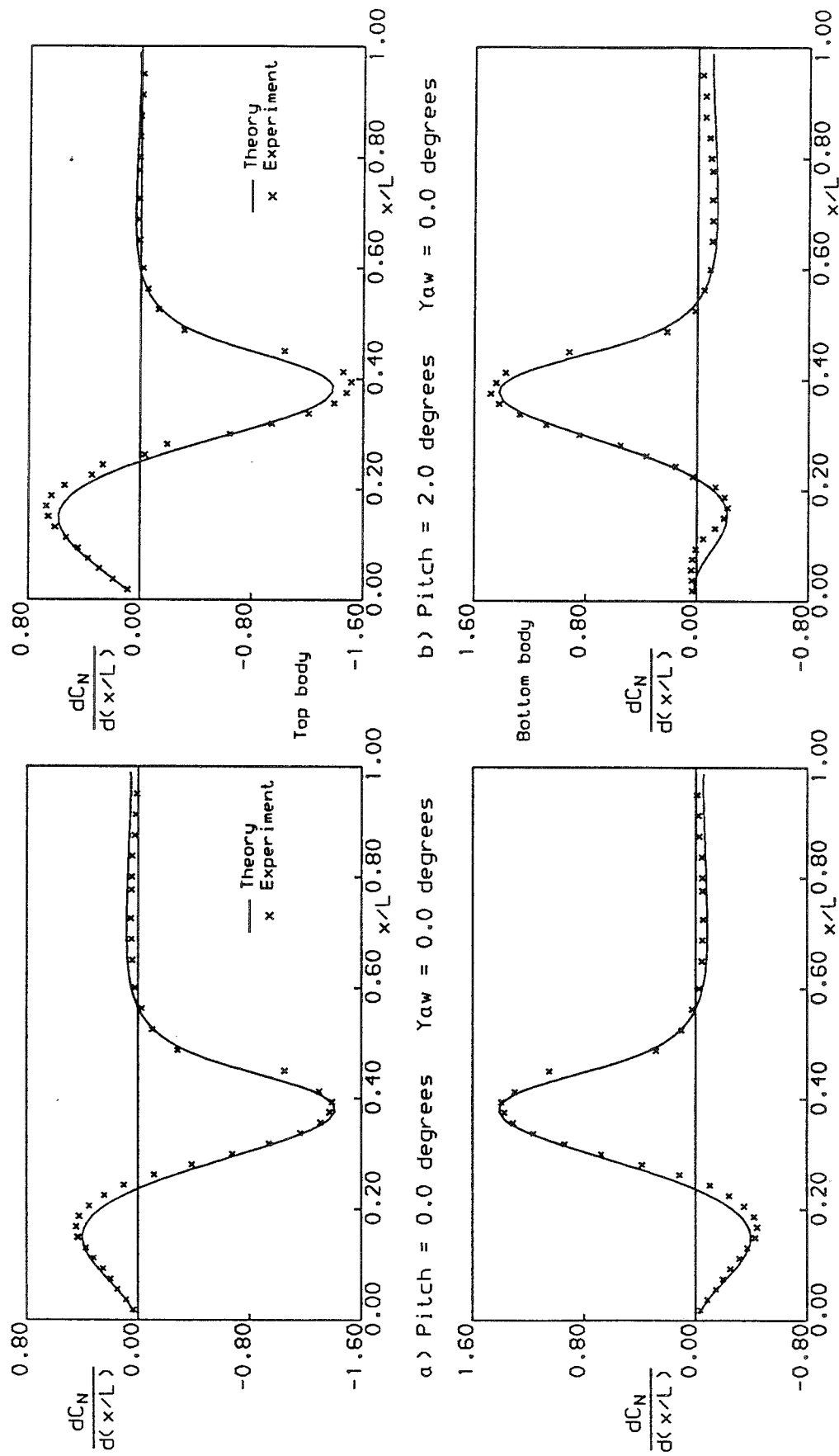


Figure 25. Two-body combination. Comparison of experimental and theoretical normal-force loading distributions as pitch is varied

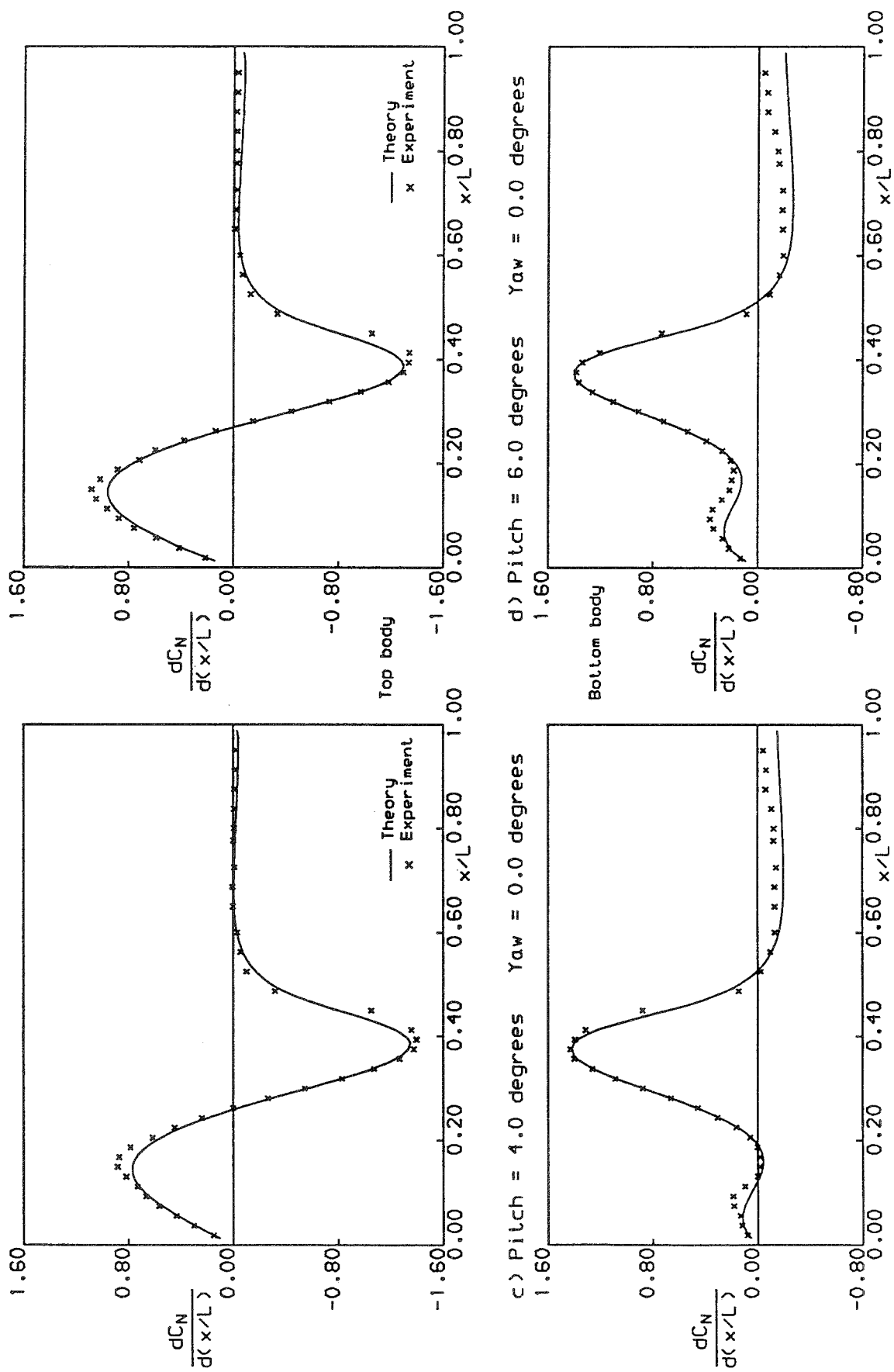


Figure 25 continued

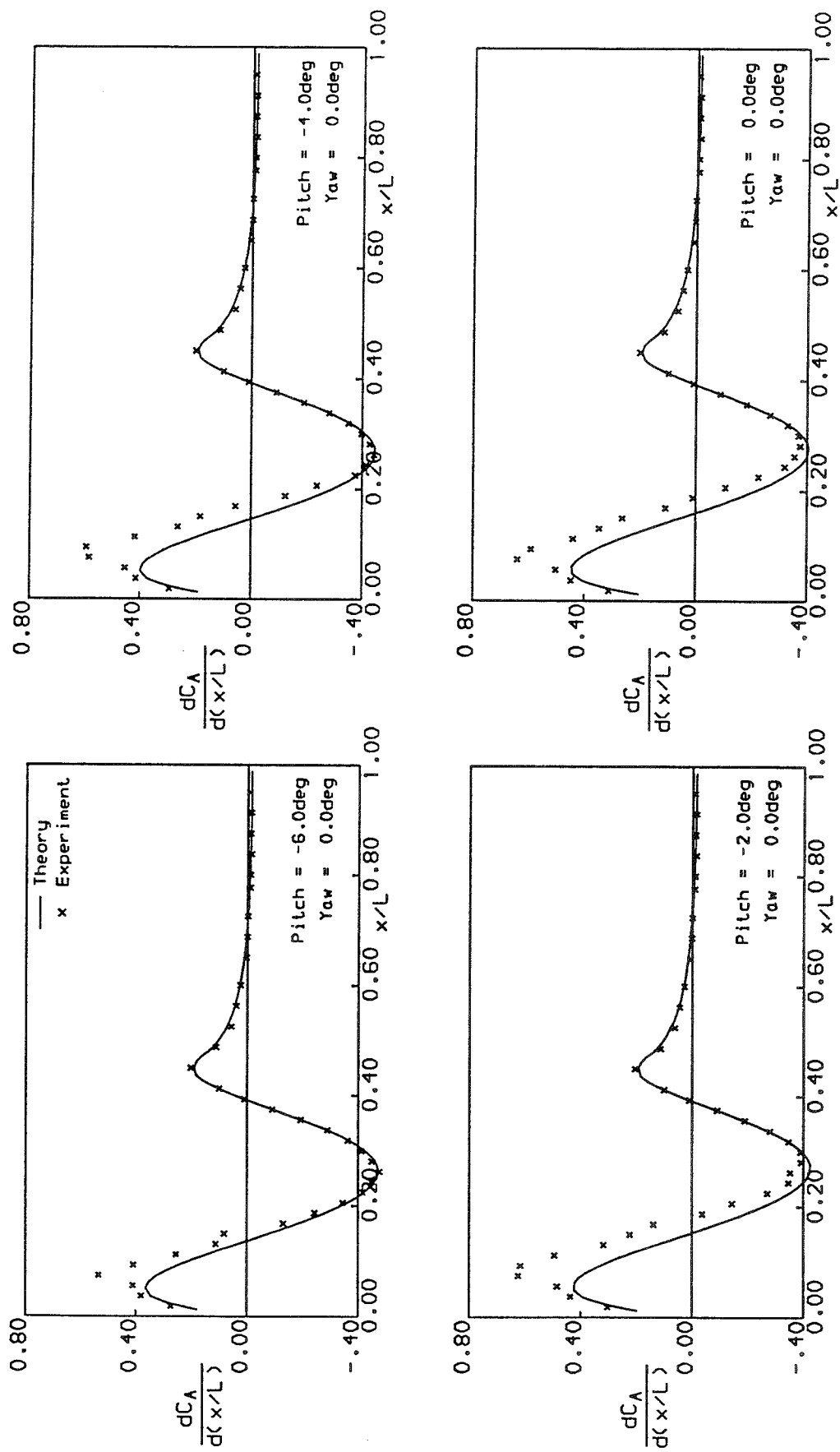


Figure 26. Two-body combination. Comparison of experimental and theoretical axial-force loading distributions as pitch is varied

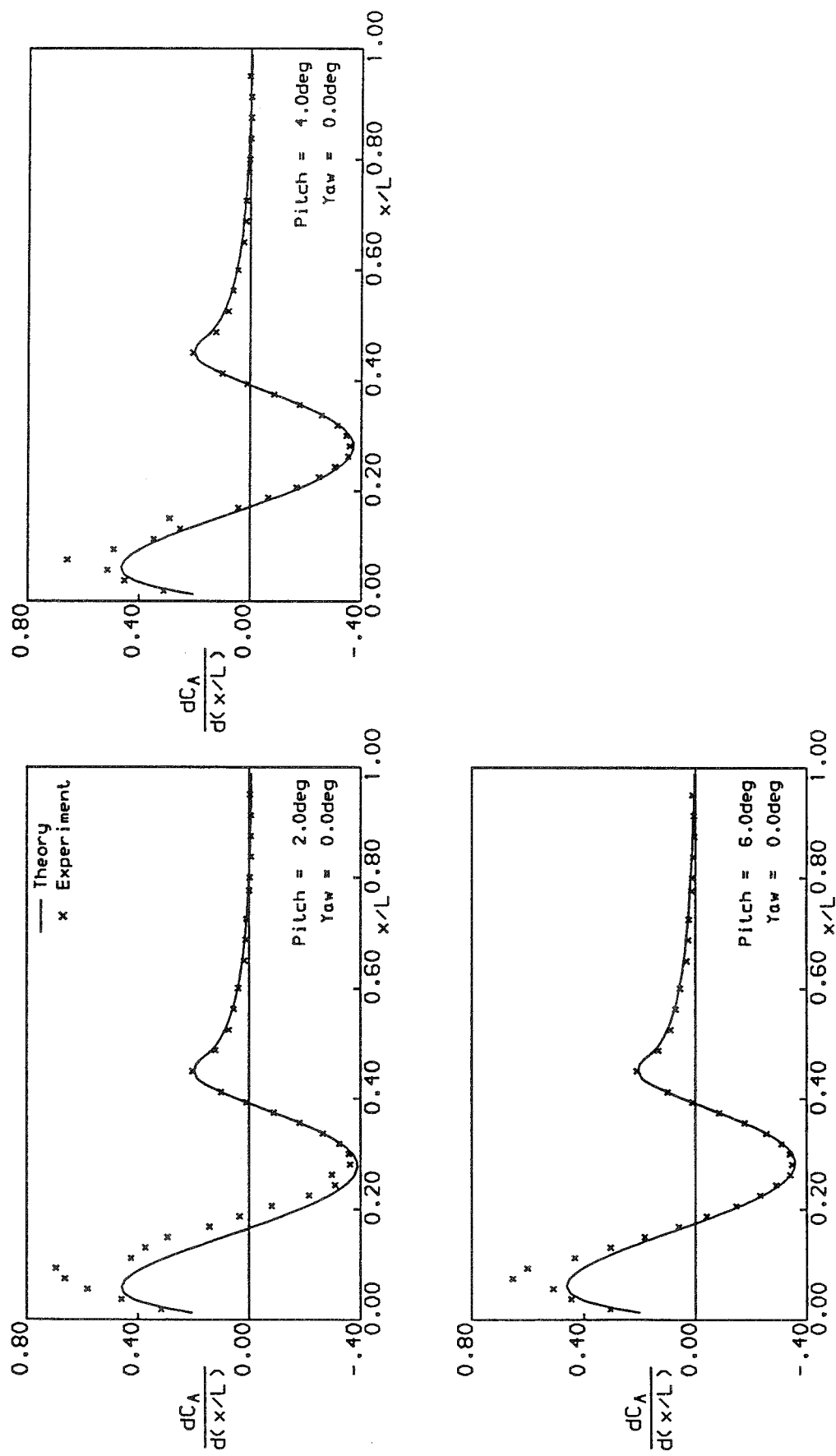


Figure 26 continued

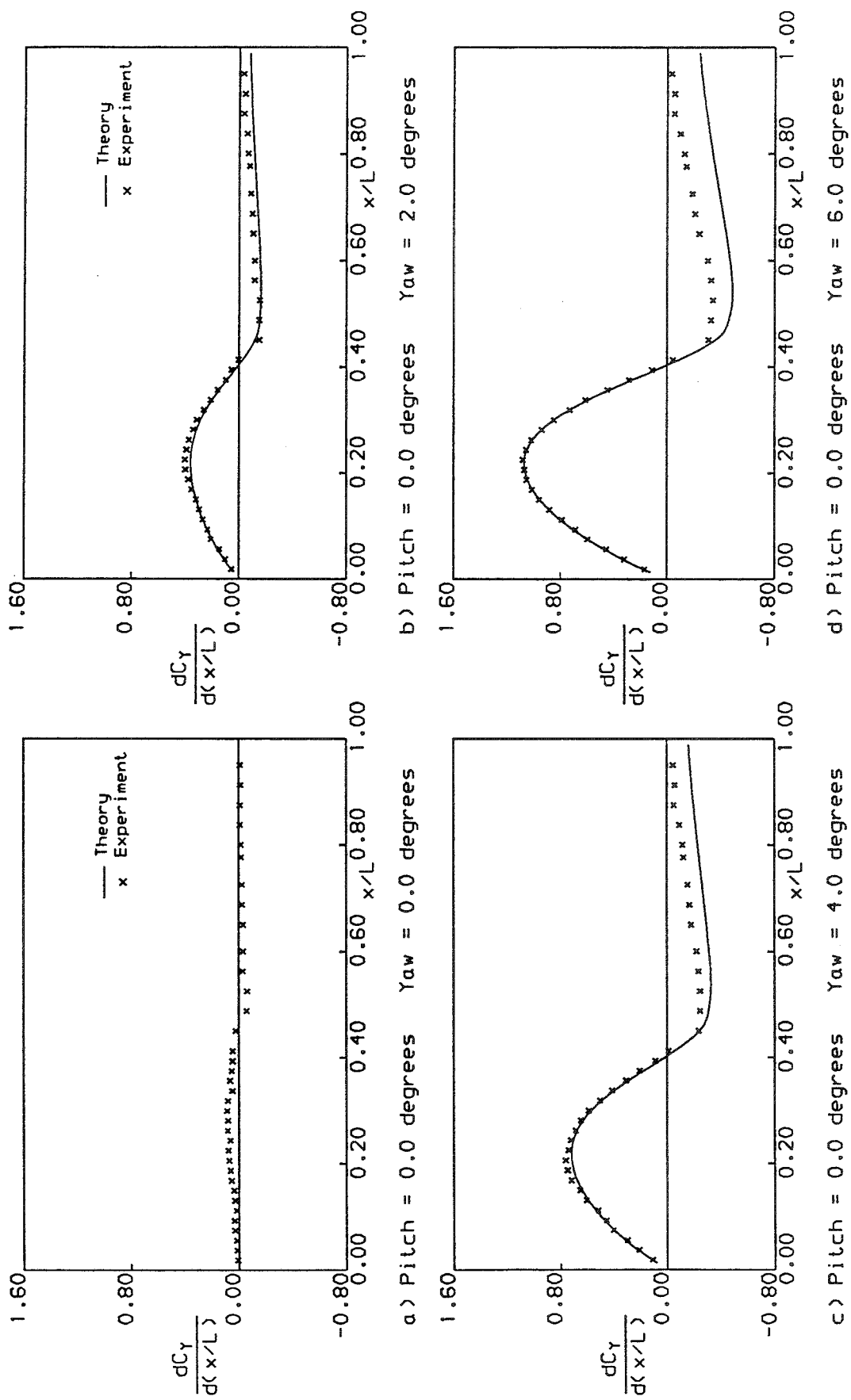


Figure 27. Two-body combination. Comparison of experimental and theoretical side-force loading distributions as yaw is varied

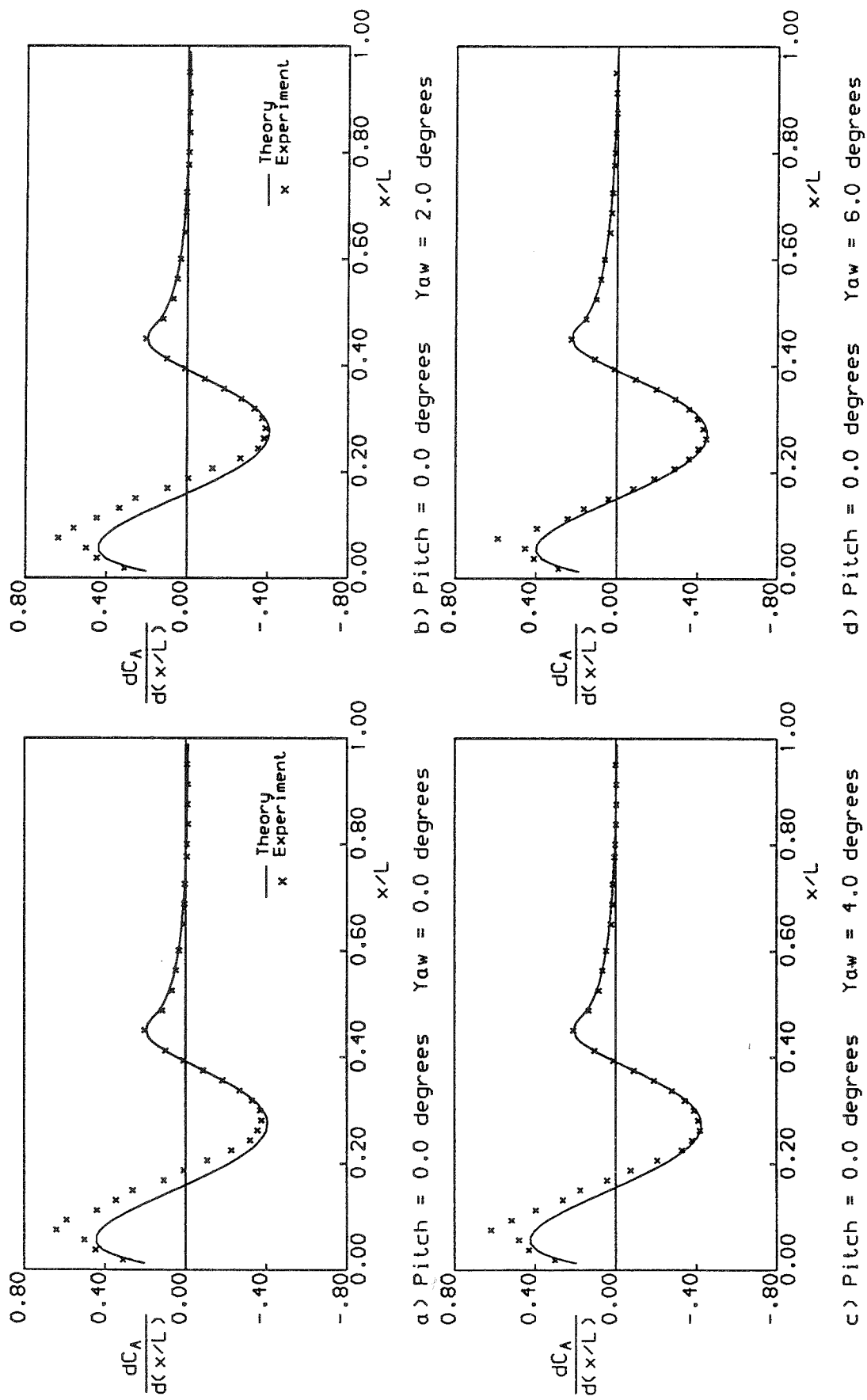


Figure 28. Two-body combination. Comparison of experimental and theoretical axial-force loading distributions as yaw is varied

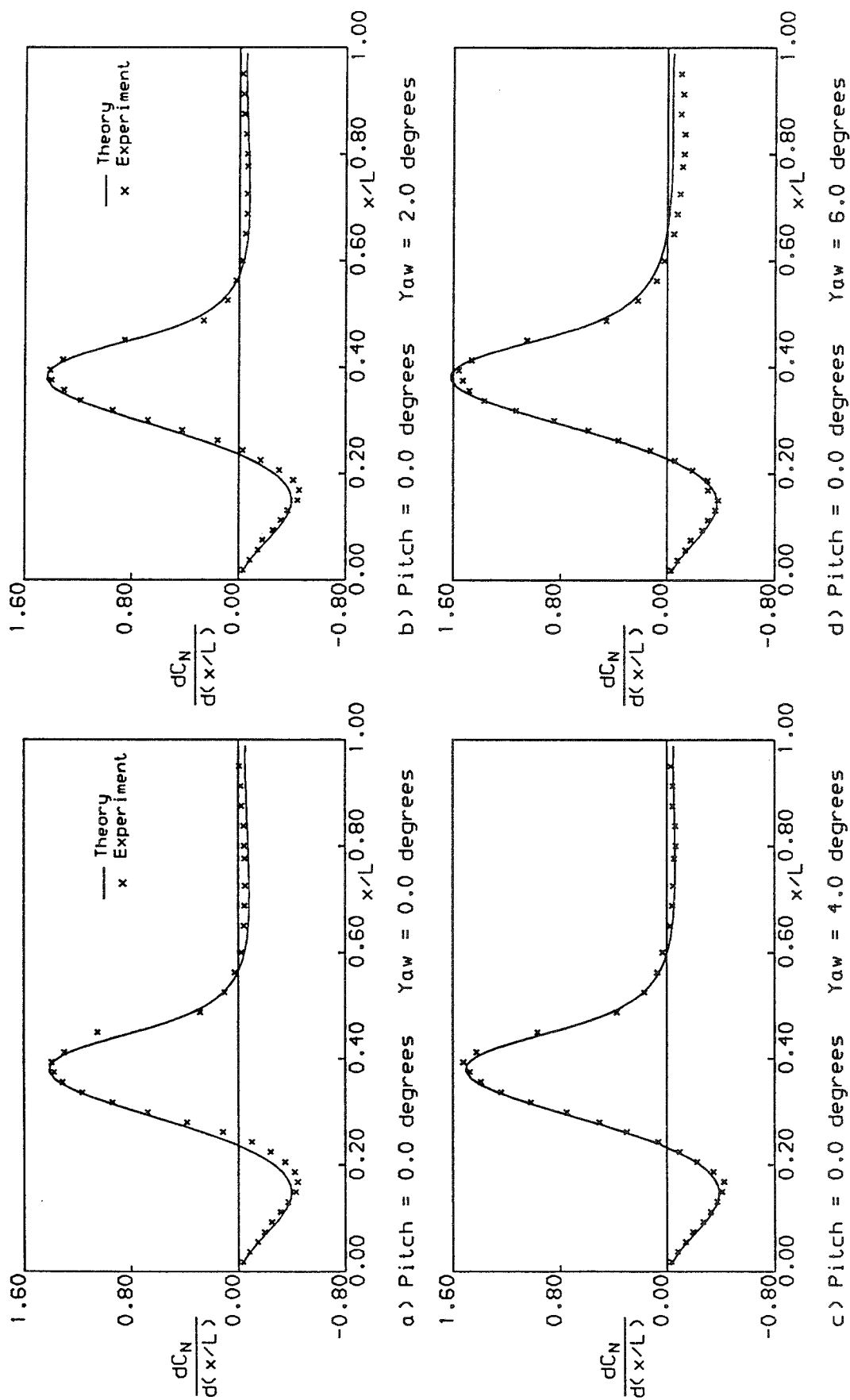
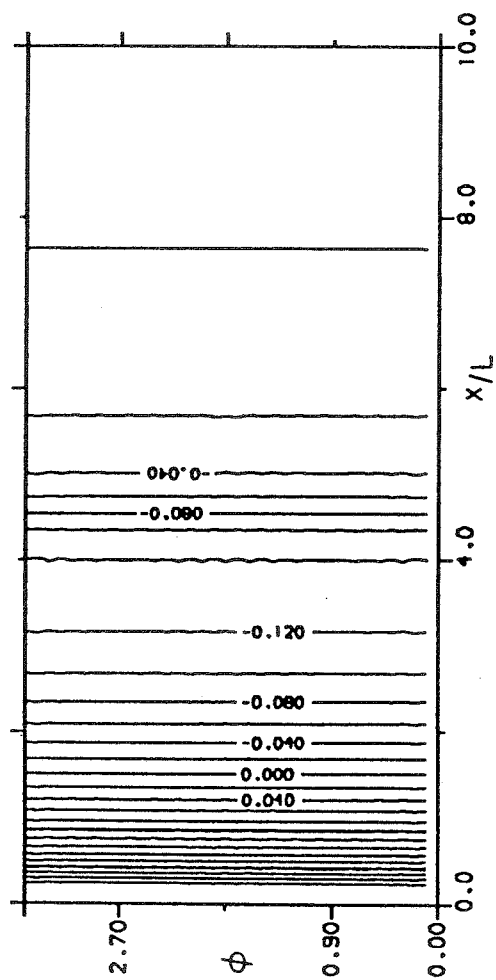
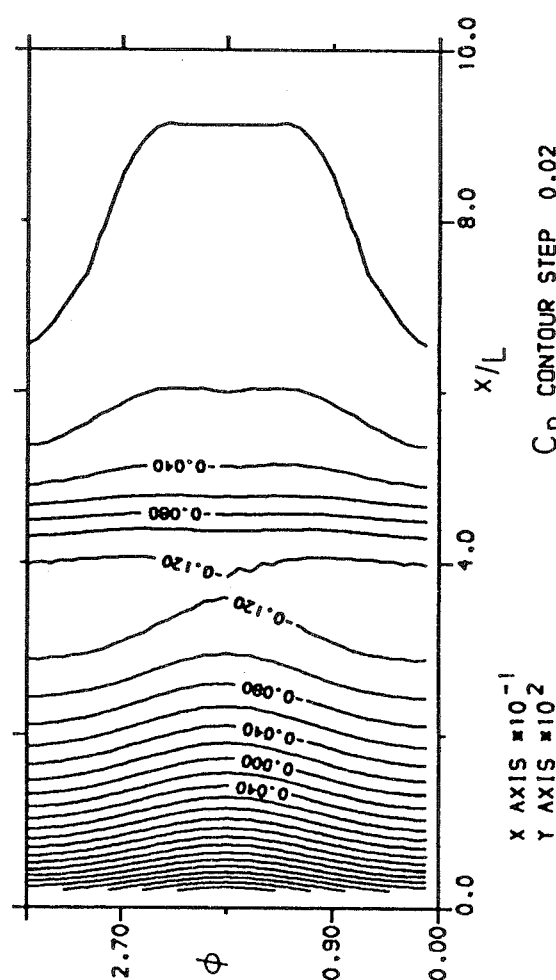


Figure 29. Two-body combination. Comparison of experimental and theoretical normal-force loading distributions as yaw is varied



C_p CONTOUR STEP 0.02
a) pitch = 0.0 degrees yaw = 0.0 degrees



C_p CONTOUR STEP 0.02
b) pitch = 2.0 degrees yaw = 0.0 degrees

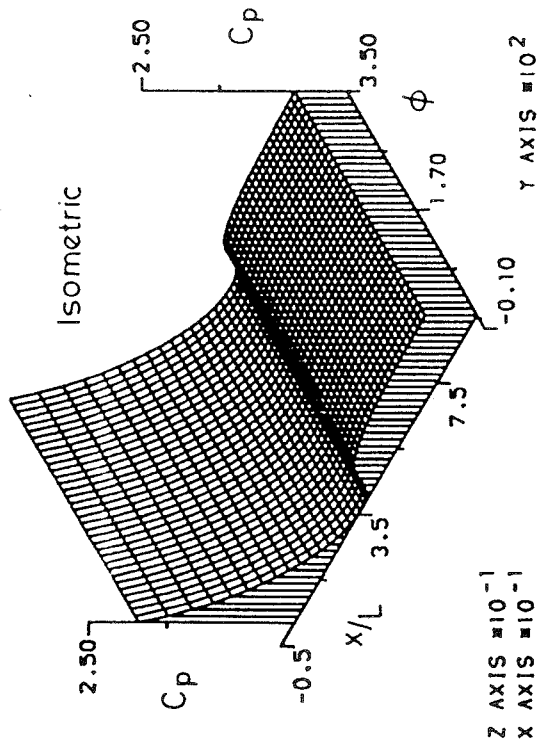
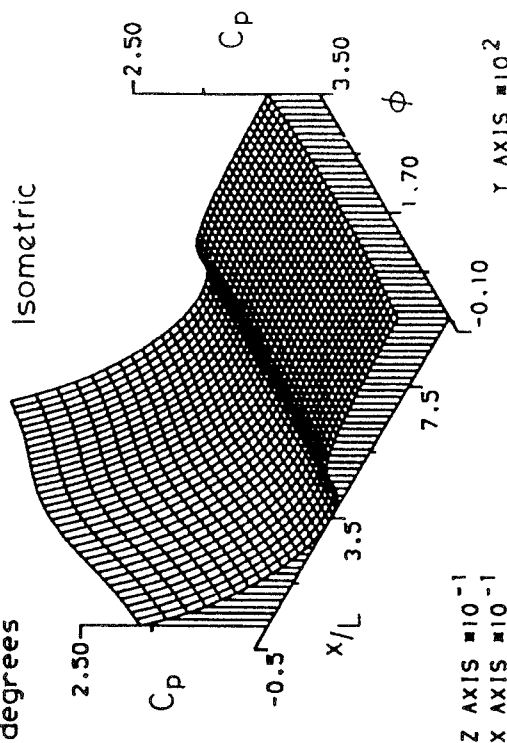
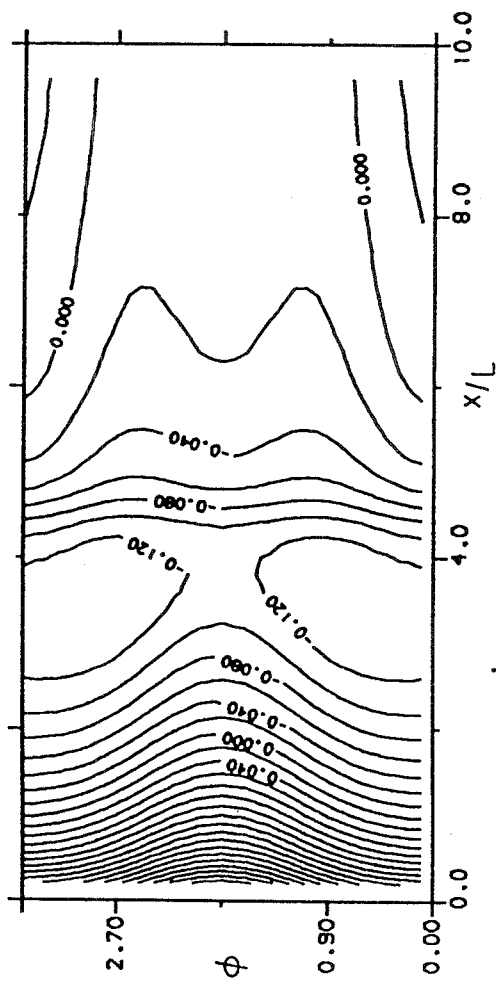


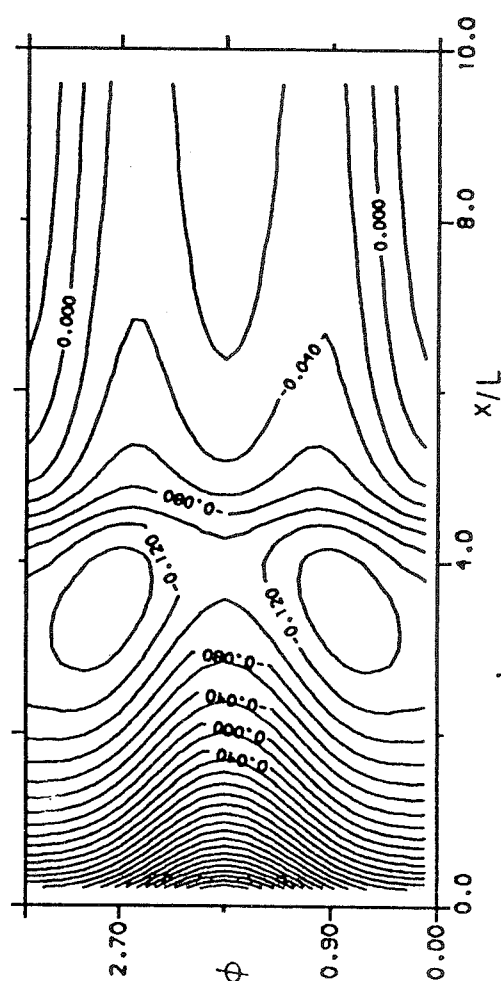
Figure 30. Single-body. Variation of the calculated pressure distributions with pitch



X AXIS $\times 10^{-1}$
Y AXIS $\times 10^2$

C_p CONTOUR STEP 0.02

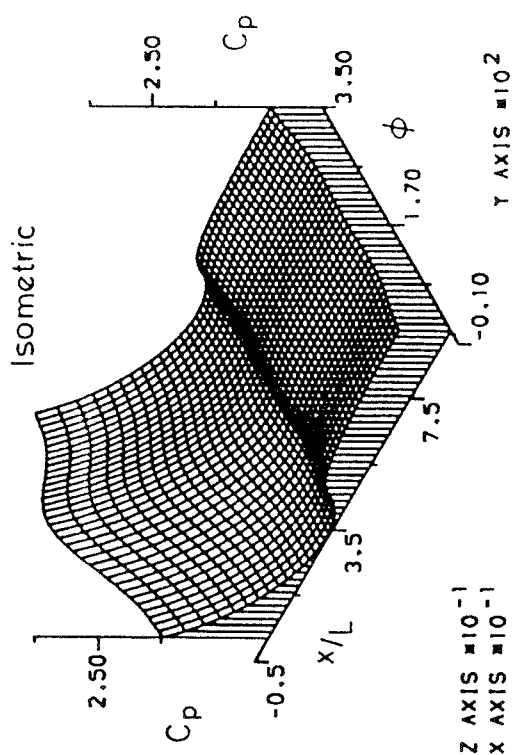
c) pitch = 4.0 degrees yaw = 0.0 degrees



X AXIS $\times 10^{-1}$
Y AXIS $\times 10^2$

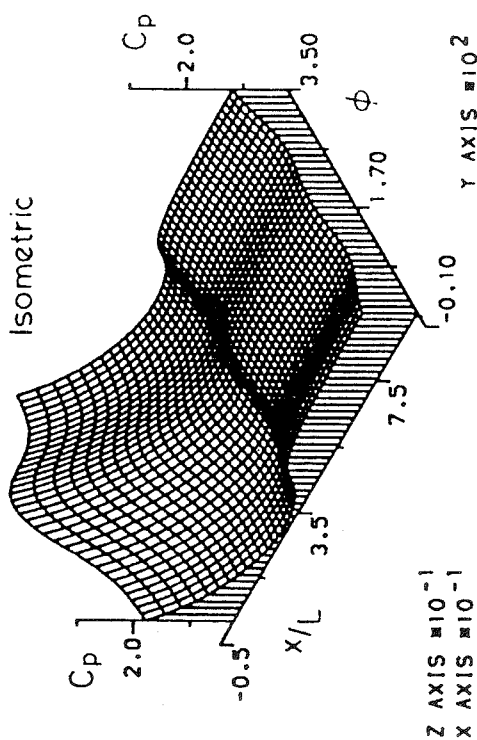
C_p CONTOUR STEP 0.02

d) pitch = 6.0 degrees yaw = 0.0 degrees



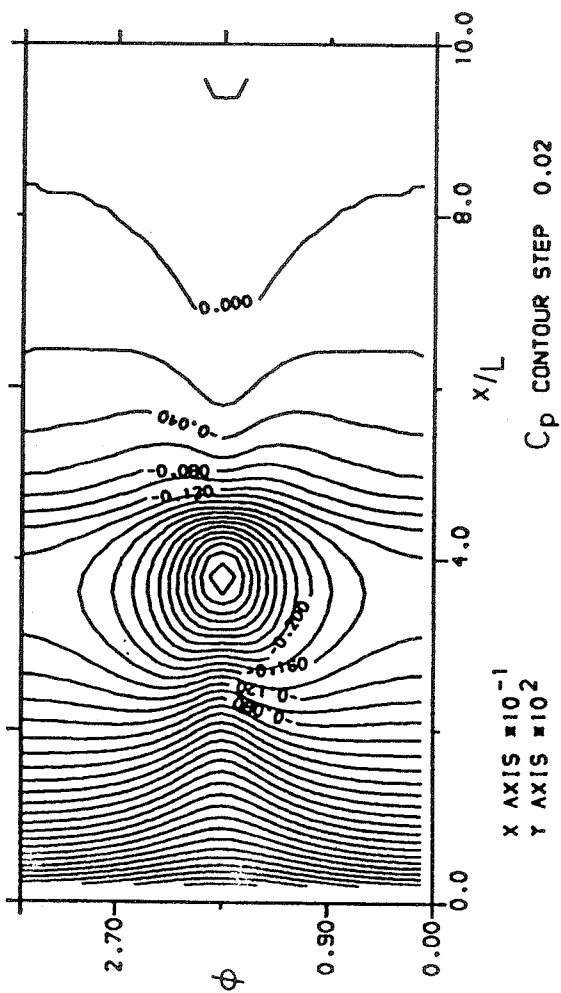
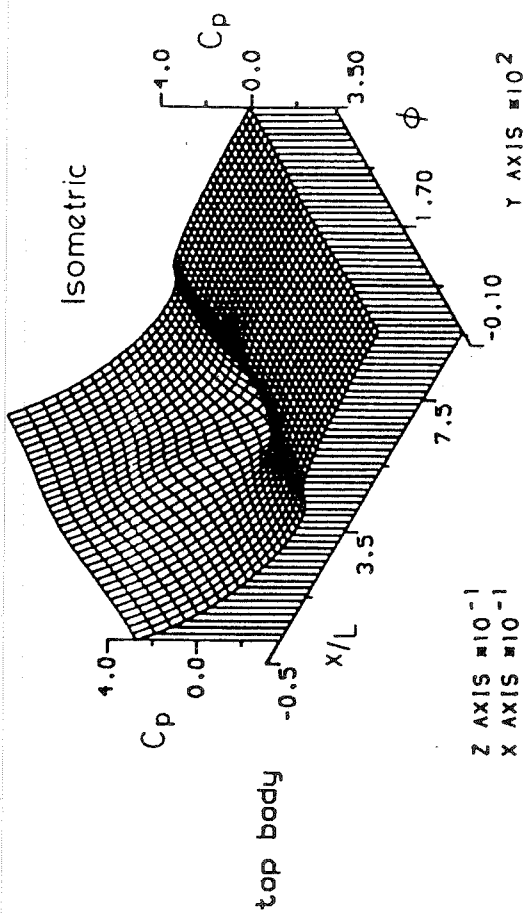
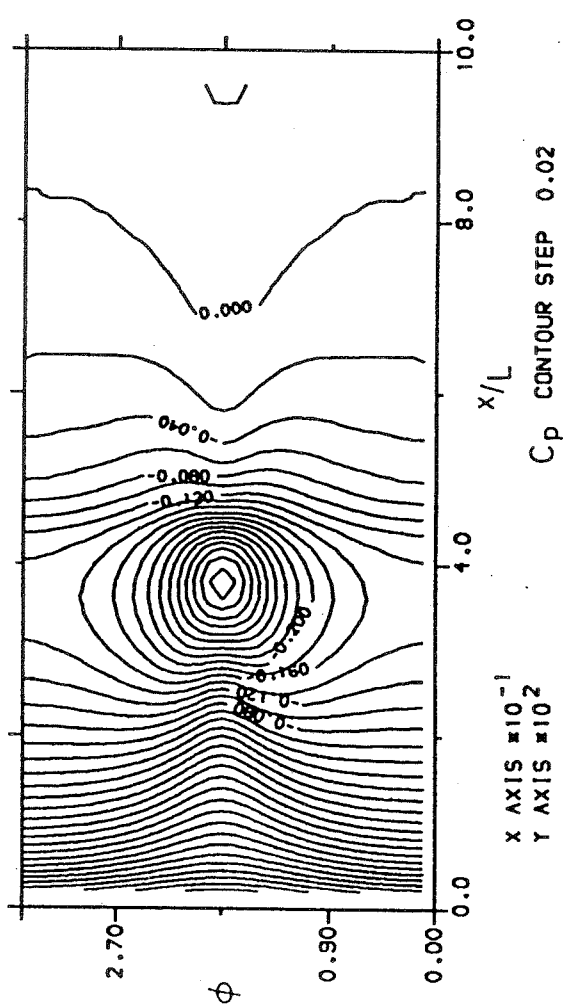
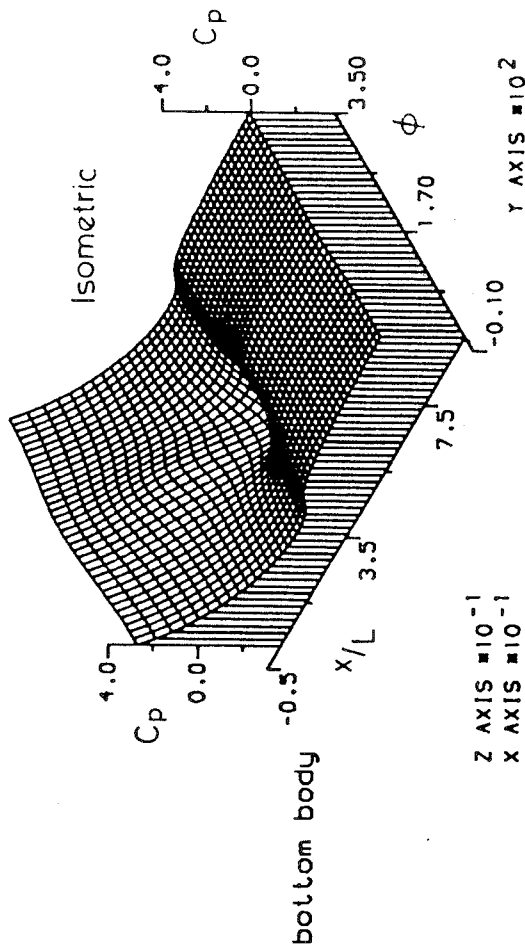
Z AXIS $\times 10^{-1}$
X AXIS $\times 10^{-1}$

yaw = 0.0 degrees



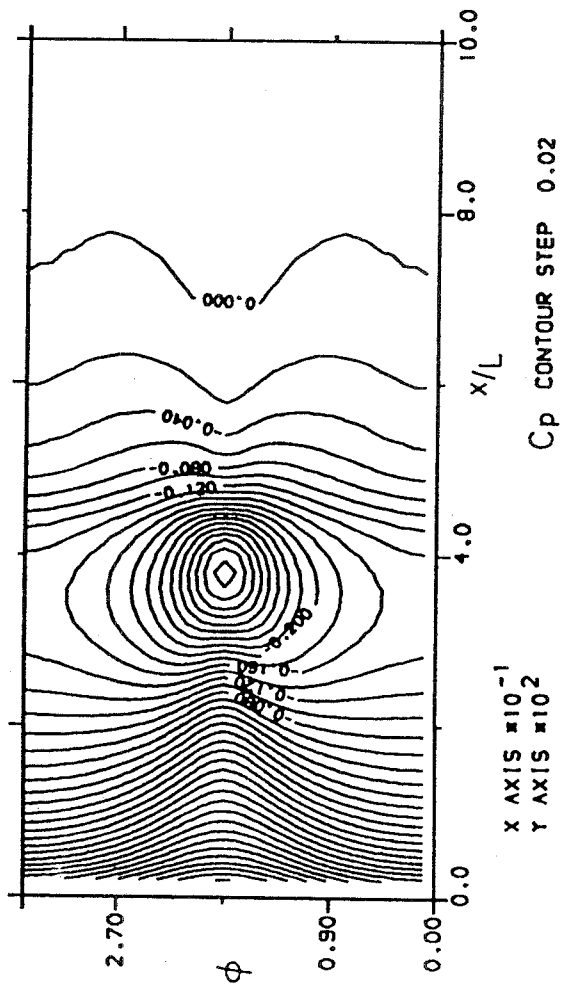
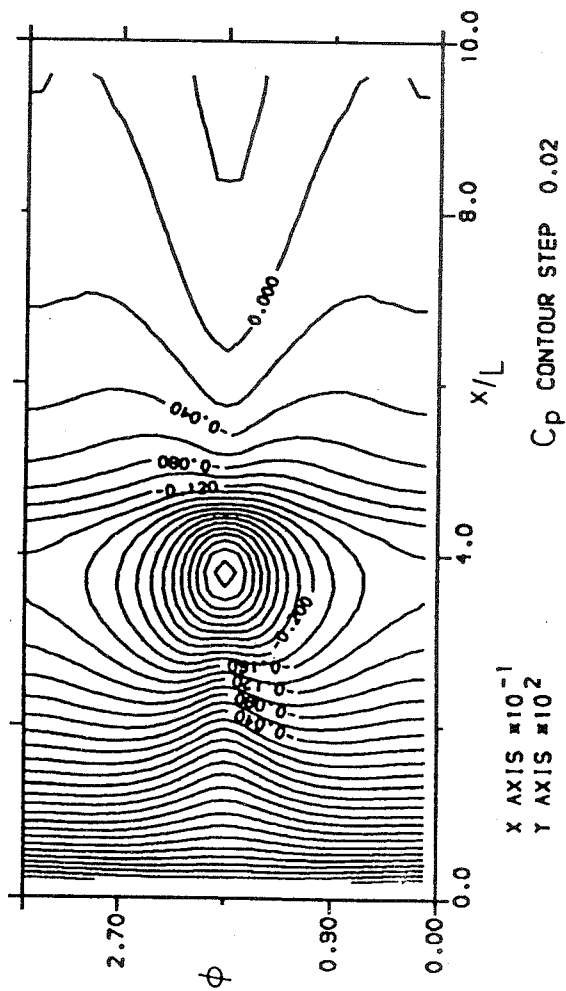
Z AXIS $\times 10^{-1}$
X AXIS $\times 10^{-1}$

Figure 30 continued



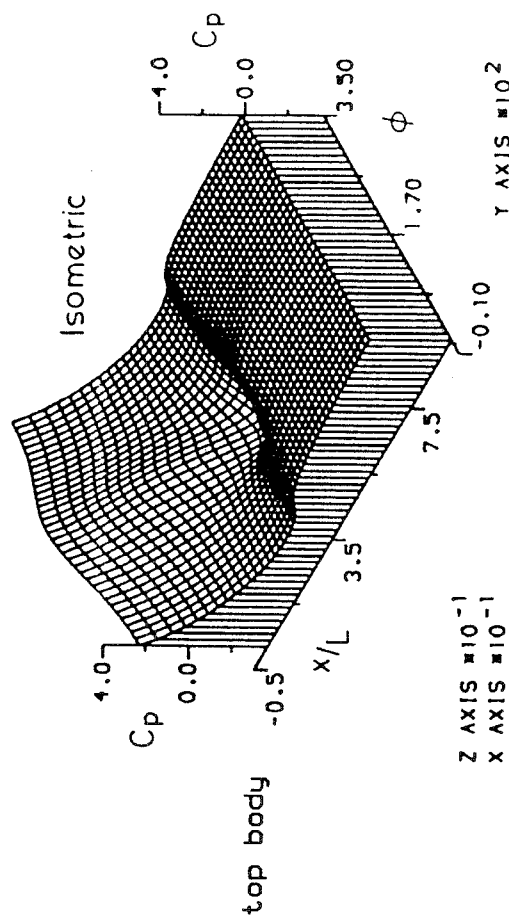
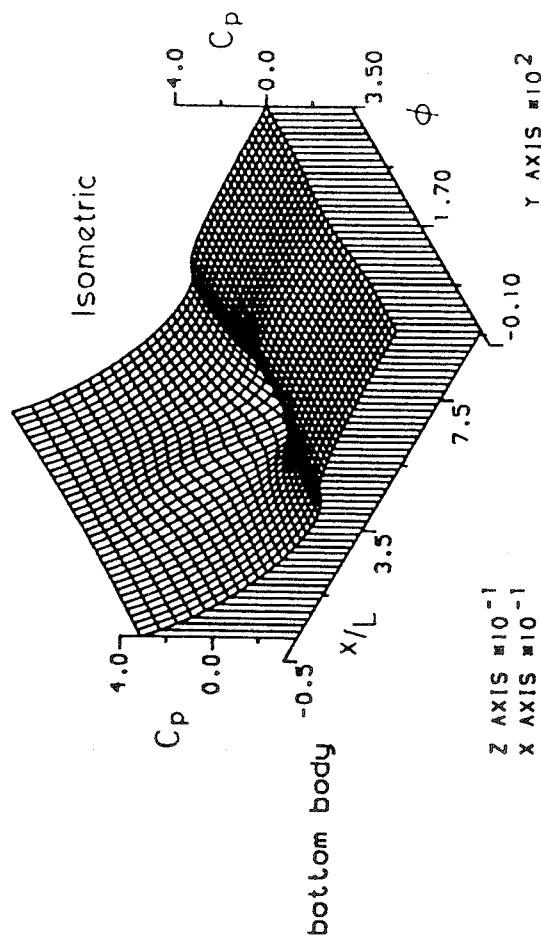
a) pitch = 0.0 degrees yaw = 0.0 degrees

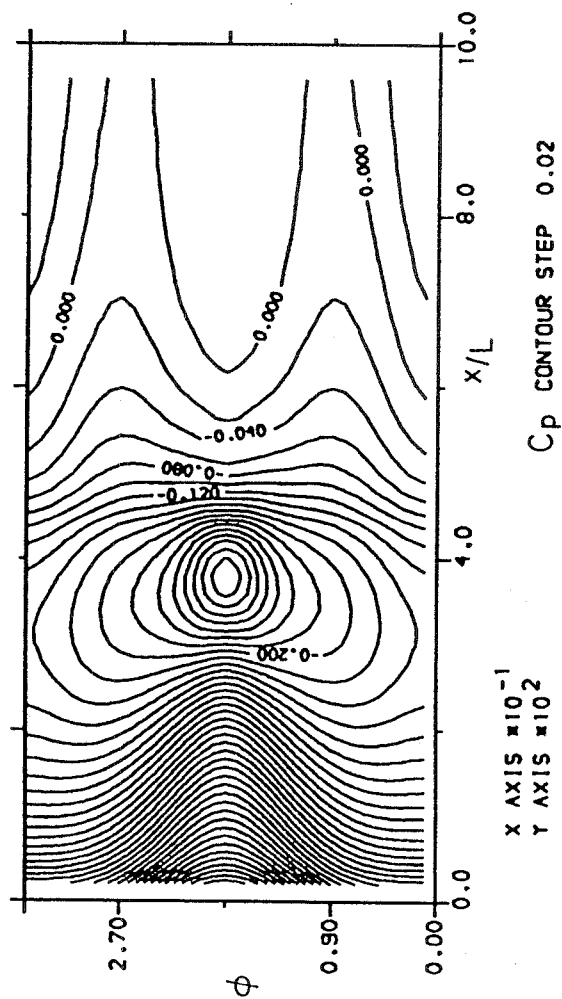
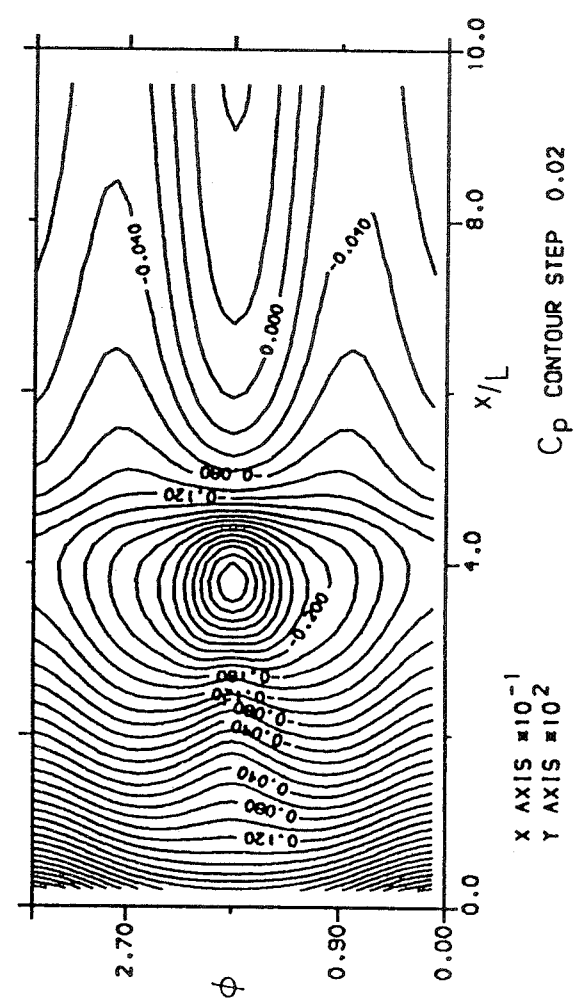
Figure 31. Two-body combination. Variation of the calculated pressure distributions with pitch



b) pitch = 2.0 degrees yaw = 0.0 degrees

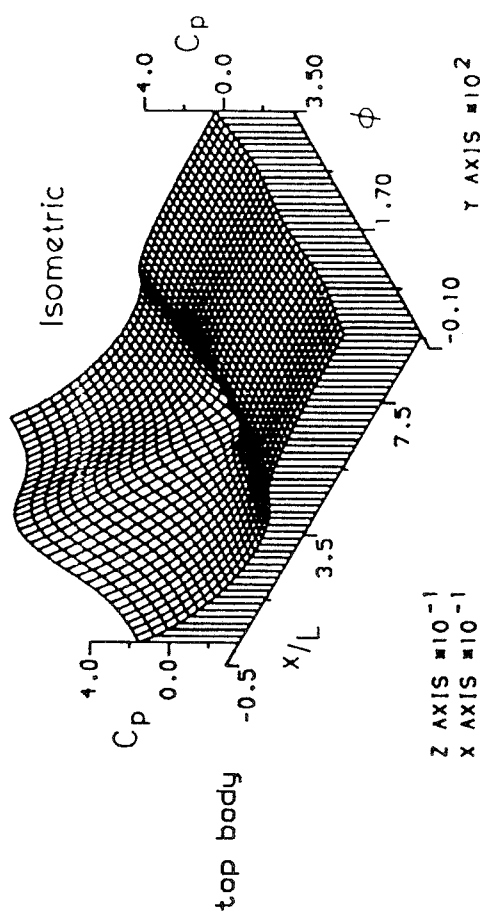
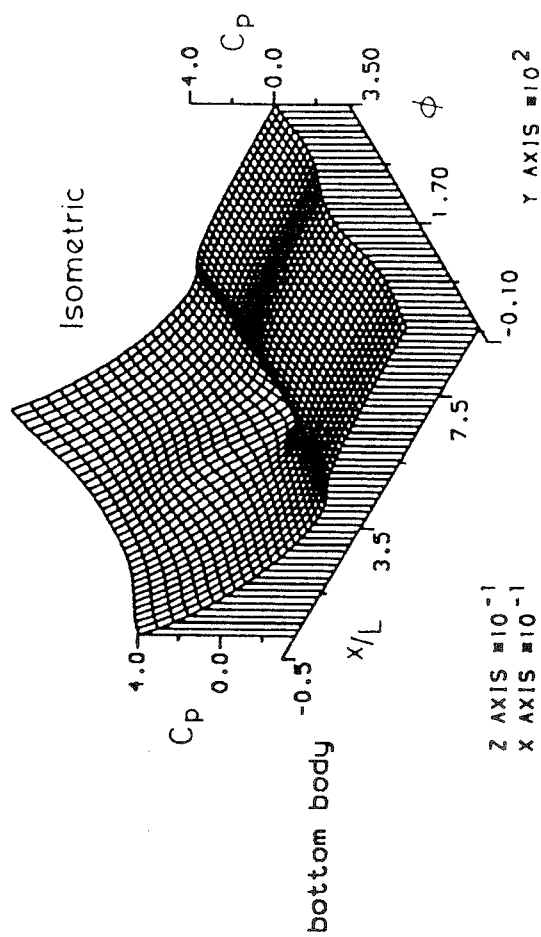
Figure 31 continued

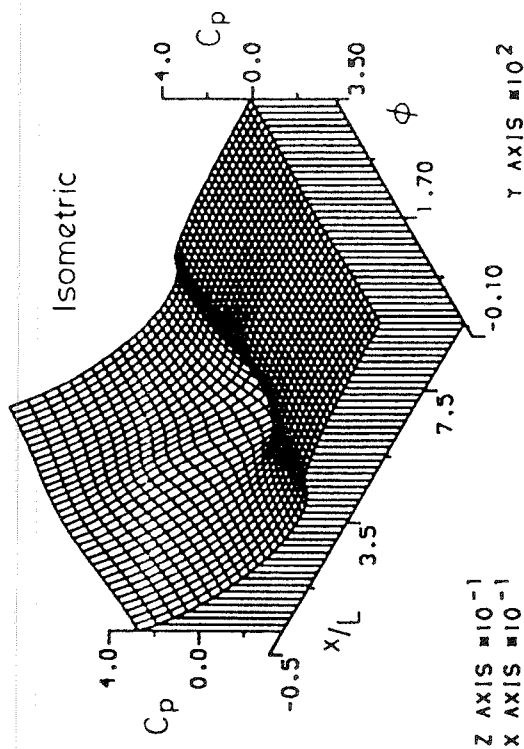




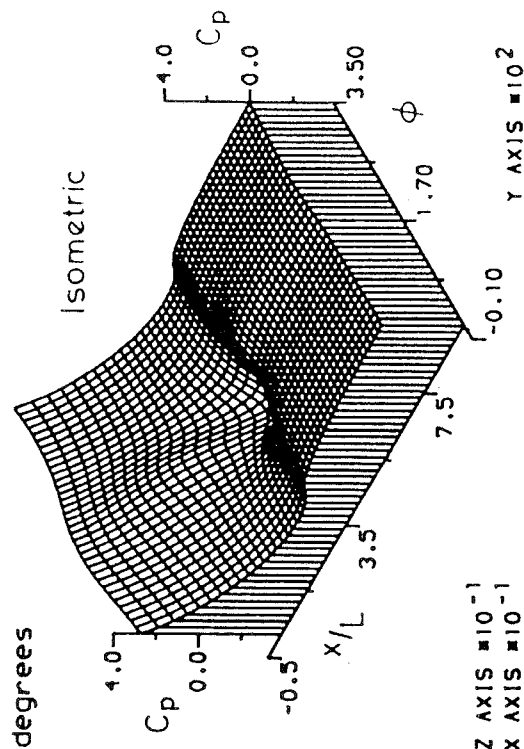
d) pitch = 6.0 degrees yaw = 0.0 degrees

Figure 31 concluded

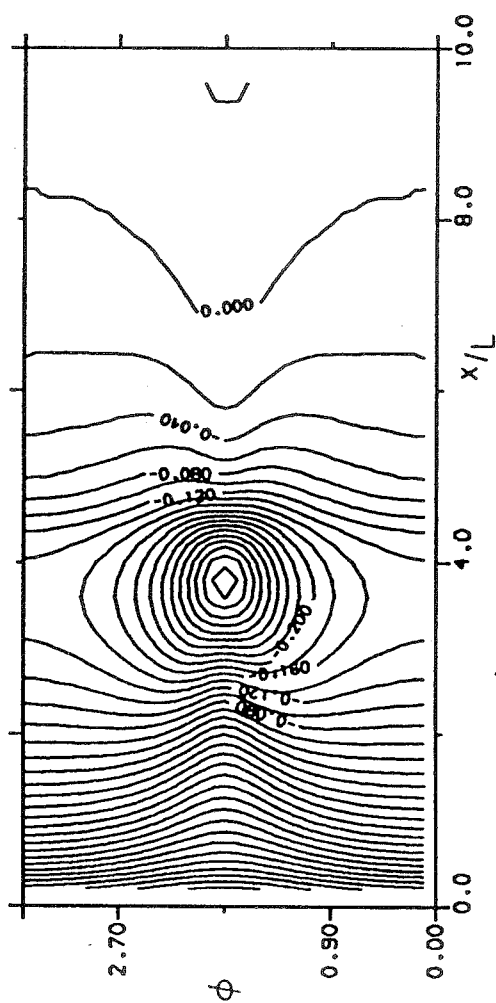




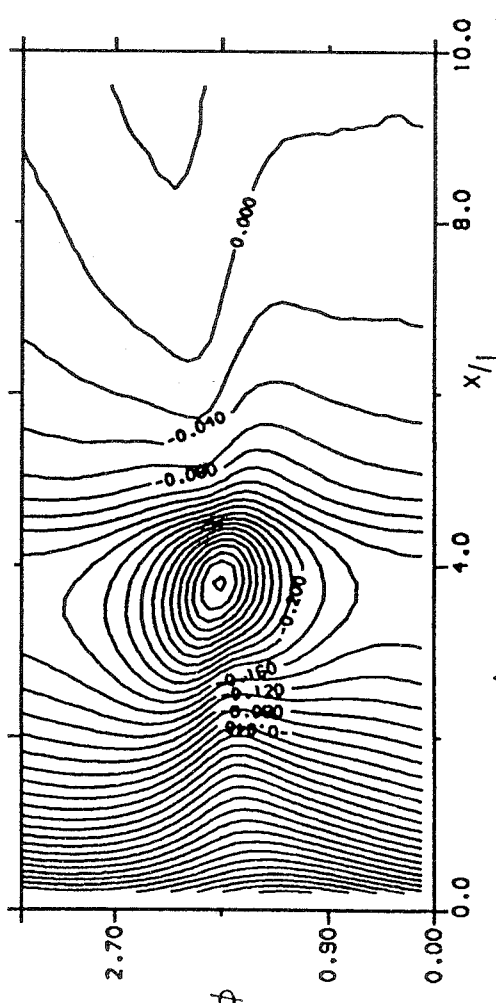
Z AXIS $\times 10^{-1}$
X AXIS $\times 10^{-1}$
Y AXIS $\times 10^2$



Z AXIS $\times 10^{-1}$
X AXIS $\times 10^{-1}$
Y AXIS $\times 10^2$



C_p CONTOUR STEP 0.02
a) $\text{pitch} = 0.0$ degrees $\text{yaw} = 0.0$ degrees



C_p CONTOUR STEP 0.02
b) $\text{pitch} = 0.0$ degrees $\text{yaw} = 2.0$ degrees

Figure 32. Two-body combination. Variation of the calculated pressure distributions with yaw

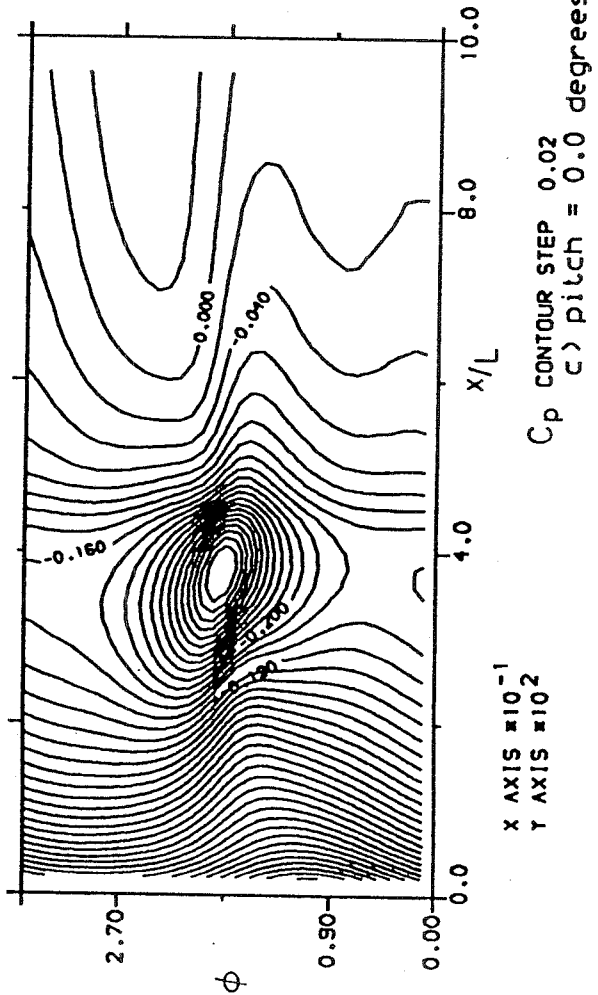
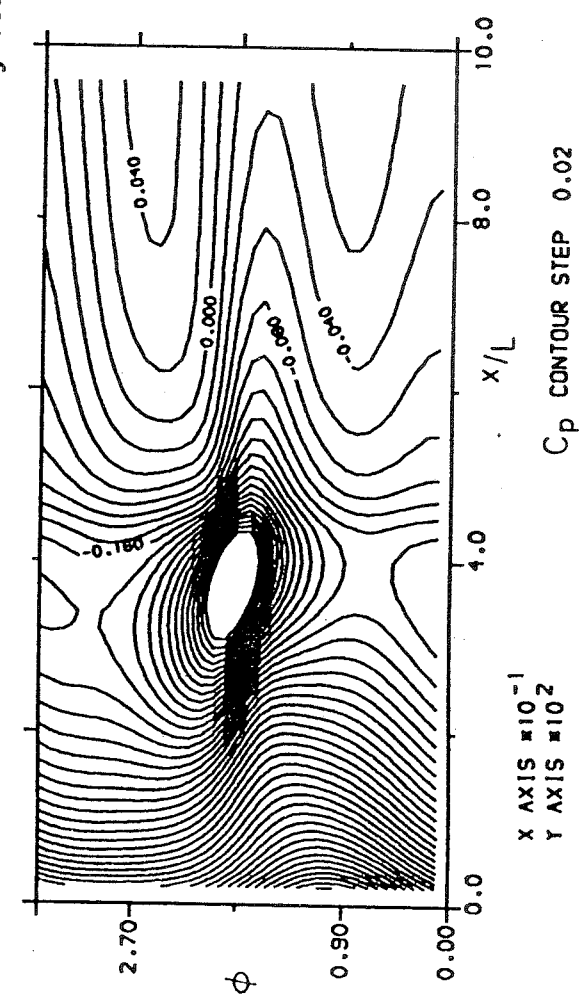
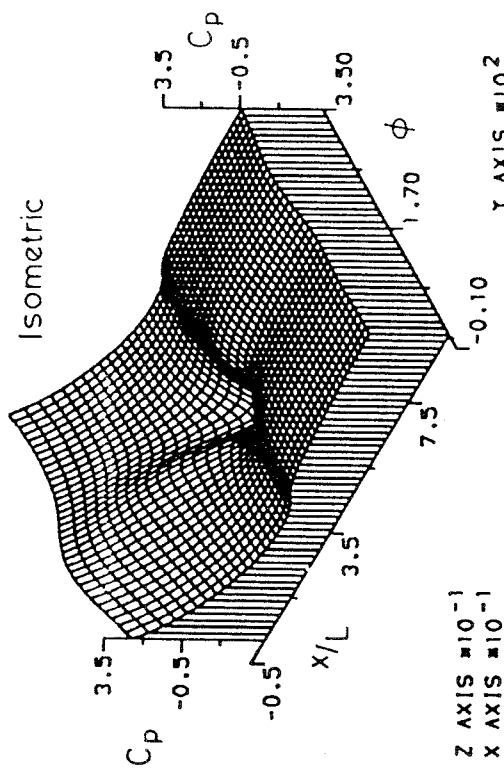
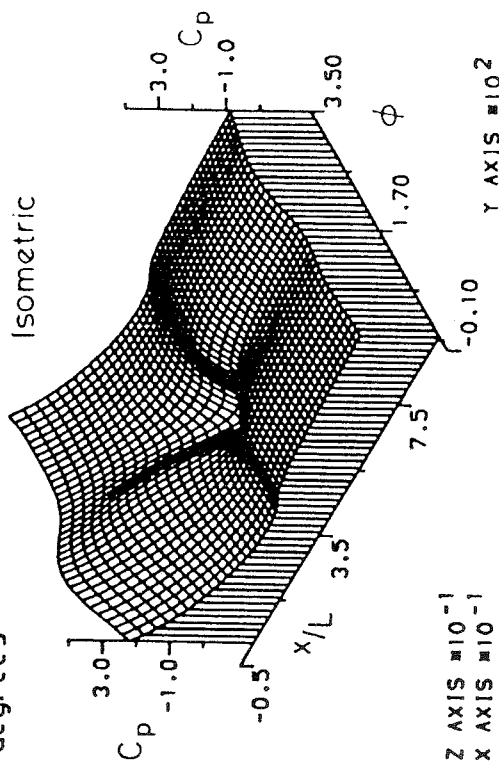
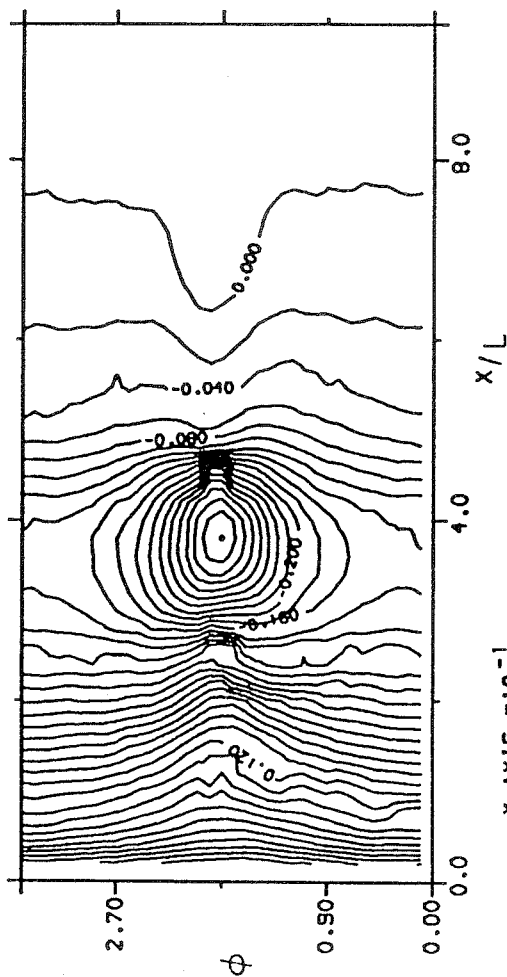
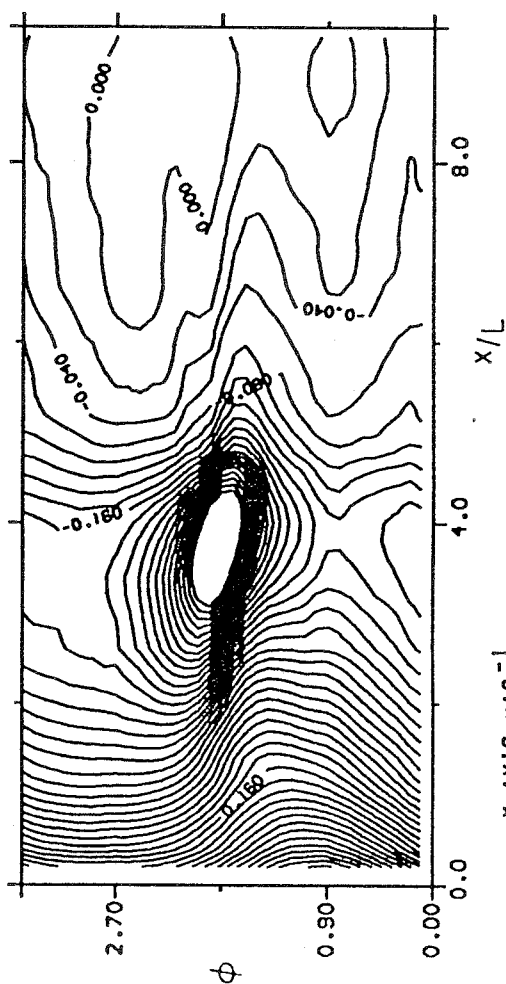


Figure 32 continued



C_p CONTOUR STEP 0.02
a) pitch = 0.0 degrees yaw = 0.0 degrees



C_p CONTOUR STEP 0.02
b) pitch = 6.0 degrees yaw = 6.0 degrees

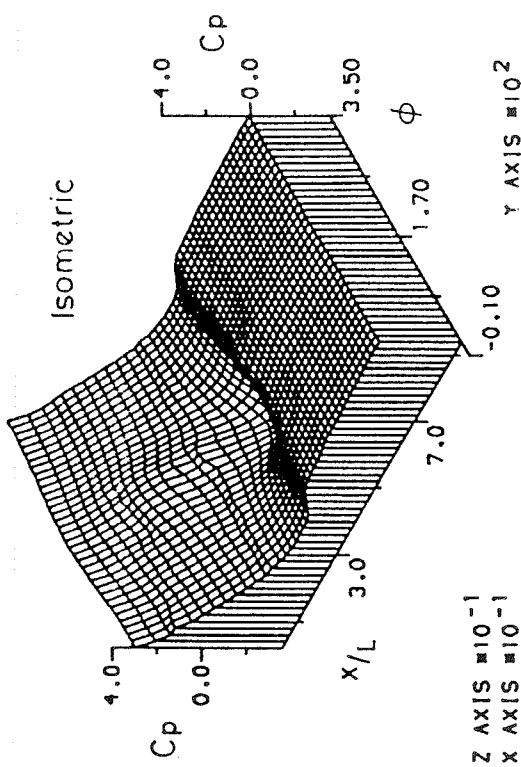
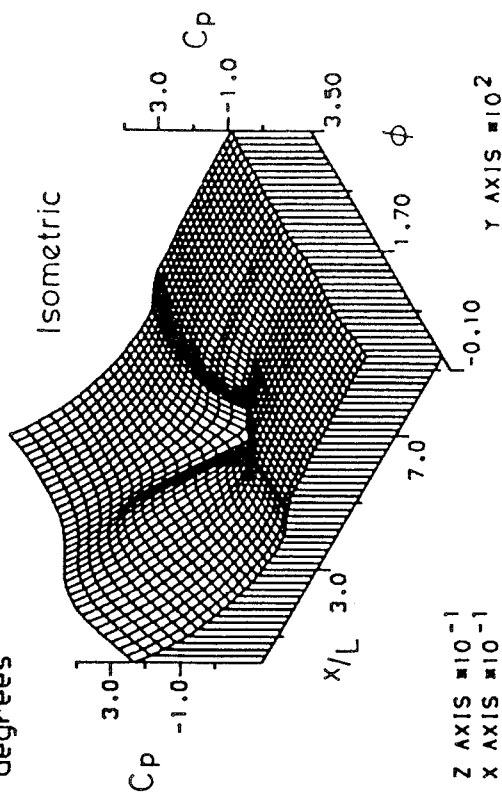
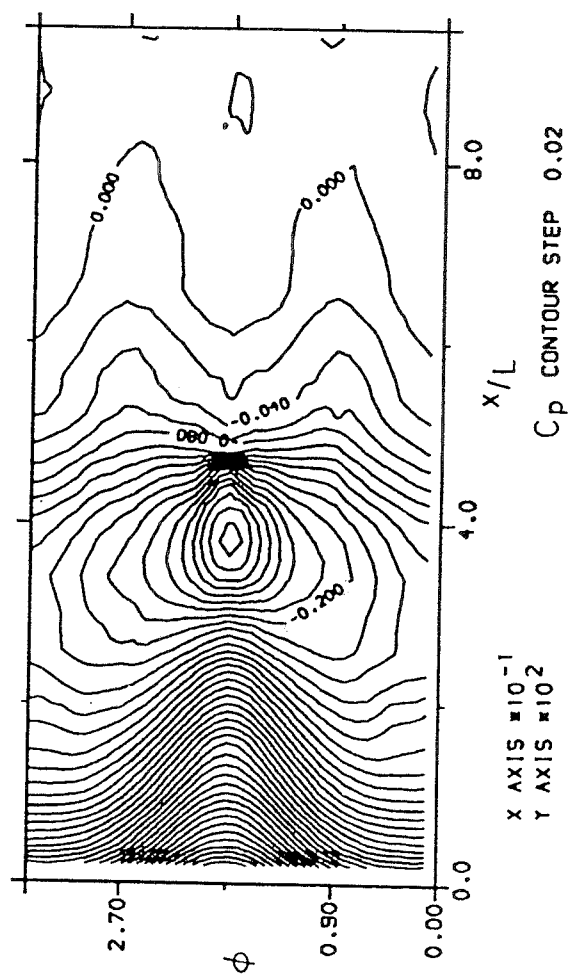
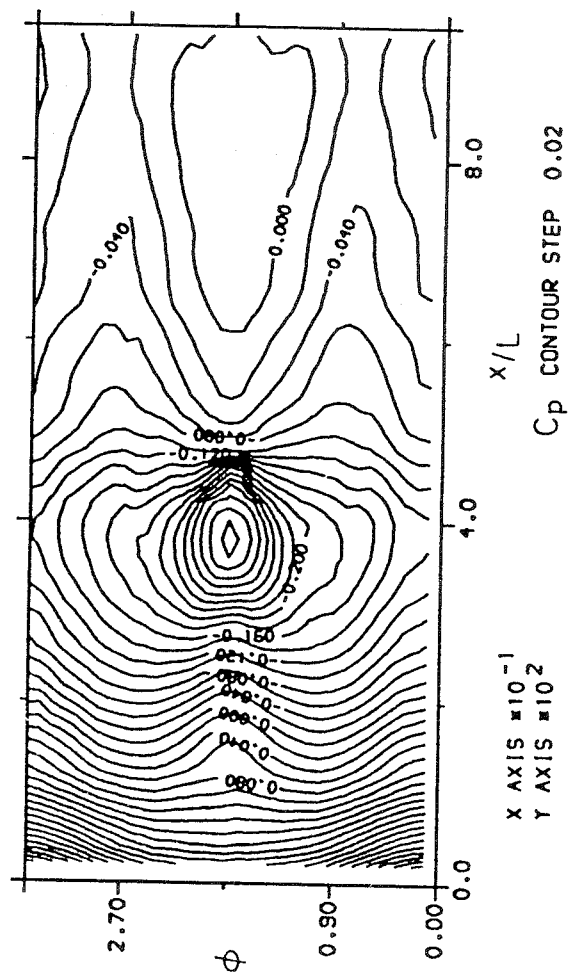
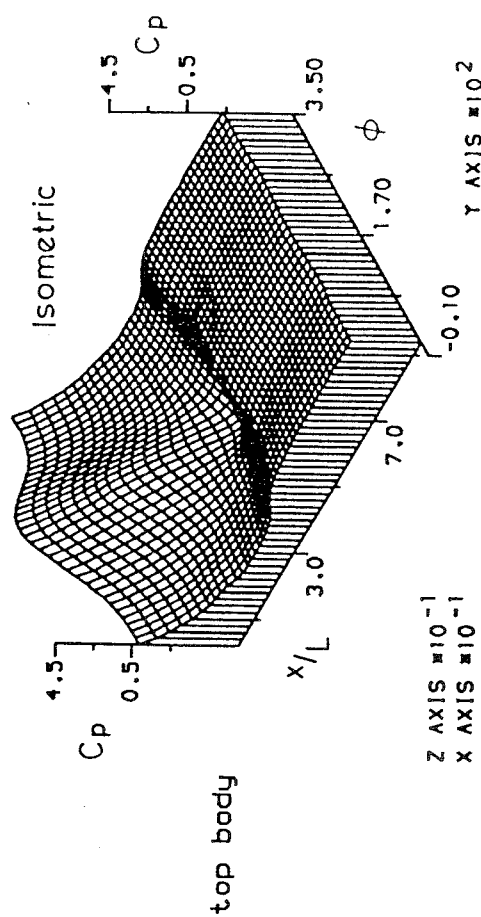
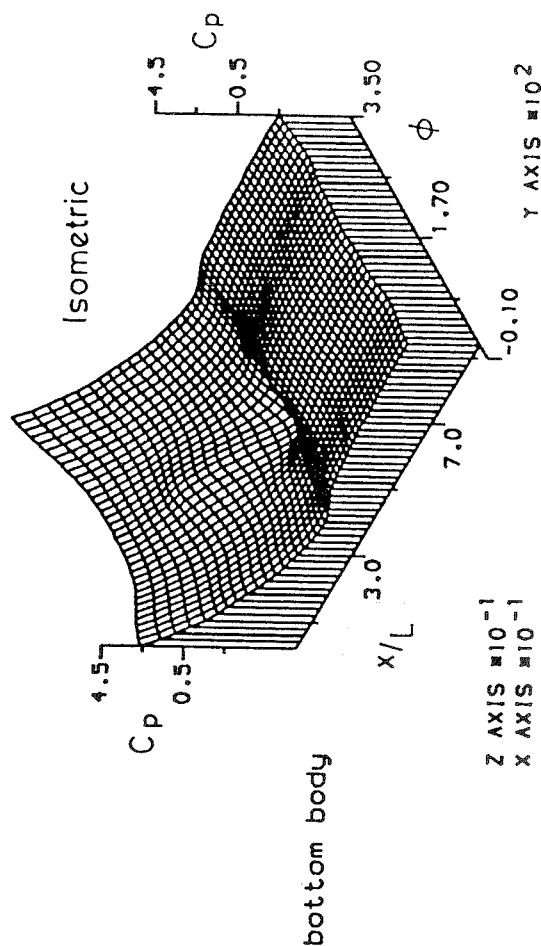
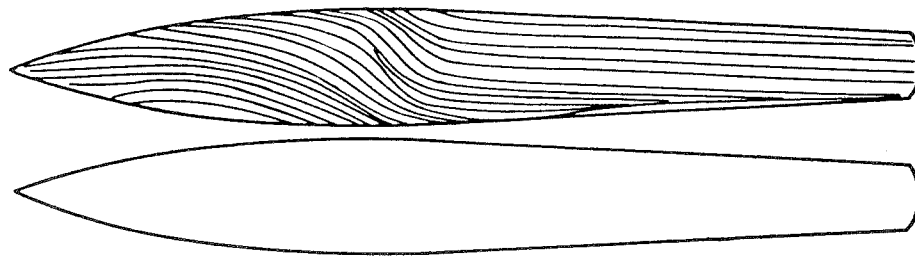


Figure 33. Two-body combination. Variation of the experimental pressure distributions with yaw

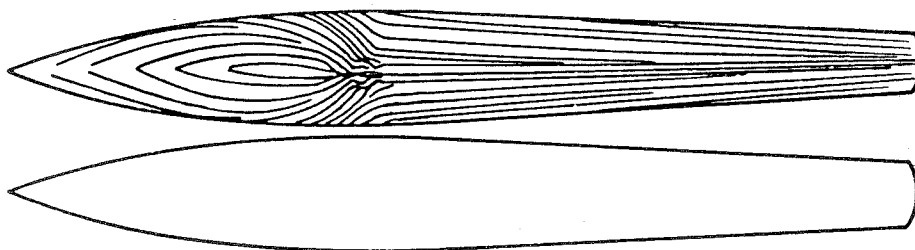


a) pitch = 6.0 degrees yaw = 0.0 degrees

Figure 34. Two-body combination. Variation of the experimental pressure distributions with pitch



(a) Rotation = 0°



(b) Rotation = 90°

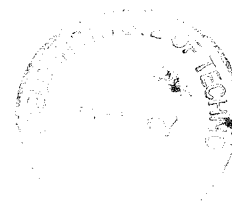
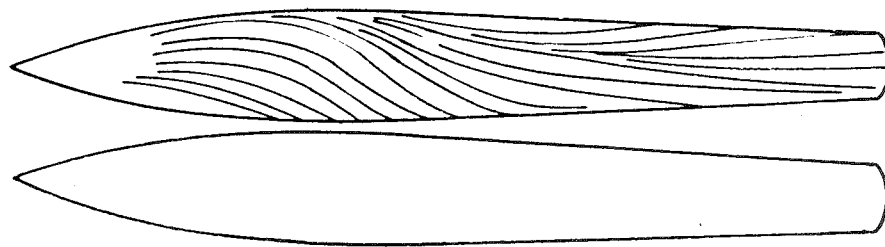
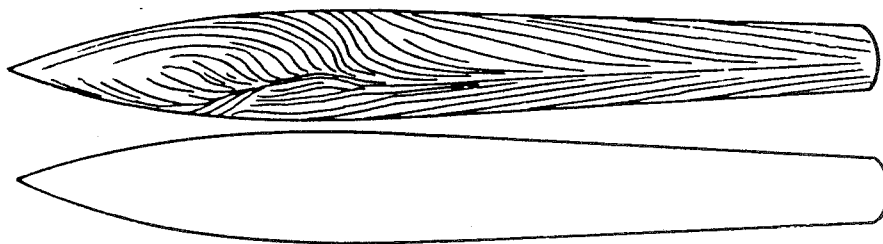


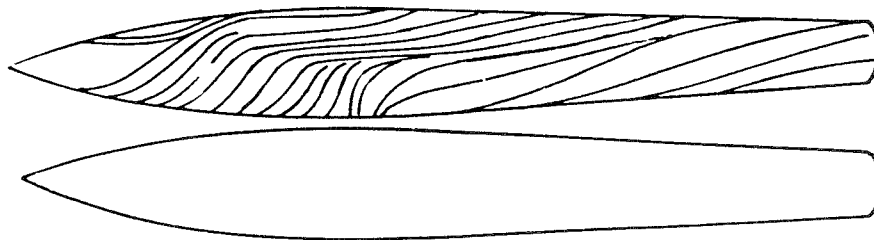
Figure 35. Oil-flow patterns ; pitch = 0° , yaw = 0° .



(a) Rotation = 0°

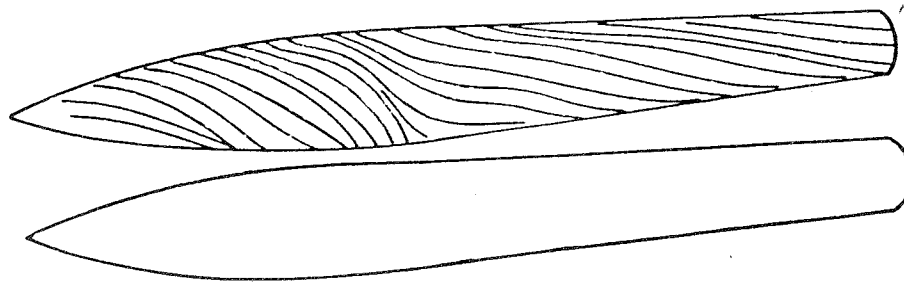


(b) Rotation = 90°

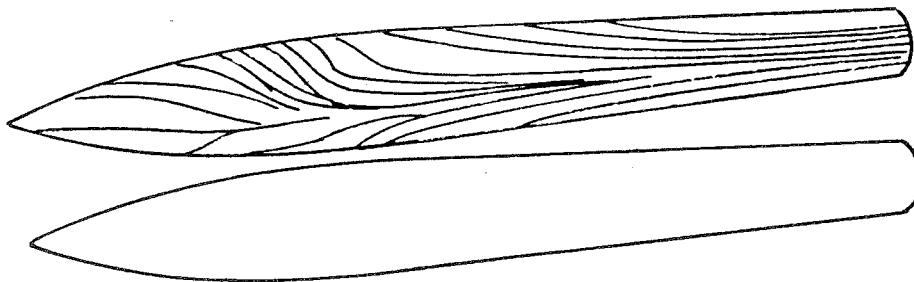


(c) Rotation = 180°

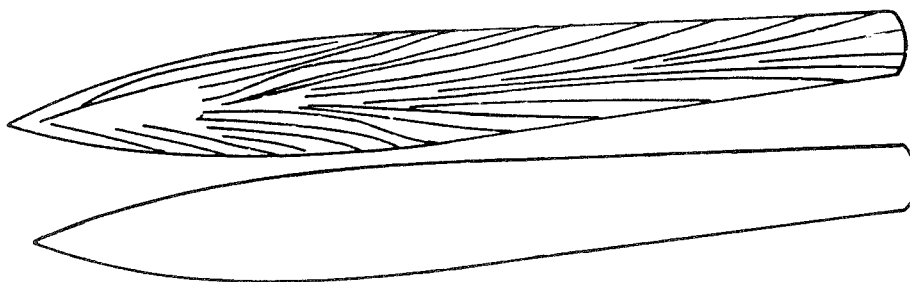
Figure 36. Oil-flow patterns ; pitch = 0° , yaw = 6° .



(a) Rotation = 0°

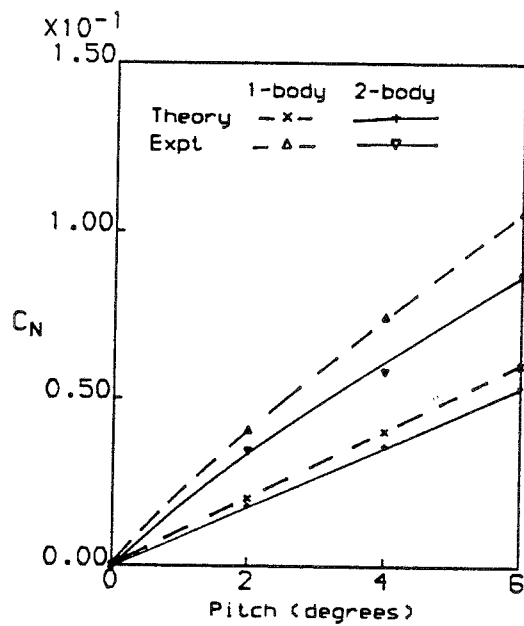
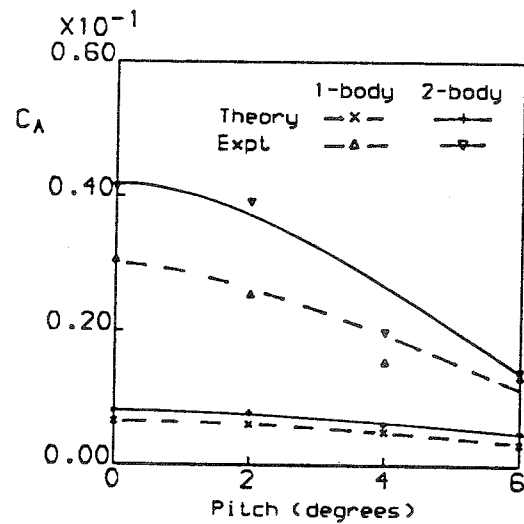


(b) Rotation = 90°

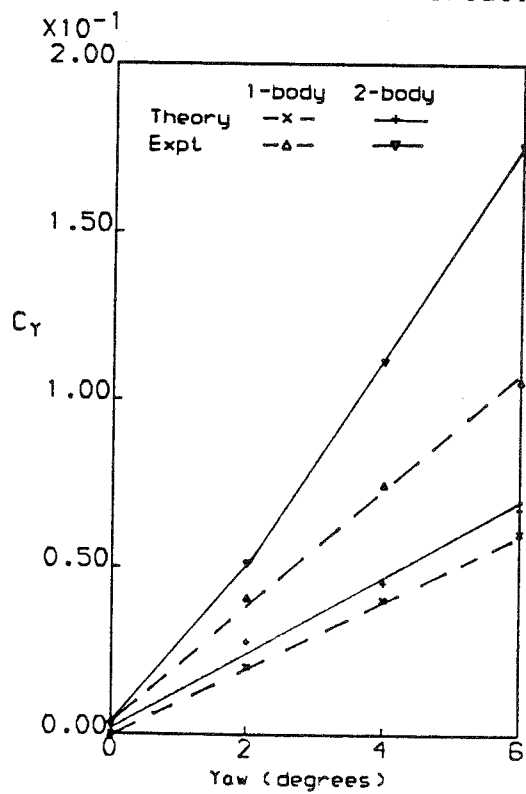
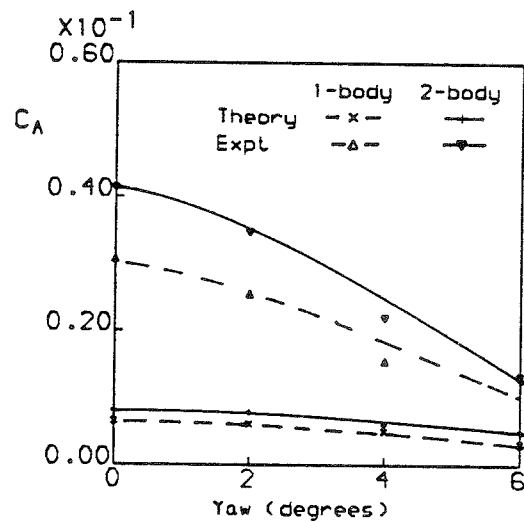


(c) Rotation = 270°

Figure 37. Oil-flow patterns ; pitch = -6° , yaw = 0° .



a) Variation with pitch



b) Variation with yaw

Figure 38. Complete configurations. Variation of aerodynamic coefficients with pitch and yaw