N87-24422

EFFECTS OF GROUND PROXIMITY ON A LOW ASPECT RATIO PROPULSIVE WING/CANARD CONFIGURATION

V. R. Stewart
Rockwell International Corp.
Columbus, Ohio

G. T. Kemmerly
NASA Langley Research Center
Hampton, Virginia 23665

ABSTRACT

The effects of near proximity to the ground are investigated on a low aspect ratio propulsive wing/canard concept at STOL conditions. Data have been obtained on a wing/body and wing/body/canard configuration at various heights above the ground, ranging from free air to approximately 1/4 of the mean aerodynamic chord (MAC) above the ground. The data presented and discussed include, force and moment coefficients, surface pressure distributions, and downwash angles measured one MAC behind the wing. The test technique, model requirements, and special considerations required for testing these configurations are also discussed. Special model requirements included evenly distributed exit nozzle pressures along four separate nozzles of lengths of one and two feet with only one air supply to the model. Test techniques must recognize and deal with the ground boundary layer as well as the air supply pressure measurement and management.

SYMBOLS

BP	Butt Plane
c	chord
$\bar{c}$	Mean Aerodynamic Chord
C_{LA}	Aerodynamic Lift Coefficient
C_L	Lift Coefficient
C_P	Pressure Coefficient
C_μ	Blowing Coefficient
h or H	Height Above Ground
δ_N	Nozzle Angle
δ_F	Flap Angle
θ	Thrust Angle
α	Angle of Attack

Subscripts

c	Canard
w	Wing

PRECEDING PAGE BLANK NOT FILMED

P	Pressure
V	Velocity
X	Longitudinal Distance
Y	Lateral Distance

INTRODUCTION

The testing of any powered configuration requires that several special considerations must be made if the results are to be satisfactory. These begin with the concept of the model and continue until the final data reduction. This paper first describes some of the more critical concerns which have been encountered in the tests of a distributed jet or jet flap configuration and in the second part describes some of the results obtained during testing in the presence of a fixed ground board. The testing in the presence of the ground imposes other constraints on the model and on the test facility. The model design and fabrication restraints to provide a slot nozzle with the required even flow distribution are discussed and the tunnel requirements to most nearly simulate the airplane are pointed out. Data recording and reduction requirements are also described. In the second part of the paper the test results are analyized and discussed briefly.

MODEL CONSIDERATIONS

The powered model requirements are not specifically altered for testing in the presence of the ground. Equal care is required for either free air or ground effects testing. The first major consideration of the model is the method of delivery of the air to the nozzle. Care must be exercised in the design of blown models to isolate the air supply from the parameters of importance that are to be recorded during the testing. The purpose of the tests determines the type of installation required. For certain types of tests it may be possible to completely isolate the air supply, piping, and the nozzles from the force carrying portions of the model. In other cases, most likely in the majority of the cases, it becomes necessary to bring the air supply across the balance without imposing large forces on the balance. Models representing each of these approaches have recently been tested under contract to the Navy (NADC) and to NASA Langley, see References 1 and 2.

The first model concept, that which isolates the air supply from the metric (force measured) portions of the model, is shown mounted in the Rockwell V/STOL tunnel in Figure 1. Figure 2 shows the drawing of the air supply and model. The high pressure air is delivered to the model through the mounting strut and to the nozzles without crossing the balance. The balance is between the air supply and the model shell and records only the forces induced on the shell by the free stream or by the air jets. This model was utilized for both concentrated jets and for distributed jets near the wing trailing edge as seen in Figure 1, although it was less than satisfactory for the distributed jet case due to the external ducting of the distributed jet air. This air supply approach is generally used when only the induced loads are desired, a pressure instrumented model is being used, or for other special test cases such as a ground flow study.

An example of the second model is shown installed in the NASA Langley low speed 4- by 7- Meter Tunnel in Figure 3, and discussed in Reference 2. In this installation the high pressure air is delivered through the sting by a single pipe. The air is directed inside the model into each of the individual wings and canards where it is internally ducted to a full span nozzle in the aft portion of the surfaces. This model has also been tested as a semi-span model utilizing the same air delivery principle, see Figure 4. The internal ducting provides a means of distributing the air from one inlet pipe to four linear nozzles with equal pressure ratio for each and relatively constant pressure distribution across the entire nozzle span. This is accomplished by maintaining a high pressure ratio in the internal ducts to the plenum just upstream of the nozzle. Figure 5 shows the internal ducting used in this particular model. The high pressure air from the tunnel source enters a common fuselage plenum From there it is divided into the four flow paths. Adjustable valves are utilized to maintain pressure balance to each surface. The air then exits into a high pressure plenum in each surface and from there into the nozzle plenum through a series of spanwise ducts which may be closed to control the spanwise distribution. These techniques resulted in spanwise pressure distributions as shown in Figure 6. Obtaining a satisfactory and a repeatable spanwise pressure distribution is essential to the test program, not only for repeatable data but also for test efficiency. The nozzle pressure ratio can be changed by control of the supply pressure. When the pressure drop from the supply to the nozzles and constant spanwise distributions for all nozzles have been established,the relationship between nozzles will not change as the pressure ratio changes. A pressure drop from approximately 150 psig at the supply to 15 psig at the nozzle is typical for this model or for any model of this type.

TEST AND TUNNEL REQUIREMENTS

Those items discussed above relating to the models do not pertain exclusively to testing of those models in near proximity to the ground, but rather, refer to all of the testing of powered models in any case. The data recorded and the special data reduction, likewise, are not limited to ground effects. However, some discussion of these also is in order. The flow parameters necessary to calculate the nozzle characteristics and thrust must be included. The forces of the propulsive wing concept and other propulsive lift systems are composed of two major forces. An induced or aerodynamic force and a direct thrust force make up the total force on the model. Analysis of the configuration is simplified if these forces can be separated during the data reduction cycle. The thrust removed (aerodynamic) force and moment coefficients are calculated by subtracting the direct thrust component from the total force, ie,

$$C_{LA} = C_L - C_\mu \sin(\theta+\alpha)$$

The method used by the low speed tunnel to compute thrust removed coefficients required a wind-off run each time the thrust configuration was changed. The forces on the balance from this tare run were then used to obtain the thrust removed coefficients. This method is prefered as the actual thrust component is used in the data reduction. Also the wind off data is very valuable in understanding the thrust characteristics and should be obtained even though it was not to be used in the data reduction. This wind off data was used extensively in trouble shooting during and after the test. The wind off data was used to determine the thrust angles during the test and for this particular setup was used to discover and eliminate a model/sting foul.

The results of the test of the model described with the non-metric thrust system were used to determine the shape of the ground vortex with the distributed jet. The objective of the overall test and model was to investigate the induced forces on the model in the presence of the ground. The primary thrust devices to be tested were deflected thrust nozzles and for these nozzles the induced forces would be small relative to the thrust forces. An isolated thrust system appeared to offer the best setup to accomplish this goal. The isolated balance was used and it was then determined that the distributed jet tests would be limited in the data gathered. Model force data was recorded but the accuracy was rather limited. This result had been expected, however; the main desire of the test was to investigate the concentrated jets and the distributed jet case was an add on to get as much data as possible without a major system change. The thrust supply pipe which supplied the nozzle was external to the wing and reduced the area available to provide lift. This model, however, did provide a great deal of insight into the particular requirements of testing powered models and especially distributed jet models in ground effect. The ground board pressures and flow interference measurements were used to develop the model and test procedures for later testing of the propulsive wing/canard model.

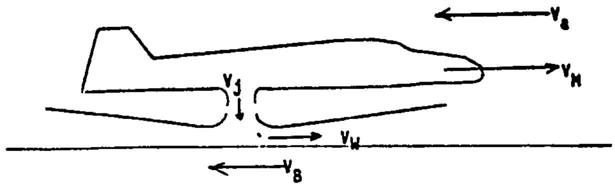
A wall jet is formed when a concentrated jet strikes the ground and radiates out from the point of contact. The wall jet has been shown to roll up and form a ground vortex when it interacts with the oncoming airstream, see Figure 7. A similar condition exists for the distributed jet. The effects of the ground boundary layer on the vortex formed by the concentrated jet has not been adequately determined but the boundary effect on the distributed jet is expected to be more pronounced and should be eliminated when testing in the near proximity to the ground.

The ground vortex is one factor which determines the requirement to eliminate the ground boundary layer. Turner (Reference 3) investigated essentially the same effect by observing where a significant lift loss occured and recommended a test area in which a moving ground board would be required, see figure 10. Data obtained on the model tests of Reference 1 indicate that the critical ground conditions may exist at lower lift coefficients than those described by Turner. The presence of a ground vortex is shown by significant negative pressures on the ground. Reference 1 presents a discussion of the ground vortex and its formation. The ground pressure measurements under the wing of the distributed jet indicate that a ground vortex has formed at quite low lift coefficients. Figure 8 indicates that at ninety degrees deflection of the distributed jet a ground vortex has formed under the wing at a height of two chord lengths above the ground. Figure 9 shows the location of the ground vortex at a jet deflection of 45 degrees and 3/4 of a chord length above the ground (approximate wheel height for this configuration). The location of the vortex greatly influences the lift in the presence of the ground. In the first case, figure 8, the vortex is under the wing and a large lift loss is experienced; whereas, in the second case, figure 9, with the vortex behind the wing, an increase in lift greater than would be expected was seen. Both of the results are questionable and care must be taken to eliminate the boundary layer in the test procedure. The formation lift coefficients of the ground vortex are compared to the requirements of Turner in Figure 10. The lift coefficients for the ground vortex formation may be somewhat low due to the fabrication difficulty discussed earlier, but indicate the importance of removing the ground boundary layer. It appears that if a distributed jet configuration is to be tested with jet deflections at which ground impingement can likely be expected that the ground boundary layer should be removed.

Removal of the boundary layer can be accomplished by any of several techniques. The landing approach of an aircraft, of course, does not have the same boundary conditions as those developed in the wind tunnels unless a moving model technique is used. This more nearly duplicates the true ground effects to be experienced by the approach and landing. The real task with the moving model is the instrumentation and data retrieval task, and if these are solved, the technique is quite valuable. Two methods of boundary layer removal are suction to remove the boundary layer ahead of the model and blowing to speed up the boundary layer to match the free stream flow. The use of a moving belt in conjunction with the suction provides the best means of boundary layer control in the wind tunnel. The use of a moving belt does limit the instrumentation capability of the test setup. The use of the ground pressure as a measurement of the extent of the ground vortex is lost, at least in the case of a belt which extends the full width of the test section. Table 1 shows the effect of each of these simulations as related to an airplane during landing. Note that only the moving model is the same as the airplane and then only if there are no ambient winds which could be a fair percentage of the approach speed of a STOL configuration. In order to simulate the ambient wind, a moving model in a large tunnel would be required.

TABLE 1

V_∞ - A/P RELATIVE TO AIR
V_M - A/P RELATIVE TO GROUND
V_a - AIR RELATIVE TO GROUND
V_J - JET VELOCITY
V_W - WALL JET VELOCITY
V_B - BELT VELOCITY



CONFIGURATION	V_M	V_a	V_W	V_B	RETARDING FORCE: AIR	RETARDING FORCE: GROUND FRICTION	PUSH BACK FORCE: AIR	PUSH BACK FORCE: GROUND	GROUND BOUNDARY LAYER: OUTSIDE JET	GROUND BOUNDARY LAYER: IN JET
A/P	V_∞	0	$V_J + V_\infty$	0	$V_J + V_\infty$	$V_J + V_\infty$	0	0	0	YES
MOVING MODEL	V_∞	0	$V_J + V_\infty$	0	$V_J + V_\infty$	$V_J + V_\infty$	0	0	0	YES (SAME)
FIXED MODEL - FIXED G.B.	0	V_∞	V_J	0	$V_J + V_\infty$	$\boxed{V_J}$	$\boxed{V_\infty}$	0	$\boxed{\text{YES}}$	$\boxed{\text{NOT SAME}}$
FIXED MODEL - MOVING BELT	0	V_∞	V_J	V_∞	$V_J + V_\infty$	$V_J + V_\infty$	$\boxed{V_\infty}$	$\boxed{V_\infty}$	0	$\boxed{?}$
STATIC	0	0	V_J	0	V_J	V_J	0	0	0	YES

The propulsive wing/canard model shown in Figure 3 was tested in the presence of the ground during the tests of the effects of the relative wing/canard placement. Suction was used to remove the boundary layer ahead of the model during the tests. Measurements of the ground vortex or the ground boundary were not made. However, previous testing in the presence of the vortex has shown that either of two conditions can exist when the vortex is present. If the vortex is located under the wing, a negative pressure will be seen on the lower surface of the wing; and, when the vortex is located just aft of the wing these pressures will be positive and excessive lift increases will be indicated. The propulsive wing/canard model has extensive surface pressure instrumentation. Figure 11 presents wing pressure instrumentation locations. These static pressure measurements may be used to determine if a ground vortex is between the wing and the ground. Figure 12 presents the wing pressure distributions at a mid span location, BP 12. Pressures on the flap upper surface are not shown in order to remain on scale. A significant ground effect is seen in the surface pressures indicating that even though the suction was used to remove the boundary layer, the vortex is still present under the wing. The negative pressures at C = 2.0 indicate the vortex to be trapped under the wing. These results are not indicative of unsatisfactory test results. The vortex may be trapped under the airplane wing in actual flight at these conditions. Additional testing is required to define the effect of the test procedures on the vortex and related aerodynamic increments.

EFFECTS OF THE GROUND ON THE AERODYNAMIC CHARACTERISTICS

The remainder of this paper will deal with the general aerodynamic phenomena that can be expected with a jet flap in ground effects. Force and pressure data taken specifically from the propulsive wing/canard investigation will be used to illustrate these flow characteristics.

With most wings in ground effects, upwash at the leading edge occures as ground height is reduced. This effect is magnified in the case of the jet flap because the jet acts as a flap extension and, thus, more of an obstruction below the wing than a mechanical flap. At even lower heights the jet can impinge on the floor (Ref. 4) and run foreward to form a vortex against the freestream, obstructing flow under the wing even further. This vortex formation will be discussed later. Figure 13 shows the development of this leading edge pressure spike at three different ground heights, and illustrates how sensitive it is to thrust coefficient. In this case there is no canard in front of the wing. A canard will provide a downwash field for the wing, thus, reducing this spike, and, as in the case of the example in Figure 14, can actually reverse the pressures very near the leading edge.

A jet flap on a wing increases circulation around the wing. This results in increased upwash at the leading edge, and, at high thrust coefficients, can separate the leading edge (Ref. 5). The combined effects of ground proximity and a jet flap can lead to leading edge separation at even moderate thrust coefficients. The data from the propulsive wing seem to indicate separation as can be seen by returning to Figure 13. A separation bubble apparently forms at $x/c=0.1$ and due to the strong boundary layer control properties of jet flaps, the flow appears to reattach near the line $x/c=0.55$. These flat pressure distributions may be the result of the supercritical airfoil section used rather than a separation bubble. There is insufficient data available to determine conclusivly. The effect can be seen to spread spanwise to the outboard portion of the wing as shown in Figure 15. Here, if separation has occured, it has occured behind only a mild, leading edge pressure rise. By comparing Figure 13 to Figure 14, the downwash of the canard is seen to improve the pressure gradient on the wing upper surface enough to aviod separation.

Another flow problem associated with jet flaps in ground effects is the separation of the jet from the upper surface of the flap. This can generally be avoided by careful flap design, but, indeed can occur. During the propulsive wing/canard investigation, because of proper design and the moderate blowing rates tested, this flow problem was not encountered, however, it should still be addressed. At very high thrust coefficients the back pressure caused by close proximity to a ground plane can be sufficient to keep the jet from following the contour of the flap and, thus force it to separate from the flap. This will be noticed several places in the data obtained Downwash data will show a significant decrease in downwash angle and pressure data on the upper surface of the flap will indicate separation. Force data will also be a good indicator; drag and lift will both drop dramatically and pitching moment will, in general, either increase (for a low wing) or decrease (high wing) quickly.

The flow phenomenon most effected by a boundary layer on the floor of a wind tunnel is the vortex flow that can occur under a jet flapped wing in ground effects. Out of ground effects, the high speed flow issuing from the trailing edge of these wings entrains flow along the lower surface of the flap. The result is the reduced lower surface flap pressures seen in Figure 16. As the wing is moved closer to the ground the jet impinges on the ground and spreads both foreward and aft from a stagnation line. The foreward moving flow rolls up into a vortex very near the flap. Reduced ground height or increased blowing coefficient delivers higher energy jet flow to the ground. This more powerful flow drives the vortex front farther upstream, but the trailing edge of the vortex remains at the interface between the jet sheet and the low energy flow under the wing. An example of this type of vortex can be seen in Figure 17. If ground height is further reduced or if blowing coefficient is increased, the wall jet will travel even further upstream before being turned up into a vortex front by the freestream. The pressures indicate that the trapped vortex may then break into two disinct vorticies - one driven by the wall jet and rolled up by the oncoming flow; the other driven by the strong shear layer at the wing trailing edge. An example of this type of trapped pair can be seen in Figure 18. Again, the available data is not conclusive in this determination. The lower surface pressure distribution may be indicative only of a single oval vortex. Flow visualization of this area is required to finally isolate the shape of the vortex.

Figure 19 depicts a vortex system located under a wing with no canard in front of it. The location and strength of this system is heavily dependent on thrust coefficient. Consequently, the ground effects on pitching moment can be unpredictable and severe - especially at high thrust coefficients. Positioning a canard (also with a blown flap) in front of the wing moves the system farther back under the wing as the canard jet interacts with the wing's foreward moving wall jet. The new flow field is quite complex. Where the two jets meet on the inboard portion of the wing they create the fountain that can be seen in the pressure data in Figure 20. Moving outboard the fountain quickly looses its strength and two vorticies are seen to develop and continue outboard. One is the weak vortex formed in front of the fountain and the other is the stronger vortex formed behind it. From the available pressure data the location of this fountain/vortex system appears to remain relativly constant with increasing thrust coefficient. This would be expected as long as the flow split between the wing and canard remains constant. Also, the total strength of this fountain/vortex system is only slightly dependent on thrust coefficient because increased blowing both increases the fountain's high pressure and decreases the low pressure of the vorticies.

CONCLUSIONS

The presence of a ground boundary layer will greatly effect the actions of these under-wing vorticies. Low energy flow near the floor will, initially alter the ground height and blowing coefficient necessary for the jet to establish a stagnation line on the floor. Also, a low energy boundary layer will allow the wall jet to travel much farther upstream before rolling up into a ground vortex. There is a need for either a moving model or a flight test data base of powered ground effects that can be directly correlated to wind tunnel data. This data base would perhaps provide a way to correct wind tunnel ground effects data or at least quantify the limits to which they could be measured accurately in wind tunnels.

Testing of STOL configurations in the near proximity to the ground requires that special considerations be given to the model, the tunnel, the instrumentation, and to the data reduction. The reaction of the jet with the ground is the most significant and the most difficult interference problem to solve.

The reaction of the jet and the ground form a wall jet which in turn is reacted on by the oncoming air stream to form a vortex. Careful planning must be accomplished to assure that this vortex and its effect on the model duplicate the effects which the airplane will encounter during the approach to the ground.

A test plan utilizing all ground board techniques and a generic model should be undertaken to answer questions regarding the use of each technique. Such a test should involve both deflected thrust as well as distributed jets (jet flaps) as the results will be considerably different.

REFERENCES

1. Stewart, V. R., and Kuhn, R. E.: "A Method for Estimating the Propulsion-Induced Aerodynamic Characteristics of STOL Aircraft in Ground Effect," NADC 80226-60, Aug. 1983

2. Stewart, V. R. and Paulson, J. W. Jr.: "The Aerodynamic Characteristics of a Propulsive Wing/Canard in STOL," AIAA Paper 84-2396,Oct. 1984

3. Turner, T. R. : " Endless Belt Technique for Ground Simulation," NASA SP-116, April 1965, pp. 435-446

4. Lowery, J. G., Riebe, J. M. and Campbell J. P.: "The Jet-Augmented Flap," IAS Paper 715, Jan. 1957

5. von der Decken, J.: "Aerodynamics of Pneumatic High-Lift Devices", Agard 1970

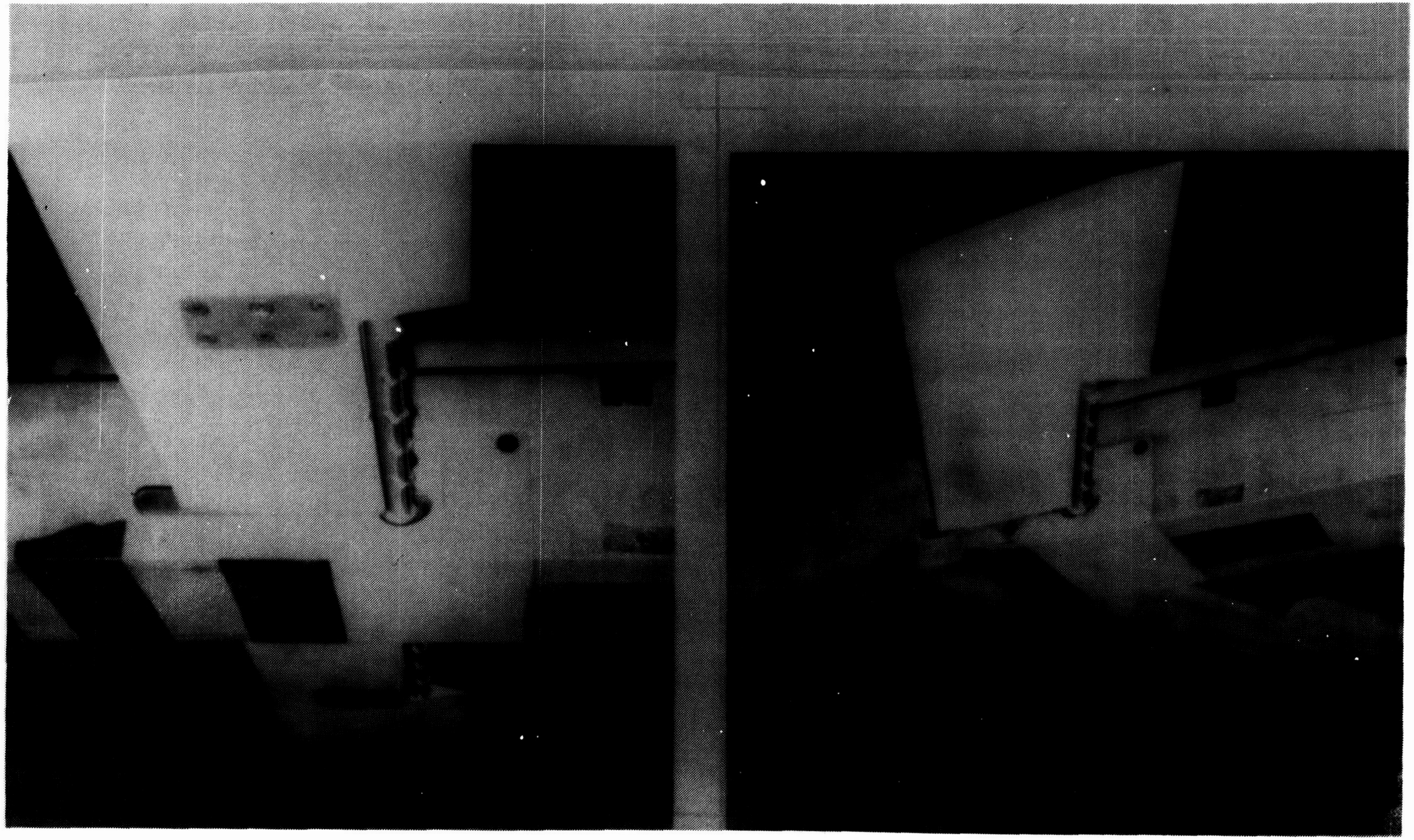


Figure 1. Distributed Jet Model in Wind Tunnel.

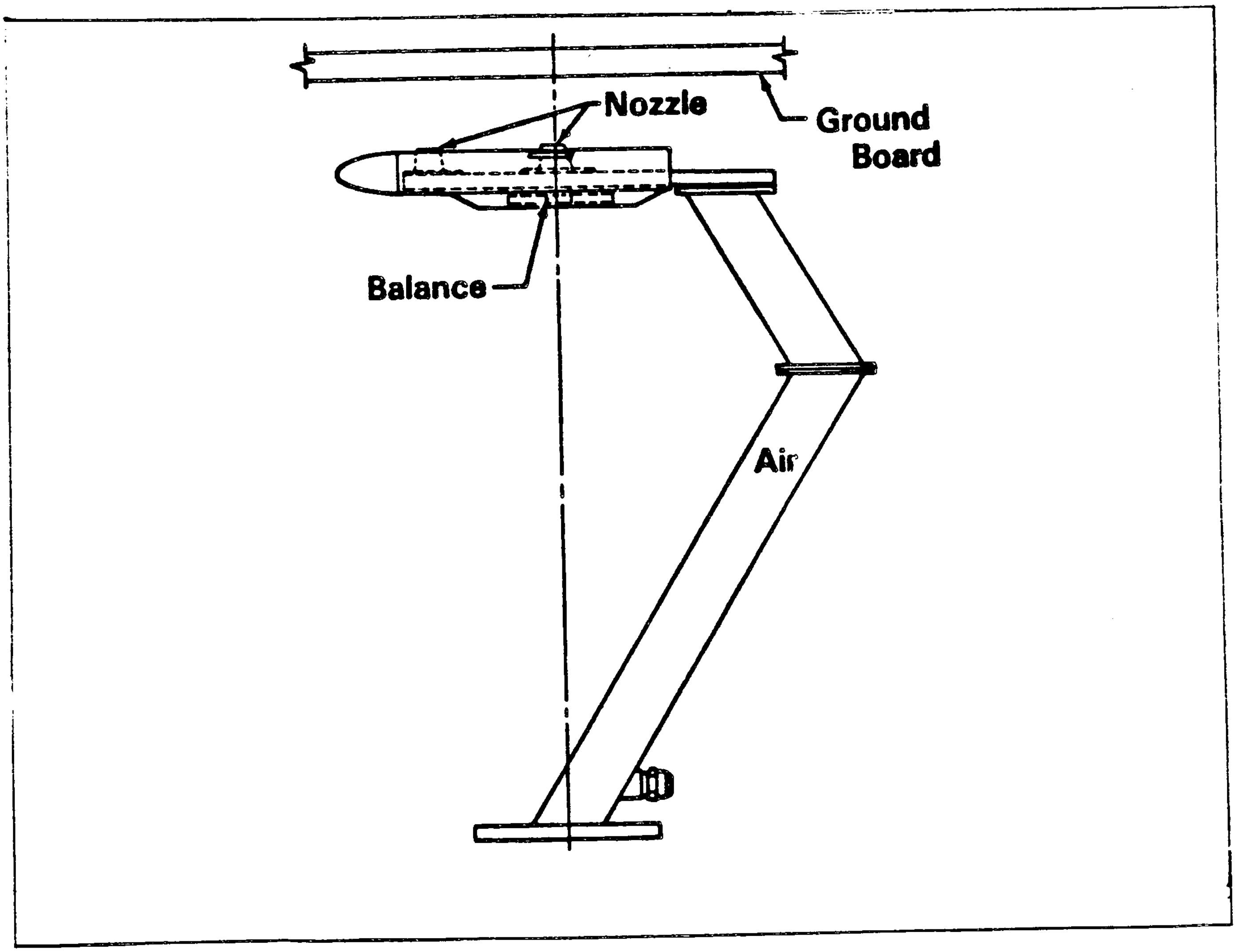


Figure 2. Model Installation

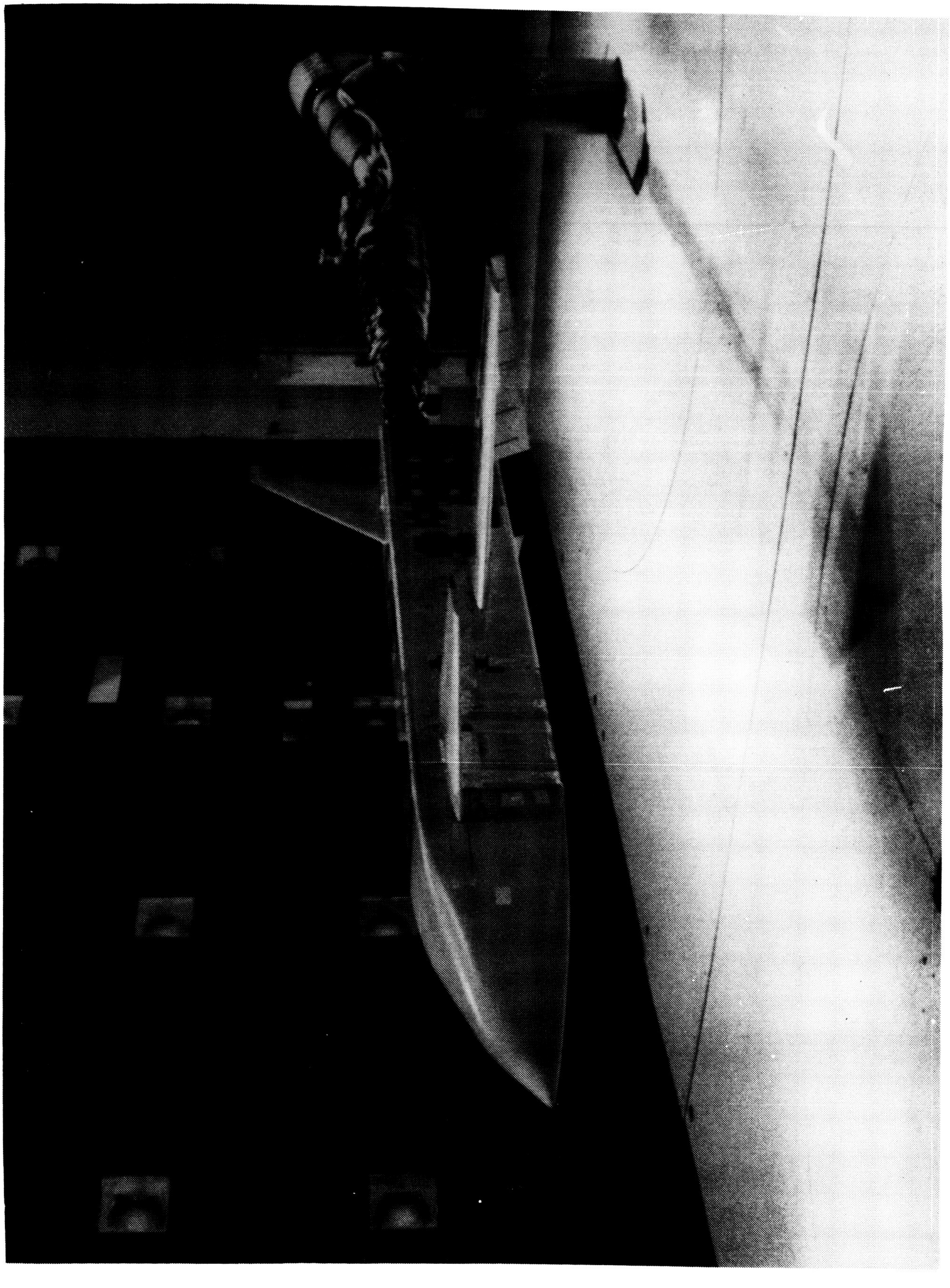


Figure 3. Propulsive Wing/Canard Full Span Model

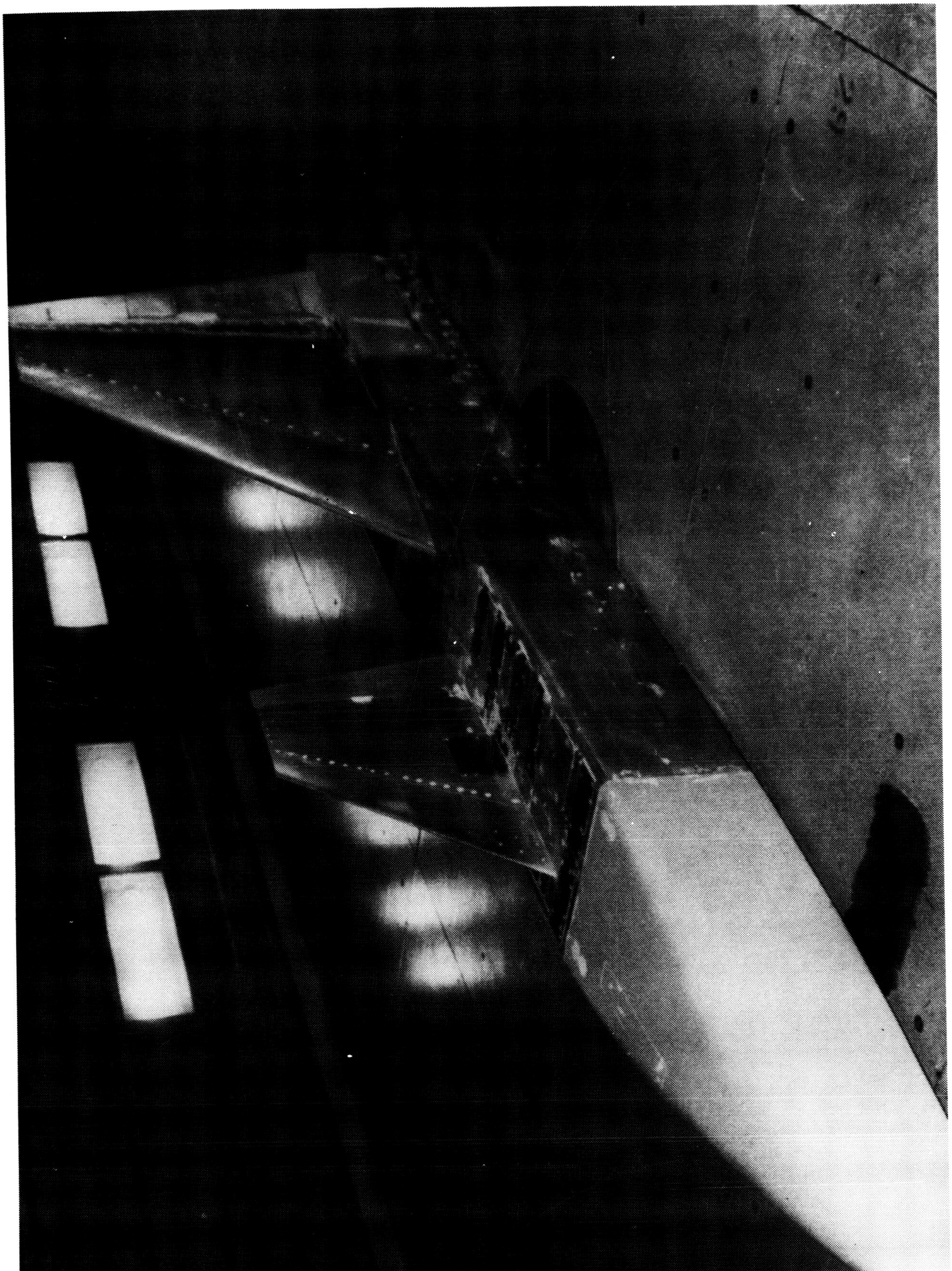


Figure 4. Propulsive Wing/Carnard Semi-Span Model

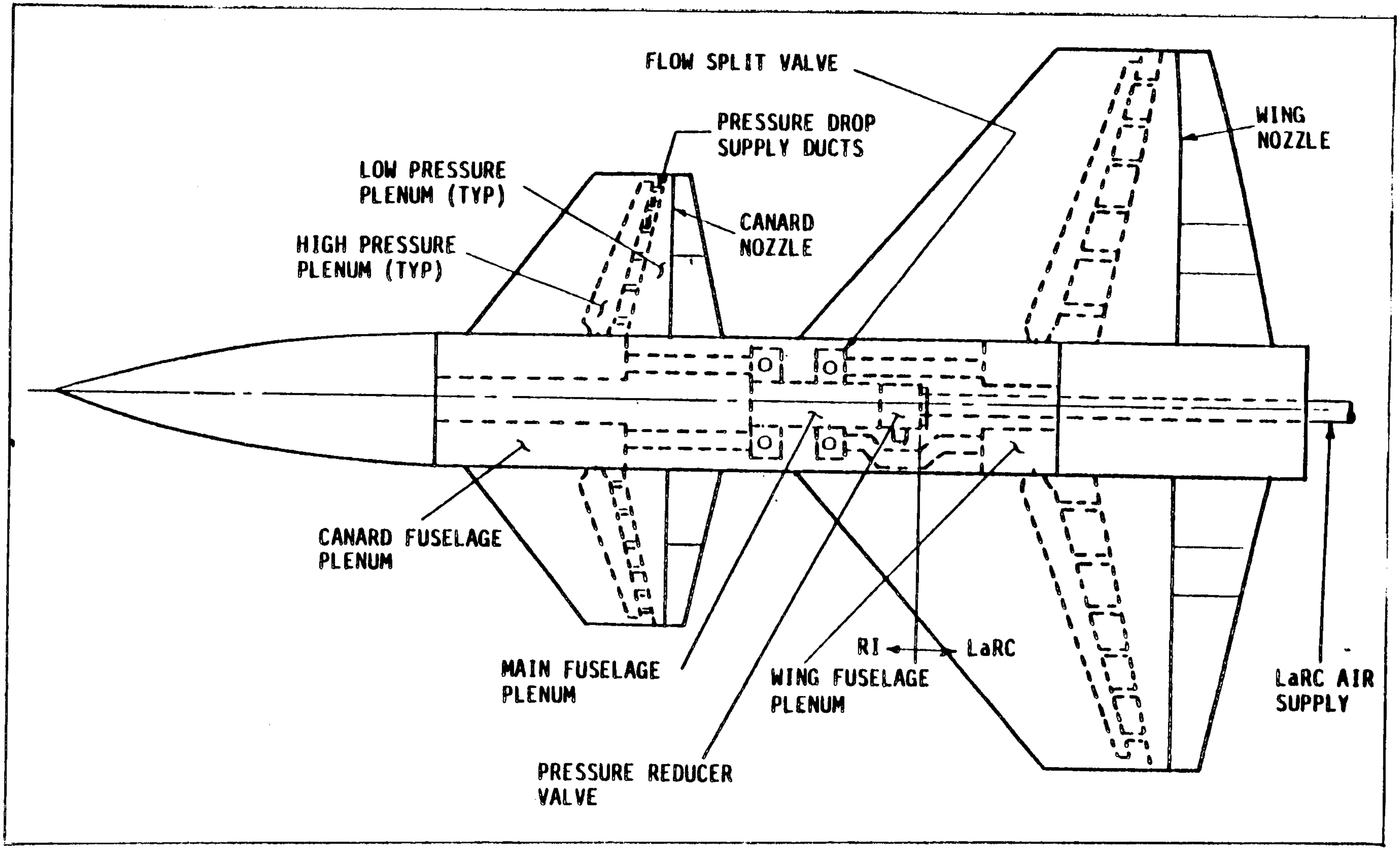


Figure 5. Air Supply System

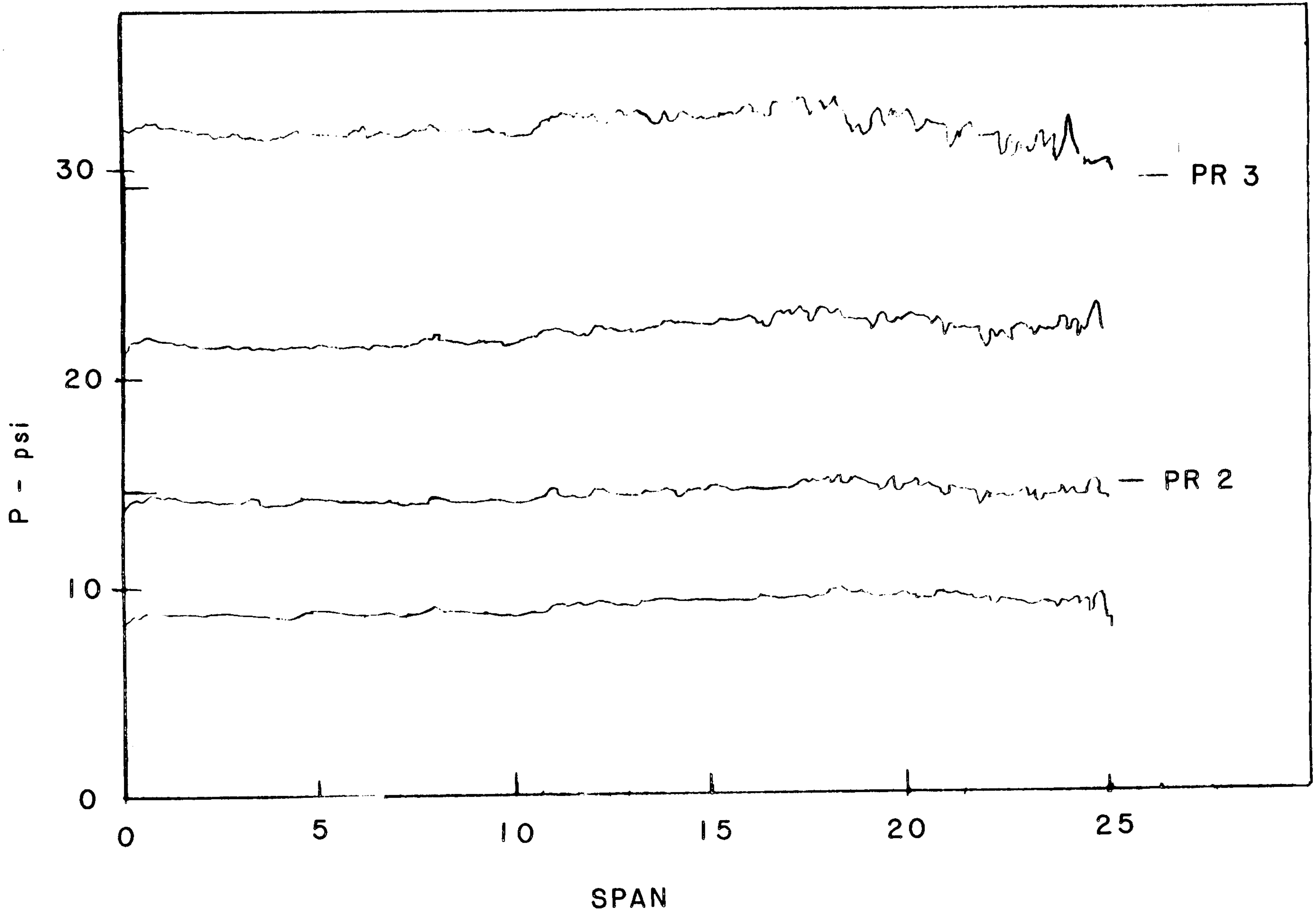


Figure 6. Nozzle Calibration, Left Hand Wing

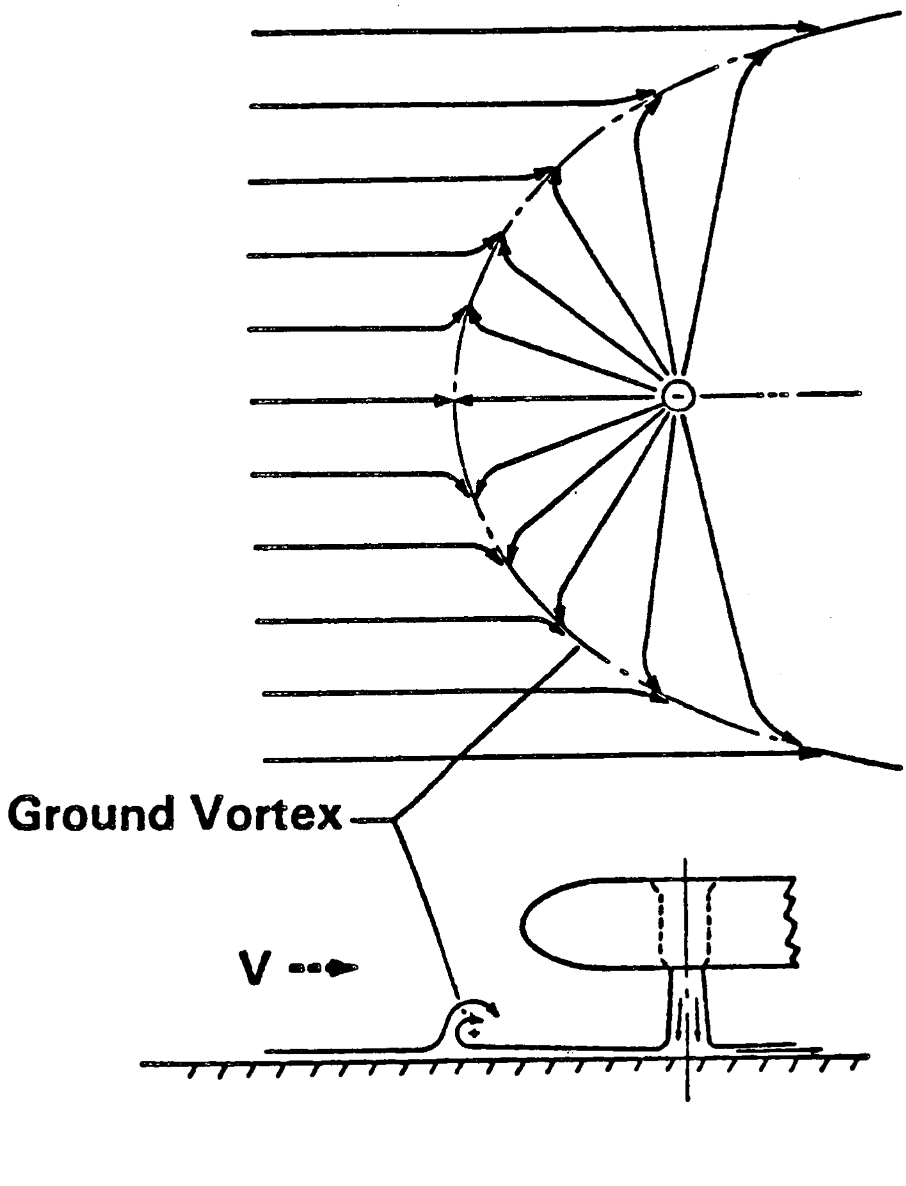


Figure 7. Ground Vortex Formation

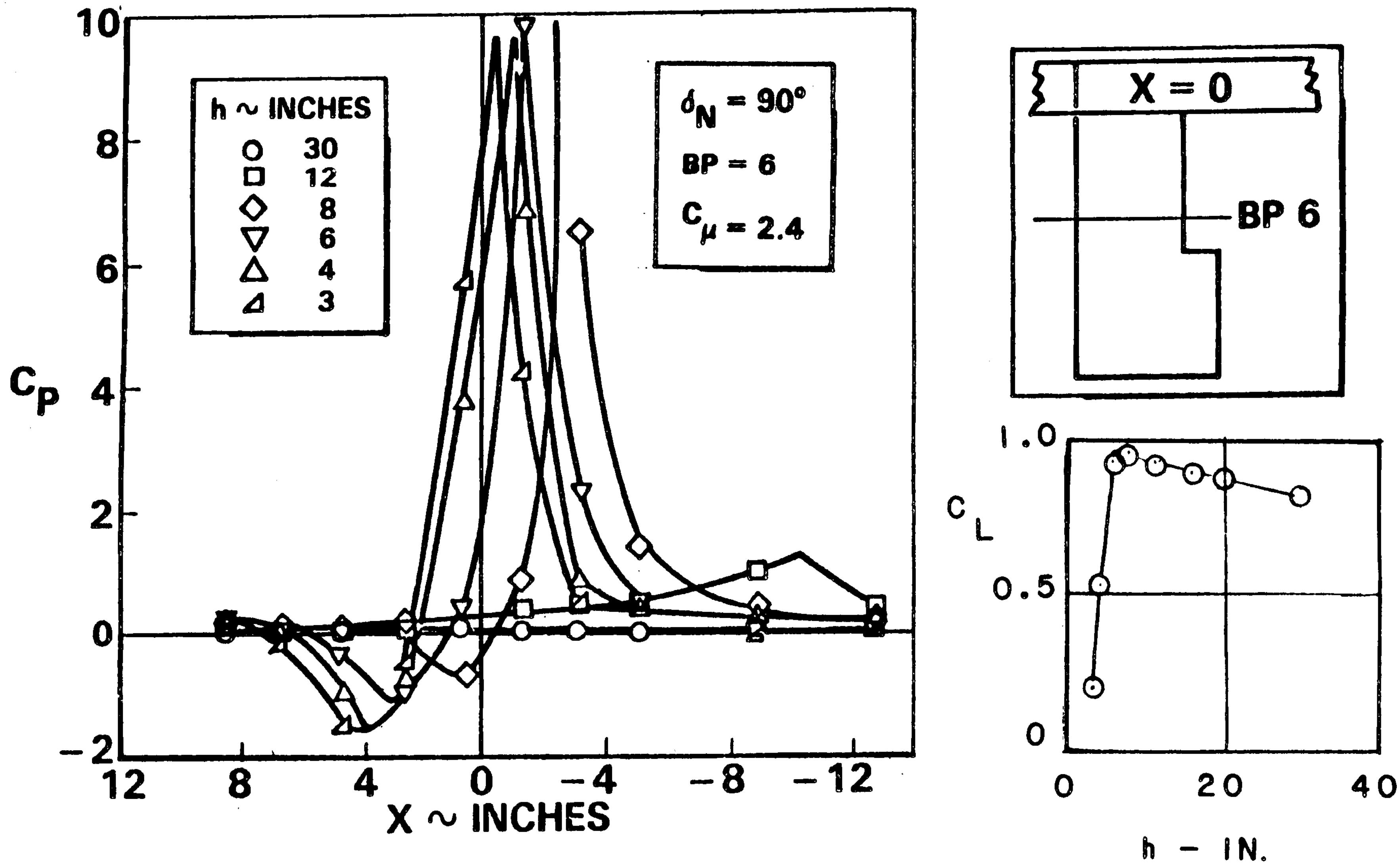


Figure 8. Ground Board Pressure Distribution

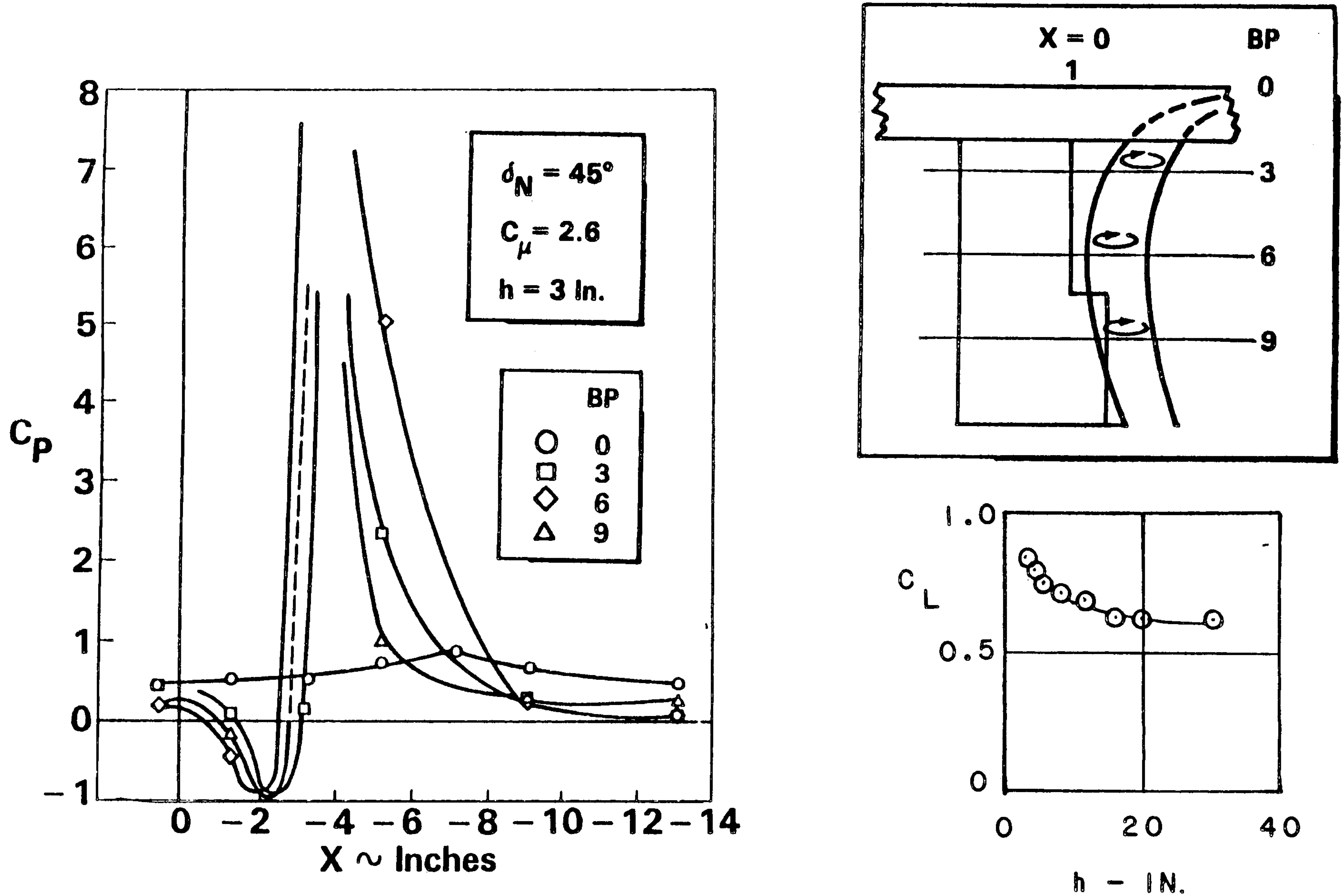


Figure 9. Ground Vortex Location

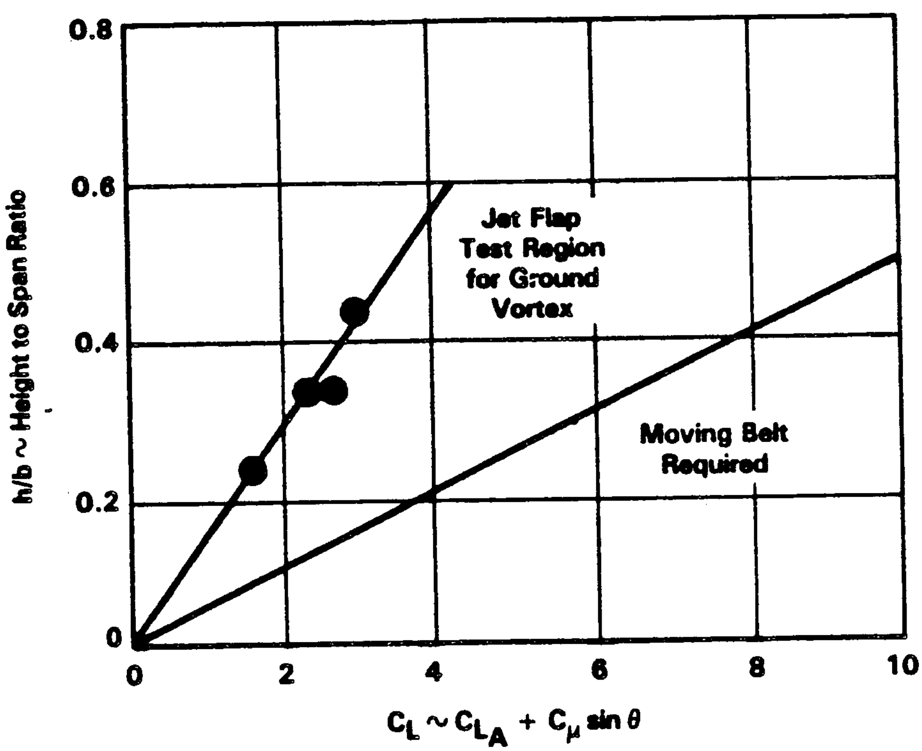
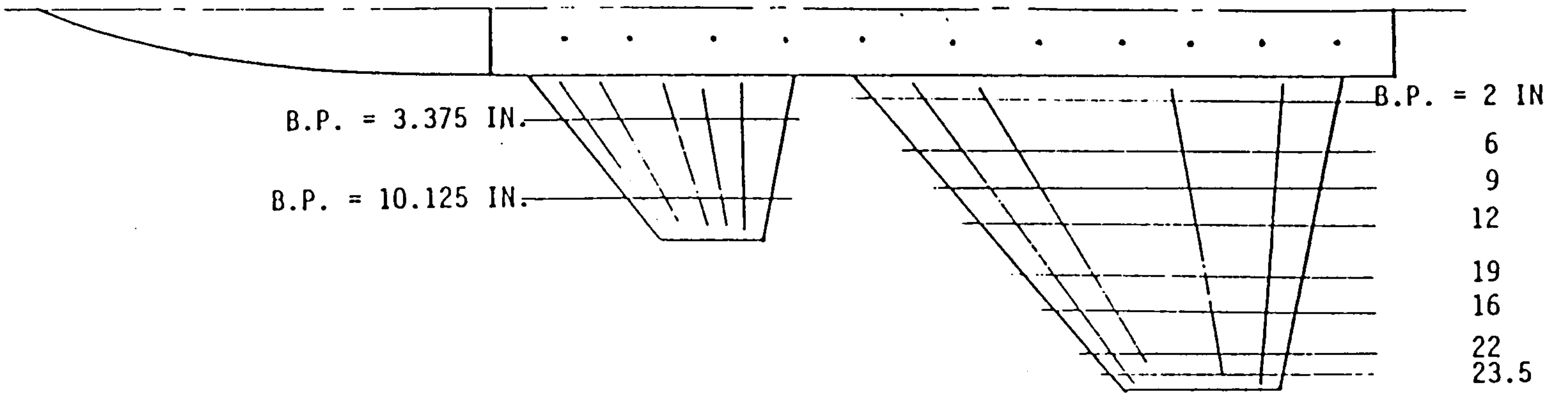


Figure 10. Moving Ground Board Requirement



CANARD STATIC PRESS. TAP LOCATION				
	Yc (Dist. to Root Chord)			
	3.375		10.125	
% Chord	Up	Lwr	Up	Lwr
0	L.E.		L.E.	
2.5	X	X	X	X
5	X	X	X	X
10	X	X	X	X
15	X		X	
25	X	X	X	X
35	X	X	X	X
50	X	X		X
56	X		X	
65	X		X	
73		X		X
78	X		X	
79	X		X	
80.5	X		X	
81	X		X	
82	X		X	
84	X	X		X
87	X			
89	X		X	
93	X			
96	X	X	X	X
100	T.E.		T.E.	

WING STATIC PRESSURE TAP LOCATIONS																
	Yw (Distance to Root Chord)															
	2		6		9		12		16		19		22		23.5	
% Chord	Up	Lwr	Up	Lwr	Up	Lwr	Up	Lwr	Up	Lwr	Up	Lwr	Up	Lwr	Up	Lwr
0	L.E.		L.E.				L.E.		L.E.				L.E.			
2.5	X	X	X	X			X	X	X	X			X	X		
5	X	X	X	X			X	X	X	X			X	X		
10	X	X	X	X			X	X	X	X			X	X		
15	X		X				X		X				X			
24	X	X	X	X			X	X	X	X			X	X		
33	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
54	X	X	X	X			X	X	X	X			X	X		
65	X		X				X		X				X			
73.5		X		X				X		X				X		
78.5	X		X				X		X				X			
79.5	X		X				X		X				X			
80.5	X		X				X		X				X			
81.25	X		X				X		X				X			
82	X		X				X		X				X			
84	X	X	X	X			X	X	X	X			X	X		
87	X		X				X		X				X			
89	X		X				X		X				X			
93	X						X		X				X			
96	X	X		X			X	X	X	X			X	X		
100	T.E.		T.E.				T.E.		T.E.				T.E.			

Figure 11. Model Pressure Instrumentation

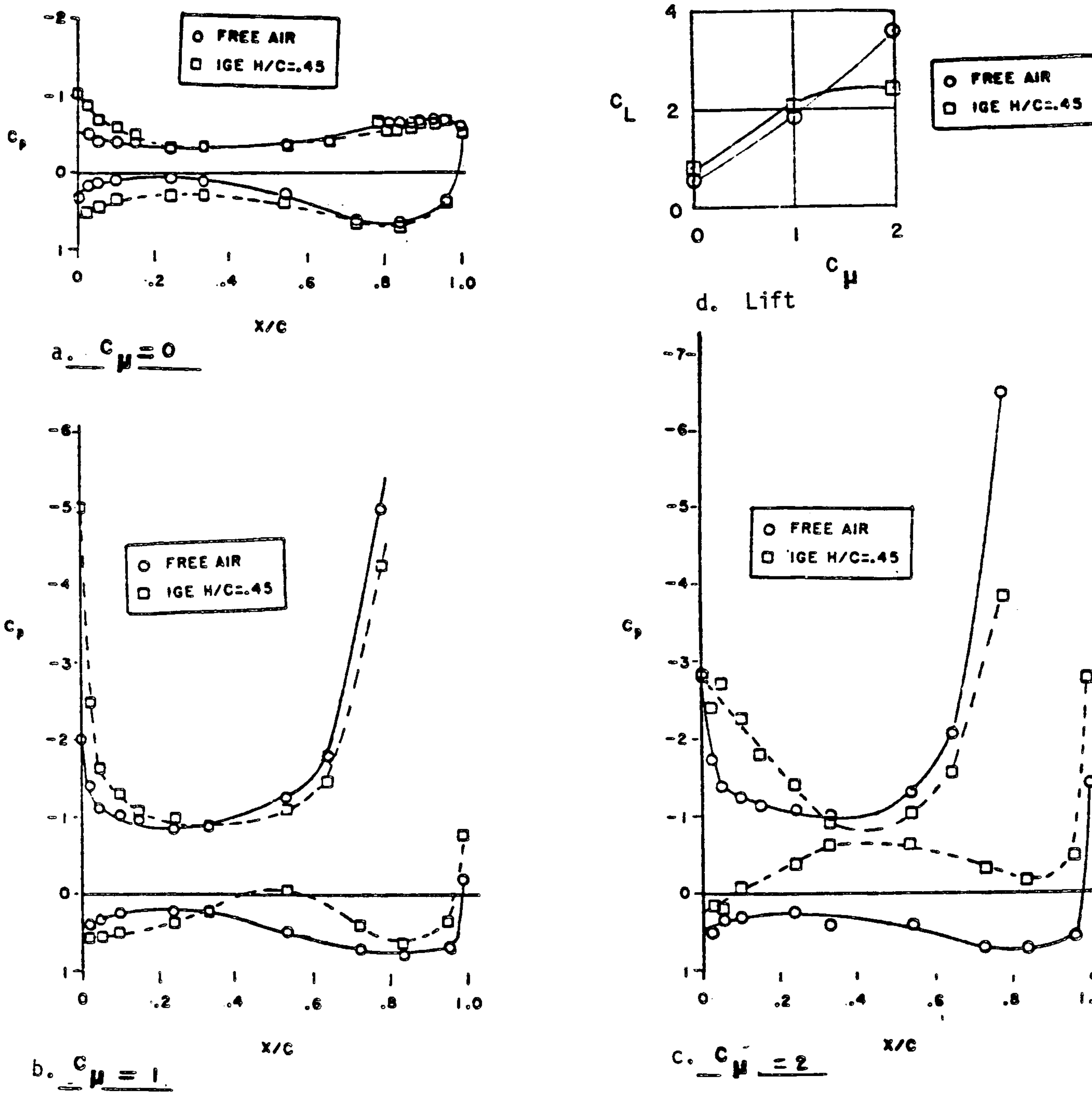


Figure 12. Effect of Ground Proximity on the Wing Pressures

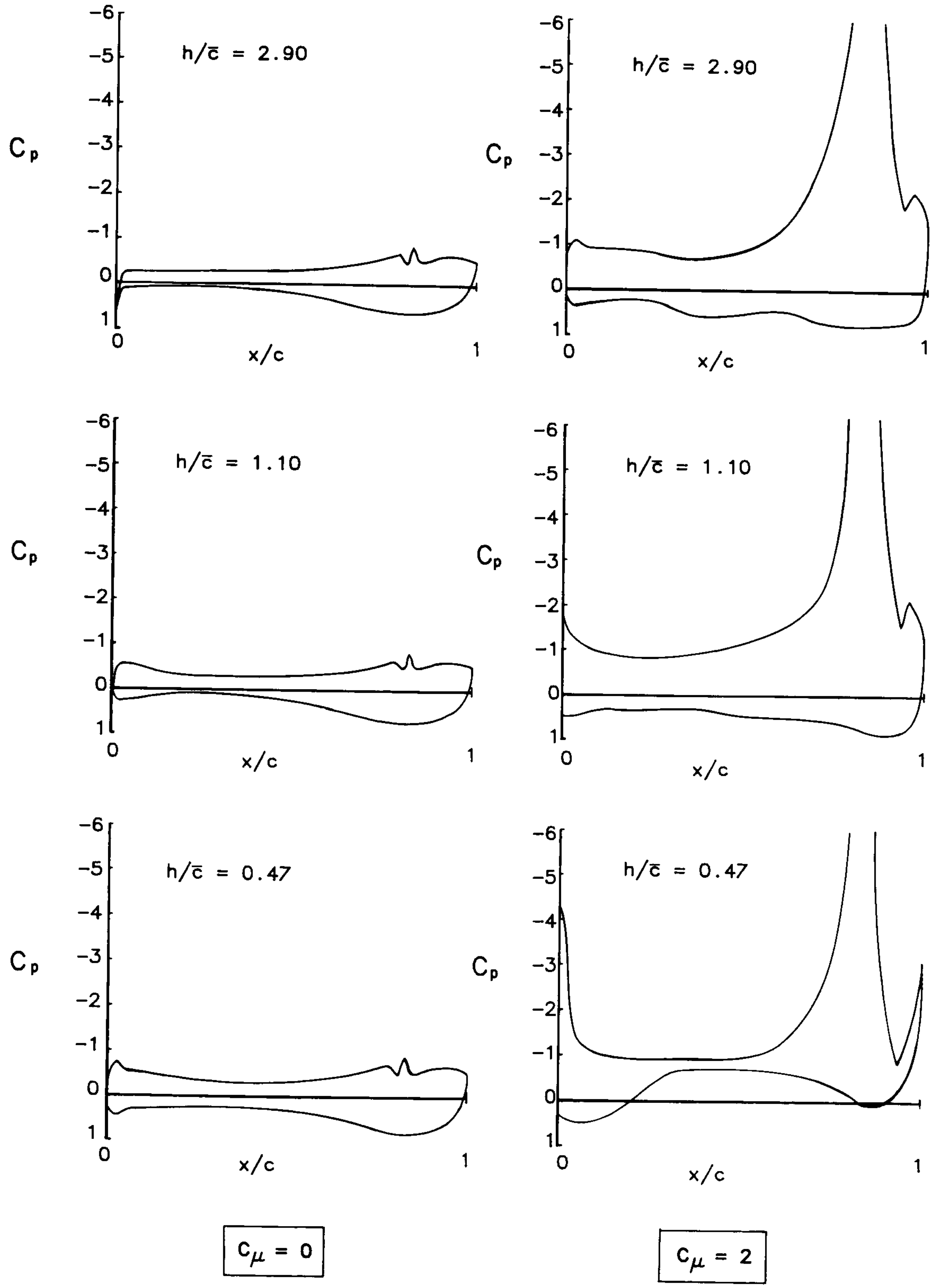


Figure 13. Ground effect on leading edge pressures.
$\alpha = 0^\circ$, $\delta_f = 45^\circ$, No canard

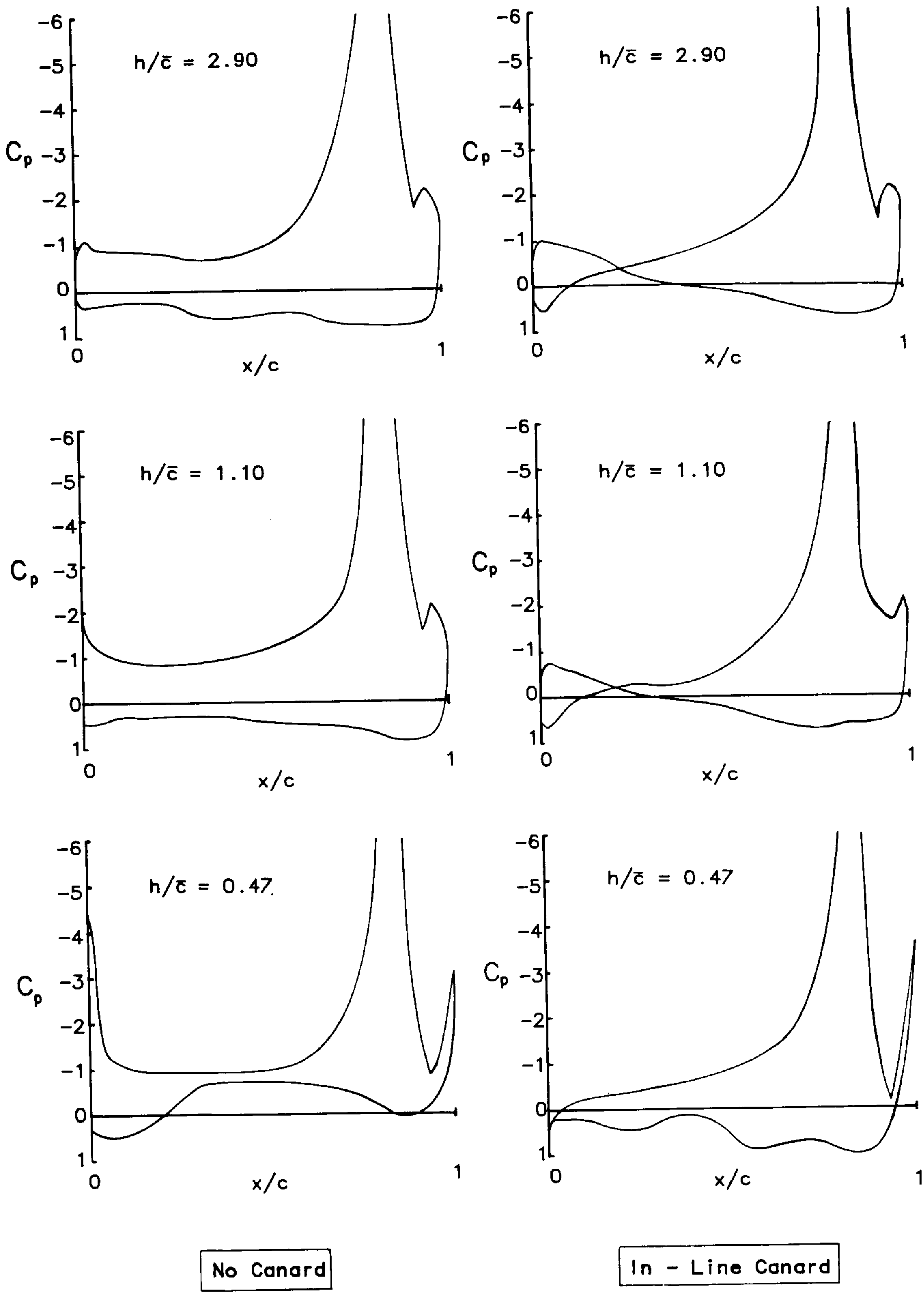


Figure 14. Canard effect on leading edge pressures in and out of ground effects. $\alpha = 0^{\circ}$, $\delta_f = 45^{\circ}$, $C_{\mu} = 2$

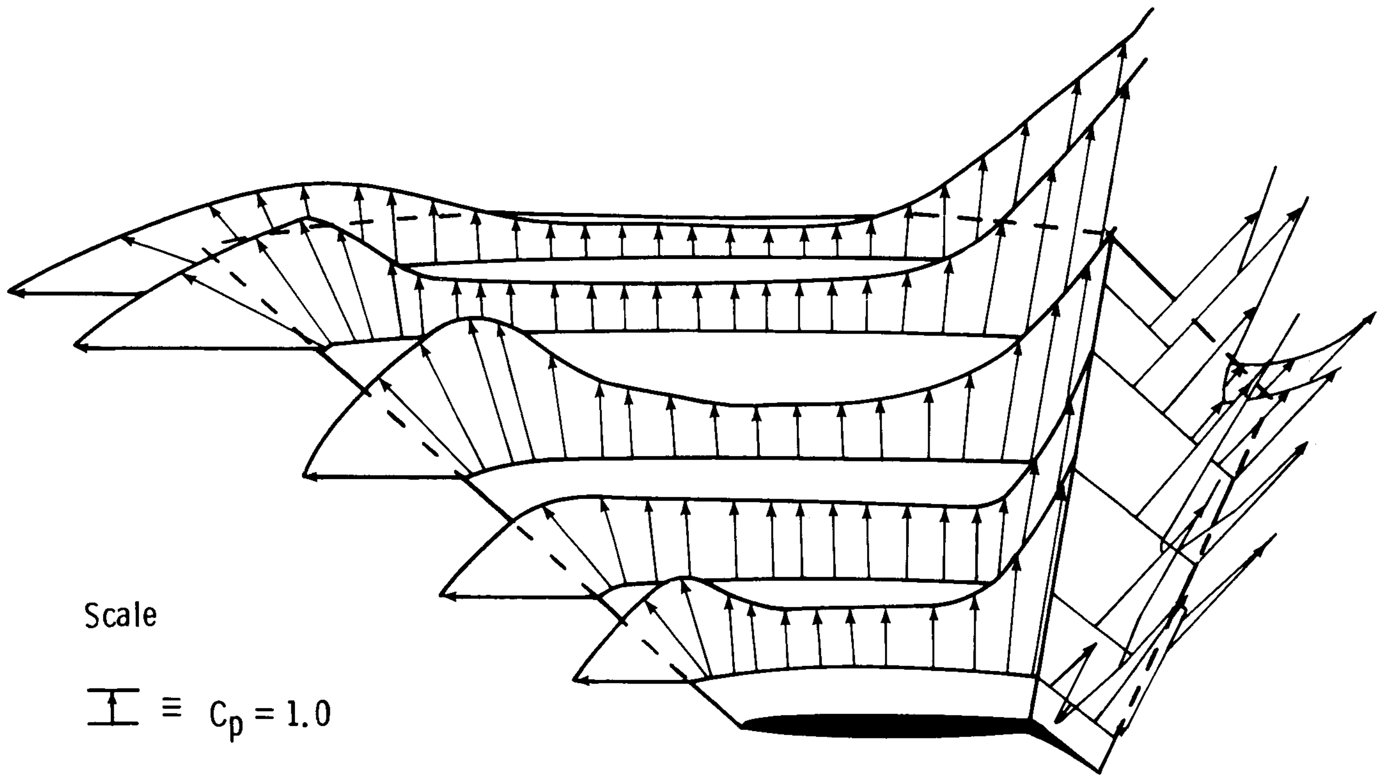


Figure 15. Upper surface pressures of a jet - flapped wing in ground effects with a separated upper surface.
$\alpha = 0^\circ$, $\delta_f = 45^\circ$, $C_\mu = 2$, $h/\overline{c} = 0.47$

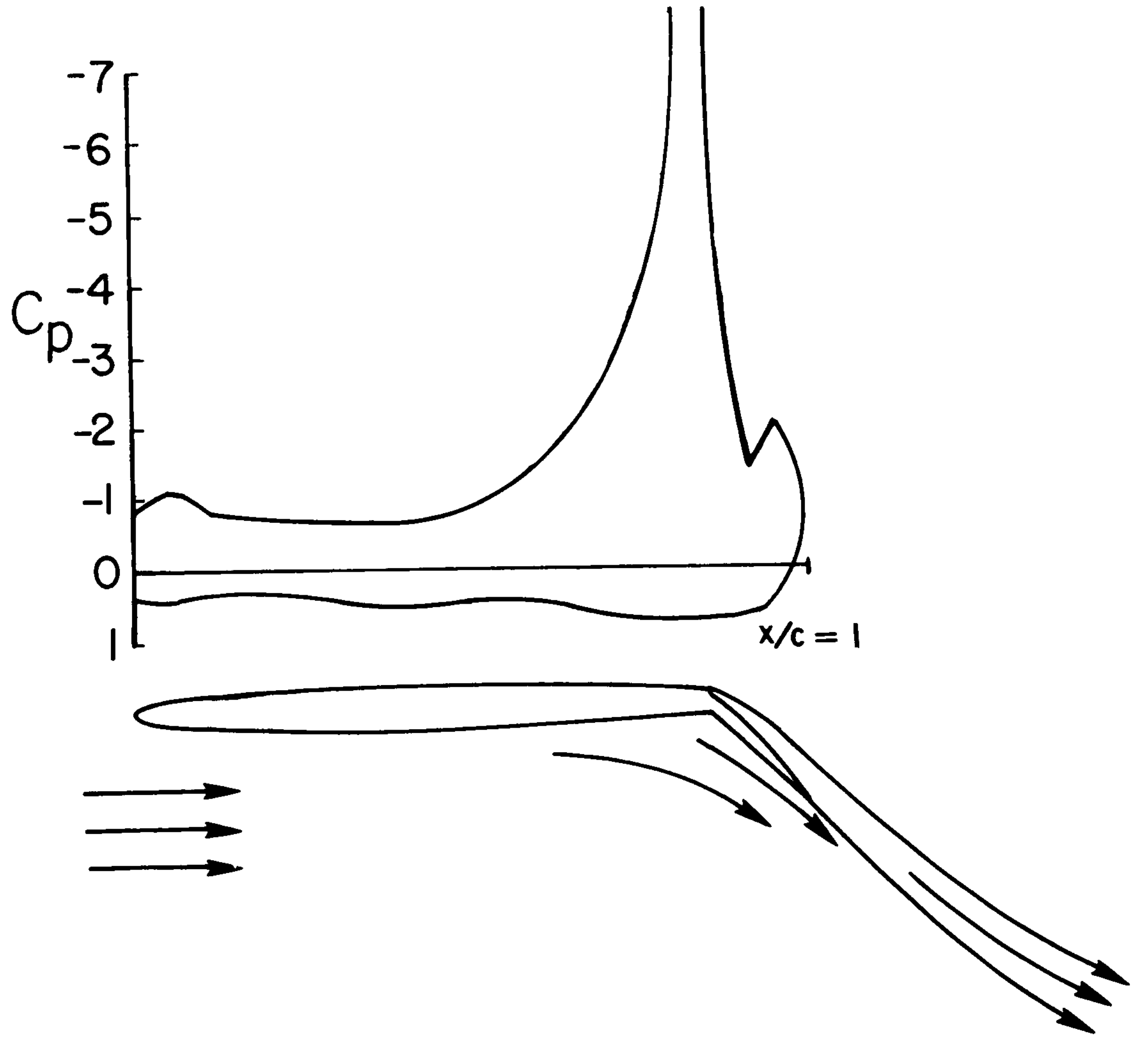


Figure 16. Pressure distribution on a jet - flapped wing out of ground effects. $C_\mu = 2$, $\alpha = 0^\circ$, $\delta_f = 45^\circ$, $h/\bar{c} = 2.90$

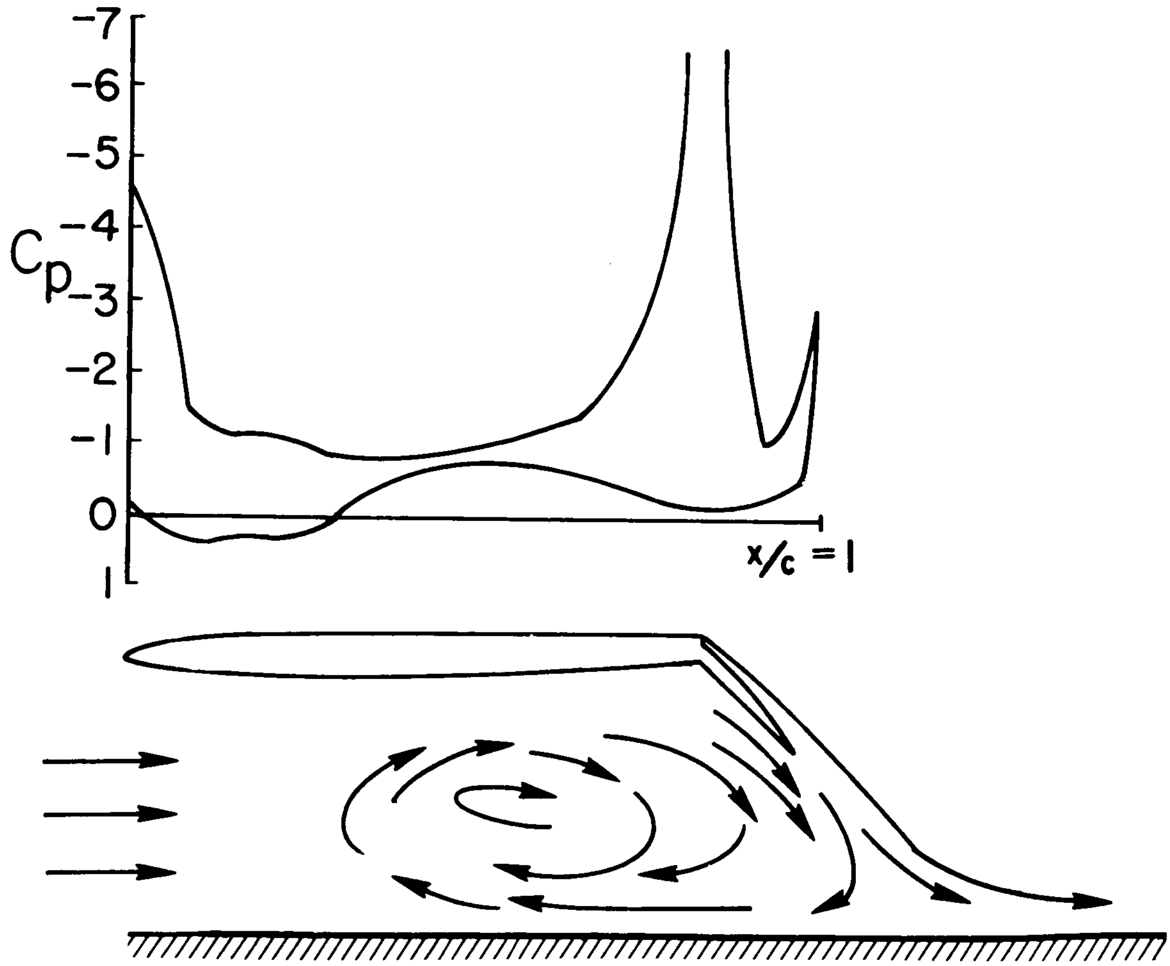


Figure 17. Pressure distribution on a jet - flapped wing with a ground vortex. $C_\mu = 2$, $\alpha = 0^\circ$, $\delta_f = 45^\circ$, $h/\bar{c} = 0.53$

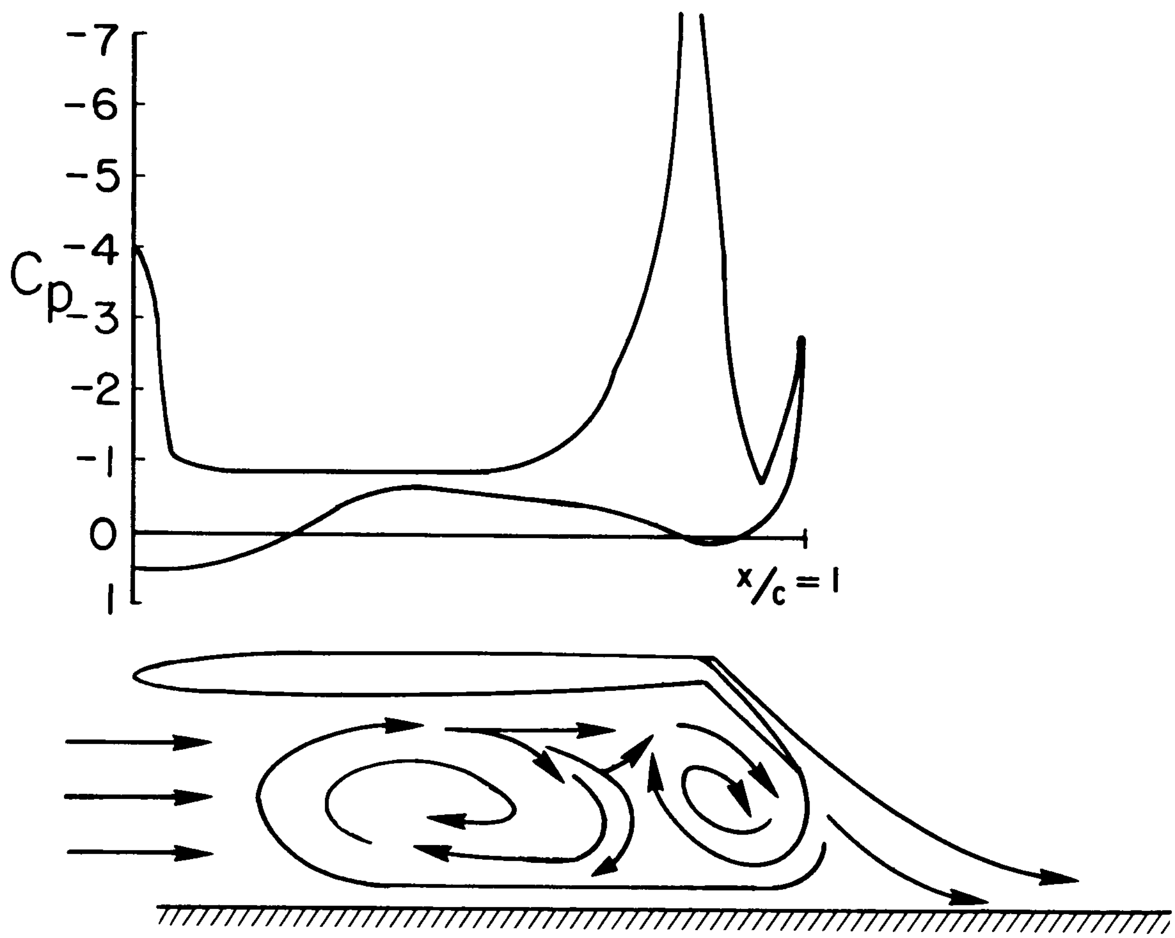


Figure 18. Pressure distribution on a jet - flapped wing with a trapped vortex pair. $C_\mu = 2$, $\alpha = 0°$, $\delta_f = 45°$, $h/\bar{c} = 0.47$

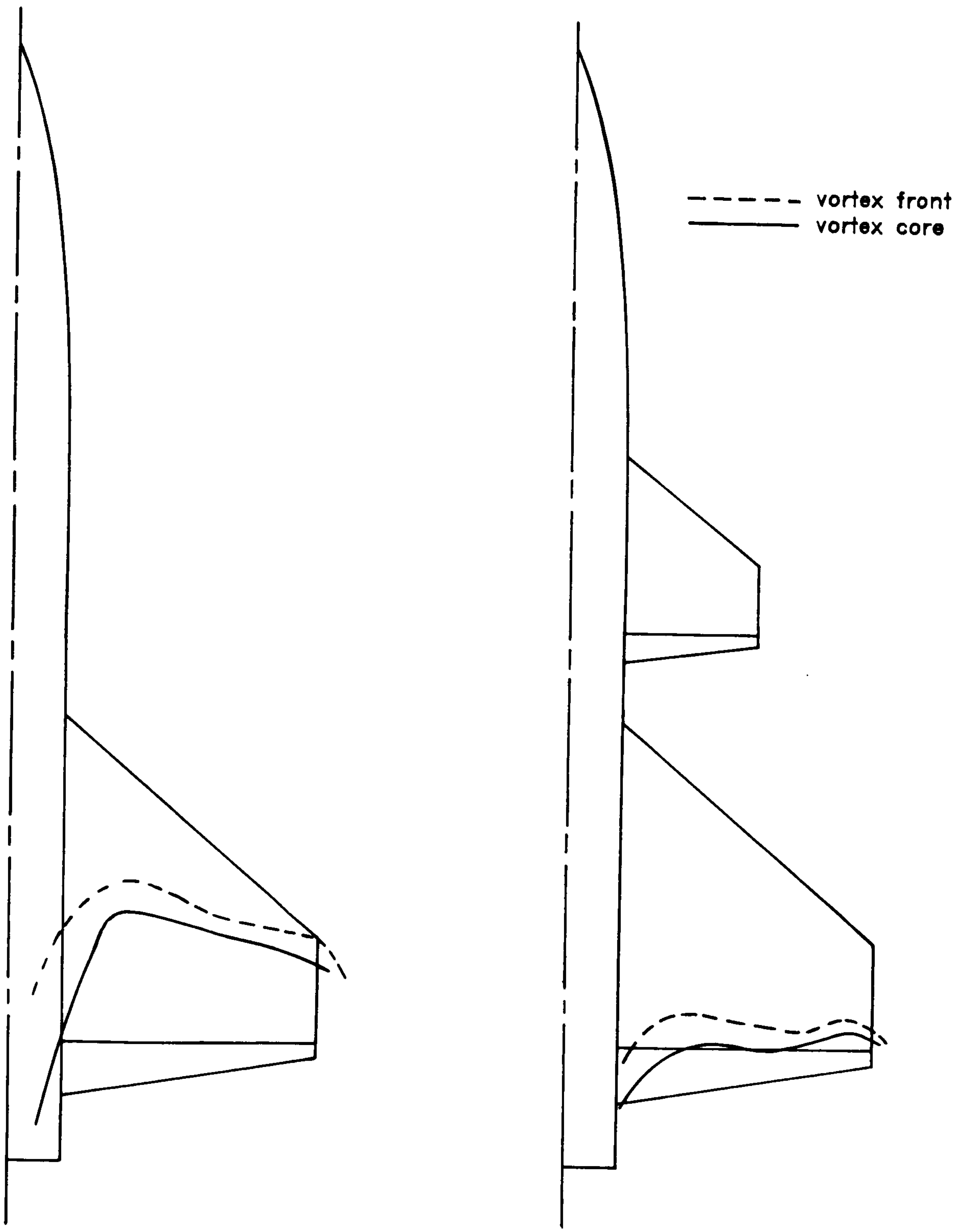


Figure 19. Blown – canard effect on ground vortex.
$\alpha = 0°$, $\delta_{f_w} = \delta_{f_c} = 45°$, $C_\mu = 2$, $h/\bar{c} = 0.47$

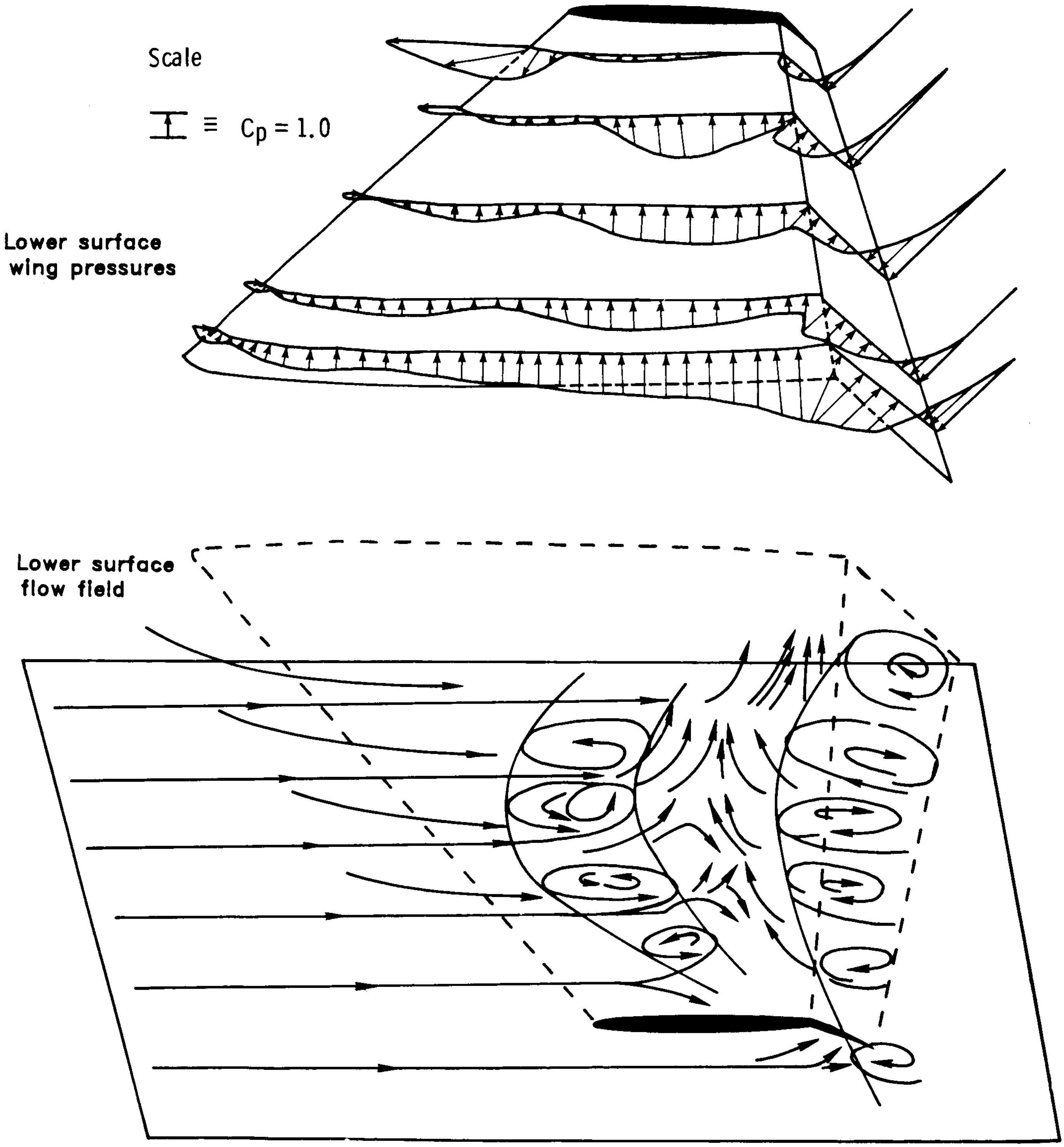


Figure 20. Resulting flow field when the canard jet interacts with the wing's wall jet. $\alpha = 0^\circ$, $\delta_{f_w} = \delta_{f_c} = 45^\circ$, $C_\mu = 2$, $h/\bar{c} = 0.47$