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EFFECTS OF A GROUND VORTEX ON THE AERODYNAMICS OF AN AIRFOIL

by

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ABSTRACT

An experimental investigation was carried out to study the aerodynamics of an airfoil with a rectangular jet exiting from its lower surface at fifty percent of the chord. The airfoil was tested with and without the influence of a ground plane. Surface static pressures were measured on the airfoil at jet to free stream velocity ratios ranging from 0 to 9. From these pressures, the variation of C_L with velocity ratio was easily determined.

The measurements indicated significant positive and negative pressure regions on the lower surface of the airfoil ahead of and after the nozzle exit respectively. The presence of a ground plane enhanced these pressure regions at low velocity ratios but at a particular ratio for each plate location, a recirculation zone or a vortex formed ahead of the jet resulting in decreased pressures and a drop in C_L.

INTRODUCTION

During the past several years there has been increased interest in V/STOL aircraft configurations which utilize lift jets and thrust augmentors mounted in the wings and/or the fuselage. One such configuration of interest uses a high lift system consisting of a wing with a long rectangular jet along the span issuing from below. Such a jet could be produced by installing two dimensional ejectors along the span of the wing. While these configurations usually exhibit improved lift characteristics, the interaction of the jet and the free stream can result in undesirable aerodynamic loading characteristics influencing the aircraft performance. For example, in hovering entrainment of the surrounding air by the jet induces a suction pressure on the lower surface of the wing causing a downward or suck-down force. During the transition from hovering to conventional forward flight this interaction produces a region of positive pressures upstream of the jet and a region of negative pressures downstream of the jet resulting, under certain conditions, in a net loss of lift and a nose-up moment. When the aircraft is operating in STOL mode, all the induced effects discussed above are present but modified by the presence of the ground. Close to the ground, the jet impinges on the ground and forms a wall jet that flows outward from the impingement region. The wall jet formed upstream of the jet exit, rolls up forming what is commonly known as a "ground vortex". This is a result of the interaction of the wall jet with the oncoming free stream. The location of this ground vortex and its induced effects on the nearby lifting surfaces is of importance in predicting the performance of the STOL aircraft.

Various aspects of the jet induced effects on wings and fuselages have been the subject of many studies; and most of these have been experimental investigations. Currently, in most V/STOL aircraft designs, a semi-empirical approach guided by experimental data is followed to model the specific jet-induced flow field. Several researchers, over the years, have surveyed and described these jet-induced or propulsive effects (Margason[1], Skifstad[2]). More recently Kuhn[3] gave a comprehensive account of the induced aerodynamics of jet and fan powered aircraft. And recent advances in prediction methods for these effects on V/STOL aircraft were described by Agarwal[4]. Since these reviews are quite extensive, no attempt is made here to discuss the previous work on jet induced aerodynamics.

The problem addressed here is the determination of the various aerodynamic forces of the airfoil resulting from a jet issuing normal to its chord line into a uniform cross flow and in the presence of a ground plane, as shown in Figure 1. The interaction between the jet and the cross flow in the presence of an airfoil is characterized by the following parameters: the geometry of the airfoil, angle of attack of the airfoil, free stream Mach number, free stream Reynolds number based on the chord of the airfoil, the geometric parameters of the nozzle, location and orientation of the nozzle with respect to the airfoil, Mach number of the jet, the location of the ground plane with respect to the airfoil and the nature of the conditions at the nozzle exit and the free stream.

The airfoil used was the NACA 0018. A rectangular nozzle of aspect ratio 87 was selected for the nozzle and the nozzle was oriented lengthwise along the span. The nozzle was located at 50 percent of the chord. The exit section of the nozzle was designed such that the jet exits normal to the chord. The free stream velocity was varied from 20m/sec to 60m/sec. The corresponding Reynolds number $R_\infty = U_\infty C/\nu_\infty$, varied from 2×10^5 to 6×10^5. The mean velocity at the nozzle exit was varied from 20 m/sec to 250m/sec. The angle of attack of the airfoil was kept at zero degrees.

APPARATUS, INSTRUMENTATION AND PROCEDURES

The wind tunnel used in this experiment was subsonic closed circuit type. The test section has the dimensions of 90.2 x 45.7 x 45.7cm. The flow speed in the test section can be varied between 20m/sec and 65m/sec. The model was situated midway between the upper and lower walls of the test section.

A NACA 0018 symmetric airfoil was chosen for the experiment. The airfoil was made in several sections using aluminum and stainless steel. It has a 15cm chord and spans the entire 45.7cm width of the test section. The aspect ratio of the wing was therefore equal to about 3.05. A rectangular slot with its long dimension in spanwise direction was cut into the lower surface at midchord. The length and width of the nozzle exit were 25cm and 0.3cm respectively. Before air reaches the nozzle exit, it passes through a settling chamber placed inside the wing and extends along the span of the wing. Compressed air was supplied to the settling chamber from both ends of the wing. To ensure a uniform flow at the nozzle exit, adjustable vanes were placed inside the settling chamber. The inlet section of the slot was designed in such a manner that the jet stream exhaust perpendicular to the chord of the airfoil. With the optimum position of the vanes, a uniform flow was obtained. The variation of the mean velocity along the span was within ten percent of the value at the center of the nozzle exit. The jet exit velocity was varied from 0m/sec to 240m/sec. For simulation of a ground plane, an aluminum plate of 45.7cm wide, 61cm long and 0.3cm thick was used. The leading edge of the plate was rounded into parabolic shape and a flap was attached at the trailing edge to insure a attached flow at the leading edge. A transition strip was placed 10cm from the leading edge. The distance between the ground plane and the airfoil chord was varied from 3.75cm to 15cm.

Surface pressure measurements were made at several velocity ratios (nozzle exit mean velocity/free stream mean velocity). To obtain the aerodynamic force coefficients, the surface pressure data was integrated around the airfoil at mid-span location. The lift due to the jet reaction is not included in most of the data presented.

A Cartesian coordinate system (x,y,z) was used with the x-axis oriented along the center line of the wing section and with the origin located at the leading edge as shown in figure 1.

For most of the measurements errors were estimated to be of the order of five percent.

The testing of V/STOL models in wind tunnel presents many problems that are not encountered in the testing of the conventional airfoils, where the testing techniques are relatively well understood[5]. V/STOL models such as the one tested have a relatively large wake deflection angle which presents one of the most difficult problems that is encountered in wind tunnel testing. The primary work on wind tunnel wall effects and their corrections for V/STOL configurations was done by Heyson[6]. Studies covering the limits on the minimum speed in V/STOL wind tunnel test were done by Rae[7]. Recently Margason and Hoad[8] gave an account of V/STOL aircraft model wind tunnel testing from model design to data reduction. In most of the instances, the model used is a fan-in-wing configuration. Since these correction techniques are highly configuration dependent, and the present wing model is not representative of any flight vehicle, no attempt is made here to correct the data.

One particularly important aspect of V/STOL model testing is the need to describe a "jet-off reference configuration" for each jet-on configuration tested. These data are then used to provide a basis for determining the interference of the jets on aerodynamic characteristics. Such a procedure was used in this experiment.

Another factor to take into account is the flow impingement on the ground plane. In a wind tunnel with the air moving with respect to the model and to the ground plane, there is a boundary layer on the floor. The effect of this can be minimized by using a moving belt ground plane. Several investigations have been carried out on this subject by Hackett et al[9]. In the experiments described here the ground plane was fixed and no attempts have been made to bleed the boundary layer.

RESULTS AND DISCUSSION

Typical variations of the surface pressure on both upper and lower surfaces of the free airfoil, at zero angle of attack with and without the jet, are shown in Figure 2. The pressures are plotted in the form of the pressure coefficient C_p given by

$$C_p = (p - p_\infty)/q_\infty$$

It is observed that without the jet, the pressure distribution on both sides of the airfoil are very nearly identical, confirming the symmetric property of the airfoil. For a velocity ratio (jet exit velocity/freestream velocity) of 6, the influence of the jet on the surface pressure is quite significant as shown in the figure. When comparing this distribution with the jet-off condition, the following observations are made: on the lower surface, in the region upstream of the jet, an increase in pressure occurs, while a decrease in pressure is noticed in the region behind the jet. The positive pressure ahead of the jet is a result of the blockage of the free stream by the jet. The effect of this is an increase in effective angle of attack of the airfoil, resulting in a relatively low pressure on the upper surface of the airfoil. At very low velocity ratios, the recirculation zone behind the jet is small and the flow reattaches to the lower surface. As the jet strength is increased by increasing the exit velocity, the flow in the region between the jet and the trailing edge forms a recirculation region and it extends into the wake. The magnitude of the pressure coefficient in this region was observed to be fairly constant as depicted by its distribution in the region between the jet and the trailing edge in figure 2. The "Kutta Condition" requires that the pressure on both lower and upper surfaces at the trailing edge be equal. This being the case, the pressure on the upper surface near the trailing edge is fixed by its value in the recirculation region on the lower surface or vice-versa.. It is interesting to note that very little variation in the magnitude of C_p is observed on the upper surface for x/c greater than about 0.6, thus suggesting that only the pressure changes in the first half ($x/c < 0.5$) of the airfoil are mostly responsible for the generation of the induced lift. From these observations it may be suggested that the positive and negative pressure regions on the lower surface are essentially responsible for many changes in the gross aerodynamic characteristics of the airfoil to be noted later.

From the chordwise pressure distribution determined, the sectional lift was easily obtained by numerical integration of pressure over the span wise section. For each value of the velocity ratio in the range tested, a corresponding sectional lift coefficient C_L was obtained at mid span location. The reaction force due to the jet is not included in the definition of the lift. Figure 3 shows the variation of C_L with the velocity ratio. It can be seen from the figure that the C_L

increases monotonically up to a velocity ratio of about 5. This is a result of the pressure increasing rapidly in front of the jet on the lower surface. In the range of velocity ratios between 5 and 8, the pressure in the recirculation regions behind the jet decreases rapidly with increasing velocity ratio, thus resulting in a drop of C_L as shown in the figure. The detailed discussion of these regions and their effect on the aerodynamics of a free airfoil is given by Krothapalli and Leopold[10]. For velocity ratios greater than 8, an increase in C_L is observed, and this is attributed to the influence of the tunnel wall or ground effect.

At low velocity ratios, the influence of a ground plane on the flow around the airfoil seems to enhance the same general trends found for the free airfoil. The regions ahead of and behind the jet both increase and decrease respectively with increasing velocity ratio but the variations are more pronounced; the degree of which depends strongly on plate position. This phenomenon is shown in figure 4 where the pressure distribution for two plate locations are compared to the free airfoil distribution at a velocity ratio of 2. As this ratio is increased, the pressure in front of the jet drops dramatically resulting in a sharp decrease in C_L. The velocity ratio at which this occurs depends strongly on plate position.

The variation of lift coefficient throughout the velocity ratio range is shown in figure 5 for three plate locations and are compared with the free airfoil. These curves indicate a unique velocity ratio for each plate location where C_L reaches a maximum. As the ratio increases further, the pressure in front of the jet on the lower surface decreases thus resulting in a reduced C_L. These unique points represent a boundary between favorable and unfavorable operating conditions which are shown in figure 6. In region 1, favorable conditions exist. The lift coefficient increases as the jet velocity increases. In region II, unfavorable conditions exist since the lift coefficient decreases as the jet velocity increases. The relation in figure 6 also indicates the beginning of a new type of flow structure in front of the jet; the influence of which on the overall aerodynamics of the airfoil increases as the velocity ratio increases. This complex flow is best visualized in figure 7 where case I corresponds to the flow condition occurring in region 1 of figure 6. For this case, the momentum of the jet is small enough for the jet stream to be bent by the oncoming free stream. The recirculation is confined to the region behind the jet therefore creating a low pressure zone behind the jet and a high pressure zone in front of the jet. In case II, the jet momentum reaches a high enough value that the jet impinges normal to the plate creating two recirculation regions. The region in front of the jet drops in pressure resulting in a decreased C_L. As the jet velocity increases, the recirculation zone in front of the jet increases in intensity and eventually forces C_L to a negative value. The recirculatory region in front of the jet is commonly known as the ground vortex.

CONCLUSIONS

From this preliminary experimental investigation, the following conclusions can be drawn. The static pressure distribution around the airfoil shows two distinct regions on the lower surface, which greatly influence the overall aerodynamics. First there is the positive pressure region upstream of the jet. This is attributed to the "blockage" of the freestream by the jet. The second is the region between the jet and the trailing edge, marked by the negative pressure coefficient, and the magnitude of the pressure coefficient in this region is found to be nearly constant. The pressure on the upper surface of the airfoil is also influenced by the presence of the jet, and the influence is such that only the pressure distribution for the leading half of the airfoil contributes to the lift coefficient. The presence of the ground plane, for moderate heights, and at low velocity ratios, improves the aerodynamic characteristics of the airfoil. However, a further increase in the velocity ratio for a fixed ground plane height, a large vortex develops in front of the jet, commonly known as "ground vortex", resulting in a sharp decrease in C_L.

ACKNOWLEDGMENTS

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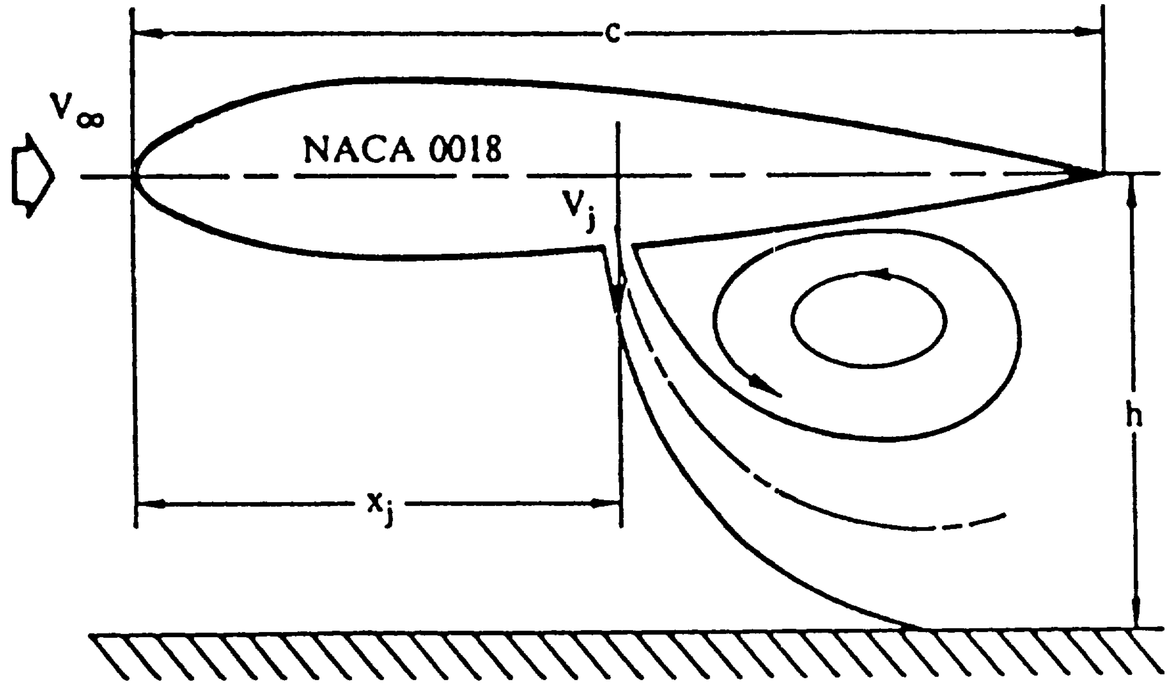

Figure 1. Schematic of the model and nomenclature.

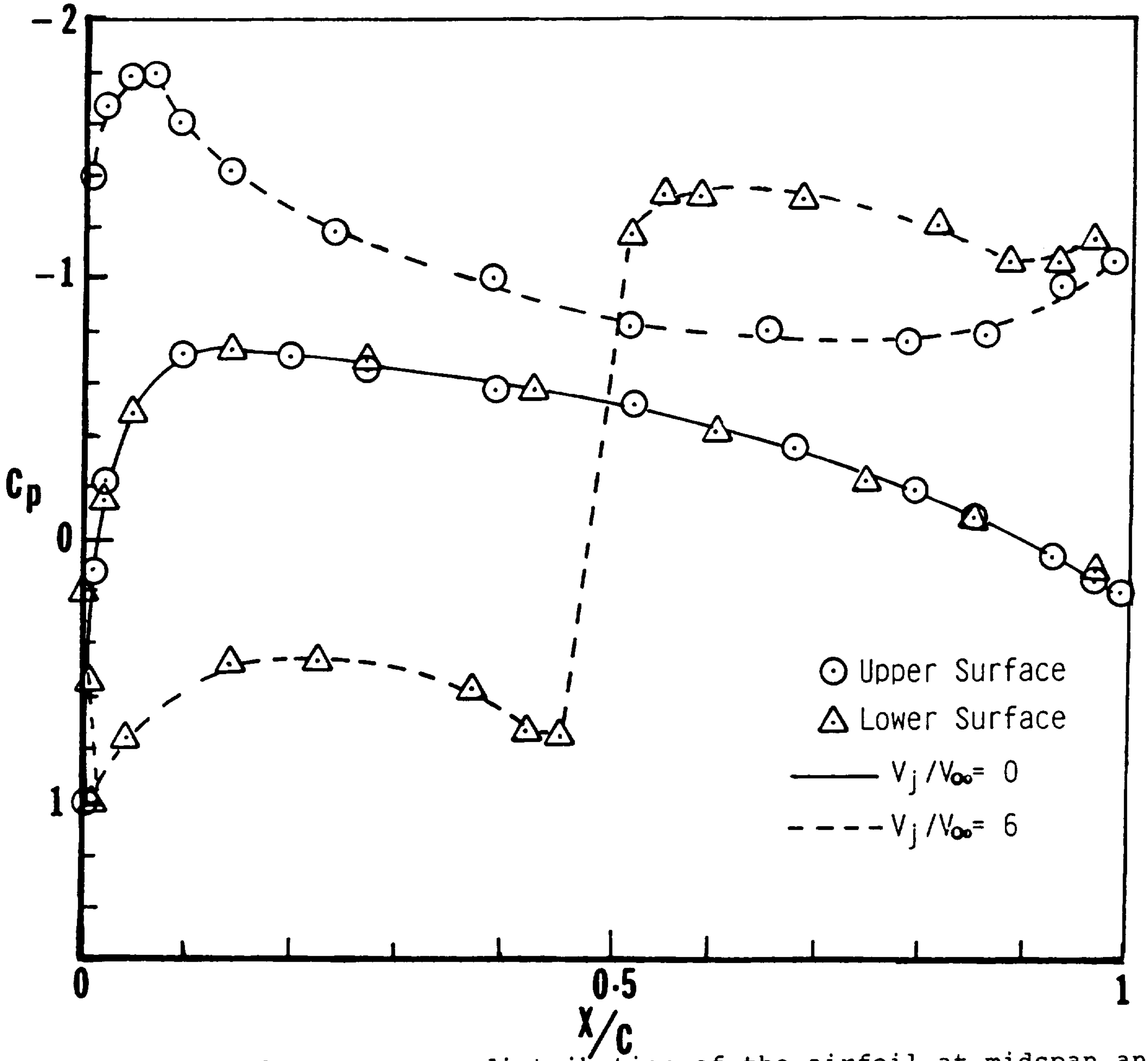

Figure 2. Surface pressure distribution of the airfoil at midspan and out of ground effect.

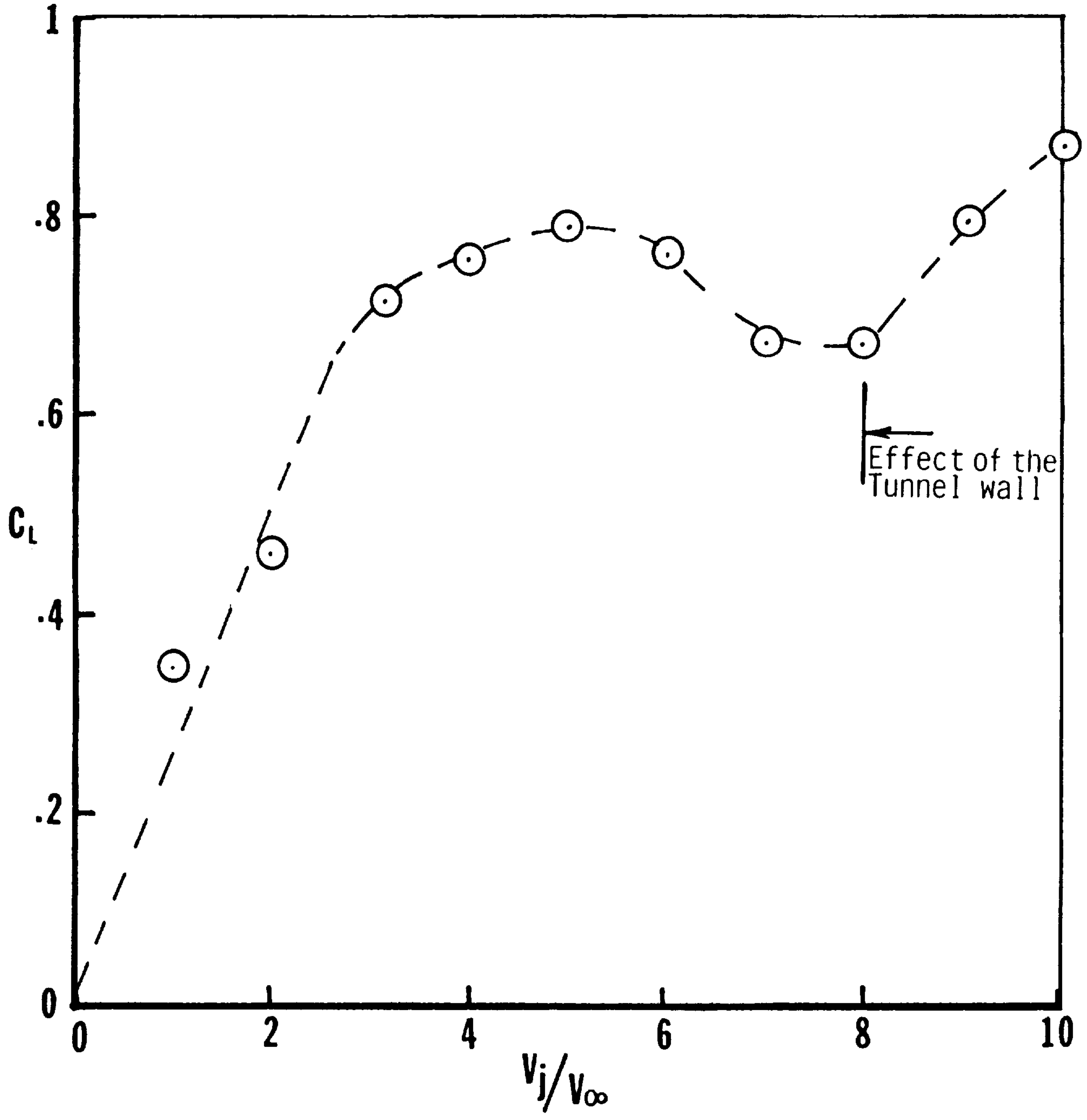

Figure 3. Variation of the sectional lift coefficient with velocity ratio for the case of the free airfoil.

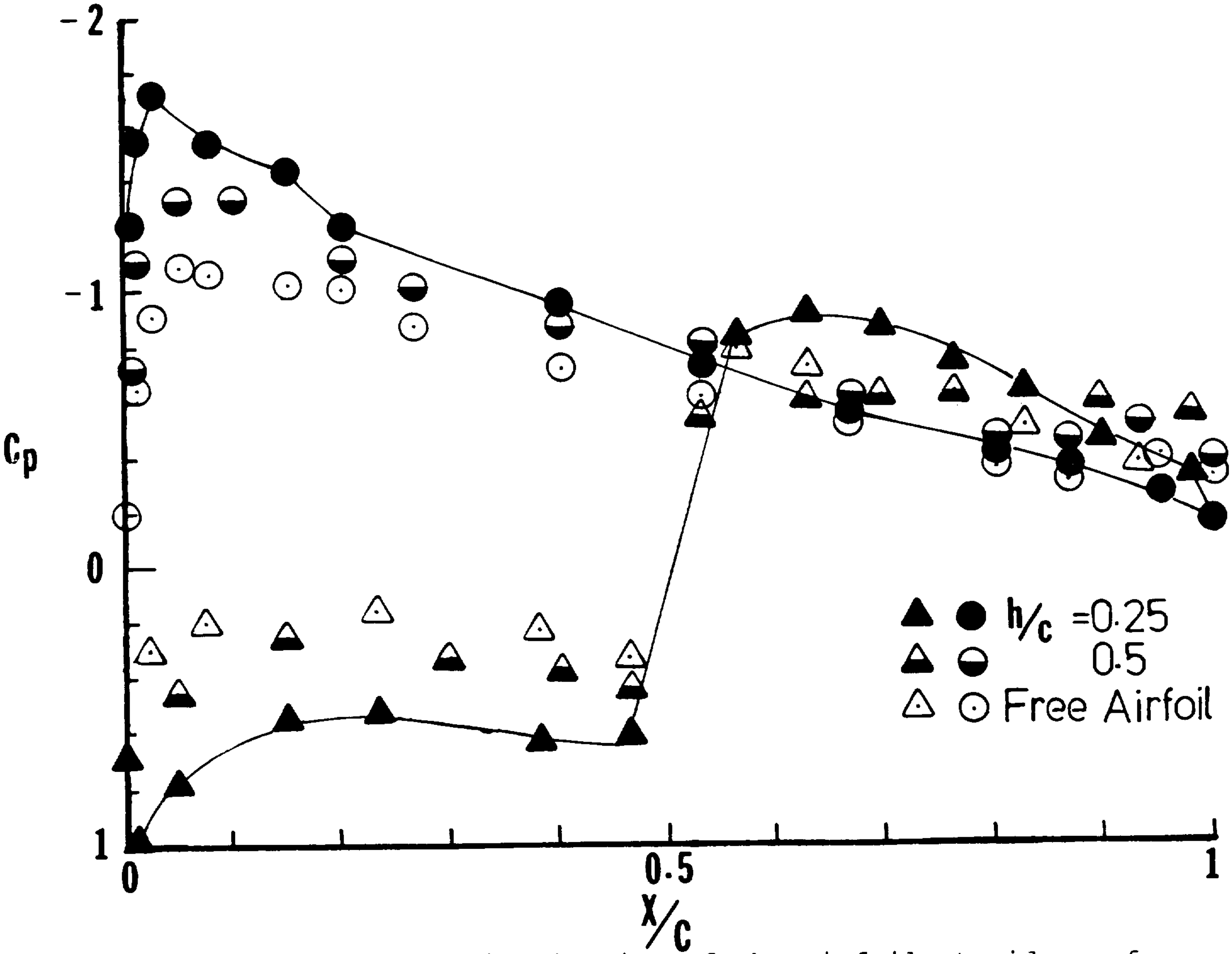

Figure 4. Surface pressure distribution of the airfoil at midspan for different ground plane locations; velocity ratio = 2.

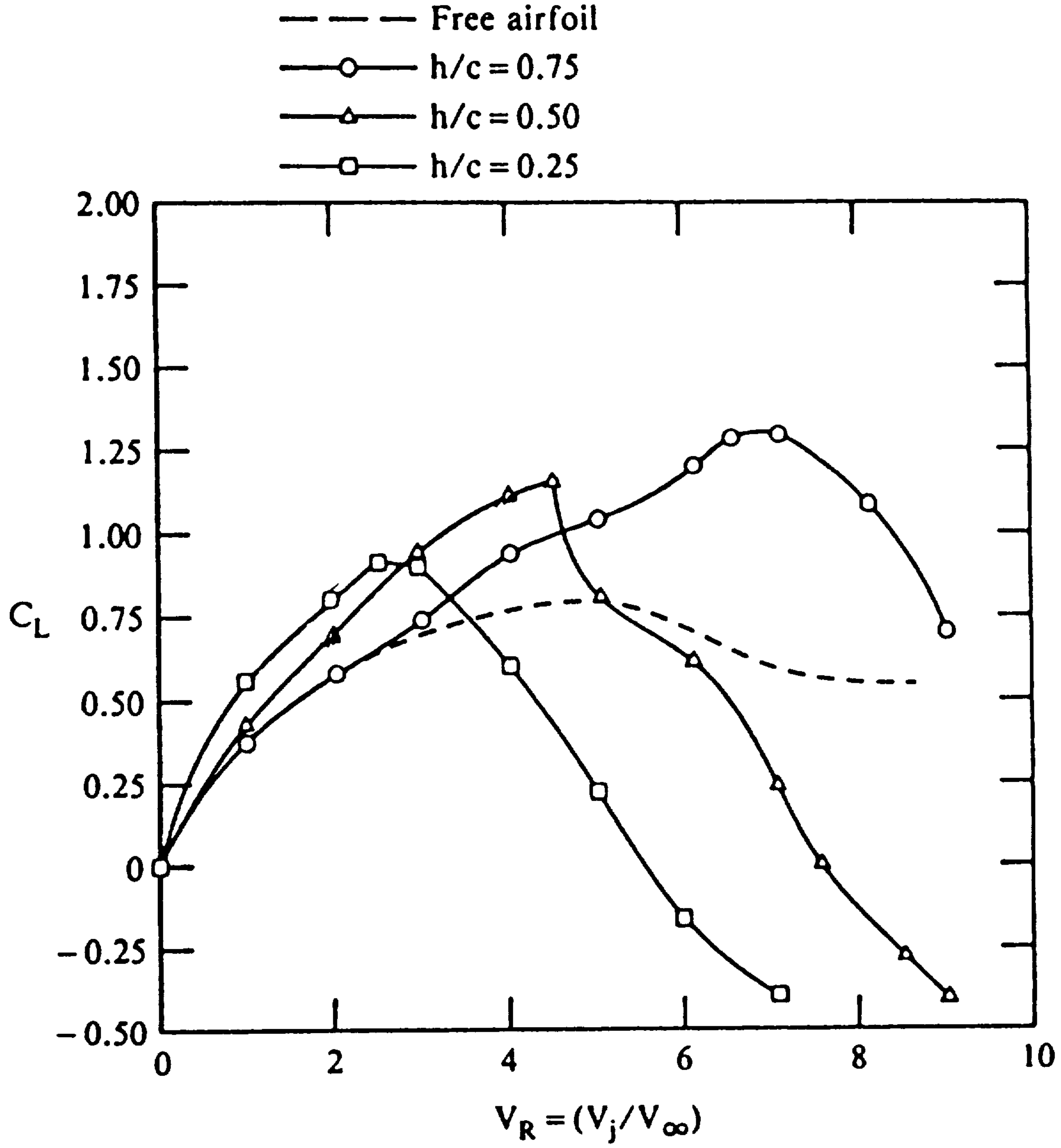

Figure 5. Variation of the jet induced sectional lift coefficient with velocity ratio for different ground plane locations.

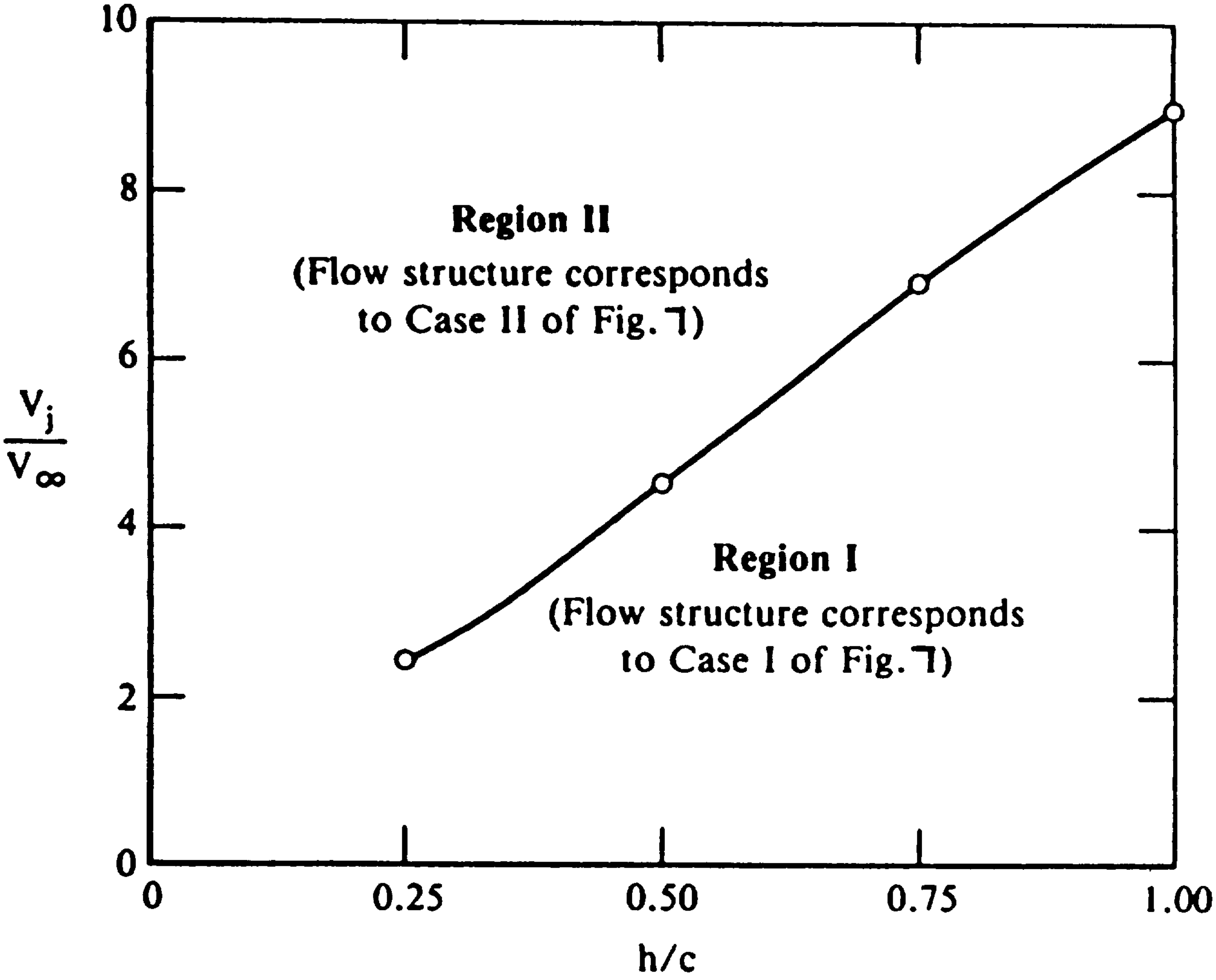

Figure 6. The loci of the maximum C_L for different ground plane locations.

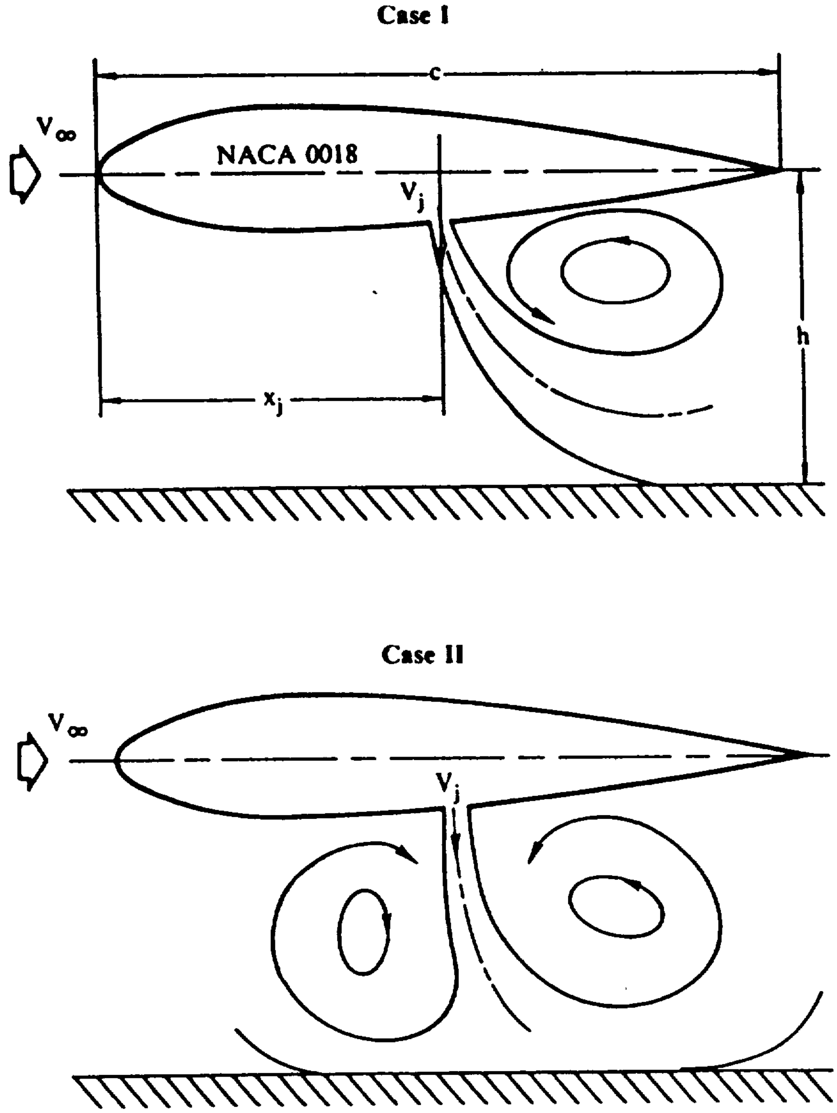

Figure 7. The flow structure corresponding to regions identified in figure 6.