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WING-TIP JETS AERODYNAMIC PERFORMANCE

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ABSTRACT

This paper presents the preliminary study of wing-tip jets blowing techniques to achieve improvements in the wings aerodynamic performance. The feasibility of utilizing wing-tip jets to replace the currently popular winglets has been conducted. The idea is to study the potential of replacing solid winglets by more flexible wing-tip jets to suit changing flight conditions. The wing-tip jets modify the flow-field near the wing tip and could achieve better aerodynamic performance of the wing.

A first order calculation has been made to check the air-jet advantage versus the disadvantage in degrading the jet-engine performance by bleed-off of compressed air. The result indicates that the power (or thrust) saved is significant enough to encourage us to explore this new concept. Munk's minimum induced drag criterion has been extended to formulate the split branched wing-tips by utilizing multi-ports jet. Moreover, it is also conceived that an added jet swirling effect may induce a circulatory motion. The induced local downwash could alter the near wing-tip flow and thus surpress the main wing-tip-roll-up vortex. For this purpose, wind-tunnel testings with a half-wing model has been conducted to verify this concept. This is done by controlling the jet blowing direction and magnitude.

Introduction

Ever since it was recognized that the three-dimensional wing produced an *induced drag*, many efforts have been made to reduce the induced drag and to increase the overall lift/drag ratio by properly modifying the wing configuration including its tips. It is astonishing to learn that as early as 1897, a patent was issued to Lanchester for installing a vertical surface at the wing tips (Ref. 1). The search for better means of reducing the induced drag has never ceased. Indeed it has had a long history, almost as long as the history of aviation itself.

Among enormous works done on this subject, a few significant decisive milestones were made by Munk (Ref. 2) in 1921, Reid (Ref. 3) in 1925, Hemke (Ref. 4) in 1927, Von Karman and Burgers (Ref. 5) in 1934, Mangler (Refs. 6 and 7) in 1937 and 1939 of early theoretical methods, Reiba and Watson (Ref. 8) in 1950, Riley (Ref. 9) in 1951, Clements (Ref. 10) in 1955 all contributed in early experimental observations. Later, Weber (Ref. 11) in 1956, Cone (Ref. 12) in 1962, Lundry and Lissman (Ref. 13) in 1968 all contributed in further developments of the wing-tip end-plate theory.

In 1976, Whitcomb summerized all these ideas and proposed a now well-known winglet concept (Ref. 1-14). Subsequently, NASA Langley Research Center has conducted a series of tests (Refs. 15 - 24) which proved that the winglet concept is sound if properly designed. Since then, within a relatively short time, a few new aircrafts have rolled off the assembly lines with winglets installed. In spite of this sudden love with *winglets*, the winglets cannot provide improved performance over the various flight phases. The off-design performance can be worse than without the winglets. This is not surprising, if one realizes that a fixed solid surface mounted on a wing-tip is just not flexible enough to tailor various phases of flight.

Instead of using a solid device as traditionally followed, an idea of using many wing-tip-jets to control the tip-flow field is conceived and has been studied. The wing-tip-jet not only can also be designed with sufficient flexibility, it can be turned on or off according to various flight conditions. Clearly, such an idea is worthwhile to be explored.

The use of air-jets to improve the wing performance has been studied extensively in the past, especially in the form of jet-flaps and upper surface blowing (Refs. 25 and 26). Some limited studies are also availiable using an air-jet in an attempt to break-up the wing tip vortex roll-up (Ref. 27). However, wing tip jets concept has never been studied as we are suggesting in this paper. As a first step, it is needed to consider the effect of bleeding the compressed air from the jet-engines because it reduces the engine performance. Based on the available data a first order calculation has been performed which indicates that the gain in lift/drag ratio is more than sufficient to compensate for the loss of engine thrust. The required trimming drag, because of change in the pitching moment, is probably small due to the fact that a wing-tip-jet modifies only the local flow near the wing-tip surface. Moreover, a proper design can minimize the required trimming. The key problem is in finding a feasible way of jet control at the wing-tip such that to achieve better performance as well as a fundamental understanding of wing-tip-jet generated flow field. This is the major objective of this study.

Technical Discussion

Recently much attention has been focused on the problem of the wing-tip flow field control by applying Whitcomb's winglet concept (Ref. 1). Several new airplanes have adapted winglets in their latest wing designs. Aerodynamicists and designers have used the merits as well as the deficiencies as focal points for arguments.

A winglet effectively increases the aspect ratio of a wing to reduce the induced drag. The benefits obtained by winglets should be large to overcome the additional structural weight penalty. A winglet should yield better performance than a simple wing-span extension. Gates Learjet's series 50 (Longhorn) claims that the installation of winglets has reduced the total drag by almost eight percent at optimum operating conditions (Ref. 28).

NASA Langley Research Center has conducted a series of wind tunnel experiments (Refs. 18 to 24) using a realistic airplane model with winglets installed The results obtained are very encouraging at design conditions. The NASA winglets consists of two airfoil-shaped upper and lower end-plates mounted at the wing tip, with three fixed angles with respect to the wing (Fig. 1). These three angles are: sweep, inclination and cant angles. Due to this complexity, a proper design is not simple. Moreover, one may immediately sense that such winglets will not yield better performance during *all* flight conditions. As a matter of fact, birds adjust their wing-tip configurations as flying conditions vary (Fig. 2) (Ref. 29).

The aerodynamics of winglets are examined and illustrated in Fig. 3. For the upper winglet, the wind velocity is composed of the free stream U_0 and the side-wash velocity w as shown. Proper orientation of the upper winglet will result in a lift component P_1, that produces a thrust component T_1, which could compensate the drag created by the winglet itself. The lift component P_1 modifies the loccal pressure distribution near the wing tip surface as shown in Fig. 3.

Due to the side-wash velocity running in the opposite direction, the lower winglet must be mounted in the opposite way as shown. However, it is important to note that the lower winglet is not as effective as the upper one.

In an experimental study of wake vortex minimization (Ref. 30) it was learned that by applying downward jets, at the trailing edge of the wing tip, tremendous improvement in the lift/drag could be obtained. These experiments were conducted using distributed jets from a circular tube extended from the wing tip as shown in Fig. 4.

Other similar experiments (Ref. 31) have shown to result in an increase in the effective aspect ratio of wings using either solid surface(s) or air jet blowing. It is the purpose of this study to identify changes in the wing tip aerodynamics due to wing tip jet blowing.

In the actual application of this concept to aircrafts, the air blown off at the wing tip must be bled-off the plane's power plant. Calculation is made to estimate how much loss may the jet engine suffer in comparison with the gain of the increase in lift. The available data of the extended tube blowing cited above in Ref. 30 has been used for a first order computation. The calculation has been made for a fictitious airplane, similar to a Boeing 707 with NACA0012 airfoil and assumed flying 0.8 Mach number at 26,000 feet altitude.

The published data on the measured force components with variations of angle of attack are used (Ref. 30). Note that because the tube has been actually extended in the spanwise direction, the apparent aspect ratio is changed. The equivalent conventional wing tip as well as the increased apparent aspect ratio have been taken into consideration. It is interesting to note that a great performance improvement is achieved by the tube-blowing jets.

Based on these data a first order calculation, for cruising and take-off conditions, has been made. According to this crude calculation a net gain in power savings has been observed. Therefore, wing tip jets have been considered practically feasible and warrant study. The phenomenon responsible for the wing tip flow field modification is very complicated for theoretical analysis. Therefore an experimental study has been conducted.

Description of Experiments

All experiments reported here were performed in the University of Tennessee Space Institute (UTSI) low speed wind tunnel. The UTSI low speed wind tunnel is an open circuit, closed test section and continuous tunnel. The test section measures 14 inches (35.56 cm) high by 20 inches (50.80cm) wide by 42 inches (106.68cm) long, and has two plexiglas sidewalls to allow for observation and photography of the model. The tunnel velocities range from 20 to 100 ft/sec. Pressure measurements are made with ±1 psid transducers which are used with two twenty-four port "wafer swiches". Data acquisition are managed by a minicomputer specially designated for this purpose.

The model used for these tests was a NACA0012-64 airfoil with 17.99cm cord length and 30.48cm half span. The model was made from many modular pieces so that access into the model inside for the purpose of instrumentation as well as air supply to the wing tip jets was readily possible. Pressure ports were provided at four span row stations. There were nine pressure ports on the uppersurface and seven ports on the lower surface per each row. The model was supported by a sting through the side wall to a turn-table with the capacity of continuous incident angles setting of 0° to 360°. A boundary layer fence was installed between the model and tunnel wall to ensure two dimensional flow. Although the model was designed to be used for force and moment measurements, these measurements were not made available at this time of writing.

The model was equipped with interchangeable tips and these tips were designed for various blowing configurations. The data presented here were obtained with the wing tip jets shown in Fig. 5. Blowing air was supplied to the tip through 0.64cm diameter tubing and the flow rate was measured by a "Dwyer" flow meter. To vary flow rate a pressure regulator was used to control the total pressure in the air supply line.

Numerical Computation

To provide a basis of comparison toward wing tip jet blowing experimental result, the pannel method (Ref. 32) was used to compute basic wing tip flow fields with different winglet configurations. These computations are performed for incompressible potential flow; thus the viscous effects are not included. The type of airfoil chosen was also NACA0012-64. The pannel method can be used for arbitrary planform, camber, twist, and thickness distribution.The numerical computations have shown that the upper winglet is more effective than the lower winglet as has been anticipated. The results of the numerical work will be reported in a separate paper later. The basic wing pressure distribution obtained by computation will be used for comparison with the experimental results only.

Experimental Results and Discussion

Due to the lack of a firm theoretical knowledge of the wing-tip jet blowing, it is rather difficult if not impossible at this time to design and test the optimum wing tip jet configuration. Therefore, to shed more light into the understanding of this complicated wing-tip flow field in presence of tip-jets, a systematic parametric investigation has formed the basis of this experimental work.

Baseline pressure distribution data were obtained using the solid wing tip section. These data indicated a variation in lift along the half wing span as shown in Fig. 6 for 10° incidence angle with no blowing. Considering that the model aspect ratio was 3.4, the model may be essentially representing the viscous flow field near wing tip only. This effect is also indicated in Fig. 7-9.

Jet blowing in the tip region was applied by installing the specially designed three port wing tip section shown in Fig. 5. Air was supplied to the jet ports from inside the model. Blowing combination of ports number I, II and III with three angles of incidence were measured. Considering the port design was not an optimized configuration, some significant improvements in the C_p distribution were observed at all the three span measurement stations.

In Fig. 7-9, a set of typical data, at three span locations for 10° incidence, jet blowing data as well as the computations results are shown. It is clear from these figures that, this combination of blowing has produced increased lift over the entire model. The parameters identifying test conditions are shown on each figure. It is important to note that the surface pressure distribution measured is different than that of the winglet. In the present case a more global influence is observed. Other tests with C_μ of nearly twice the value for the above tests did not show major changes in the results described so far. It is believed that the optimum jet port geometry is one of the main parameters to be experimentally obtained. In Fig. 10 the above data as well as other blowing combinations have been plotted on the normal force coordinate.

Conclusion

A new concept to use jets at the wing tips to replace winglets has been investigated. The preliminary results obtained here have shown that using wing tip jet blowing one could produce effects similar to winglets. Such possibility would lead to the elimination of structural modifications needed for the installation of winglets as well as addition of controls simplicity and flexibilities otherwise impossible. It is conceivable that an additional improvement could be achieved by introduction of swirling effect in the tip jets. This jets swirling needs to be applied such that the net effect suppresses the natural wing tip vortex roll-up. This task is still under investigation and will be reported later.

Of course much work is due to be done on this problem to obtain physical and theoretical understanding of this complex flow field interactions. We hypothesize that the final solution to the wing tip problem is a combination of winglet and wing tip blowing for the future aircrafts.

Acknowledgement

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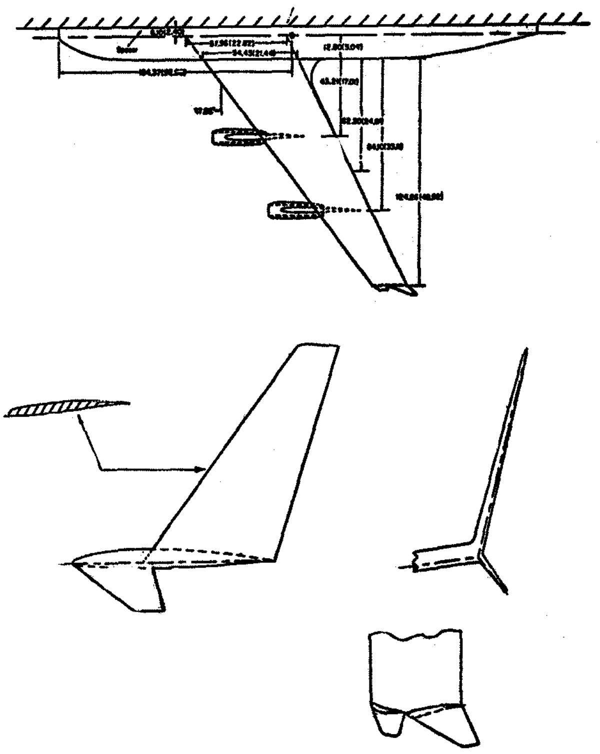


Figure 1. Details of Upper and Lower Winglets (Ref. 18).

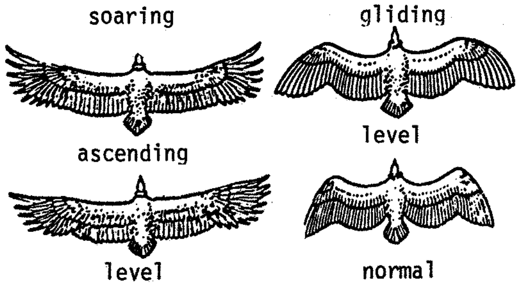


Figure 2. Birds adjust wingtips according to flight conditions (Reference 29).

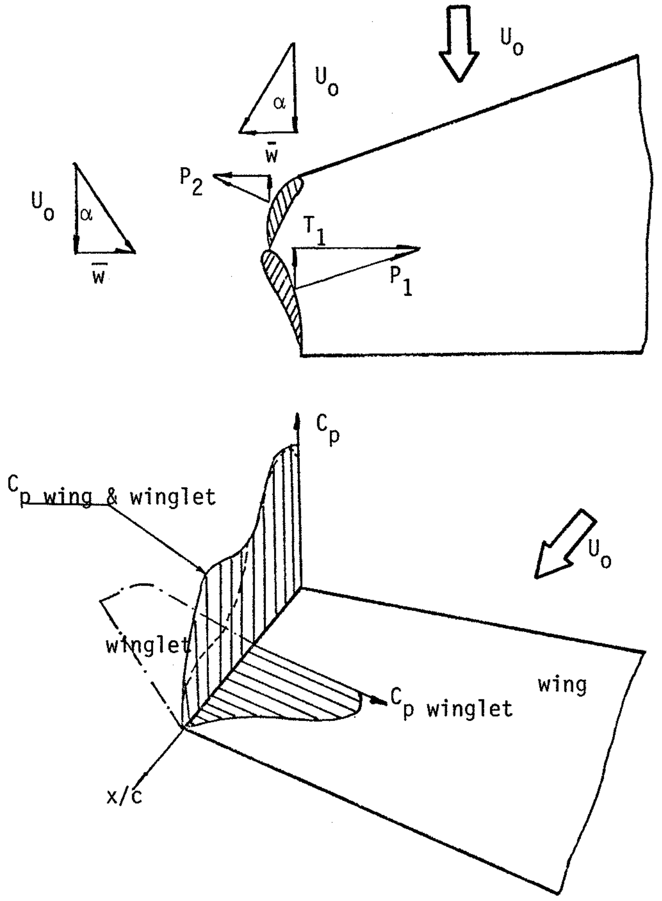


Figure 3. Winglet Aerodynamics Principle

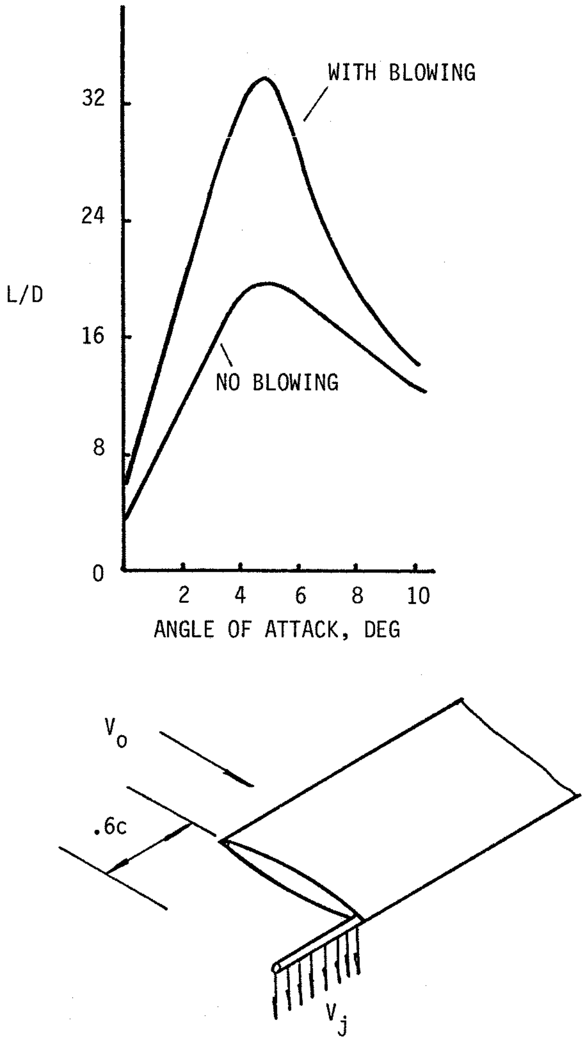


Figure 4. Extended From Wing-tip Circular-Tube-Jets Blowing and Measured Results (References 30 and 31).

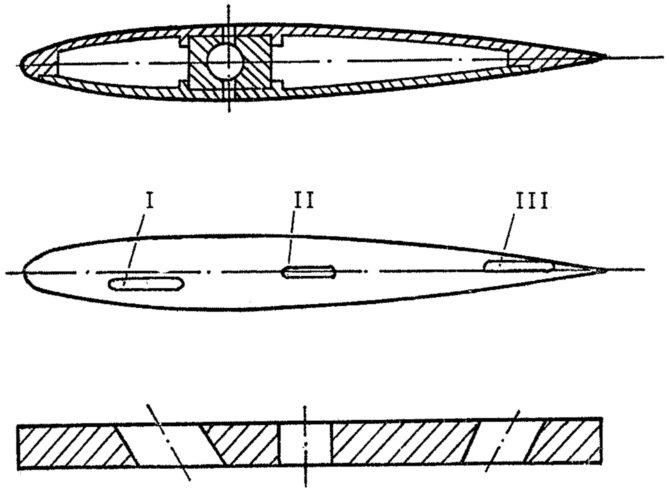


Figure 5. Details of the Wing Model Cross-section and tip-jets.

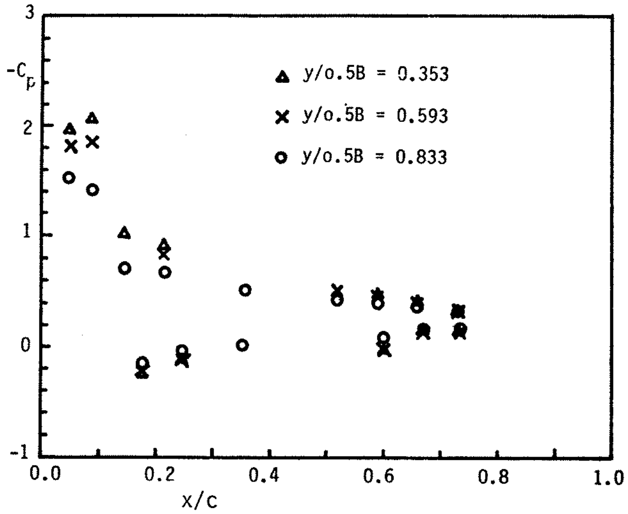


Figure 6. Pressure distribution on the wing for Alpha = 10^0, no blowing.

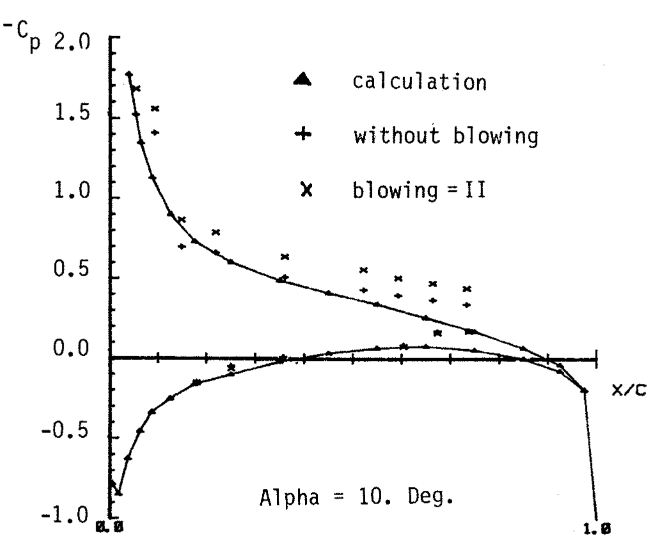


Figure 7. C_p distribution on the wing at y/0.5B = 0.833

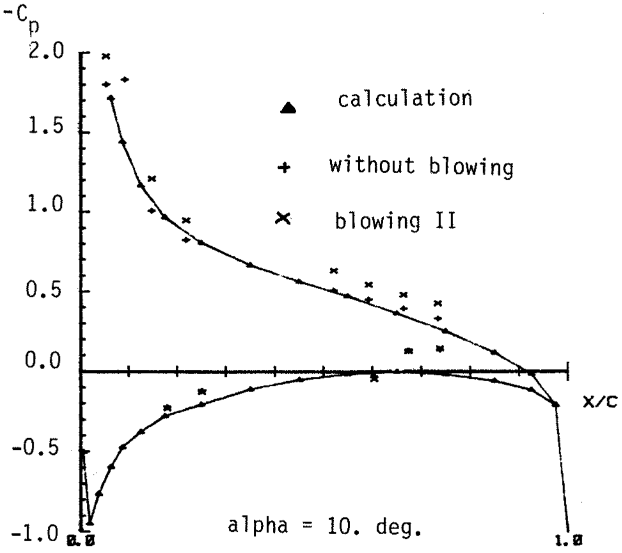


Figure 8. C_p distribution on the wing at y/0.5B = 0.593

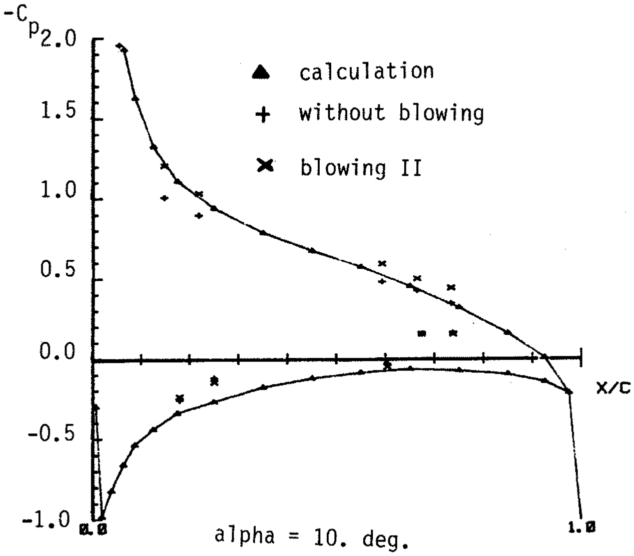
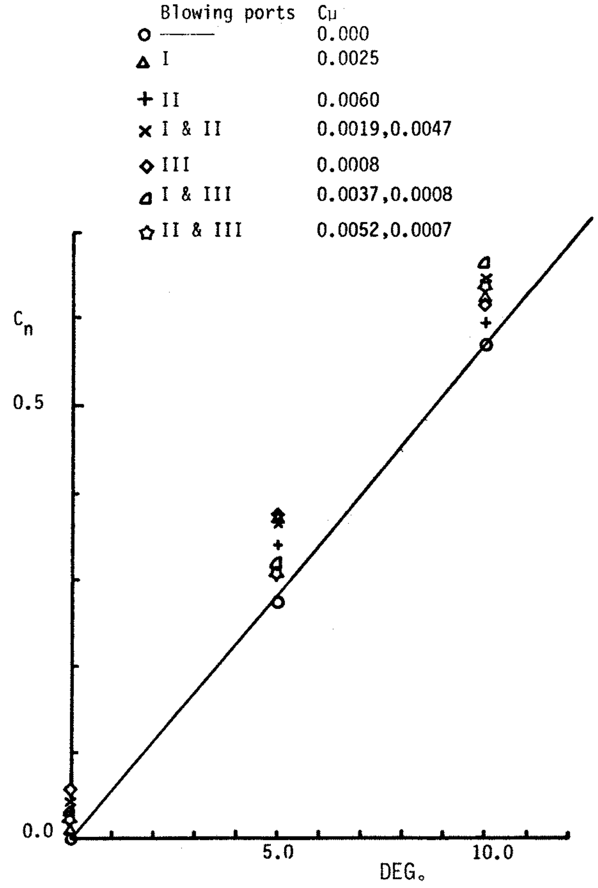


Figure 9. C_p distribution on the wing at y/0.5B = 0.353



	Blowing ports	C_μ
○	———	0.000
△	I	0.0025
+	II	0.0060
×	I & II	0.0019,0.0047
◇	III	0.0008
△	I & III	0.0037,0.0008
☆	II & III	0.0052,0.0007

Figure 10. Normal force over the wing integrated from C_p data, for various conditions of blowing.