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EFFECT OF GURNEY FLAPS ON A NACA 0011 AIRFOIL

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Abstract

The effect of Gurney flaps on a NACA 0011 airfoil was tested in a low speed wind tunnel. Aerodynamic forces, quarter chord moment, and airfoil pressure distribution were measured. A rake of total pressure probes was used to measure the wake one-half and one chord length behind the airfoil. Boundary layer profile measurements were taken using a mouse at the 70% and 90% chord locations on the suction side. Gurney flaps provide a significant increase in lift with very little drag penalty. The lift increase is accomplished by a change in the effective camber. The typical Gurney flap height is only 1-2% of chord length. Thus, the device remains within the boundary layer and very little drag penalty results.

Nomenclature

c	Chord length
C_d	Drag coefficient
C_l	Lift coefficient
C_m	Quarter chord pitching moment coefficient
C_p	Pressure coefficient
u/U	Measured/freestream velocity
x, z	Streamwise and normal directions
α	Angle of attack

Introduction

Today, the cost of designing and manufacturing a new aircraft is becoming more and more prohibitive. In light of this, aircraft companies are oftentimes updating existing planes with modern avionics and engines as well as other modest modifications. Thus, building a brand new wing for a new version of an aircraft may not be economically feasible. Nevertheless, customers demand increased performance which may require some sort of aerodynamic enhancement. One possible solution is to add a simple passive device, called the Gurney flap, onto the wing.

The Gurney flap is a short flat plate, typically 1-2% of chord in height. This flat plate is attached to the trailing edge perpendicular to the chordline on the pressure side of the airfoil. Figure 1 shows a schematic of the Gurney flap configuration. The Gurney flap was originally developed by race car driver Dan Gurney in order to increase the down force and thus the traction generated by the inverted wings used on race cars. Liebeck[1] conducted wind tunnel tests on the effect of a 1.25% chord height Gurney flap. He used a Newman type airfoil which had an elliptic nose and a straight line wedge for the rear section. He found that the Gurney flap increased the airfoil lift while the drag at a given lift was slightly decreased. According to Liebeck, increasing the Gurney flap height beyond 2% of chord continues to increase the lift, but at the cost of substantially increased drag.

Storms and Jang[2] measured aerodynamic loads and pressure distributions on a NACA

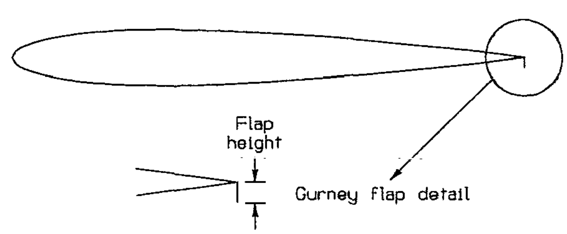

Fig. 1. Gurney flap configuration.

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4412 airfoil. Their tests were performed on Gurney flap heights ranging from 0.5% to 2% of chord at a chord Reynolds number of $2x10^6$. Compared to the clean airfoil, the lift was substantially increased with the Gurney flap while the drag was decreased at high lift coefficients. However, the drag was increased using the Gurney flap at low to moderate lift coefficients. They also found that the Gurney flap generated an additional nose-down pitching moment compared to the clean airfoil. These results suggest that the Gurney flap serves to increase the effective camber of the airfoil.

Giguère *et al*[3] studied the effect of Gurney flaps ranging in height from 0.5% to 5% of chord. They conducted their tests on two different airfoils, LA 203 and Göttingen 797, at a relatively low chord Reynolds number of 250,000. They found that the Gurney flap significantly increased the lift with very little penalty in drag. Based on their results as well as a review of past studies, they found that the optimum Gurney flap height scales with the boundary layer thickness.

Neuhart and Pendergraft[4] present unpublished pressure distribution results taken by Robert McGhee on an advanced technology airfoil at a chord Reynolds number of $3x10^6$. They found a decrease in pressure on the upper surface and an increase in pressure on the lower surface using a Gurney flap as compared to a clean airfoil. This effect is most noticeable at the peaks of the pressure distribution and at the trailing edge. They conclude that this indicates a downward turning of the flow compared to a clean airfoil. This is then substantiated by their flow visualization results, albeit at a low chord Reynolds number of 82,000.

Kentfield and Clavelle[5] tested a NACA 0015 airfoil at a chord Reynolds number of 550,000. They obtained some limited boundary layer data near the trailing edge with and without a 1.5% chord height Gurney flap. At $\alpha = 0°$, they found that the boundary layer profile with the Gurney flap is fuller than the clean airfoil profile. However, they found that the clean airfoil profile is fuller at $\alpha = 10°$.

The objective of the present study was to obtain detailed measurements on the effect of 1%, 2%, and 4% chord height Gurney flaps on a NACA 0011 airfoil. The extent of the quantitative information obtained during the course of this project include: (1) aerodynamic loads - lift, drag, and quarter chord pitching moment, (2) airfoil pressure distributions, (3) wake measurements, (4) boundary layer profile measurements, and (5) static pressure measurements along the wind tunnel walls to provide boundary conditions for future computation studies. Previous studies on Gurney flaps have included *some* of these measurements, but not all of these types of measurments for a single (i.e. particular) airfoil-Gurney flap configuration. The present paper discusses the general effect of Gurney flaps with detailed emphasis on the 2% chord height Gurney flap under pre-stall conditions.

Experimental Set-up

The experiment was conducted in the Wichita State University Beech memorial low speed wind tunnel. This closed-return type wind tunnel consists of four screens for flow conditioning, a 6:1 ratio contraction section, a 7 feet high by 10 feet wide by 12 feet long test section, a diffuser section, a four-bladed 11 feet diameter variable pitch propeller and a 1000 horsepower electric motor section followed by the four corners with turning vanes. The maximum speed of the Beech wind tunnel is 160 mph (235 ft/s). The facility is equipped with a truncated pyramid-type external balance which is capable of measuring up to six components of aerodynamic force and moment data simultaneously. Since the present experiment consists of two-dimensional tests, only the lift, drag, and quarter chord pitching moment were measured by the balance. Two-dimensional wall inserts were used to support the 3 feet span NACA 0011 airfoil as shown in fig. 2. The airfoil was pitched about its quarter chord location using the motor-driven base plates on the two-dimensional wall inserts.

The NACA 0011 airfoil used in this experiment had a 2 feet chord length. A total of 76 surface pressure taps were available for airfoil pressure distribution measurements. All

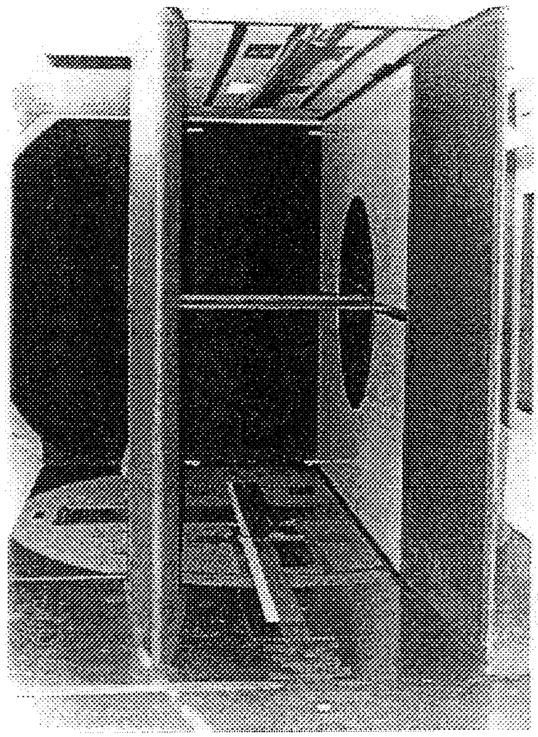


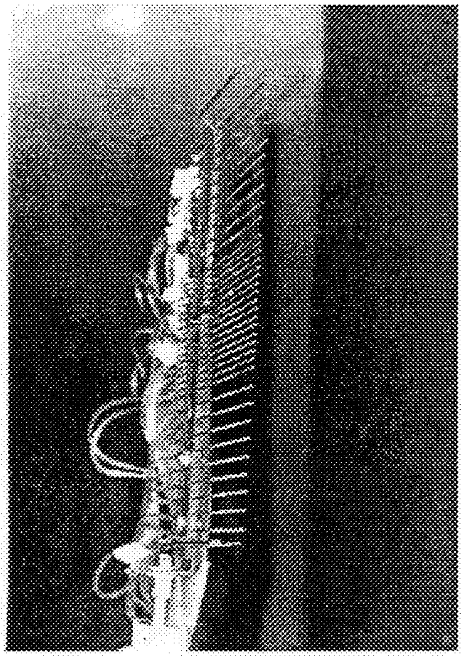
Fig. 2. Set-up viewed from downstream: two-dimensional wall inserts (vertical) and NACA 0011 airfoil (horizontal). Note the pitch-rotatable base plate visible in the right wall.

pressures were scanned electronically using Pressure Systems Inc. (PSI) 8400 Industrial System Processor. A total of six PSI pressure scanner units were used, allowing a maximum of 192 simultaneous pressure measurements. The PSI units are rated with a 0.1 percent accuracy over a full scale range of 2.5 psid. The remaining pressure measurement channels (i.e. less the airfoil surface pressure taps) were used to measure either (1) wind tunnel wall static pressures, (2) total pressures in the wake, or (3) total pressures in the airfoil boundary layer. Wake measurements were taken using a 14 inch (1.17 feet) high total pressure rake shown in fig. 3a. This rake was mounted on an airfoil-shaped support which was traversed to a downstream location either ½ or 1 chord length behind the trailing edge of the NACA 0011 airfoil as shown in fig. 3b. Boundary layer measurements were taken with a boundary layer mouse consisting of a series of miniature total pressure probes as shown in fig. 4a. The mouse was located at either the 70% or 90% chord location, slightly offset spanwise from one of the surface pressure taps as shown in fig. 4b. This then allowed the determination of boundary layer velocity profiles based on Bernoulli's equation. The entire mouse and support mechanism was mounted on the pitching base plate (see fig. 4c), allowing airfoil pressure distribution and boundary layer measurements to be taken over the entire angle of attack range. Additional details about the facility and instrumentation are given in reference 6.

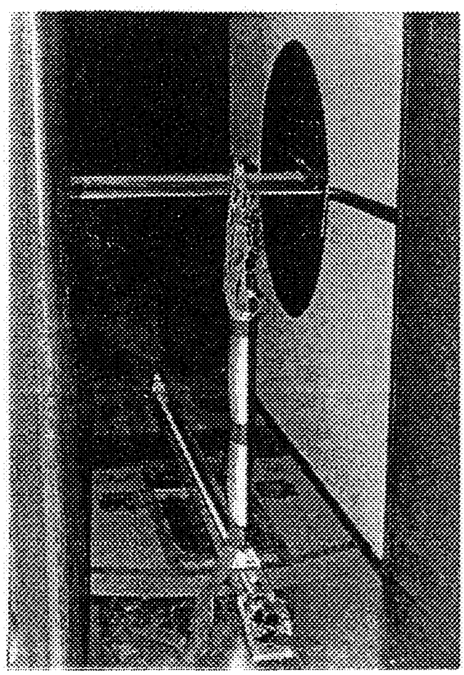
The dynamic pressure was set to a constant value of 25 lb/ft^2 throughout the course of this experiment. This corresponds to a freestream velocity of about 155 ft/s and a Reynolds number of 1.1×10^6 per foot. Thus, the Reynolds number based on airfoil chord length was 2.2 million. According to Papadakis and Miller[7], the turbulence intensity is approximately 0.3 percent when the NACA 0011 airfoil is set to zero angle of attack while supported by the present two-dimensional wall inserts. When only the aerodynamic loads and airfoil surface pressure distribution measurements were taken, the airfoil angle of attack ranged from -2° to +20° (i.e. to post-stall). When either the wake rake mechanism or boundary layer mouse was utilized, the airfoil angle was brought up to stall. Post-stall measurements were not taken in this case due to the fluttering of the rake and mouse.

Results and Discussion

Figure 5 shows the lift and drag coefficient results. The effect of the Gurney flap is to substantially increase the maximum lift coefficient as shown in fig. 5a. Compared to the clean NACA 0011 airfoil, the maximum lift coefficient is increased 25%, 35%, and 45% for the 1%, 2%, and 4% height Gurney flaps, respectively. The figure also shows that the stall angle is decreased while the zero lift angle of attack appears to become increasingly more negative as a larger Gurney flap is utilized. These results suggest that the effect of the Gurney flap is to increase the effective camber of the airfoil. The significant increase in lift

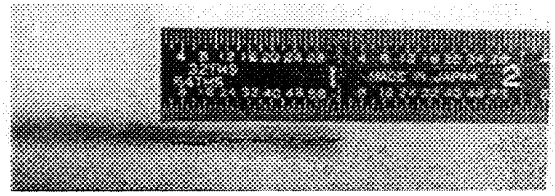


(a) Rake probe details

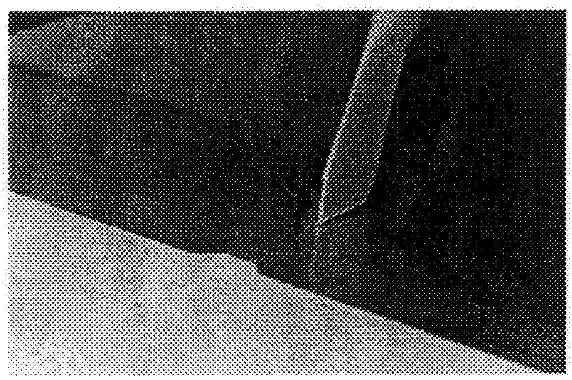


(b) Rake probe support & traversing mechanism, view from downstream

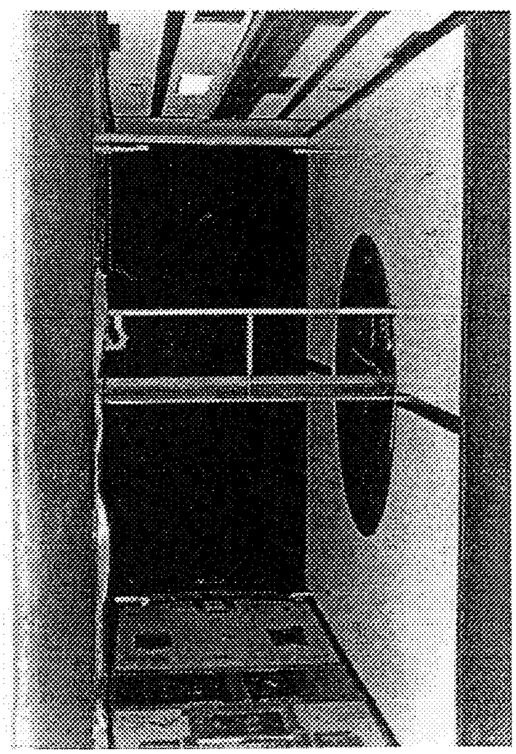
Fig. 3. Rake probe.



(a) Mouse probe details

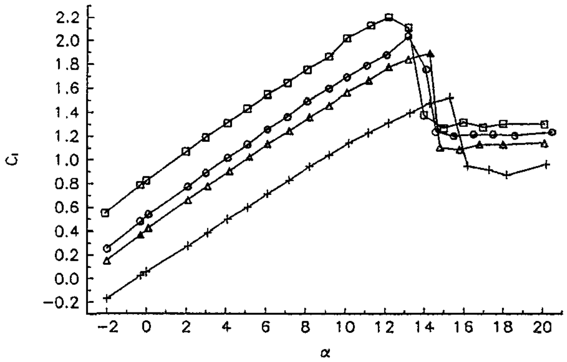


(b) Mouse probe at 70% chord location

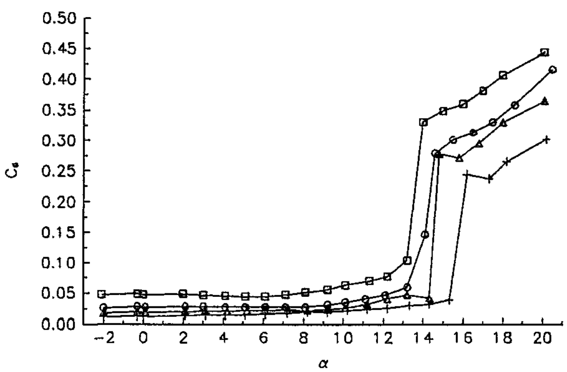


(c) Support mechanism, view from downstream.

Fig. 4. Mouse probe.



(a) Lift coefficient versus angle of attack.



(b) Drag coefficient versus angle of attack.

Fig. 5. Lift and drag coefficients. +, clean NACA 0011; △, 1% height Gurney flap; ○, 2% height Gurney flap; □, 4% height Gurney flap.

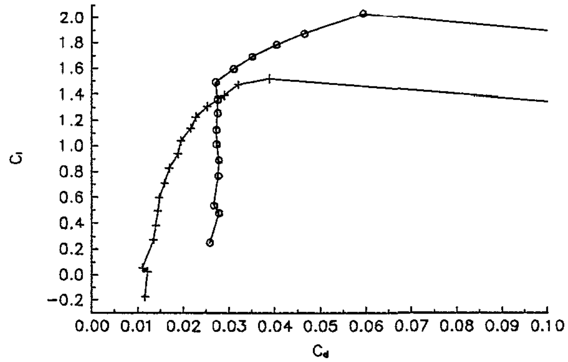


Fig. 6. Lift coefficient versus drag coefficient. +, clean NACA 0011; ○, 2% height Gurney flap.

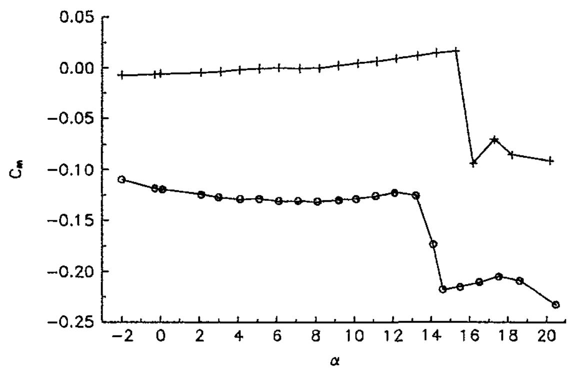


Fig. 7. Quarter chord pitching moment versus angle of attack. +, clean NACA 0011; ○, 2% height Gurney flap.

coefficient for the 4% height Gurney flap comes at the price of substantially increased drag as shown in fig. 5b. This is in agreement with Liebeck[1] who concluded (based on Gurney's field tests) that flap heights larger than 2% chord significantly increase the drag.

Figure 6 compares the lift and drag coefficients of the NACA 0011 airfoil with and without the 2% height Gurney flap. If a high lift coefficient is desired (e.g. $C_l \approx 1.4$), the 2% height Gurney flap can provide this lift at slightly less drag than the clean NACA 0011 airfoil. At low and moderate angles of attack, however, fig. 6 shows that the airfoil with Gurney flap has more drag than the clean airfoil. Some previous studies[1,3,5] have found a reduction in drag *overall* using the Gurney flap. Liebeck[1] has theorized that if a clean airfoil has separation bubbles, the wake momentum deficit and drag may be reduced by using a Gurney flap. This is a plausible explanation for thick airfoils with large trailing edge angles (e.g., the Newman, LA 203, Göttingen 797, and NACA 0015) used in these previous studies.[1,3,5] However, relatively thin airfoils (e.g., the NACA 0011) would not have separation bubbles near the trailing edge at low to moderate angles of attack. Thus, it is reasonable that reduced drag was not found at low angles of attack in this experiment. It should be noted that Storms and Jang[2], using a NACA 4412 airfoil, did not find reduced drag *overall* using the Gurney flap.

Figure 7 shows that nose-down pitching moment is increased with the Gurney flap. This again suggests that the effective camber is increased with the use of a Gurney flap.

Figure 8 shows the pressure distribution for the clean NACA 0011 airfoil and the 2% height

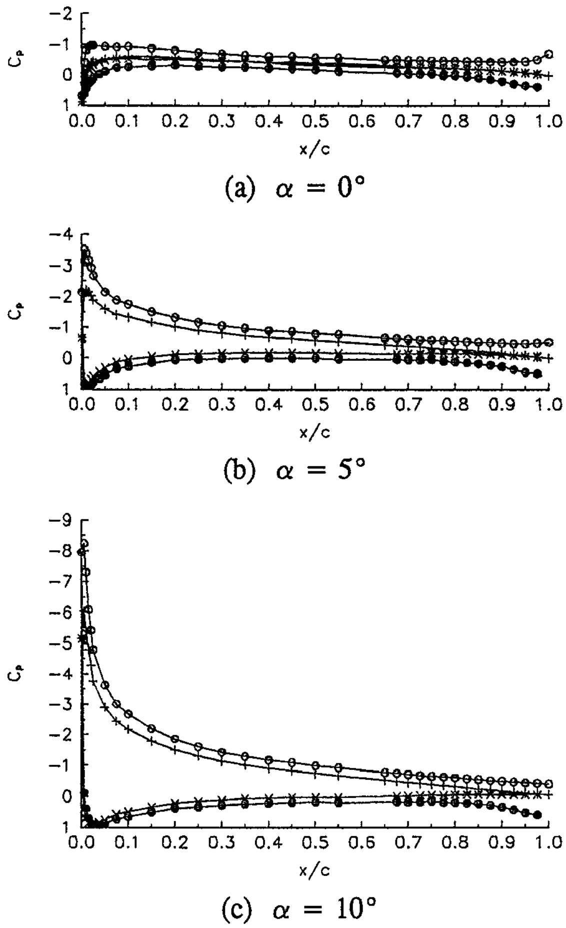


Fig. 8. Pressure distribution comparison. Clean NACA 0011: +, upper surface; ×, lower surface. 2% height Gurney flap: ○, upper surface; •, lower surface.

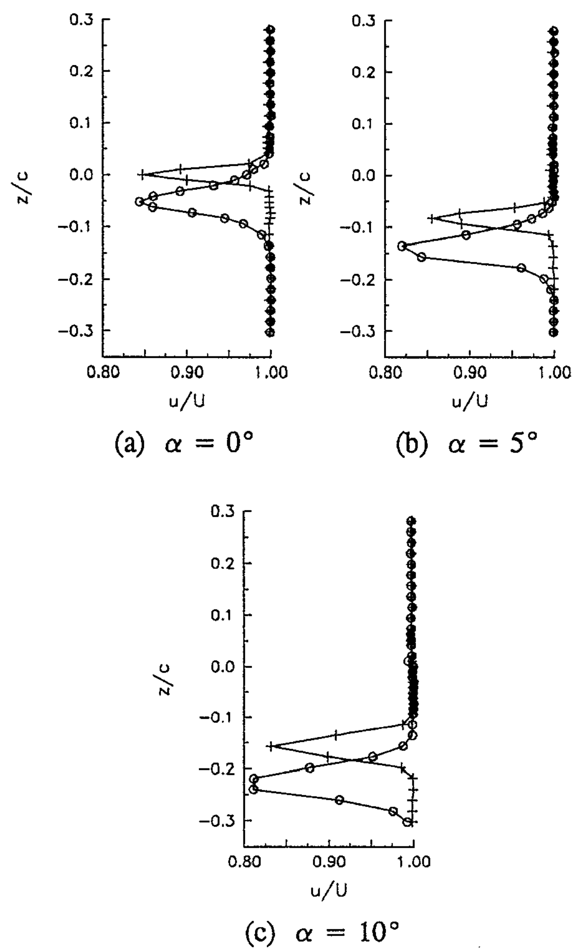
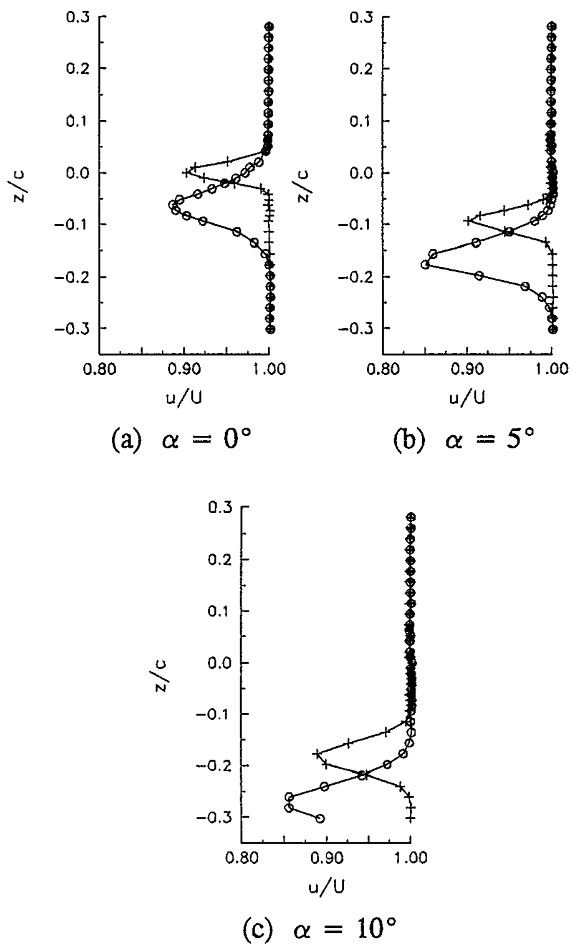


Fig. 9. Wake velocity profile, ½ chord downstream of trailing edge. +, clean NACA 0011; ○, 2% height Gurney flap.

Gurney flap at three different angles of attack. There is a small mismatch in pressure distribution between the upper and lower surfaces for the clean NACA 0011 airfoil at zero angle of attack (fig 8a). This is due to a small flow angularity of about -0.3° in the wind tunnel (see fig. 5a). Using the Gurney flap, fig. 8 shows that increased suction is evident everywhere on the upper surface while the lower surface experiences increased pressure. This results in the substantially increased lift coefficient with the Gurney flap which was discussed earlier. Note the adverse pressure gradient near the trailing edge on the lower surface due to the presence of the Gurney flap. Such an adverse pressure region is to be expected in front of the flap, and was found in all previous studies with pressure distribution measurements.[2-5] Liebeck[1] has theorized that a recirculating vortex may be associated with this adverse pressure region just upstream of the flap on the lower surface.

Figures 9 and 10 show wake velocity profiles based on rake probe measurements taken ½ and 1 chord length downstream of the airfoil, respectively. The sharp edges in the profile shape is probably due to the coarse resolution (¼ to ½ inch spacing) in the total pressure rake. The figures show that the wake momentum deficit is deeper and wider with the Gurney flap than with the clean airfoil. This means that the drag is increased with the Gurney flap compared



(a) $\alpha = 0°$ (b) $\alpha = 5°$

(c) $\alpha = 10°$

Fig. 10. Wake velocity profile, 1 chord downstream of trailing edge. +, clean NACA 0011; ○, 2% height Gurney flap.

to the clean airfoil at the same angle of attack. This is in agreement with the drag coefficient results of fig. 5b. Note that the wake velocity profile misses an important point about the Gurney flap; it does not show the substantial increase in lift associated with this small increase in drag. Figures 9 and 10 show that there is a downward shift in the wake position with the Gurney flap. This is consistent with the flow visualization results of previous studies[1,4] where a downward turning of the flow was observed behind the Gurney flap. Furthermore, such a vertical shift in the wake is to be expected for an airfoil with increased camber.

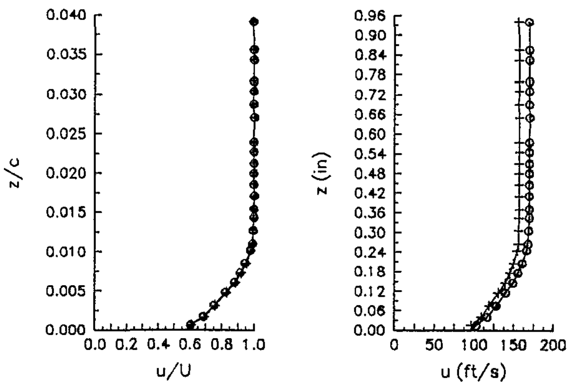
Figures 11 and 12 show the boundary layer velocity profiles based on mouse probe measurements taken at chord locations of 70% and 90%, respectively. The results are shown in both normalized and dimensional forms. Focusing on the dimensional form, it is quite clear that in all cases the velocity over the airfoil upper surface is physically increased with the Gurney flap. This result is reasonable since the overall circulation of the airfoil (and thus the lift) is increased with the Gurney flap. When the normalized velocity profiles at x/c = 0.9 are compared, fig. 12 shows that the Gurney flap profile is fuller than the clean airfoil profile. This is consistent with the airfoil pressure distribution results of fig. 8 where the clean airfoil case has a more adverse pressure gradient near x/c = 0.9 than the Gurney flap case. When the normalized velocity profiles are compared at x/c = 0.7, both cases have similar profile shapes. This result is reasonable since fig. 8 shows that both cases have roughly the same pressure gradient at x/c = 0.7.

Figure 12a shows that the boundary layer thickness is about 1.5% of chord in height near the trailing edge (on the upper surface at zero angle of attack). Thus, a Gurney flap with a height of about 2% or less would not significantly increase the drag since most of the device remains within the airfoil boundary layer. This is indeed consistent with the drag coefficient results of fig. 5b.

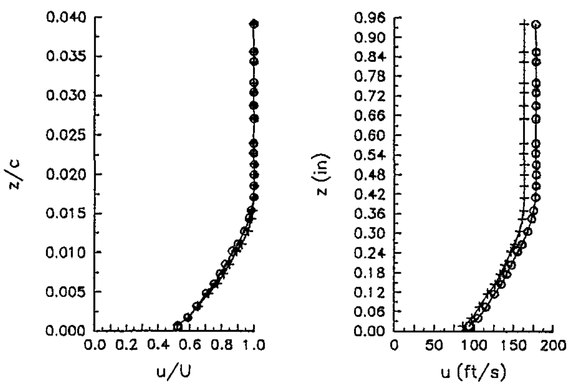
Figure 13 summarizes the boundary layer and wake profile results. The flow behind the airfoil is turned downward so much that it lies below the extended chordline. This is consistent with the behavior of an airfoil with high camber.

Summary

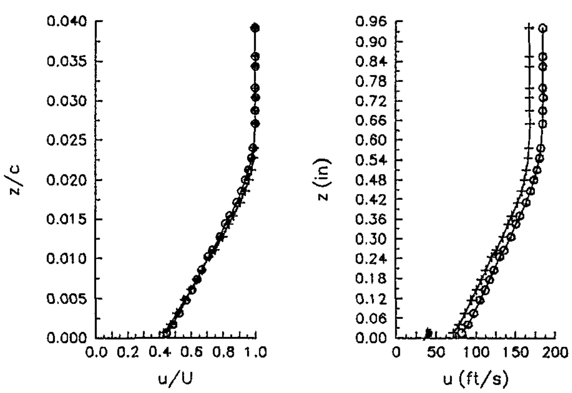
Low speed wind tunnel tests were conducted on the effect of Gurney flaps on a NACA 0011 airfoil. The maximum lift coefficient compared to the clean airfoil increased by 25%, 35%, and 45% using the 1%, 2%, and 4% chord height Gurney flaps, respectively. The addition of a Gurney flap increased the nose-down pitching moment of the airfoil. Airfoil pressure distribution results show that the Gurney flap increases the upper surface suction and the lower surface high pressure.



(a) $\alpha = 0°$

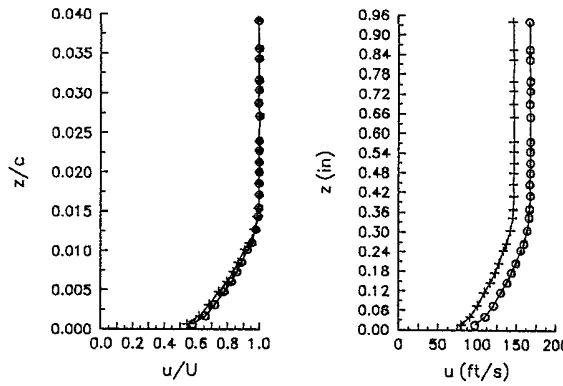


(b) $\alpha = 5°$

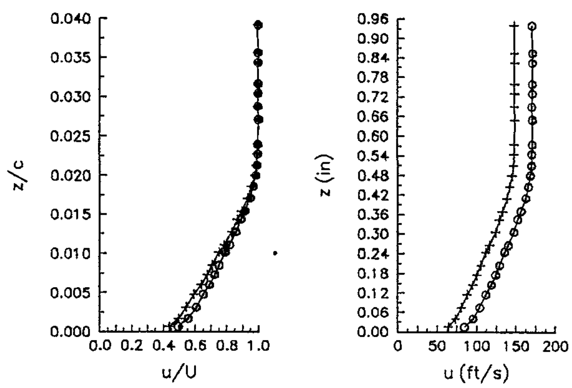


(c) $\alpha = 10°$

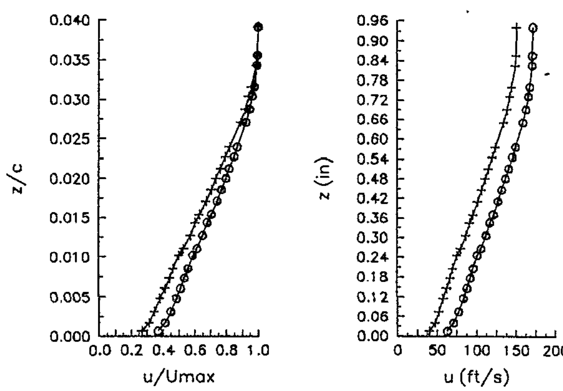
Fig. 11. Boundary layer velocity profiles taken at x/c = 0.7. +, clean NACA 0011; ∘, 2% height Gurney flap. Left figure is normalized while right figure is left in dimensional form.



(a) $\alpha = 0°$



(b) $\alpha = 5°$



(c) $\alpha = 10°$

Fig. 12. Boundary layer velocity profiles taken at x/c = 0.9. +, clean NACA 0011; ∘, 2% Gurney flap. Left figure is normalized while right figure is left in dimensional form. In (c), velocity is normalized by maximum value since boundary layer thickness is greater than 1 inch.

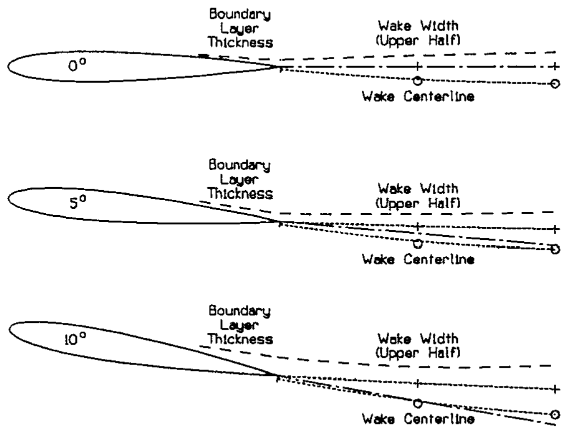


Fig. 13. Boundary layer and wake behavior. —·—, extension of chordline; — — —, velocity deficit (boundary layer and upper half of wake); ··+··, clean NACA 0011 wake centerline; ··o··, 2% height Gurney flap wake centerline.

Wake velocity profiles show that the addition of the Gurney flap resulted in a downward turning of the flow behind the airfoil. All of these results indicate that the Gurney flap works by increasing the effective camber of the airfoil. With the exception of the 4% Gurney flap, substantial increases in drag did not result because the flap physically resides inside the boundary layer of the airfoil.

Future Work

The results discussed in this paper is part of a larger study on the effect of Gurney flaps. Post-stall results for the NACA 0011 with Gurney flap will be discussed in a future paper.[8] Wind tunnel testing on the effect of Gurney flaps has also been completed on: (1) two-dimensional two-element GA(W)-2 airfoil with flap deflections, (2) three-dimensional reflection plane wings with and without taper, and (3) twin-engine reflection plane models. Future papers discussing these additional test cases are planned.

Acknowledgements

The authors acknowledge Bonnie Johnson and the Beech Wind Tunnel staff for their assistance during the course of this experiment.

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Fig. 2

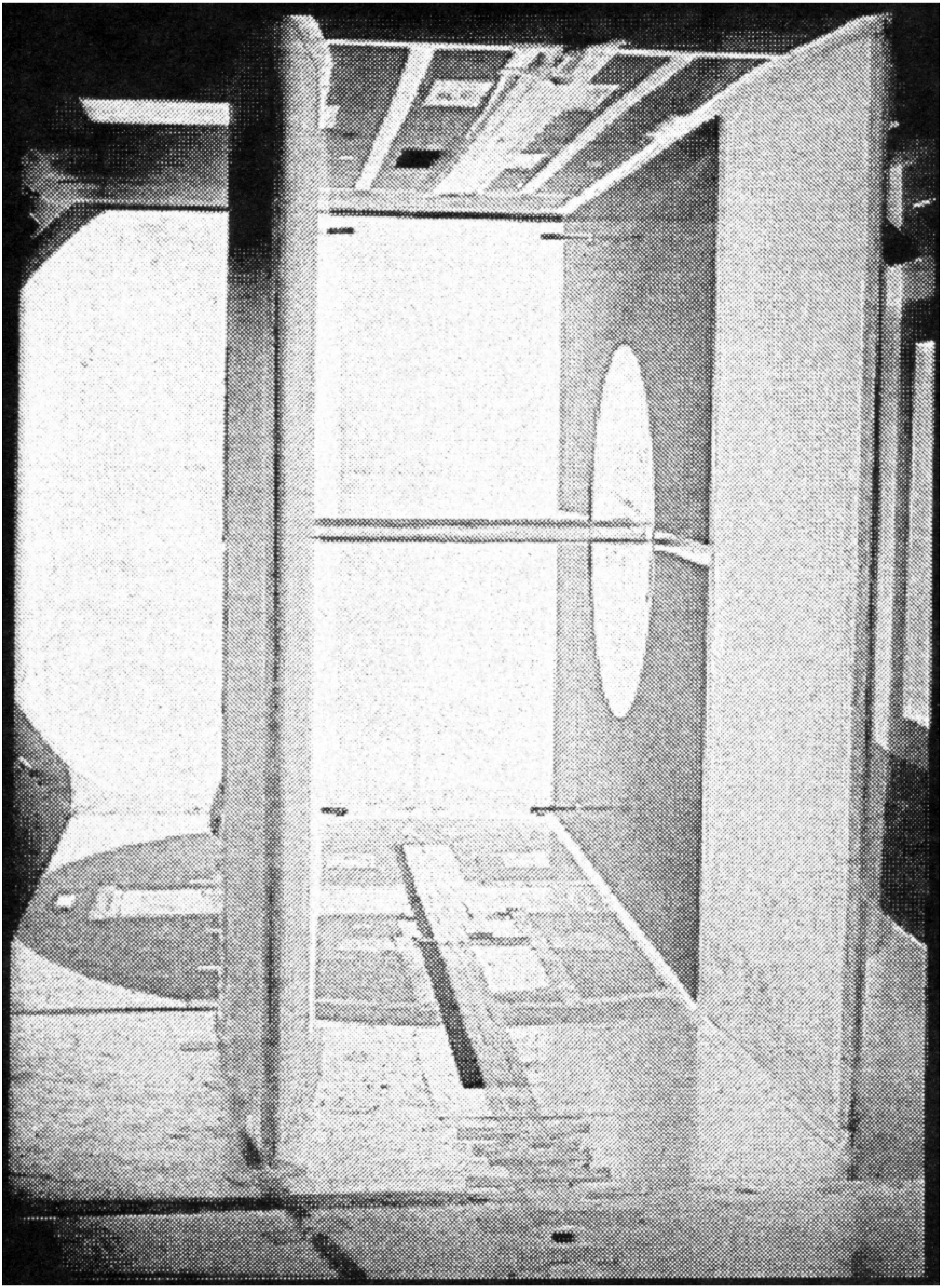
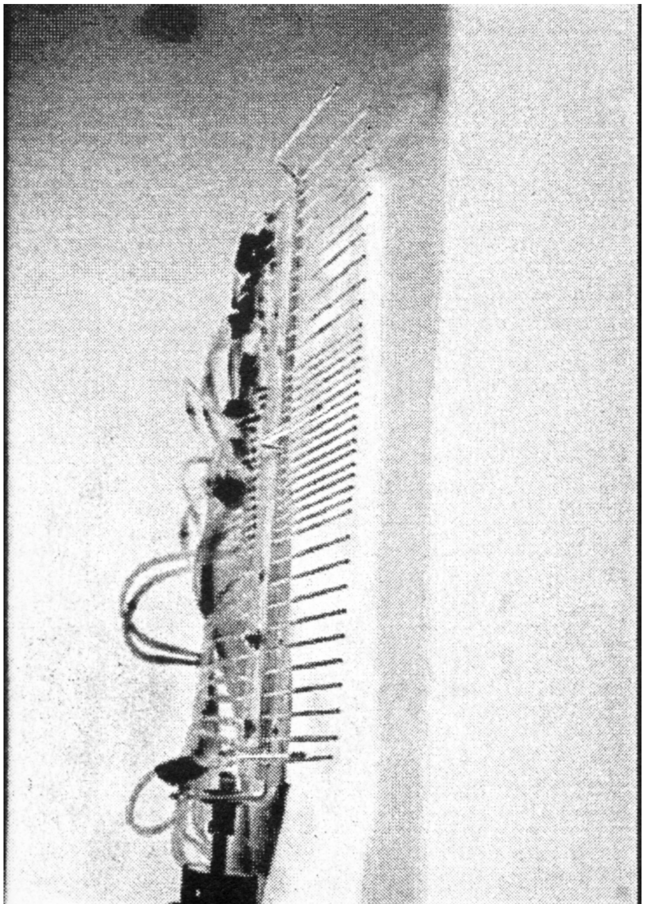


Fig. 3



(a) Rake probe details

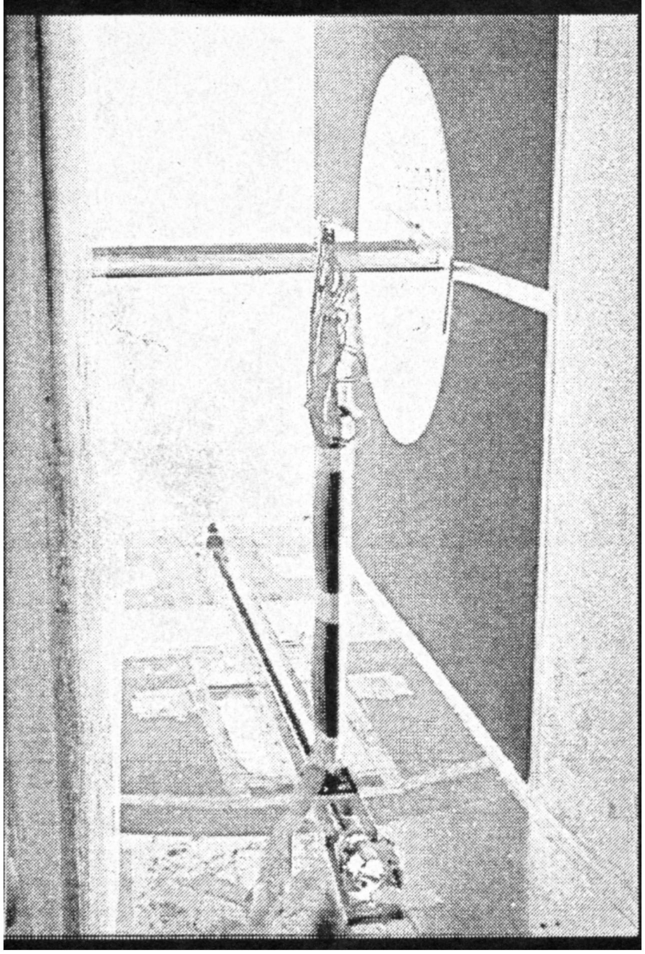
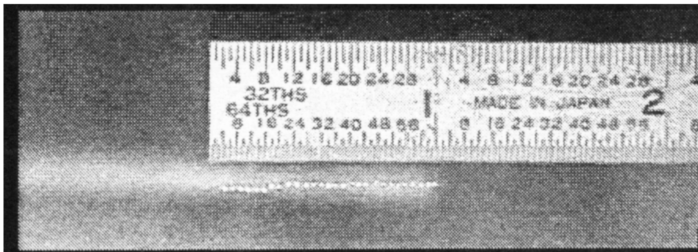
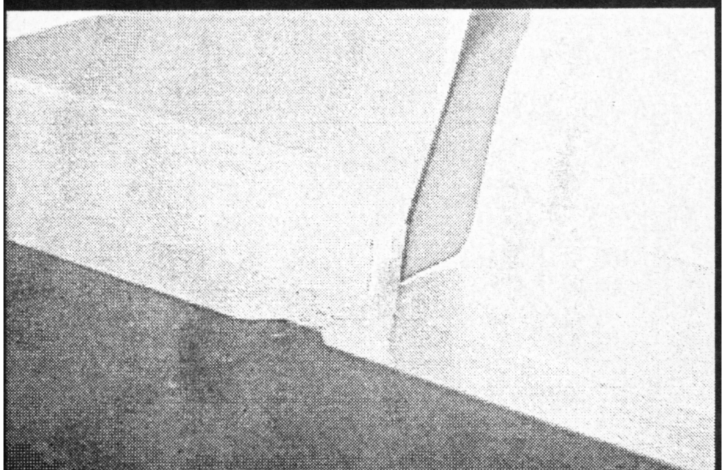


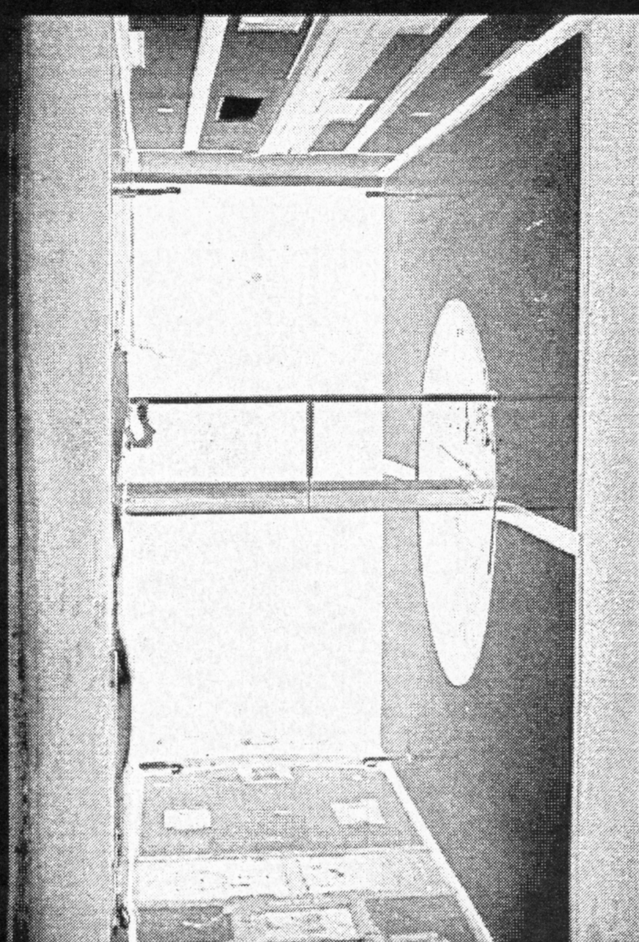
Fig. 4



(a) Mouse probe details



(b) Mouse probe at 70% chord location



(c) Support mechanism, view from downstream.