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Final Technical Report to NASA Langley Research Center on NAG-1-1614 "Flow over Swept Flaps and Flap Tips"

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Abstract

Preliminary measurements have been made of the flow over the tip of an unswept wing flap. To achieve an acceptable Reynolds number based on flap chord, the flap chord was chosen equal to the chord of the main airfoil (c=19 in. $\approx$ 0.48 m). The model was mounted in a 30 in. $\times$ 30 in. wind tunnel running at up to 100 ft/sec. (30 m/s): severe wind-tunnel interference was accepted, and any computations would be done using the tunnel walls as the boundaries of the computational domain. Maximum Reynolds number based on flap chord and tunnel speed was about 1.0×10^6. The grant ended before a full set of measurements could be made, but the work done so far yields a useful picture of the flow. The vortex originates at about mid-chord on the flap and rises rapidly above the chord line. It has a concentrated core, with total pressure lower than the ambient static pressure, and there is no evidence of large-scale wandering.

A simple method of model construction, giving light weight and excellent surface finish, was developed.

Introduction

The motivation for the present work is nicely illustrated in Fig. 1, which shows an MD-80 landing on a humid day (the photograph was evidently taken with a telephoto lens and distances from the viewer are foreshortened). The pressure in the core of the flap vortex is low enough for condensation to occur. Note that condensation does not occur in the main wing tip vortex: the pressure decrement is proportional to [(circulation)^2], and the decrease in sectional C_L (based on m.a.c.) and circulation is much larger at the flap tip than at the wing tip. Thus the "wingtip vortex problem" is – on final approach at least – the "flap tip vortex problem".

Unless an extremely large wind tunnel is used, a representative airfoil or wing, of sufficiently small size for tunnel interference corrections to be acceptably accurate, has a Reynolds number based on flap chord which is so small that the results are dominated by the transition behavior. Of course even a full-scale aircraft may have quite a low Reynolds number based on the chord of a small (say $0.1c$) flap element: in the case of recent Langley tests on the NASA Boeing 737 Transport Systems Research Vehicle[1], the Reynolds number based on the flight speed and the chord of the smallest flap element was no more than 2×10^6.

The usual assumption, or hope, in wind-tunnel tests is that the results will be useful if the Reynolds number is *not* an order of magnitude less than the flight value. However, it has been known for many years (e.g. Thain[2]) that the performance of high-lift systems can vary significantly with Reynolds number all the way up to full scale (evidently because the Reynolds number of some full-scale elements may still be low, as stated above). This is one reason for making special efforts to keep Reynolds numbers for high-lift tests as high as possible. In the case of tests in university-size wind tunnels, a further reason is that at element chord Reynolds numbers below roughly one million, laminar separation bubbles fail to close, transition on the lower surface moves far aft and – in the case of flap tip vortex studies – the effects of viscosity on the trailing vortex may become even more problematical.

Therefore the present experiment was planned to achieve the highest possible Reynolds number at all costs. The flap chord was chosen approximately equal to the chord of the main airfoil (19 in, 0.48 m: this is equivalent to 20 in. chord at the design sweep of 20 deg.), and the model was mounted in a wind tunnel with a test section 30 in (0.76m) square, i.e. 1.5 times the flap chord or roughly 0.75 of the total chord of the model.

The two disadvantages of a large model in a small tunnel are that wind tunnel interference becomes too large to be corrected by standard methods; and that (in a near-square test section) the model aspect ratio becomes so low that displacement effects due to the sidewall boundary layers may be significant.

The first disadvantage only applies to tests on models of a real aircraft: in a generic test, the data correspond to free-air tests on a somewhat different model shape. That model shape is unknown but either for fundamental studies or for code validation tests this is unimportant. Provided that the flow over the generic model contains all the physical phenomena likely to occur on a real aircraft, it is an acceptable test case for a prediction method. In the case of an "oversize" model one simply uses the tunnel walls as the boundaries of the computational domain: this complicates grid generation but has been done by (e.g.) Dacles-Mariani et al. [3]. At least two previous experiments on oversize models have been successfully completed: the European GARTEUR swept-wing experiment[4], and the unswept-wing tip vortex study[5] which was an ancestor of the present work.

The second disadvantage, that of significant displacement effects due to the sidewall boundary layers and their interaction with the flow over the airfoil, does not apply to a computation which resolves the sidewall boundary layers, but this may be unacceptably expensive. In the present work we anticipated from the start that side wall suction would be needed to suppress separation or excessive boundary layer growth so that the tunnel walls could be treated as slip surface in a computation. The work was done in a blower tunnel, which has the advantage that overpressure in the test section can be obtained by partly obstructing the exit: suction is then obtained simply by drilling holes.

The original proposal called for detailed flow measurements but in the event the model had to be built by the Research Assistant / PhD student because of lack of funds for workshop time, and this delayed progress. The results presented here include flow visualization, with smoke and knitting-wool tufts, and total-pressure surveys. The general conclusions to date are that even near maximum lift the flap vortex has a quite concentrated core, with its origin at roughly 50 percent flap chord. There appeared to be little large-scale unsteadiness.

The work is continuing with the aid of Masters'-level students doing up to 9 hours/week of directed study. Their measurements are likely to be confined to the mean flow.

2. Model design and construction

The flap chord was chosen approximately equal to the main airfoil chord in the interests of high Reynolds number based on flap chord. The flap section was arbitrarily chosen as Clark Y, a very old design with a flat lower surface aft of about 25% chord. The main section was designed by eye to have a large enough camber to operate near its ideal incidence while bearing a reasonably high circulation and keeping a realistic trailing edge shape.

As mentioned above, the model was built by the Research Assistant, who did not have access to woodworking machines. A simple but useful technique for making cylindrical (" two-dimensional") foam-and-skin models with adequate strength for attachment points was developed and has already been communicated to NASA Langley (Barry Lazos). 1/8 in. plywood ribs, with circular holes for two spars, were cut with a computer-driven laser cutter, and a pair of ribs was then used as a template to cut further 2 in. "ribs" from polystyrene insulation slabs, using a heated wire. The plywood and polystyrene sections were threaded, alternately, on to the spars (standard cast steel pipe) and glued together, after which high spots on the polystyrene were sanded down to leave an airfoil of uniform section. A 0.010 in. thick aluminum sheet was then glued to the airfoil with epoxy adhesive, using a home-made vacuum bag to hold it in place while drying. The bag consisted of a polythene sheet wrapped over the airfoil, which rested on a surface table, with a plastic tube connection to a vacuum pump (high vacuum is not necessary: we were warned that the gases given off by drying adhesives might be harmful to a vacuum pump, and accordingly used an old pump – which did not seem to suffer). The foil was applied from trailing edge to leading edge to trailing edge, both surfaces being glued at the same time with a generous amount of adhesive at the traling edge. No trouble was experienced with the concave lower surface of the main airfoil but it is clearly necessary to allow enough slack in the polythene. Some care was needed to achieve a straight, thin trailing edge: we extended the foil a little past the trailing edge of the plywood/polystyrene section, and guillotined it to length after the glue dried (the excess having been extruded during compression). The surface quality was excellent: some chordwise corrugations at the ribs were noticeable to the eye but were far too shallow to have any effect on the airflow.

In our case the inside diameters of the spars were chosen so that the final attachment to the wind tunnel could be made by threaded "running rod" slid through the spars. This was done so that the flap section could be cantilevered from supports at the root: the two-dimensional main airfoil could have had the spars themselves threaded at each end.

After completion the airfoils were professionally painted matte black for flow visualization purposes. The final results were virtually indistinguishable from machined metal sections except that the weight of the sections was at least an order of magnitude less. This made handling and installation in the tunnel a far easier task.

The main airfoil was supported in the tunnel by commercial square perforated tubes running vertically either side of the test section. The flap rested on, and was clamped to, an inclined tube on the "root" side of the test section: it extended about 18 in. further "inboard" (i.e. outside the tunnel") to a vertical support plate, supported on the floor, to which the flap end was attached by nuts on the spars. The tunnel is built with removable roof, floor and sidewalls on longitudinal angle sections. For the flap model tests the standard sidewalls in part of the test section were replaced by masonite sheets, with generous cutouts for the main airfoil and flap. Since the main airfoil and flap could overlap, one figure-8-shaped cutout was used. Smaller masonite sheets were cut to fit over the airfoils and generously overlap the edges of the holes in the main sidewalls, to which they were secured, on the outside, with adhesive tape (small nuts and bolts could have been used if necessary). This mounting arrangement allowed the airfoils to be supported firmly but adjustably. The steps at the edges of the cutouts in the main masonite sheets were negligible for present purposes.

For the preliminary measurements reported here, the model was mounted near the exit of the test section because another experiment, examining the effects of grid-induced free-stream turbulence on the tunnel floor boundary layer, was in progress at the same time (the grids were of course removed for tests on the flap model).

3.Results

3.1 Flow Visualization

A considerable amount of flow visualization has been done, using wool tufts and oil-vapor "smoke". For safety reasons it was not possible to use a laser light source in the multi-user tunnel room, and the contrast obtainable with a camera-mounted flash was poor, so that results are presented as descriptions rather than words.

With the final configuration shown in Fig. 2 (b), tuft investigations showed that the flow over the main airfoil and the flap is just attached everywhere except in the wing root outboard of the flap (the left-hand side of Fog. 2(a)). The region of separation is small enough not to affect the flow over the flap tip. The flow at the inboard root is attached everywhere, so evidently the outboard separation is a consequence of the upwash induced over the outboard part of the main airfoil by the flap vortex, combined with the effects of the sidewall boundary layer, which is about 2 in. thick at the model position, as an undesirable consequence of the need to mount the model near the test section exit. The steps at the cutouts in the tunnel side walls obviously make things worse.

The flow near the flap trailing edge is fairly close to separation, judging by the lazy movements of the wool tufts, but the flap-airfoil system is probably well below $C_{L,max}$, which usually corresponds to a significant separated zone over the flap.

The flap tip vortex appeared to be fairly steady – no trace of large-scale meandering – but this conclusion is based on smoke visualization over and just downstream of the model, and more significant wandering may develop further downstream. The vortex core was easy to detect with a wool-tuft wand because the tuft spun violently when, and only when, it was close to the core centerline. Smoke flow visualization showed that the flap vortex core originated at about 50 percent chord and moved upwards relative to the flap at an angle of about 15 deg. to the chord line (this was also observed by the principal investigator in flight, on an MD-80 landing in conditions similar to those shown in Fig. 1). There was a slight inboard deflection over the last half of the chord. The vortex trajectory downstream of the trailing edge is affected by the presence of the tunnel floor, which is about 0.4 flap chords below the flap trailing edge, and is therefore not relevant to free-air conditions.

3.2 Total-Pressure Measurements

Total-pressure traverses were made in a plane 0.4 flap chords downstream of the flap trailing edge, and a plot generated by the FAST plotting package is shown in Fig. 3. Static-pressure measurements have not been made: a single static tube would be unsuitable because of its sensitivity to yaw angle, and five-hole yawmeter measurements (which would give total and static pressures as well as pitch and yaw angles) were temporarily abandoned because of a previously-undetected software bug or hardware fault in the data-logging computer.

Total pressure is probably the most useful single variable to measure in a viscous or turbulent flow, because it identifies the edge of the region affected by viscous or turbulent stresses. In the present case the edge of the wake, with the partly-rolled-up vortex, is clearly seen. The total pressure in the vortex core is actually lower than the undisturbed static pressure (the local static pressure must necessarily be smaller still).

4. Conclusions

The present state of the work is that the model has been built, using an innovative method of construction which may have further uses, and preliminary measurements have been made. The flap tip vortex appears to originate at about mid-chord and rapidly rises above the flap. Flow visualization, and the presence of a concentrated region of low measured total pressure in the core, suggest that the vortex is free of large-scale wandering. The model has been qualified for further measurements of the details of flow over the flap edge and the vortex rollup region. Full measurements would provide a useful test case for methods intended to predict high-lift flows.

5. Acknowledgements

We are grateful to Mr Carlos Garcia for assistance with the experimental work

6. References

[1] Yip, L.P., et al. "In-flight pressure distributions and skin-friction measurements on a subsonic transport high-lift wing section", AGARD Conf. Proc. 515, paper 21, 1993.

[2] Thain, J.A. "Reynolds number effects at low speeds on the maximum lift of two-dimensional aerofoil sections equipped with mechanical high-lift devices", Canadian Nat. Aero. Estab. Rept. DME/NAE 1973(3), 1973.

[3] Dacles-Mariani, J., et al. "A computational study of wingtip vortex flow field", AIAA-93-3010, 1993.

[4] Gleyzes, C., et al. "Three-dimensional turbulent flow around the Garteur swept wing. Selected features", presented at 9th Sympo. on Turbulent Shear Flows, Kyoto, paper 4-4, 1993.

[5] Chow, J.S., Zilliac, G.G. and Bradshaw, P. "Turbulence measurements in the near-field of a wingtip vortex" Turbulence in Complex Flows (ASME FED vol. 203), p. 61, 1994.

Main Airfoil

x (20°)	x (0°)	Upper y	Lower y
0	0	0.47	0.47
0.2	0.188	0.94	0.1316
0.6	0.564	1.4476	0.0188
1	0.94	1.786	0
1.4	1.316	2.068	0.0188
2	1.88	2.4064	0.094
3	2.82	2.82	0.3384
4	3.76	3.196	0.47
6	5.64	3.666	0.8836
8	7.52	3.8164	1.128
10	9.4	3.76	1.316
12	11.28	3.478	1.4852
14	13.16	3.196	1.598
16	15.04	2.7824	1.692
18	16.92	2.3312	1.7296
19	17.86	2.1056	1.7296
20	18.8	1.75216	1.7484

Flap (Clark Y)

x (20°)	x (0°)	Upper y	Lower y
0	0	0.658	0.658
0.25	0.235	1.0246	0.36284
0.5	0.47	1.222	0.27636
1	0.94	1.4852	0.17484
1.5	1.41	1.6638	0.11844
2	1.88	1.8048	0.07896
3	2.82	2.00784	0.0282
4	3.76	2.13568	0.00564
6	5.64	2.1996	0
8	7.52	2.1432	0
10	9.4	1.97776	0
12	11.28	1.7202	0
14	13.16	1.3818	0
16	15.04	0.98136	0
18	16.92	0.5264	0
19	17.86	0.28012	0
20	18.8	0	0

Table 1 Airfoil ordinates (inches)

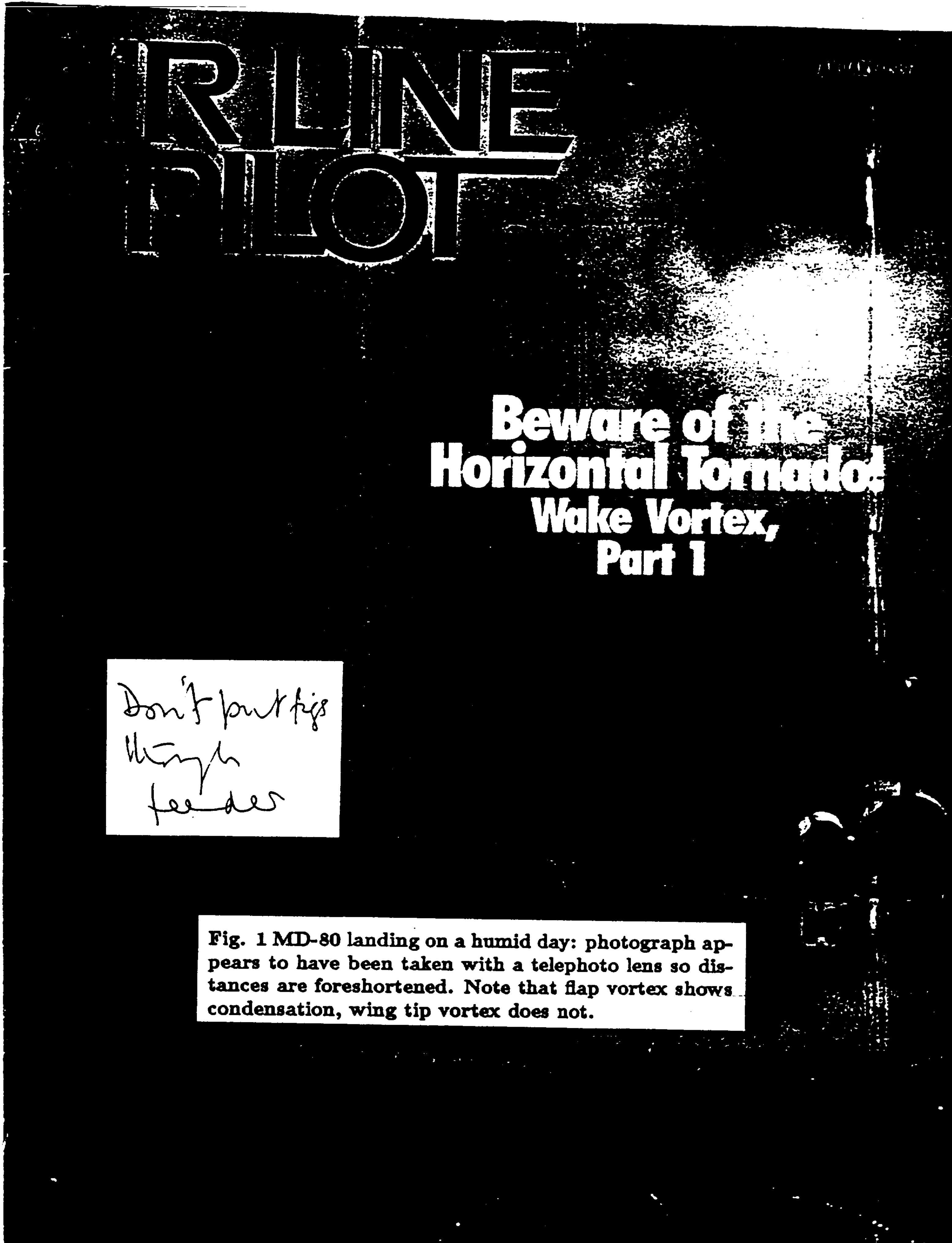

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Fig. 1 MD-80 landing on a humid day: photograph appears to have been taken with a telephoto lens so distances are foreshortened. Note that flap vortex shows condensation, wing tip vortex does not.

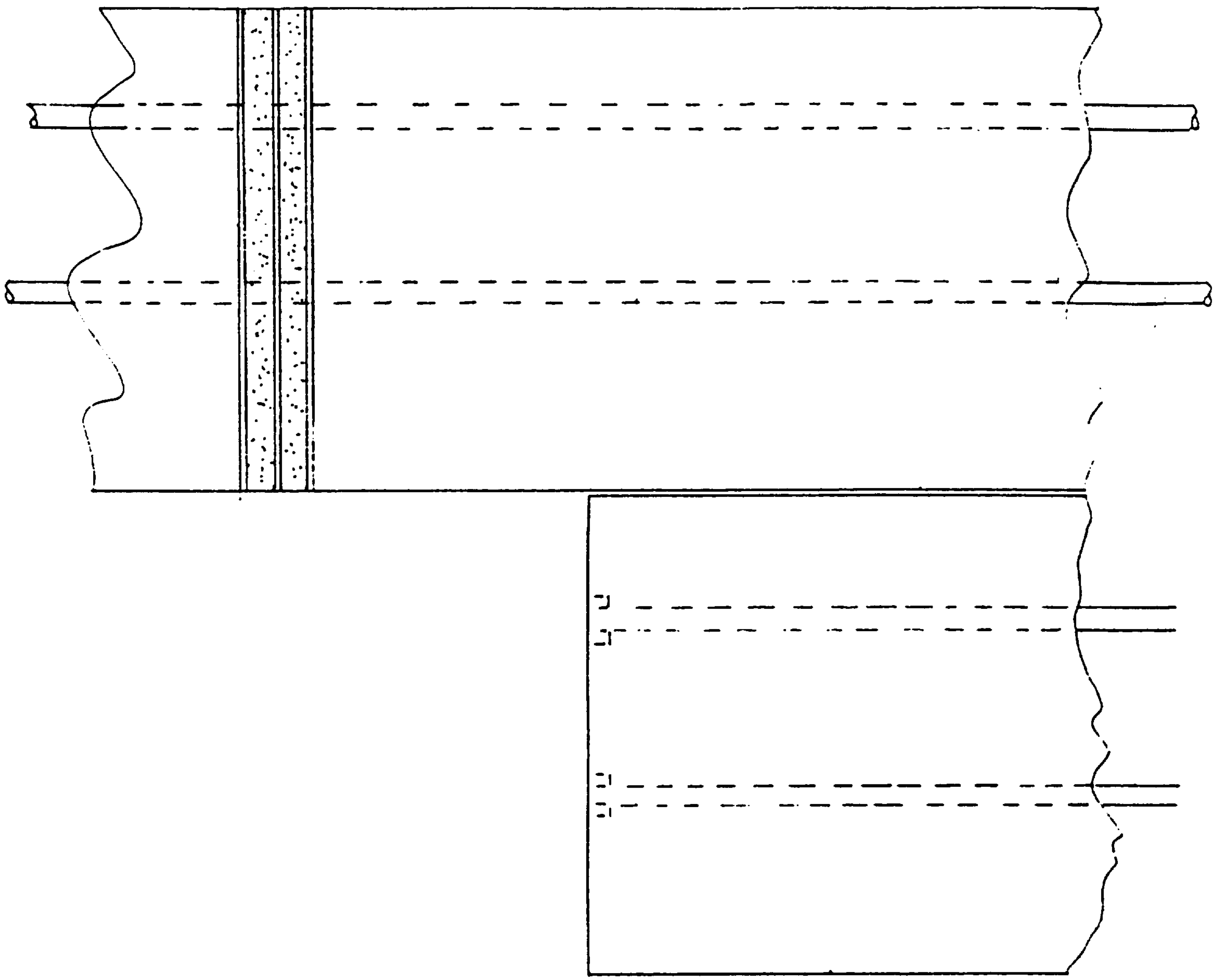
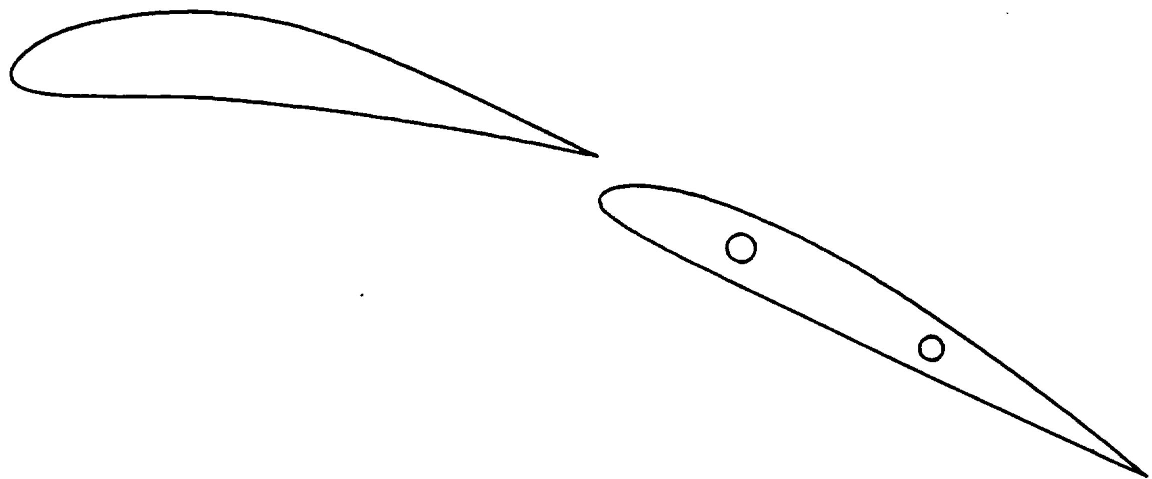


Fig. 2 Flap model configuration for unswept tests.

(a) Plan view showing plywood ribs and polystyrene fill, with tubular metal spars. Aluminum sheet cladding not shown.



(b) Side view: main airfoil incidence 6-1/2 deg., flap angle 25 deg., lap zero, gap 0.87 in. = 0.046c.

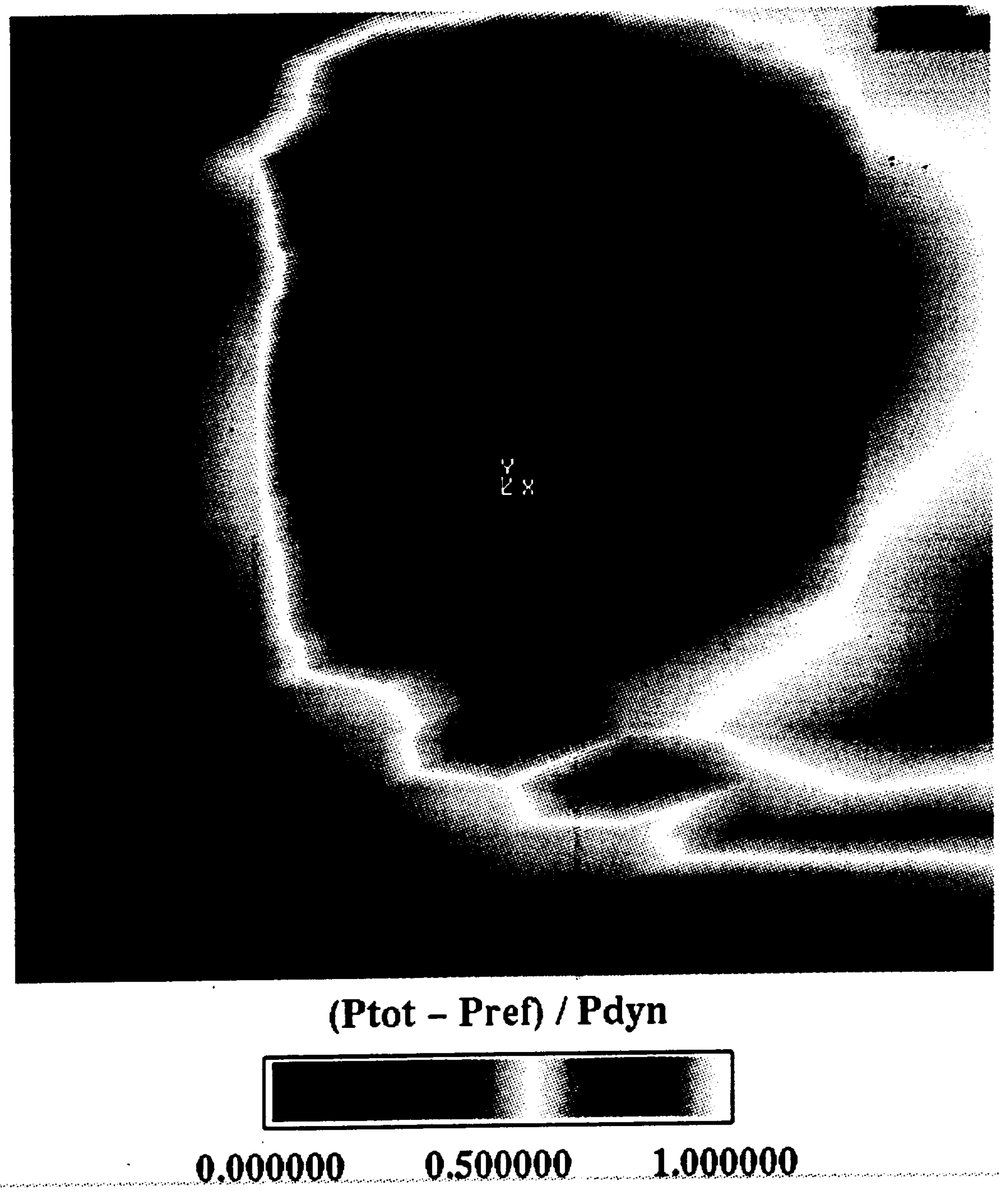


Fig. 3 Total pressure contours 0.4c downstream of flap trailing edge. Coordinate origin exactly downstream of tip T.E., real size of plot 10 cm × 10 cm (approx. 4 in. × 4 in.)