Rapid Technique for Wind-Tunnel Model Manufacture

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Introduction

IN wind-tunnel-based experimental aerodynamic projects a substantial proportion of project resources in terms of both time and cost is consumed by the design and manufacture of wind-tunnel models. This can limit the scope of experiments and cause long lead times. Thus, methods that can expedite the model-building process are highly beneficial.

The manufacture of wind-tunnel models has traditionally been a highly skilled and time-consuming process.[1] By their nature aerodynamic bodies can have complex three-dimensional curvature and often the experiment requires internal details such as the provision for surface-pressure tappings. Thus, wind-tunnel models are often constructed from a number of parts, which require accurate fitting and hand finishing to obtain the necessary high surface finish. Ideally, the wind-tunnel experiment is an integral part of the design process, which may call for a prescribed range of model configurations to be tested, or alternatively for the iterative optimization of a particular feature of the model. In the former case the range of configurations that can be tested is limited by the cost of each model and in the latter case by the speed at which a model feature can be changed.

A number of studies[2–5] have demonstrated the advantages of rapid prototyping techniques for building wind-tunnel models in speed and cost relative to traditional techniques. Dimensional tolerances and surface finish may be inferior, which in turn increases experimental uncertainty, but nevertheless the method is quite adequate for preliminary studies. In this Note we outline the use of rapid prototyping for producing wind-tunnel models with internal features. A most advantageous aspect of the rapid-prototyping method is the ability to produce internal forms, that would be difficult to design and manufacture by traditional techniques. Rapid-prototyping technology is reviewed briefly in context and two case studies from the work of the authors are presented.

Rapid-Prototyping Technology

Rapid-prototyping technology has evolved swiftly in recent years. Whereas there are a number of different rapid-prototyping processes,[5] two in particular are suitable for wind-tunnel-model manufacture, primarily because the resulting components have sufficient rigidity. Filament deposition machines (FDMs) extrude filaments of thermoplastic polymer [typically Acrylonitrile Butadiene Styrene (ABS) or polycarbonate], building up the part layer by layer. Stereolithography machines (SLAs) use a UV laser to partially cure the part in a succession of horizontal layers from a bath of epoxy resin. On removal from the machine the part is then rinsed in a solvent to remove excess resin and postcured in a UV chamber. The quality of detail achievable on FDM machines is limited by the extrusion nozzle size, which is typically 0.25 mm. SLA machines can produce very highly detailed parts with features down to 0.1 mm. Because both types of machines build in vertical steps, the reproduction of curvature in this direction is inferior to that in the horizontal plane. Therefore, orientation of the model so that, where possible, the predominant curvature lies in the horizontal plane is helpful in overcoming this limitation and maintaining geometric integrity. Surface finish on SLA parts is of high quality and requires minimal hand-finishing, whereas that from FDM machines is of lower quality and tends to be ridged with each vertical step. However, the authors have found that FDM parts can be improved to the required standard by the use of proprietary aerosol paints and hand-finishing. Both methods offer a number of key advantages over traditional methods for manufacturing wind-tunnel models:

1) Internal features can be incorporated into the model, allowing integration of surface-pressure taps, for example.

2) Models can be made with a honeycomb internal structure, allowing weight saving while maintaining structural rigidity.

3) Machines accept a common format for three-dimensional data, which may be exported from most CAD packages.

4) Time from CAD model to prototyping machine start can be a matter of minutes.

5) Machines operate unsupervised; therefore the operating cost is little more than the cost of the material.

Case Study: Tip-Blowing Model

An example of a model constructed using an FDM from polycarbonate is shown in Fig. 1 and is a rectangular planform NACA 0012 section wing with a chord of 200 mm and a half span of 500 mm. In this case the span exceeded the height that could be accommodated in the machine and therefore the model was made in two sections. To ensure accurate alignment of the two sections, holes for locating pins were incorporated into the components as they were made. The particular experiment for which the model was made was a study of wing-tip blowing and its effect on the evolution of the wing-tip vortex. To accomplish this, air was delivered to the wing tip through a tube emerging into a plenum chamber occupying the final portion of the span. The plenum chamber incorporated a baffle and fine

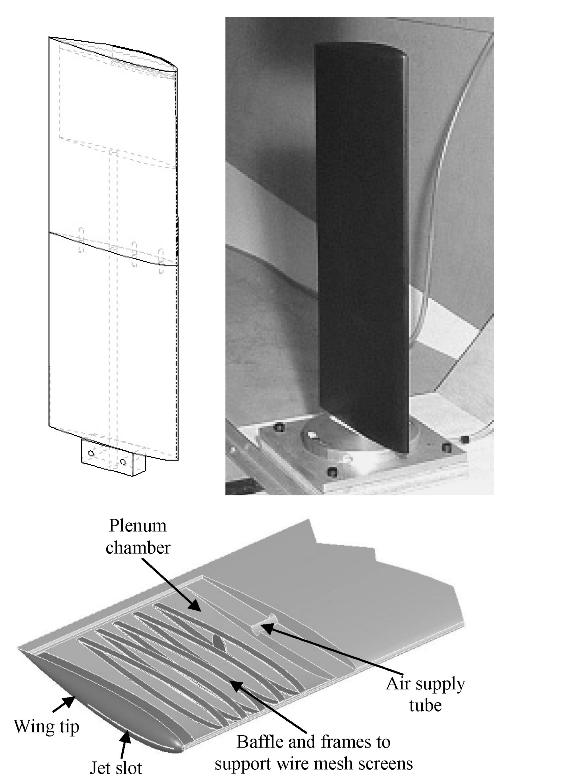

Fig. 1 Tip-blowing wing produced on an FDM: wire-frame view of CAD model, finished model installed in the wind tunnel, and cutaway view of CAD model showing tip-blowing arrangement.

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mesh screens in order to produce a uniform velocity profile along the length of the jet slot in the tip. The tip itself was removable and incorporated the 0.5-mm-wide jet slot along the front half of the chord. A cutaway view of the tip-blowing arrangement from the three-dimensional CAD model is shown in Fig. 1. All of the components, including the frames to support the wire-mesh screens, were produced by the FDM. The machine time in this case was approximately 12 h, with a further 12 h taken to assemble, paint, and finish the model. Manufacture of this model by traditional techniques would have entailed additional engineering in both design and manufacture to incorporate the plenum chamber with the wing made in two halves.

Case Study: Surface-Pressure Model

As part of the same study into wake-vortex formation and control, surface-pressure measurements were required in order to give the spanwise wing-load distribution for comparison with that derived from velocity measurements in the wake. This task was made more challenging because in this case the model was small, with a chord of 70 mm and a half-span of 220 mm. A three-dimensional CAD model was produced with a total of 416 pressure tappings at 13 chordwise positions on both the upper and lower surfaces of the wing at 16 spanwise locations. Each tapping was 0.35 mm in diameter and fed into spanwise tubes 0.8 mm in diam back to the wing mounting. Each spanwise row of holes at a given chordwise position fed to the same spanwise tube (it being impractical in such a small model to have a separate tube for every individual surface hole); therefore, during the measurements, all of the holes apart from the chordwise position at which the measurements were taken were blanked off. To increase the speed of manufacture, internal cavities were incorporated into the model to reduce the material used. The model was also split into five sections, with provision to locate the sections together with pins, again to increase the speed of manufacture.

In this case the parts were made on an SLA machine, the machine time being approximately 8 hs. Thorough washing of the parts in the solvent was required to remove excess resin, especially from the internal holes, and here a hypodermic syringe loaded with solvent was used. Postcuring of the components in a UV chamber was carried out for 2 h. Final assembly of the sections was performed using an epoxy resin adhesive, and any slight discontinuities in the wing surface between the different sections were carefully blended. The surface-pressure holes were carefully cleaned out using a 0.35-mm drill and tubes attached at the wing-mounting end for connection to a manometer. The assembly and finishing time in this case was approximately 8 h, mainly due to the time-consuming cleaning of

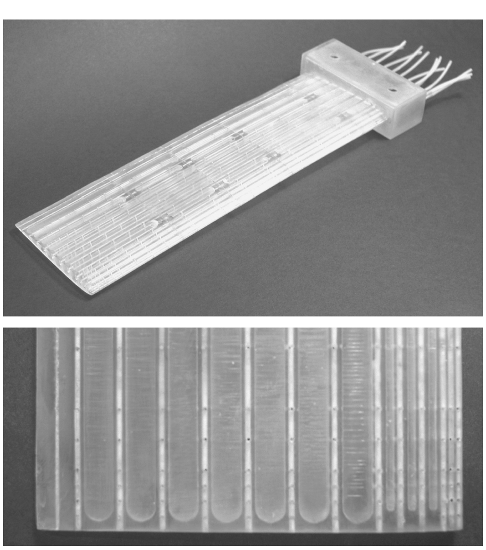

Fig. 2 Surface-pressure model made on a stereolithography rapid-prototyping machine. Lower photograph shows a closeup of the wing-tip region. The chord was 70 mm and each pressure tapping is 0.35 mm in diameter.

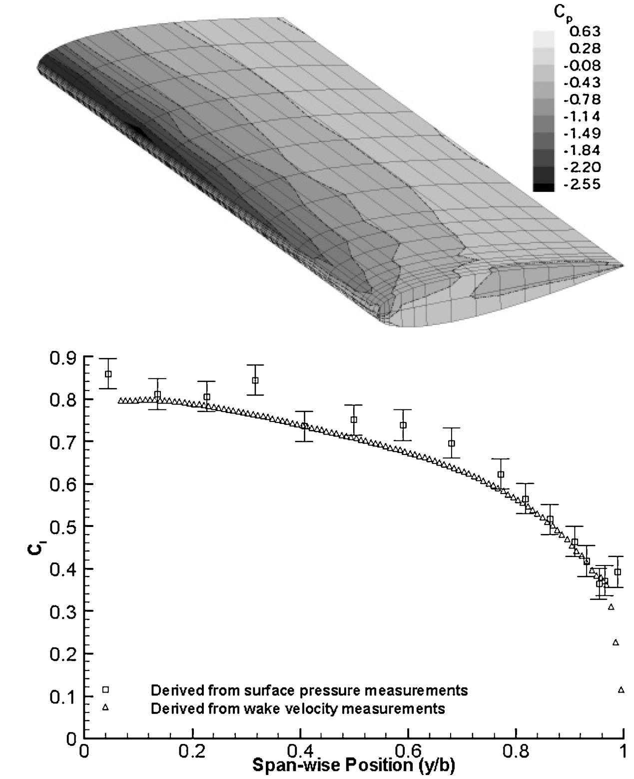

Fig. 3 Results derived from surface pressure measurements. Top: Contours of C_p on upper surface of the wing. Bottom: Comparison of span-wise lift distributions derived from surface pressure and wake velocity measurements.

the surface-pressure holes. Nevertheless it is still anticipated that this process will be less time-consuming than manufacture in a traditional manner, for example by embedding the spanwise tubes in slots milled in the wing surface. A photograph of the finished model is shown in Fig. 2.

The wing was mounted at an angle of attack $\alpha = 7.5$ deg in a small blower-type wind tunnel with a freestream velocity of 22 m/s, giving a chord Reynolds number of $Re_c = 1 \times 10^5$. The pressures were measured using a liquid-in-glass manometer to a precision of ± 0.5 mm H_2O. The results are plotted as contours of C_p over the wing surface in the top half of Fig. 3; the lower plot of Fig. 3 shows the spanwise lift distribution derived from chordwise integration of the surface pressures. The error bars shown were determined from the reading uncertainty of the manometer, which is responsible for the relatively large scatter observed. The same distribution derived from wake-velocity measurements made with hot wire 1 mm behind the trailing edge and calculated by summing circulation inboard of the tip has also been plotted for comparison. As a point of interest it may be seen that the tip vortex that grows on the upper surface of the wing just inboard of the tip manifests itself in different ways in the spanwise lift distribution. In the surface-pressure measurements, the low pressure under the vortex creates an increase in lift at the tip, whereas in the values derived form the wake-velocity measurements it causes a high gradient in lift at the tip.

Conclusions

In this Note, the use of rapid prototyping techniques for the production of wind-tunnel models has been demonstrated with two examples from the work of the authors. The advantages over traditional model-building methods offered by these techniques are considerable; they decrease the time and cost of model manufacture so that the scope of wind-tunnel tests may be increased and lead times reduced. In particular it has been demonstrated that these techniques can be used to incorporate internal features into models that would entail a great deal of extra engineering in both design and manufacture by traditional techniques.

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Aerodynamic Characteristics of Deflected Surfaces in Compressible Flows

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Nomenclature

C_p	=	pressure coefficient, $(p_w - p_\infty)/q_\infty$
M	=	freestram Mach number
p_w	=	surface static pressure
q_∞	=	dynamic pressure
x	=	coordinate along the surface of the corner
x^*	=	x/δ_0
x_d^*	=	downstream influence region, x_d/δ_0
x_u^*	=	upstream influence region, x_u/δ_0
Δc_D	=	lift-induced-drag coefficient
Δc_L	=	incremental lift coefficient
δ_0	=	incoming boundary-layer thickness
η	=	deflected angle

Introduction

THE flap can be used as the high-lift device, in which a deflection downward results in the gain in lift at the given geometric angle of attack. For the influence of small flap deflections, a straight line from the leading to trailing edges of a symmetrical airfoil at zero angle of attack is treated as the fictitious chord line. The problem is reduced to a camber airfoil at an angle of attack. The incremental lift coefficient and moment coefficient about the aerodynamic center vary with the flap deflection and can be predicted by thin-airfoil theory. The magnitudes are related to the distance of the hinge line behind the leading edge.[1] Note that the agreement between theory and experiment is poor due to the boundary-layer effect. Furthermore, Bolonki and Gilyard[2] indicated that the deflected control surfaces could be used in combination to provide variable camber control within the operational flight envelope of a civil aircraft. At cruise speeds, the benefits of variable camber using a simple trailing-edge control surface system could approach more than 10% in maximizing the lift-to-drag ratio, especially for nonstandard flight conditions. However, the critical Mach number, onset of boundary-layer separation, and drag are also strongly related to the allowable deflection of the control surfaces.

A simplified model of a deflected surface was studied by Chung.[3–5] On the upper deflected surface (or convex-corner flow), strong upstream expansion and downstream compression are observed near the corner in compressible flows. The interaction region can be scaled with the freestream Mach number and the convex-corner angle, $M^2\eta$. The boundary layer downstream of the corner is separated at $M^2\eta \geq 8.95$. The separation position moves slightly upstream and the reattachment position moves downstream with increasing convex-corner angle. On the lower deflected surface (or concave-corner flow), the flow decelerates upstream of the corner, followed by the downstream acceleration. The characteristics of the flow, for example, upstream compression, downstream expansion, and interaction region, are associated with the freestream Mach number and the concave-corner angle, $M\eta$.

To characterize the aerodynamic performance of a deflected surface in compressible flows, the present study reexamined a turbulent boundary layer past the convex and concave corners at $M = 0.64$ and 0.83 (Fig. 1). This investigation involved the analysis of mean surface pressure distributions of the convex- and concave-corner flows. The incremental lift and lift-induced-drag coefficients are estimated based on the characteristics or the integration of surface pressure distributions.

Experiment

Transonic Wind Tunnel

The Aerospace Science and Technology Research Center, National Cheng Kung University transonic wind tunnel is a blowdown type.[6] Major components of the facility include compressors, air dryers, cooling water system, storage tanks, and the tunnel. The dew point of high-pressure air through the dryers is maintained at -40°C under normal operation conditions. Air storage volume for the three storage tanks is up to 180 m^3 at 5.15 MPa. The test section is 600 mm square and 1500 mm long. In the present study, the test section was assembled with solid sidewalls and perforated top/bottom walls to reduce the background acoustic noise. The freestream Mach numbers were 0.64 and 0.83 ± 0.01, and the stagnation pressure p_0 and temperature T_0 were 172 ± 0.5 kPa and room temperature, respectively.

For the data acquisition system, the NEFF Instruments System 620 and the LeCroy waveform recorders were used. The test conditions were recorded by the NEFF system, whereas the LeCroy 6810 waveform recorders were used for the pressure measurements. A host computer with CATALYST software controlled the setup of LeCroy waveform recorders through a LeCroy 8901A interface. All input channels were triggered simultaneously by using an input channel as the trigger source.

Test Model

The test model consists of a flat plate and an interchangeable instrumentation plate. The test model is 150 mm wide and 600 mm long, which is supported by a single sting mounted on the

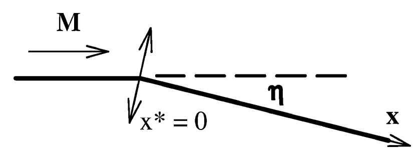

Fig. 1 Test configuration.

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