ISSN 1355-2546
Volume **17** Number **5** 2011

Rapid Prototyping Journal

The international journal for research on additive manufacturing technologies and rapid product development

Rapid Prototyping Journal is published in association with GARPA

www.emeraldinsight.com

LESSONS FROM WIND TUNNEL MODELS MADE BY RAPID PROTOTYPING

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ABSTRACT

Wind tunnel model design and construction has traditionally been a relatively long, tedious and expensive process. Rapid Prototyping (RP) technologies, which have been used for general geometrical modeling, have recently been applied to wind tunnel model production. In spite of our initial doubts as to the adequacy of the RP techniques for this purpose, we have produced two models of airplanes designed by students as part of their final-year project. Both models consisted of four main parts: fuselage, nose section and two wings, plus an assortment of small, interchangeable control surfaces. They had a wing span of 600 mm and their structure was reinforced with metal inserts to provide added stiffness. The results of testing the models in a subsonic wind tunnel indicate that aerodynamic data of acceptable quality can be collected from rapid prototyping models while offering significant cost and production time advantages over machined metal ones.

INTRODUCTION

The technology of Rapid Prototyping (RP), which has been around for over 20 years, allows the fabrication of a physical object directly from the CAD model in an additive, layer-by-layer manner. The prototypes are made of various materials, such as polymers, metals and paper, using different technologies. A promising application of RP is the production of wind tunnel models for checking, verifying and generating data such as lift and drag coefficients, pressure distributions, etc. Traditional wind tunnel models are made of aluminum or steel by 5-axis CNC milling, take weeks or months to fabricate, and cost tens, even hundreds of thousands of dollars [1]. A number of case studies show that making wind tunnel models by RP can produce good results in terms of aerodynamic performance and characteristics, while incurring a five- to tenfold reduction in cost and a significant shortening of acquisition time.

Landrum et al. [2] tested three ~30-cm span by ~10-cm chord airfoil models in a low-speed subsonic wind tunnel: a conventional cast polyurethane model and two photopolymer models made by stereolithography (SLA). All three models were identical except for the light sanding of one of them to produce a smoother surface finish. They reported comparable fabrication times and dimensional tolerances for the RP and conventional models, with the biggest difference being in the drag coefficient for both the RP models, which was about half the value measured for the cast model. They attributed this result to the rougher surface of the RP models inhibiting the formation of laminar separation bubbles.

Springer and Cooper [3] compared the static stability aerodynamic characteristics obtained in a trisonic wind tunnel, over a range of Mach numbers from 0.3 to 5.0, for models made by three different RP technologies, and one control model made of aluminum. They tested models made of ABS plastic by fused deposition modeling (FDM), photopolymer resin made by SLA, and glass reinforced nylon made by selective laser sintering (SLS). All the models were of a wing-body-tail configuration launch vehicle with area S_{ref} = 8.68 in^2 and length L_{ref} = 8.922 in. They concluded that at the present time (1997), only preliminary design studies and limited configurations could be used due to the RP material properties that allowed bending of model components under high loading conditions. However, for obtaining preliminary aerodynamic databases, the RP models offered significant cost savings and fabrication time reductions at acceptable fidelity.

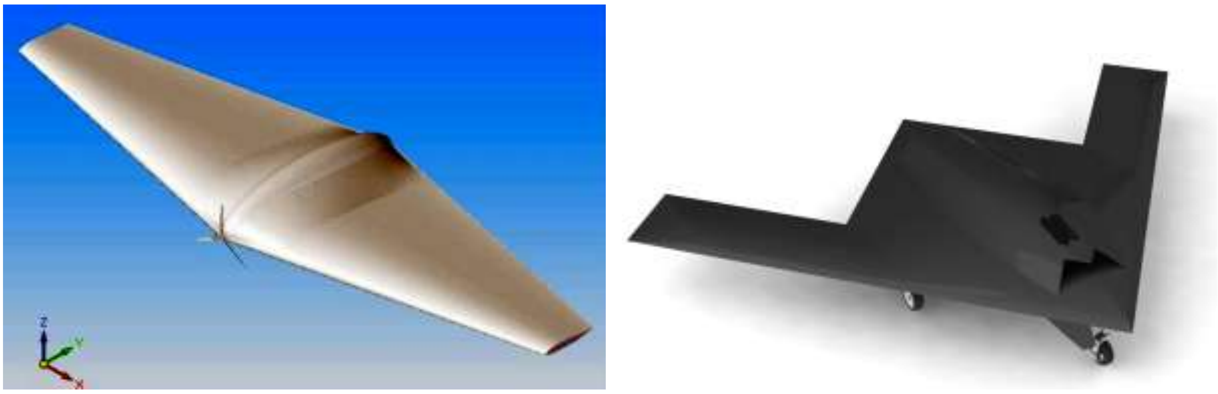
Hildebrand et al. [4] and Tyler et al. [5] described two wind tunnel models, a 4-ft span by 3-ft long X-45A UCAV, and a 20-in. span lambda wing-body configuration Strike Tanker, made by SLA (plastic) and SLS (stainless steel) techniques. They investigated issues such as the integration of pressure taps (small holes on the surface and internal airtight passageways to the transducers), model sagging under load, dimensional accuracy and cost and time of fabrication. They found that it was necessary to stiffen the Strike Tanker plastic model to prevent excessive wing deflection, and did it by building the model parts around a 1/4-in. thick support plate. This construction principle was also described by Heisler and Ratliff [6], where a steel tube constituted the strong back of missile models, and plastic RP parts (made by FDM) were attached to it to establish the outer shape.

A 2-m long model (1:8 scale) of the European Tiltrotor aircraft was built and tested at speeds up to 50 m/s [7]. RP technology was used to fabricate the external fairings of the model out of a composite aluminum- and glass-filled polyamide-based material (Windform® GF). These components were mounted onto a machined metallic central frame. Satisfactory results were reported with only two drawbacks identified: wider dimensional tolerances and worse surface finish of the RP parts compared to conventional composite lamination models.

Nadooshan et al. [8] tested a wing-body-tail configuration of a polycarbonate model made by FDM against a conventional machined steel model over a range of Mach 0.3 to 0.7 and angle of attack range of –2 to +12 degrees. The model's length was L_{ref} = 200 mm and area S_{ref} = 48 cm^2. The results were a generally good agreement between the metal and plastic models up to about 10 degrees of angle of attack, when the plastic model's deflection under the higher loading produced more noticeable differences.

The current paper presents the design of two wind tunnel models made by RP as part of final-year students' projects [9, 10] and some of the lessons learned. Both models shared the flying-wing configuration (see Fig. 1), but belonged to very different UAV designs. ILAS was a low-altitude, quiet, fuel-cell powered observation aircraft carrying a 2.5-kg electro-optical payload. It had a wing span of 3 m and was designed to fly at 20-25 m/s. CERBERUS was a low-RCS, long-range (1500 NM) UAV, carrying two 500-kg bombs and a variety of sensors. Its wing span was 13.2 m and cruise speed M=0.8.

Contrary to machining of metal models, RP technologies offer some unique characteristics, capabilities and limitations that will be discussed first. Next, the aerodynamic and structural design and manufacturing aspects of the models will be explained. The wind tunnel test results will then be presented, followed by our conclusions and recommendations for future work.



(a) (b)

Figure 1: Preliminary CAD models of the (a) ILAS [9] and (b) CERBERUS [10] UAVs.

RAPID PROTOTYPING

One of the lowest cost RP technologies, known as 3D printing, was used for this work. The model is built in layers from the bottom up, by accurately depositing liquid photosensitive polymer droplets and curing them by ultra-violet light. Another, gel-like material is used as temporary support for overhanging features, and is washed away by high-pressure water jet when the fabrication process is finished. Machines used in this study where Eden 250 and Connex 500, both made by Objet Geometries, Israel. Model materials were FullCure 720 and VeroBlue. Model fabrication was carried out at the Technion, Israel.

The following are the advantages offered by the RP technology to wind tunnel model building:

- **Cost**: RP model cost is directly related to the weight of materials (model and support) used in the fabrication. This means that producing hollow parts, and “digging out” pockets in the model, for example, lowers the cost, as opposed to the additional complexity and cost involved in such operations when done by machining. We estimate that model production using RP for the two cases described in this paper was at least 5 to 10 times cheaper than making metal models. A byproduct of the low cost is that aircraft designers can make many more models, testing multiple variants, when using RP.

- **Time**: Making a complicated and relatively large model can take on the order of one or two days because the layers are very thin (16 μm). However, the actual production process can be unsupervised, and it is very common to have the RP machine work 24 hours a day. Even when RP models are not fabricated in-house, the common standard nowadays is that the computer files are sent through e-mail to a service bureau, the model is made within a day or two, and sent back by courier. This is certainly much faster than producing a metal model by machining.

- **Geometrical complexity**: The complexity of the geometry that can be created by RP technologies is almost endless. For wind tunnel models, this allows hollowing out the models to reduce their weight, and making internal passages for pressure measurement or for smoke discharge for visualization. The common double curvature geometry of external aircraft surfaces, which makes machining them complicated and expensive, does not present any added difficulty for RP.

- **Weight**: The RP model material is a polymer whose relative density is about 1.1. This means that the model would be significantly lighter than similar steel or even aluminum models, allowing the use of a more sensitive force balance in the tests. A byproduct of making a hollow model is that its cost is lower, because less material is consumed in its fabrication.
- **Accuracy**: Horizontal (x-y directions) resolution of the machines used is better than 0.1 mm, and layer thickness (z-direction resolution) is 16 μm, so the models are very satisfactory in this sense. However, all RP techniques approximate the original CAD geometry as small facets (i.e., planar surfaces instead of real curved ones) through the conversion of the model data to STL format, and this introduces some inaccuracy.
- **Surface finish**: The thin layers assure a smooth finish. Although "step marks" can be seen and felt, they do not seem to represent a roughness that is greater than with fine machining. If smoother surfaces are desirable, than sanding can easily be applied to the polymer.
- **Small parts and details**: Some RP techniques, including the current PolyJet™ and PolyJet Matrix™ ones, allow producing small parts and fine detail. The manufacturer's recommended minimum thickness is 0.6 mm, but we managed to produce even finer detail. Figure 2 shows a set of relatively small spoilers that were made for the wind tunnel testing.

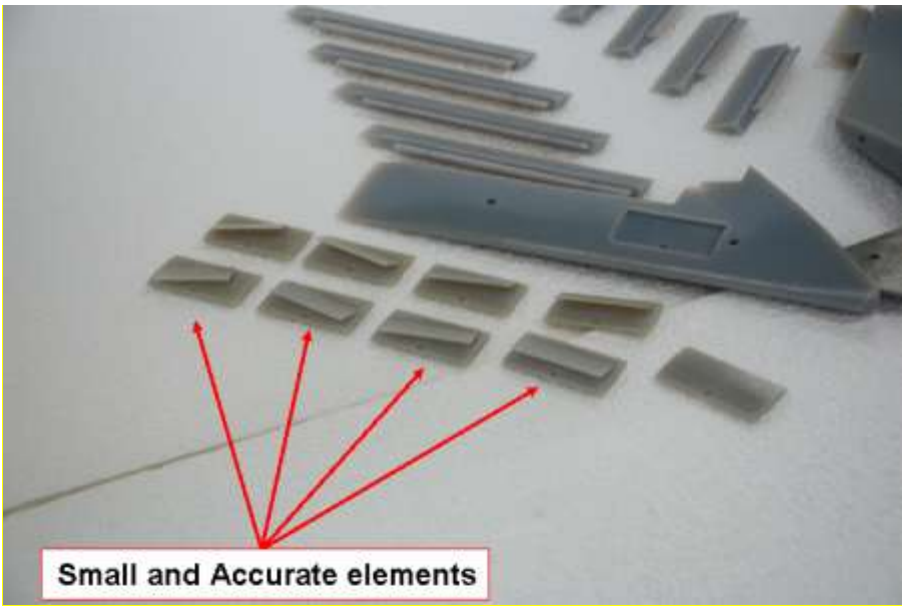


Figure 2**:** Small, detailed spoilers fabricated for the wind tunnel testing.

- **Moveable parts**: Although not utilized in the present work, complete assemblies with components that have relative motion may be produced directly by RP by specifying a proper clearance between the parts. This clearance is filled with support material during the fabrication, and when the support is washed away, the parts are free to move relative to each other.

Disadvantages of RP for wind tunnel models are:

- **Strength and Stiffness**: Both are significantly lower than for steel or aluminum. The manufacturer of our RP machines quotes 55-60 MPa of tensile strength, 79-84 MPa of compressive strength, and modulus of elasticity of 2.7-2.8 GPa [11]. These numbers are also confirmed by other experiments [12, 13] and are, of course, considerably lower than those for metals. Additionally, the strengths listed here are in the plane of the layer, while those in the build direction (vertical, z-axis, or perpendicular to the layer), dominated by the intra-layer adhesion strength, are about one-half of the quoted numbers. This anisotropy must be taken into account when designing the model and when determining the orientation of the built parts in the RP machine.
- **Durability**: The manufacturer reports [11] an Izod impact strength of 24 J/m. This means that small features may be quite vulnerable to accidental impact by other objects and consequently, to fracture.
- **Stability**: The photopolymers used in our models lose their strength when temperatures rise. Kim and Oh [12] report that the room temperature strength drops by 25% at 30°C, and by 50% at 40°C. We have also observed distortion of RP models (not the wind tunnel models of this paper) over time. Models stored at room temperature sagged significantly under their own weight over a period of several months from the date of manufacture.
- **Maximum Size**: Each RP machine has a maximum build size. We used two machines, with 250x250x200 mm and 340x340x200 mm maximum part dimensions, respectively. Larger parts are usually made of several components, which are later mechanically connected or glued together.

MODEL DESIGN AERODYNAMIC CONSIDERATIONS

The design of a wind tunnel model is a combination and tradeoff of several requirements such as cross section area of the available and economical wind tunnel, actual size and shape of the aircraft to be evaluated, actual performance (speed, Mach number) of the air vehicle, similarity parameters, Reynolds number, materials and production process of the model and more. Since the actual CERBERUS UAV design speed was 0.7-0.8 Mach number, the first iteration of the model design was based on the size of the transonic wind tunnel where the compressible flow effects could be included. This attempt, shown in Fig. 3, resulted in too small a model, scaled at 1:40 with a wing span of 350 mm.

Another problem with this design was that the sting-type strain gage balance produced an excessively large “cut” in the aft part of the fuselage, thus altering the aerodynamic shape to be tested. Therefore, an alternative wind tunnel, the subsonic one, with a larger cross section was selected, and similarity parameters applied. This resulted in a model scaled at 1:22 with a wing span of 600 mm, as shown in Fig. 4.

The aerodynamic coefficients should be corrected for compressible flow. Although the Prantl-Glauert transformation is not valid for transonic range in general, by considering the swept wing and the Mach number perpendicular to the wing, the following transformation can be used:

$$M_n = M_\infty \cdot \cos\Lambda = 0.8 \cdot \cos 45^o = 0.56$$

$$\frac{C_{comp}}{C_{incomp}} = \frac{1}{\beta} = \frac{1}{\sqrt{1-M_n{}^2}} = 1.2$$

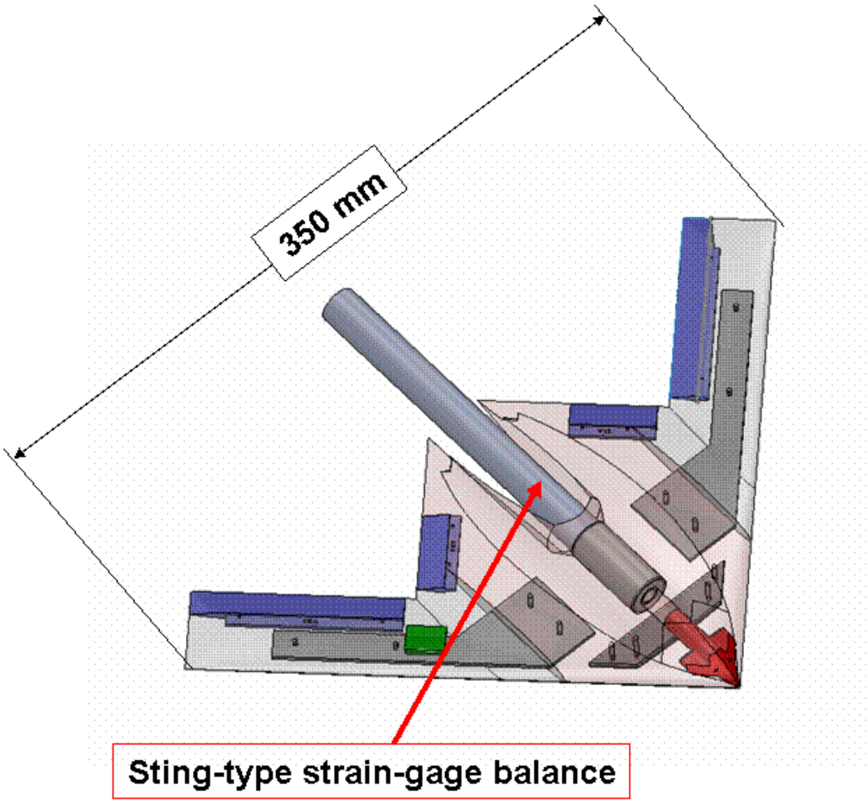


Figure 3: First CERBERUS model design iteration with scale of 1:40.

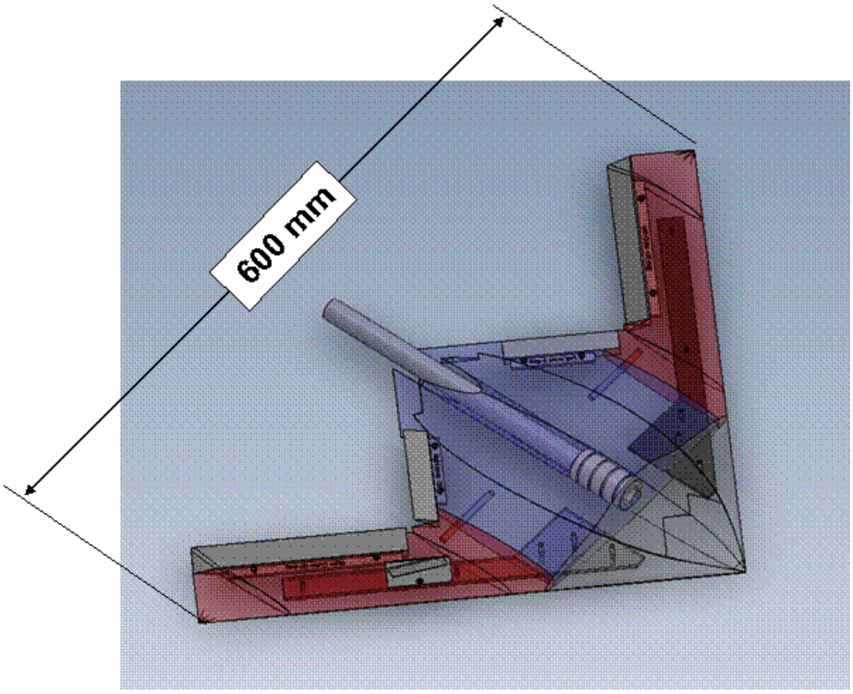


Figure 4: Second CERBERUS model design iteration with scale of 1:22.

where M_n is the Mach number perpendicular to the wing , M_∞ is the Mach number, Λ is the wing sweep angle, C_{comp} is the compressible pressure coefficient, C_{incomp} is the incompressible pressure coefficient, and β is the compressibility (relative volume change).

MODEL DESIGN STRUCTURAL CONSIDERATIONS

The wind tunnel for our experiments is fitted with a rear-mounted sting-type strain-gage balance, with its forward section tapered (Morse cone) to accept a mounting adaptor for models. Because the model plus cone adaptor are attached to the front of the balance, the design needs to provide this access. Another consideration in determining the overall model architecture is the limitation on maximum part size, which did not allow fabrication of the whole span as one piece. All this led to a configuration that consisted of four main parts: fuselage, nose section, left wing and right wing for both models. These components are shown in Fig. 5 for the ILAS model.

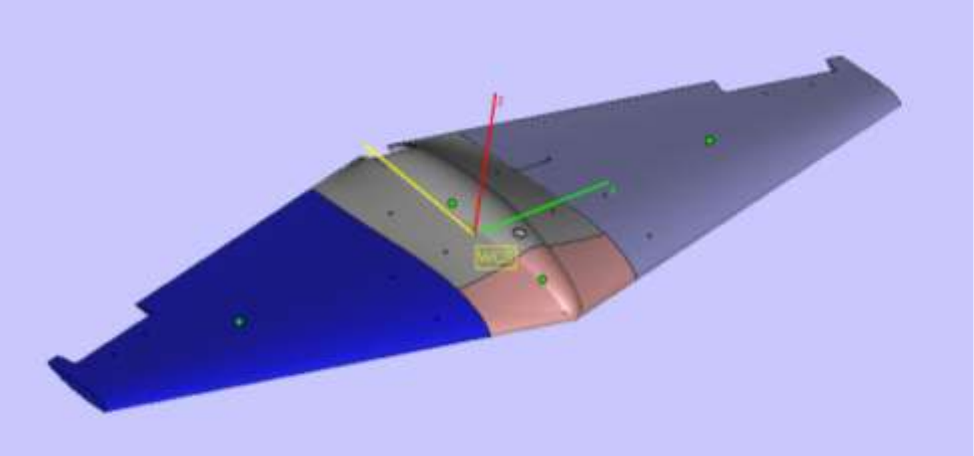


Figure 5: Model architecture for the ILAS model showing the four main parts: fuselage, nose section and two wings.

As is common with wind tunnel testing, ailerons, elevons and spoilers in the models were manufactured as separate parts, each representing a different position of the control surface. For easy changing of these parts, the models incorporate slots and other locating features, and means of securing the interchangeable parts: pins or screws. Figure 6 is a photograph of the ILAS model showing the main parts, stiffening rods (see explanation below), and the complete set of control surfaces. Similarly, the complete set of parts made for the CERBERUS model is shown in the photo of Fig. 7.

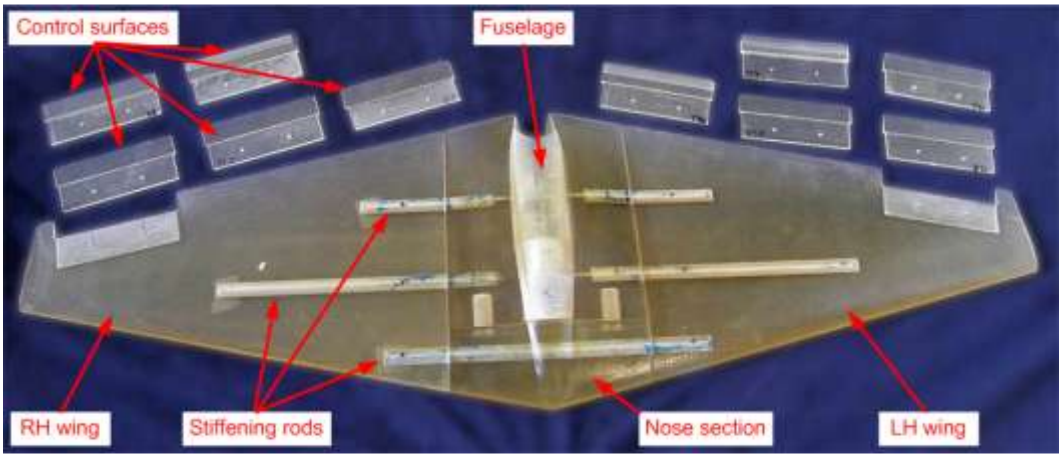


Figure 6: ILAS model parts.

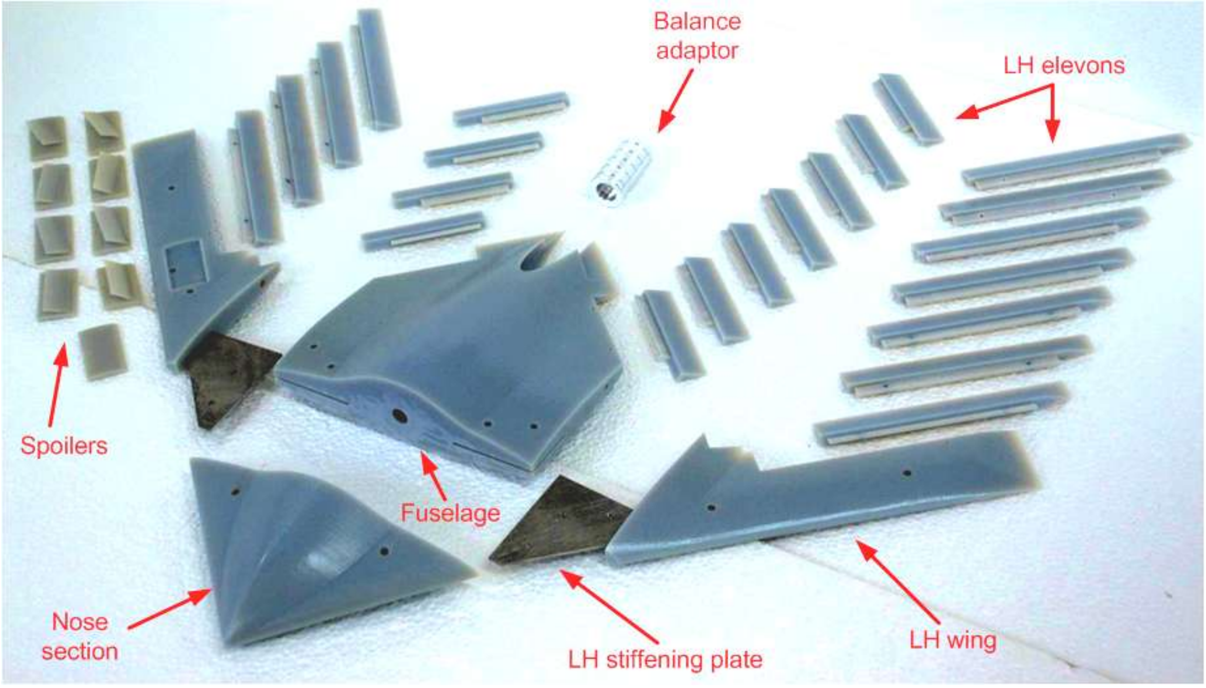


Figure 7: CERBERUS model parts.

To ensure adequate strength and stiffness, both model structures were reinforced with metal inserts. The ILAS model was designed to accept five 8-mm diameter aluminum rods as shown in Fig. 8. The rods were inserted into long bores that were part of the RP model and secured in place with small screws. The rods and screws also provided the means of securing the main model components to each other.

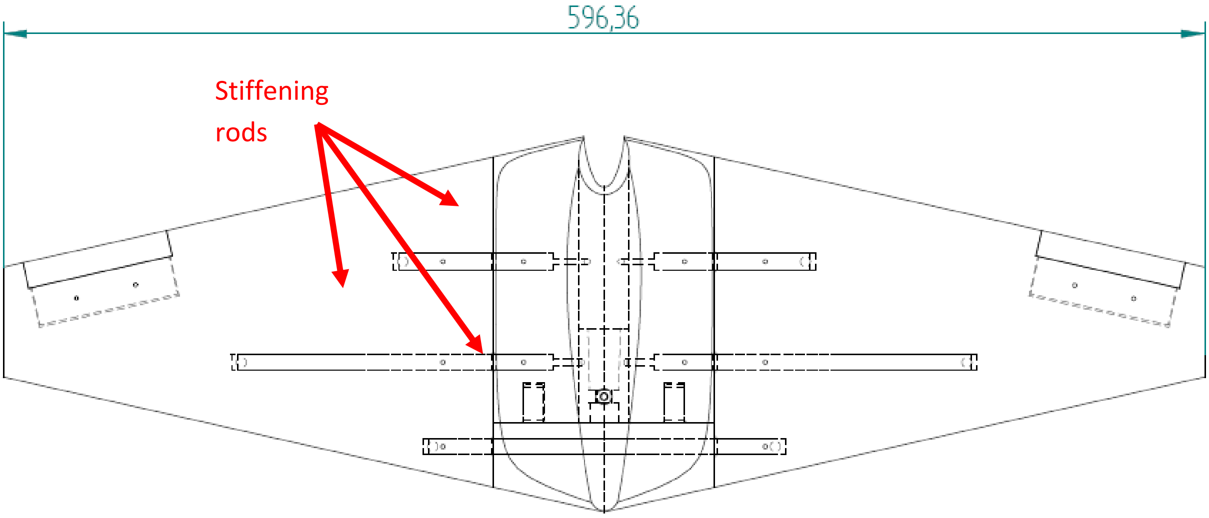


Figure 8: Top view of the ILAS model showing the five reinforcing rods.

The CERBERUS model had wings that were too thin for inserting round rods, so 2.5-mm thick stainless steel plates were used instead, as shown in Fig. 9. In this case too, the model parts were fastened by small screws to the plates, thus also securing the main components to each other. Through holes for the screws were fabricated as part of the RP process (no drilling was required).

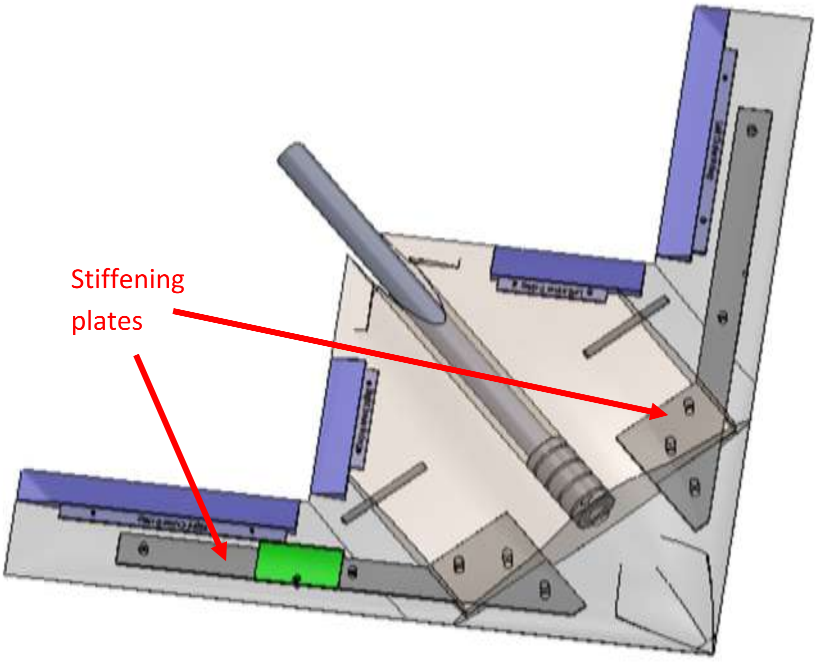


Figure 9: The CERBERUS model showing the two reinforcing steel plates.

DETAILS OF THE CERBERUS TEST MODEL

In order to measure and evaluate all the relevant parameters, the wind tunnel model included several elevons and spoilers as describes in Figs. 10 and 11. All the control surfaces were fabricated as interchangeable parts representing different hinge angles.

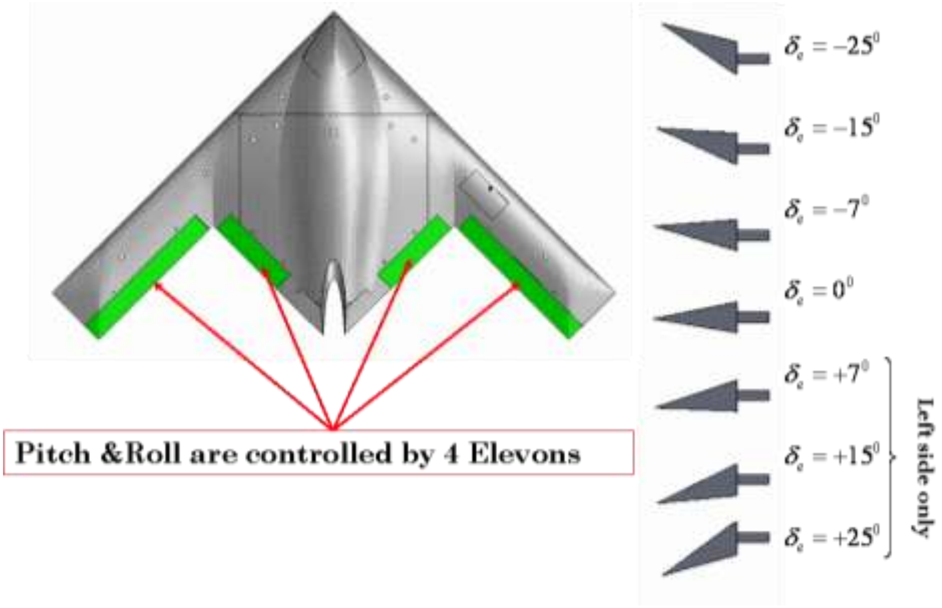


Figure 10: CERBERUS pitch and roll control surfaces (elevons).

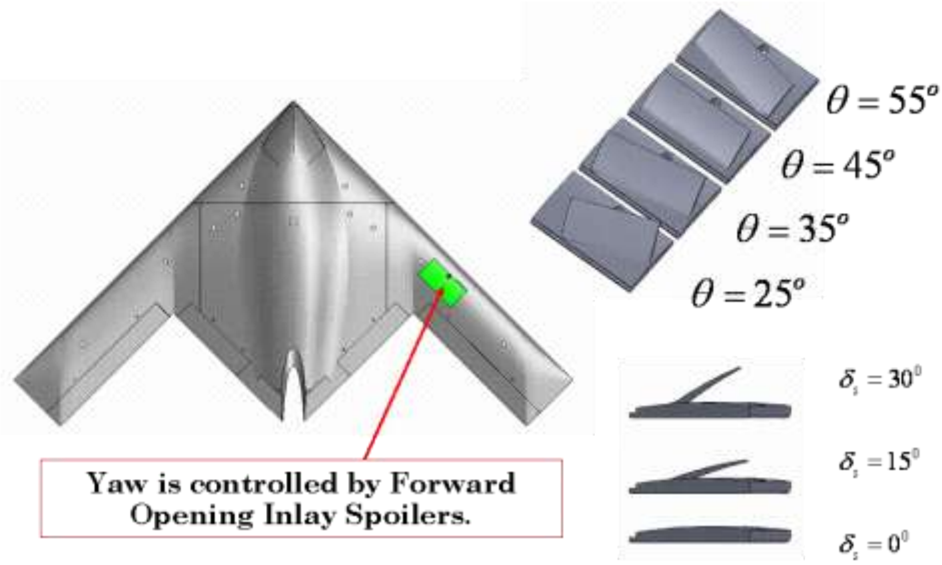


Figure 11: CERBERUS yaw control surface (spoiler).

The test model was mounted onto the sting-type balance in two different positions to allow for pitch and yaw measurements, as shown in the photos of Fig. 12.

Figure 12: Model mounted in the wind tunnel for pitch (left) and yaw (right) measurements.

TEST RESULTS

An aerodynamic analysis using the Vortex Lattice Method (VLM – 3D panel code) was performed prior to the wind tunnel testing. The wind tunnel test results showed very good compatibility with the theory and similarity to the analysis results, which indicates that the use of the RP technique for production of wind tunnel models is adequate and sufficient for obtaining quick and accurate enough results.

Figure 13 presents the wind tunnel test result and the calculated (linear) lift coefficient, C_L, as a function of the angle of attack, α. Figure 14 shows the measured lift coefficient including its maximum value. The wind tunnel test and the calculated (quadratic) results for the drag coefficient, C_D, as a function of C_L are shown in Fig. 15, while Fig. 16 presents the measured aerodynamic efficiency. All the results indicate a very reasonable and predictable behavior

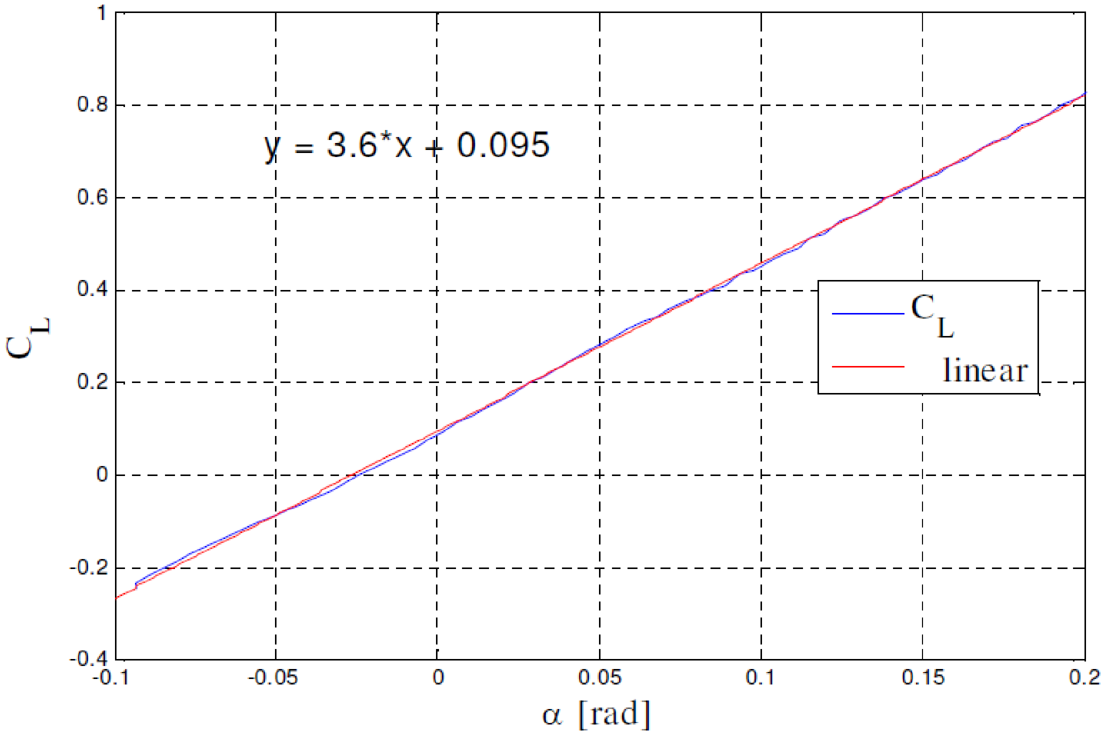


Figure 13: Comparison between the measured and calculated (linear) lift coefficients as a function of the angle of attack.

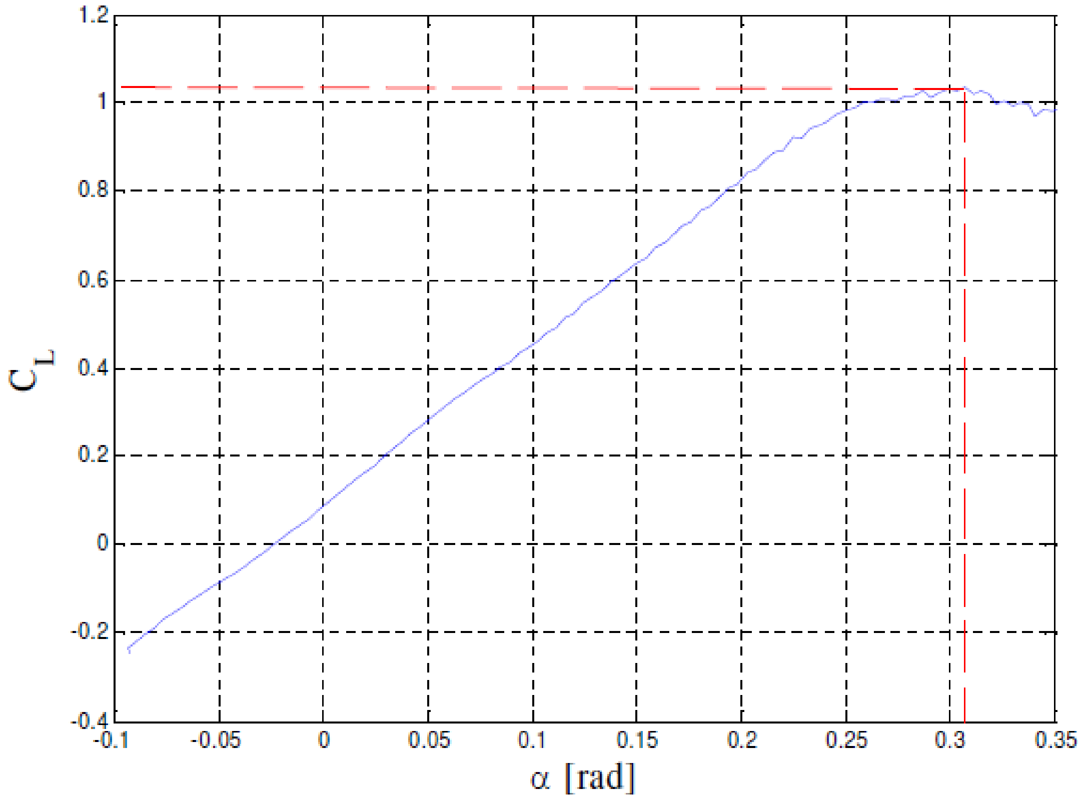


Figure 14: The measured lift coefficient as a function of the angle of attack; C_{Lmax} = 1.04 at α = 17.6°.

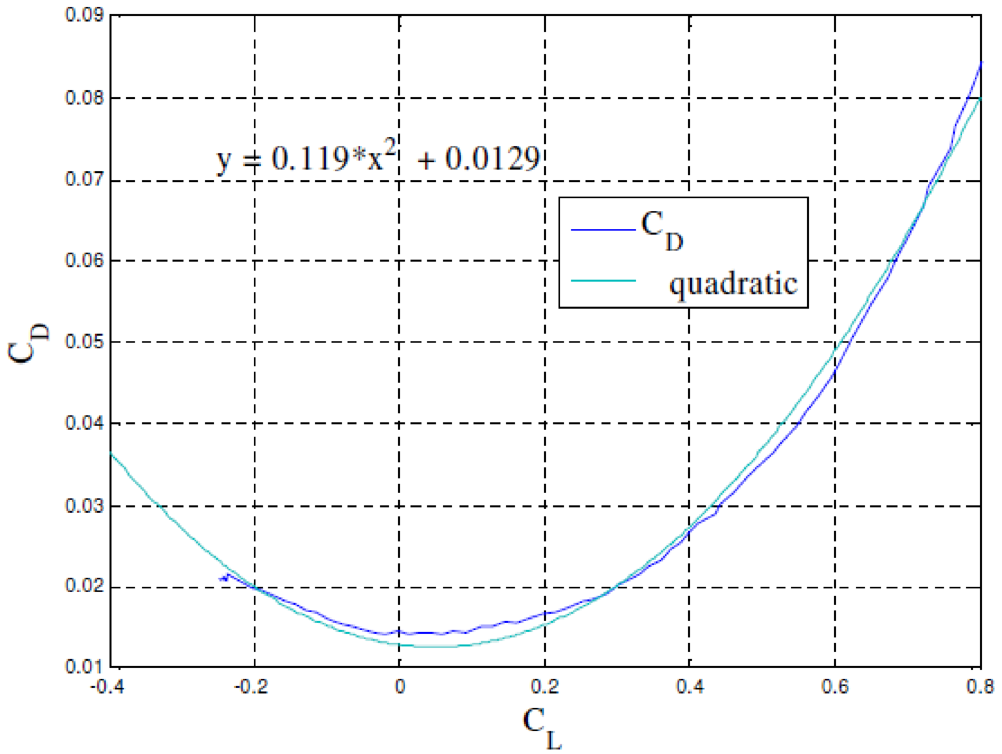


Figure 15: The measured and calculated (quadratic) drag coefficient vs. lift coefficient.

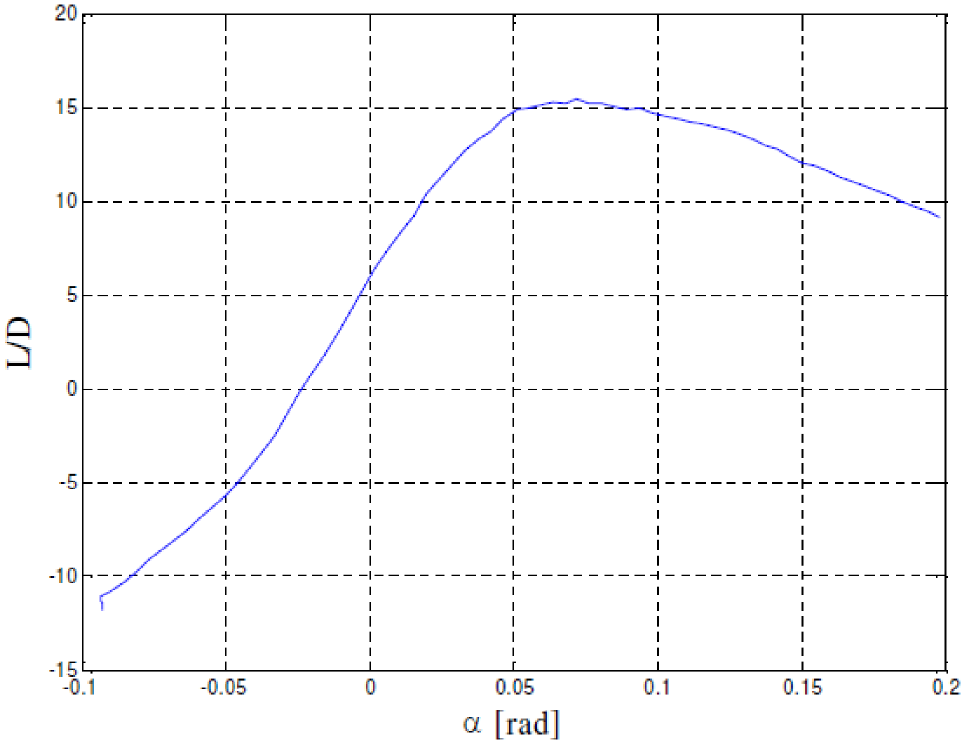


Figure 16: The measured lift-to-drag ratio vs. angle of attack.

After establishing the level of confidence and proving the adequacy of the RP model, several tests for the controllability of the air vehicle have been conducted. Figure 17 presents the wind tunnel results for the evaluation of the control surfaces.

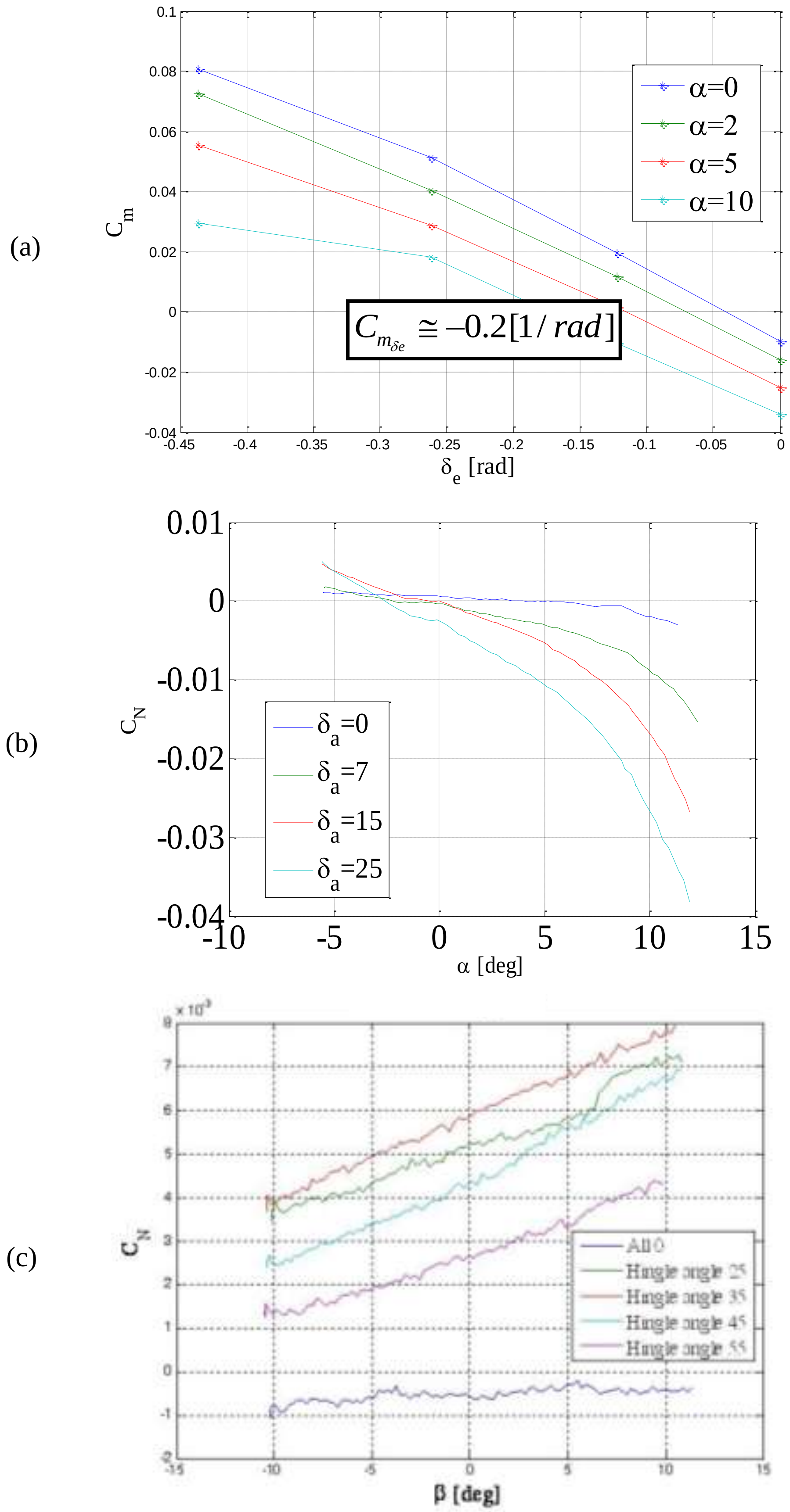


Figure 17: (a) The measured elevator's influence, (b) the yaw moment coefficient vs. angle of attack, and (c) spoiler influence on yaw for different hinge angles with 15° spoiler angle and 2° angle of attack.

CONCLUSIONS AND RECOMMENDATIONS

The advent of new RP manufacturing techniques and materials provides a means to reduce the cost and shorten the time associated with the acquisition of a wind tunnel model. Our work in this area is related to students projects and therefore has to follow a rigid timetable. Typically, the final configuration of the aircraft being designed is modeled in CAD towards the end of the project, and little time is left by then to design, fabricate and test the model in the wind tunnel, and evaluate and present the results. Together with having a limited budget for this academic activity, we have found the opportunities offered by RP very useful. The two models of this paper were built for a fraction of the cost and time required for a similar traditional steel or aluminum model.

For the sting-type back-mounted models that we have, their shape (flying wing) and size (60-cm wing span), the configuration with four main components—fuselage, nose and two wings—seems appropriate. It allows access for mounting and dismounting the model from the front, and easy incorporation of stiffening metal parts. Ideally, the stiffening rods or plates should run from one wing to the other; however, the force balance and its adaptor might not leave enough space for this arrangement, resulting in separate stiffening elements.

The major structural difficulty that we have encounter is in ensuring a tight connection between the wings and the fuselage. Tolerances for RP parts cannot, at the present time, be as tight as with CNC machining, so some creative solutions need to be incorporated in the design, or adhesives must be used for the final locating of the parts. Clearly, this problem could be avoided by using a central machined strong back and using RP for external fairings only, but this would not fully utilize the cost and time savings inherent in an all-RP model. In addition, the RP polymer is not suitable for direct screw threading, so other fastening means need to be employed, or the screws should connect to the metallic stiffening members.

We did not check the dimensional accuracy or the surface finish of the RP models scientifically, but can state that the models look and feel very satisfactory from this perspective. We also did not explore the possibility of making hollow models because of our lack of experience regarding the model stiffness issue, but even with the solid models we could benefit from their lower weight and thus higher measurement sensitivity.

In terms of the aerodynamic data fidelity, we are now confident that the quality of the test results is acceptable for preliminary design and justifies the use of RP technologies, at least for models of a size comparable to what we have tested, and for the subsonic wind tunnel. The good dimensional accuracy of the models, combined with the high quality of the testing results, suggest that RP can definitely be used for quick, low-cost performance evaluation of new air vehicles and for verification of analyses results. The capability to obtain wind tunnel results in a short time can also contribute to the marketing of the aircraft during its development phase.

Research is currently underway to study the use of RP for wind tunnel models more scientifically. We intend to compare RP model test results with those of conventional metal models, explore various ways of providing adequate strength and stiffness to the models, devise new techniques for attaching RP components to each other to ensure the required accuracy and rigidity, and investigate the prospects of making hollow, lightweight models. In addition, we shall continue to use RP for wind tunnel models of students' projects. At the present time we are working on a model of a "flying car" for one project, and will soon begin an aerodynamic investigation of a "morphing wing" aircraft for another project, using RP extensively.

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