ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 533.6.071/.072:658.53.018.2

INVESTIGATION OF RAPID MANUFACTURING TECHNOLOGY EFFECT ON AERODYNAMICS PROPERTIES

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Original scientific paper
Nowadays, rapid manufacturing methods are widely used in order to produce wind tunnel test models. Dimension accuracy, surface roughness and material strength are important parameters affecting aerodynamic properties of the models. In this research, applications and capabilities of two rapid manufacturing methods used in design and development of wind tunnel test models, built to measure aerodynamic coefficients have been investigated. In this experience, the AGARD-B model and the nose-body-tail vehicle configuration have been chosen. The first model was fabricated from metal and ABS-M30 material by machining and fused deposition modelling. The other model, AGARD-B, was fabricated by the three dimensional printing process. To improve strength and stiffness of the models and maintain balance, metal inserts have been used. Models are built to the least thickness in order to achieve acceptable dimensional accuracy and surface roughness. Aerodynamic coefficients of hybrid models including drag force, lift force and pitching moment under different angles of attack and specified speed have been measured and compared with standard models. Results imply that hybrid models developed by rapid manufacturing methods can be used for measurement of aerodynamic coefficients and calibration of wind tunnels; hence save production cost and time. Minor deviation of aerodynamic coefficients observed in hybrid models compared to metal models, can be pertained to the bending of the hybrid models under large angles of attack.

Keywords: *aerodynamic coefficient, dimension accuracy, fused deposition modelling, rapid manufacturing, three dimensional printing, wind tunnel*

Istraživanje utjecaja tehnologije brze izrade na aerodinamička svojstva

Izvorni znanstveni članak
Danas se metode brze izrade naveliko koriste u proizvodnji modela za ispitivanje u aerotunelima. Dimenzijska točnost, površinska hrapavost i čvrstoća materijala važni su parametri koji utječu na aerodinamička svojstva modela. U ovom radu ispitivane su primjene i potencijali dviju metoda brze izrade koje se koriste u konstruiranju i izradi modela za testiranje u aerotunelima, kako bi se izmjerili aerodinamički koeficijenti. Izabrani su AGARD-B model i konfiguracija nos-tijelo-rep vozila. Prvi model je bio izrađen od metala i ABS-M30 materijala strojnom obradom i oblikovanjem nanesenog rastaljenog metala. Drugi model, AGARD-B, izrađen je postupkom trodimenzijskog tiskanja. Za poboljšanje čvrstoće i krutosti modela i održavanje ravnoteže, korišteni su metalni umetci. Modeli su napravljeni što tanji kako bi se postigla prihvatljiva dimenzionalna točnost i površinska hrapavost. Mjereni su aerodinamički koeficijenti hibridnih modela uključujući silu otpora, silu uzgona i moment posrtanja pri različitim napadnim kutovima i određenim brzinama te uspoređeni sa standardnim modelima. Rezultati pokazuju da se hibridni modeli razvijeni metodama brze izrade mogu koristiti za mjerenje aerodinamičkih koeficijenata i kalibriranje aerotunela te tako smanjiti proizvodne troškove i vrijeme. Manje devijacije aerodinamičkih koeficijenata primijećene kod hibridnih modela u usporedbi s metalnim modelima mogu nastati zbog savijanja hibridnih modela kod velikog napadnog kuta.

Ključne riječi: *aerodinamički koeficijent, aerotunel, brza proizvodnja, dimenzijska točnost, oblikovanje rastaljenog sloja, trodimenzijsko tiskanje*

1 Introduction

Traditional wind tunnel models are meticulously machined from metal in a process that can take several months. Traditional methods, although precise, are time consuming and cannot be used for feasibility study of a new design [1]. We were looking for a way to generate experimental data quickly enough to verify computational fluid dynamics (CFD) results. The CFD developers were generating solutions in a matter of days or even hours, and they wanted to verify their solutions with experimental data from the wind tunnels. Rapid manufacturing (RM) technologies being developed for the space program have many applications in the commercial industry [2]. Wind tunnel models, used to provide performance test, can be produced at lower cost compared to traditional methods. Most wind tunnel models are computer numerical control (CNC) machined from aluminium or steel and even inconel (for cryogenic) tunnels [3]. The addition of pressure taps is particularly expensive, time consuming, and requires skilled workers with considerable experience. Rapid manufacturing technology makes concurrent study of air vehicle concepts via computer simulation and wind tunnels possible. It produces a model in days or hours, depending upon model complexity [4]. Some of most commonly available RM systems are: stereolithography (SLA), fused deposition modelling (FDM), selective laser sintering (SLS), and Three-dimensional printing (3DP) [5, 6]. The SLA system consists of an ultra-violet laser, a vat of photo-curable liquid resin, and a controlling system. A platform is lowered into the resin (via an elevator system), such that the surface of the platform is a layer-thickness below the surface of the resin. The laser beam receives its path instructions for each slice to trace the boundaries and fill in a 2D cross section of the model, solidifying the resin wherever it touches. Once a layer is complete, the platform descends a layer thickness, resin flows over the first layer, and the next layer is built. This process continues until the model is complete [7]. Laser sintering uses fine powders of a wide range of materials to be treated in nitrogen atmosphere. The powder is heated up to a temperature just below the melting point of the specific material, which usually will take a couple of hours. A roller spreads the powder on the building platform. The laser beam then selectively melts the powder and bonds it. As the power is already heated, the laser needs to elevate the temperature slightly to cause sintering. The platform moves down incrementally and the process starts again, until the prototype is finished [8]. Today's RM offer advantages in many applications compared to classical subtractive fabrication methods such as milling, turning etc. Thus, parts can be formed with geometric complexity or intricacy without the need for elaborate machine setup or final assembly [9]. Aerodynamic wind tunnel tests, particularly those using traditional metal models, are very expensive. As a result, program managers often rely heavily on analytical tools, such as CFD to predict how a system might perform. Although this tool can provide valuable data over a full range of operating conditions, it typically requires more time to produce final results than wind tunnel tests. Low cost modelling is allowing the air force to conduct a series of tests, based on the design phase, to compare and possibly merge various testing methods and analysis tools, such as wind tunnel tests and CFD that could increase the efficiency of aerodynamic testing. It is also allowing them to investigate experimental measurement techniques for inexpensively and accurately measuring pressure and flow velocities over an entire model during testing. Regarding RM technologies for wind tunnel testing there are some research projects that have used different rapid prototyping (RP) technologies. Springer et al. [10] compared the aerodynamic characteristics obtained in a transonic wind tunnel over a range of Mach numbers for models made by RP technologies, and one control model made of aluminium. They concluded that at that 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. Chuk et al. [11] divided aircraft model components into three categories: non-structurally loaded, lightly loaded and highly loaded, according to the stress developed during testing. Only parts from the first category, with stresses below 137,89 MPa, were judged suitable for RP fabrication. Kietzman et al. [12] studied the material strength and the interlayer strength of polyurethane in the shape deposition manufacturing process, which combines casting and machining. They showed that grit-blasting and chemical processes could improve the adhesion between layers, but that the strength could also be raised by using polyurethanes or epoxies that bond more strongly to themselves. Landrum et al. [13] tested three chord airfoil models in a low speed subsonic wind tunnel: a conventional cast polyurethane model and two photopolymer models made by stereolithography. 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. Hildebrand et al. [14] evaluated fabrication of complex wind tunnel models with internal passages, surface pressure taps, and exterior contours. Daneshmand et al. [15] and Aghanajafi et al. [16] fabricated rocket shaped SLA models with various layer thicknesses. They concluded that thick layers offer a quick method for studying preliminary designs, and that the accuracy of aerodynamic data obtained was adequate. Heyes et al. [17] demonstrated that RP technique could be utilized to incorporate internal features into models that would entail a great deal of extra engineering in both design and manufacture by traditional techniques. Karalekas et al. [18] described the addition of nonwoven glass fibre mats to stereolithography photopolymer and vacuum cast polyurethane. An improvement in tensile strength and elastic modulus was observed, together with increased brittleness and problems of poor adhesion between the cured photopolymer and the glass fibres. Researchers have introduced several RP procedures to manufacture wind tunnel test models. This research is aimed at introducing two methods for rapidly producing cheap hybrid models utilized to calibrate wind tunnels and measure aerodynamic coefficients.

2 Fused deposition modelling and three dimensional printing process

RM is the technique of manufacturing prototypes from complex 3D datasets, where all are based on layered manufacturing. The concept of layered manufacturing is the basis of all mainstream rapid manufacturing processes. The idea behind layered manufacturing is that it is easier to build a series of 2D models than it is to build a single 3D model. Any solid or surface geometry can be interpolated to generate a series of 2D cross sections called slices. These slices are generated at evenly spaced intervals along the *z*-axis direction of the geometry. Each layer is then constructed sequentially to produce a model (Fig. 1). This technology is fast developing and is more than competitive with traditional model building techniques, considering time and degree of detail.

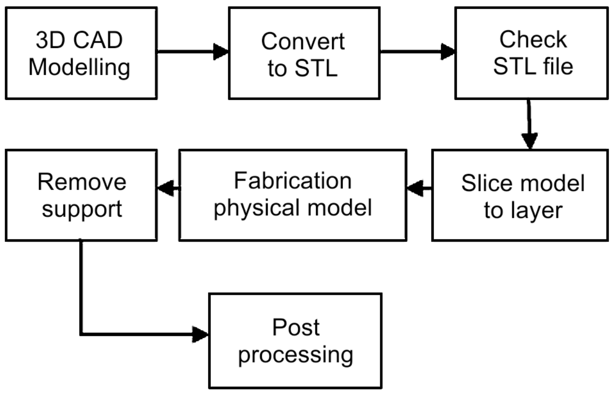

Figure 1 Rapid manufacturing process

Some of the most commonly available systems are fused deposition modelling (FDM) and three-dimensional printing. In FDM, the material is prepared in filament form, available on spools and in many different colours. This filament is heated in a nozzle, which moves in the *X* and *Y* directions according to the CAD data. The molten material is thus added layer by layer (Fig. 2). FDM is a free-form fabrication technology. Because it uses high strength ABS plastic, it is the favoured technology for prototyping plastic parts requiring strength [19].

Three-dimensional printing (3DP) uses inkjet printer technology to print fine patterns of glue onto a smooth bed of plaster powder. First, the 3DP spreads a thin layer of powder. Second, an ink-jet print head prints a binder in the cross-section of the part being created. Third, the build piston drops down, making room for the next layer, and the process is repeated. Once the part is finished, it is surrounded and supported by loose powder, which is then shaken loose from the finished part. This method is especially good at making parts that have hard-to-reach cavities, as the scrap can be poured and vacuumed out. Fig. 3 shows how the Z-Corp 3D Printer fabricates solid parts from layers of powder [20]. The ability to use models for wind tunnel testing reduces operating time, lowers cost, reducing fabrication time and allowing for procedure rehearsals.

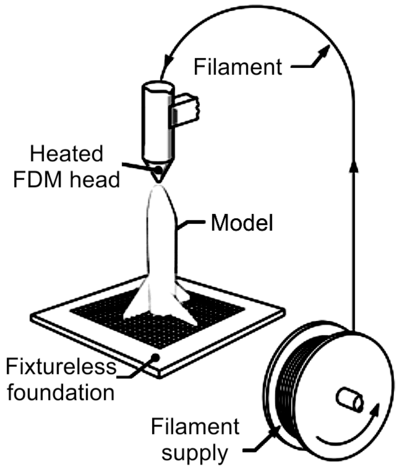

Figure 2 Schematic of the FDM process

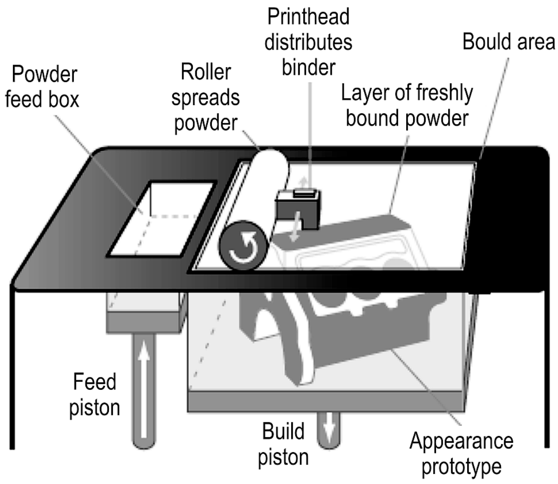

Figure 3 The three dimensional printing (3DP) process [21]

3 Wind tunnel model description

This research investigates the capabilities of FDM and 3DP in design and development of RM models. Models chosen considering their exclusive capabilities are from two different categories; the first model, AGARD-B is used to calibrate wind tunnels. Traditional production of this model, due to its curved nose and tail is time-consuming and costly. AGARD calibration model B is a configuration consisting of a wing and body combination, [22]. The wing is a delta in the form of an equilateral triangle with a span four times the body diameter. The body is a cylindrical body of revolution with a nose profile determined by the equation:

$$r = \frac{X}{3} \cdot \left[1 - \frac{1}{9} \cdot \left(\frac{X}{D} \right)^2 + \frac{1}{54} \cdot \left(\frac{X}{D} \right)^3 \right]. \tag{1}$$

Fig. 4 is a sketch of the model with the pertinent dimensions given in terms of the body diameter D. Basic model dimensions are given in Tab. 1.

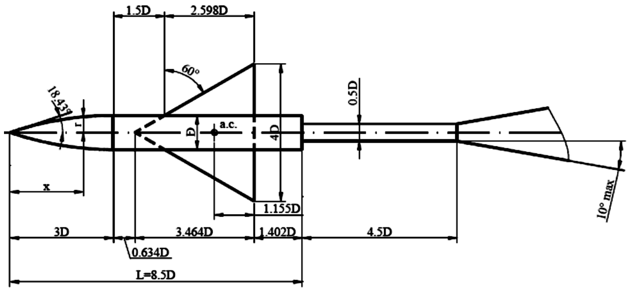

Figure 4 Basic dimensions of the AGARD-B model [22]

Table 1 Dimensions of the AGARD-B model

Model length, L / mm	282,2
Model diameter, D / mm	33,2
Wing span, B / mm	132,8
Model reference length, wing span, B_{ref} / mm	132,8
Model base area, S_b / mm^2	865,25
Reference point position for moment calculation, X_{ref} / mm	30,73

The AGARD model was fabricated using 3DP nose and 3DP body attached to cylindrical metal as depicted in Fig. 5. The cylindrical metal, fabricated from steel (AISI 1045H), is a 41 mm long cylinder with a 28 mm outer diameter and taper inner. To enhance model's strength and stiffness and maintain balance, metal cylinders were used inside the model. These metal cylinders, after being machined by traditional methods, were attached to the AGARD model by pins.

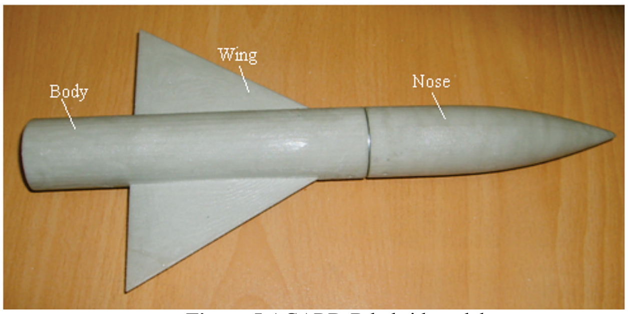

Figure 5 AGARD-B hybrid model

The second model being a configuration consisting of nose, body and tail was fabricated by the FDM method. The basic model was constructed using steel (AISI 1045H) in three parts, a nose, body and tail. The tail is in the form of an equilateral with a span twelve times the body diameter. The body is a cylindrical airframe of revolution with an ogive-cylinder head as shown in Fig. 6. Therefore, the experimental data of the metal model can be used to validate the design and manufacturing method for RM wind-tunnel models. The second vehicle configuration model had a hybrid design, which provided enough strength and stiffness for the model. The hybrid model was constructed of two parts, an outer thermoplastic configuration and a metal core body (Fig. 7). A 15 mm hole was carved through the centre of the outer thermoplastic to place the metal core body. The nose was attached to the core body by nesting mode. Design and fabrication of the metal core body had to comply with the strength and stiffness requirements of wind tunnel tests. The metal core body can be fabricated by traditional processing method, such as milling, lathe and drilling, which can shorten the processing period, hence reduce manufacturing cost and improve convenience in assembly. The outer thermoplastic configurations of the hybrid wind tunnel model are often fabricated by RM technique and facilities. FDM models can be produced within an accuracy of ±0,127 mm up to 127 mm. Accuracy on models greater than 127 mm is ±0,0015 mm per millimetre [23]. The FDM model was manufactured using an ABS-M30 and its layer thickness was 0,127 mm. For a model to be qualified for Bombardier Aerospace Inc. wind tunnel tests, the surface profile dimensional tolerance is typically ±0,127 mm [11].

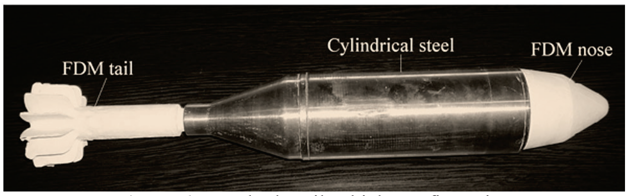

Figure 6 Nose-body-tail vehicle configuration

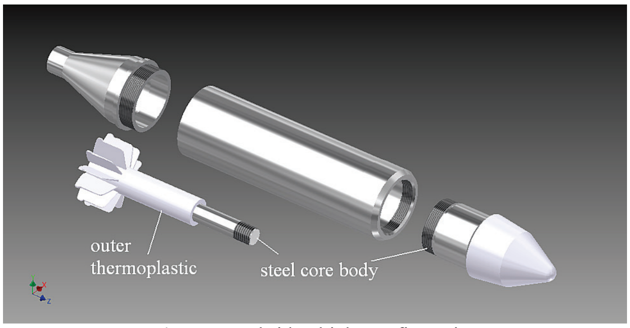

Figure 7 Hybrid vehicle configuration

4 3D printing and FDM advantages

RM models constructed using two methods constructed by two materials were compared to a machined metal model. The RM processes were FDM using acrylonitrile butadiene styrene (ABS-M30) plastic and 3DP with Zp150 as its constructing material. Zp150 is a high performance composite and the best powder system available on Z-Corporation 3D printers. Steel (AISI 1045H) was chosen as the constructing material for the machined metal model. One of the most low cost RM technologies, popularly known as 3DP was used for this study. Machines used in this study were ZPrinter 450 made by Z-Corporation. The following are the advantages offered by this technology to wind tunnel model building:

- **3D color printing**

  Z-Corp 3D printers are the only RM machines that print in 3D colour. All other technologies on the market can only print one colour at a time. 3D colour is very important for analysis and assembly of wind tunnel models.
- **World's fastest prototyping machine**

  The Z-Corp 3D Printer technology is faster than any other rapid manufacturing machine on the market. This means you have your prototypes ready in a matter of hours not days. This is especially critical for building large models.
- **Material cost**

  The Z-Corp 3D Printer technology build materials are 3 to 6 times less expensive than any other RM technologies.
- **Support structures**

  Support structures are not required using the Z-Corp technology. Other RM machines require supports to build a model. These supports must then be removed manually using sharp tools and knives or with a chemical bath system. This process costs extra money, requires extra time to remove and affects the appearance of the part.
- **Surface roughness and part detail**

  Z-Corp 3D printers create parts with a layer thickness of 0,089 to 0,203 mm. Most other 3D printers create parts at a resolution 2,5 to 4 times thicker. The smaller the layer thickness the better surface finish and details can be accomplished. This is extremely important for wind tunnel models.
- **Strength**

  Fine resolution on small features and excellent strength make this material suitable for wind tunnel testing. The ultimate strength of an uninfiltrated part will be somewhat affected by its orientation within the build bed. The part will be strongest along the *X*-Axis and *Y*-Axis and less strong along the *Z*-Axis. This is because the cross sections are printed in continuous strips along the *Y* or the fast axis (the print heads' direction of travel); in bands across the *X* or the slow axis (the gantry direction of travel); and in laminated layers along the *Z*-Axis.
- **Accuracy**

  The accuracy of models depends on printer/powder settings, and the materials chosen for post-processing.

The main advantages of using FDM technology are as follows:

- **Fabrication of functional parts**

  FDM process is able to fabricate prototypes with materials that are similar to that of the actual moulded product. With ABS, it is able to fabricate fully functional parts that have 85 % of the strength of the actual moulded part. This is especially useful in developing products that require quick prototypes for functional testing.
- **Minimal wastage**

  The FDM process builds parts directly by extruding molten semi-liquid onto the model. Thus, only the material needed to build the part and its support are needed, and material wastages are kept to a minimum.
- **Ease of support removal**

  With the use of break Away Support System (BASS) and water works soluble support system, support structures generated during the FDM building process can be easily broken off or simply washed away. This makes it very convenient for users to get to their prototypes quickly enough and there is very little or no post-processing necessary.
- **Ease of material change**

  Build materials, supplied in spool form (or cartridge form in the case of the dimension or prodigy plus), are easy to handle and can be changed readily when the materials in the system are running low. This keeps operation of the machine simple and its maintenance relatively easy [24].

The main factors determining which rapid manufacturing technology to be used are dimensional accuracy of the models, overall cost of the model, availability of technology, and strength of the model building materials.

5 Wind tunnel

The wind tunnel test was conducted in an open-return low speed wind tunnel made of plexiglass walls, in working dimensions of 60 × 60 × 100 cm, and a maximum velocity of 220 m/s. The wind tunnel (Fig. 8) is an intermittent blow down tunnel, which operates by high-pressure air flowing from storage to atmospheric conditions. The test section provides a Mach number range from 0,1 to 0,6. Downstream of the test section is a hydraulically and manually controlled pitch sector that provides the capability of testing angles-of-attack during each run. A six-hole probe or a wake rake can be used to determine the wake characteristics of a test subject. Pitot probes are used to measure velocity gradients and to calculate drag through integration. Pressure ports can be used on a test subject to determine the forces on specific parts of a model or how forces are distributed across a model. Long force and moment data refer to the three forces (lift and drag) and three moments (roll, pitch, and yaw moment) that the wind applies to the test subject. Lift and drag forces were measured at various angles of attack (AOA) and downstream velocities, by means of a load cell and a Pitot tube.

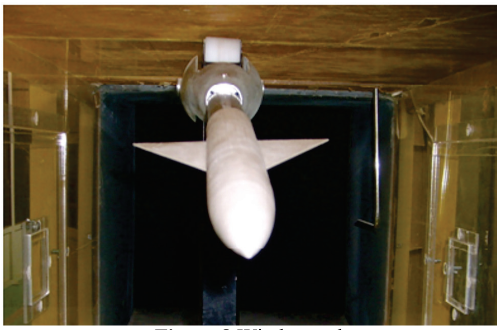

Figure 8 Wind tunnel

6 Wind tunnel tests

Considering the capabilities and applications of different models in the wind tunnel, two models, namely, the AGARD-B and the vehicle configuration were chosen for the wind tunnel tests. These models were produced by rapid manufacturing methods and their aerodynamic coefficients were compared against metal models.

6.1 The AGARD-B model

The objective of the testing was to obtain the characteristics of the AGARD-B model at Mach numbers 0,5 and 0,6, angles of attack α in the interval –4° to +12° and roll angle 0°. This geometry provided a basis for comparisons between 3DP model and machined metal model. Coefficients of drag force (C_X), lift force (C_Z) and pitching moment (C_M), are shown at these Mach number. Several axes systems were used in data reduction. These were: the wind tunnel axes system, balance, body, and wind axes systems. The origin of balance axes system was in the centre of the balance. To maintain balance of the axes system, the X axis was parallel to the model longitudinal axis and positive towards the end of the model. The Z axis lay in the model's plane of symmetry, and the Y axis was directed towards the left side of the model and completed a left-handed axes system. The origin of wind axes system was in the model reference point. The X axis was parallel to the air velocity vector and in the same direction (toward the end of the model). The Z axis lay in the flow plane and was normal to the X axis. The Y axis completed the left-handed axes system. The aerodynamic angle of attack α was the angle between the projection of the air velocity vector on the model plane of the left-right symmetry and the model axis. The aerodynamic sideslip angle β was the angle between the air velocity vector and its projection on the model plane of the left-right symmetry. The reference aerodynamic axis system and reference parameters for the precursor study are shown in Fig. 9 [10].

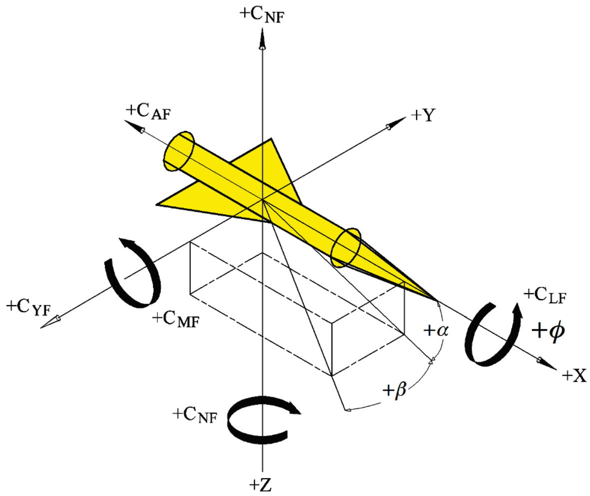

Figure 9 Aerodynamic reference axis

6.2 The Nose-body-tail vehicle configuration

A nose-body-tail configuration was chosen to test RM processes, ability to produce accurate airfoil sections and to determine the material strength, surface finish and dimensional accuracy effects related to the bending of the nose and tail under loading. A wind tunnel test over a range of Mach numbers from 0,1 to 0,6 was undertaken to determine the aerodynamic characteristics of the models. The method of model construction was analysed to determine the applicability of the FDM process in designing wind tunnel models. These Mach numbers were 0,1 and 0,3. Coefficients of pitching moment, axial force, normal force, and lift over drag are shown at each of these Mach numbers. All models were tested at angle-of-attack ranges from zero to +14° at zero sideslip.

7 Test results

7.1 The AGARD-B model

Figs. 10 ÷ 15 depict results obtained from comparison of aerodynamic coefficients between the AGARD metal and the AGARD hybrid models. Compared graphs show C_X (drag force coefficient), C_Z (lift force coefficient) and

C_M (pitching moment coefficient) in relation to the angle of attack α in the wind axes system. Testing Mach number was 0,5 and 0,6. The longitudinal aerodynamic data show very small discrepancies between the two model types. The study showed that in Mach number 0,5 and 0,6, the longitudinal aerodynamic data showed very good agreement between the metal model and hybrid model up to about 8° angle-of-attack when it started to diverge due to assumed hybrid model surface bending under higher loading.

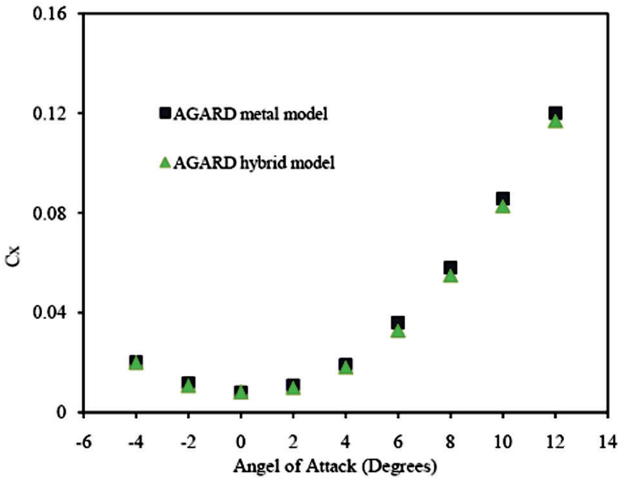

Figure 10 Drag force coefficient at Mach 0,5

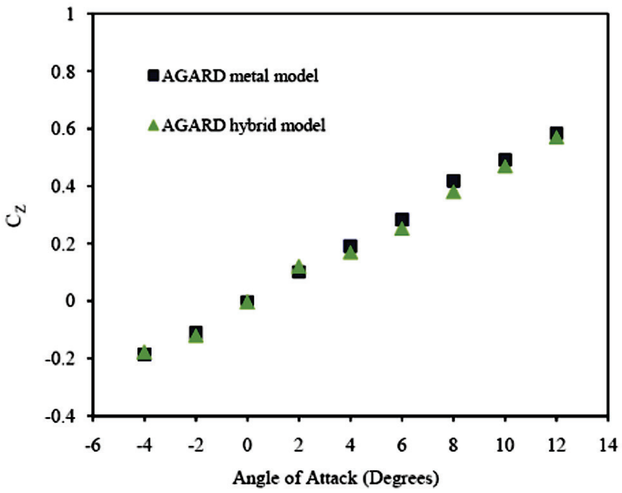

Figure 11 Lift force coefficient at Mach 0,5

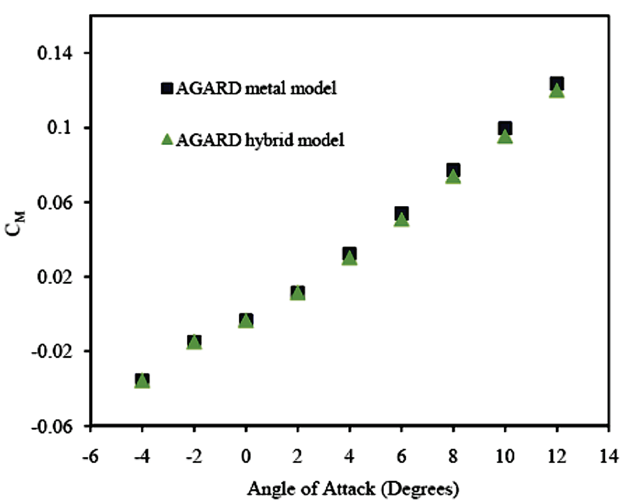

Figure 12 Pitching moment coefficient at Mach 0,5

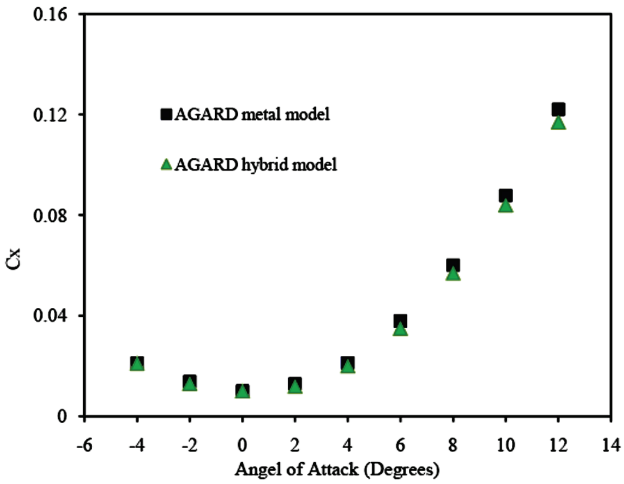

Figure 13 Drag force coefficient at Mach 0,6

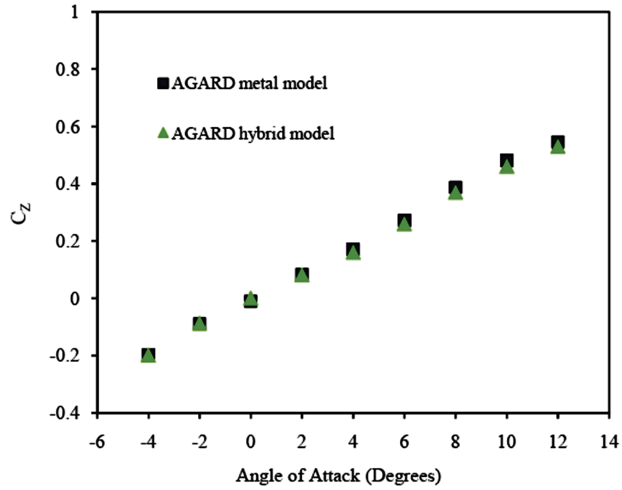

Figure 14 Lift force coefficient at Mach 0,6

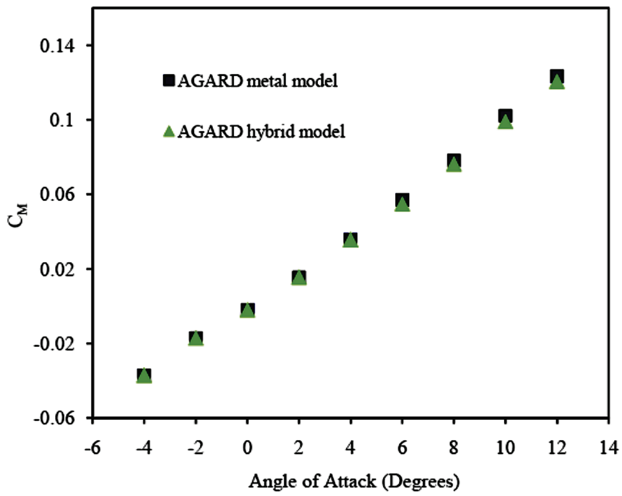

Figure 15 Pitching moment coefficient at Mach 0,6

In Figs. 10 and 13, drag force coefficient ranged between –4 to 8° angle of attack, proves good conformity of the two models and only minor deviation in the data ranged between 8 to 12° angle of attack can be traced. Figs. 11, 12, 14, and 15, depict lift force coefficients and pitching moment coefficients. A slight deviation can be traced under the above angles of attack.

7.2 The Nose-body-tail vehicle configuration

Figs. 16 to 19 show preliminary results obtained from installing the hybrid vehicle configuration model and the metal model in the wind tunnel test. The longitudinal aerodynamic data show minor discrepancies between the two model types. The study showed that in Mach number 0,3, the longitudinal aerodynamic data showed very good agreement between the metal model and hybrid model up to about 10° angle-of-attack when it started to diverge due to hybrid model surface assumed to be bent under higher loads.

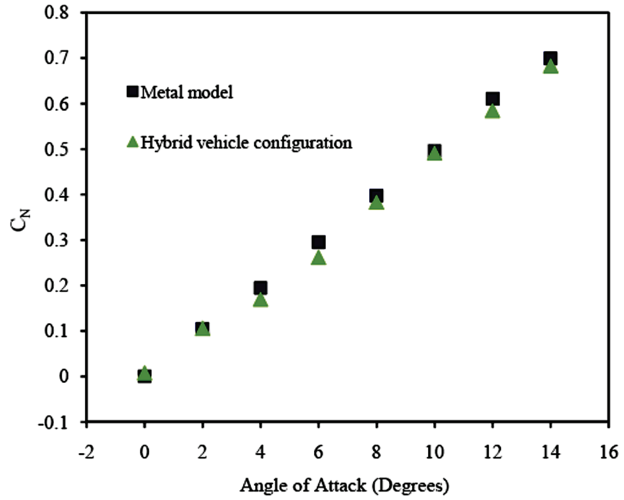

Figure 16 Normal force coefficient at Mach 0,3

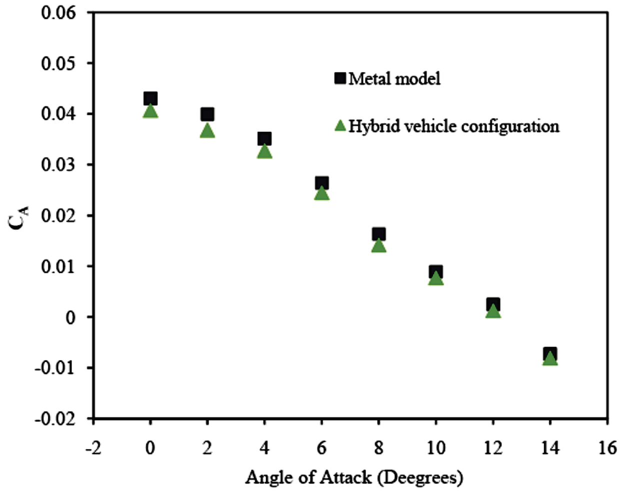

Figure 17 Total axial force coefficient at Mach 0,3

Fig. 16 shows a comparison of the normal force coefficient versus the angle of attack, for the metal model and the hybrid vehicle configuration at Mach number 0,3. It is obvious that the variation is almost linear and the normal force coefficient of the hybrid model is similar to the metal model for all angles of attack tested. The slight difference in the aerodynamic data between the models at Mach number 0,3 was in total axial force (Fig. 17). Two models showed good agreement in pitching moment (Fig. 18). To compare aerodynamic coefficients of the metal model and the hybrid model, the variation of the ratio L/D at several typical angles of attack is shown in Fig. 19. It is seen that the ratio for the hybrid model is slightly lower than that of the metal model at the same angle of attack.

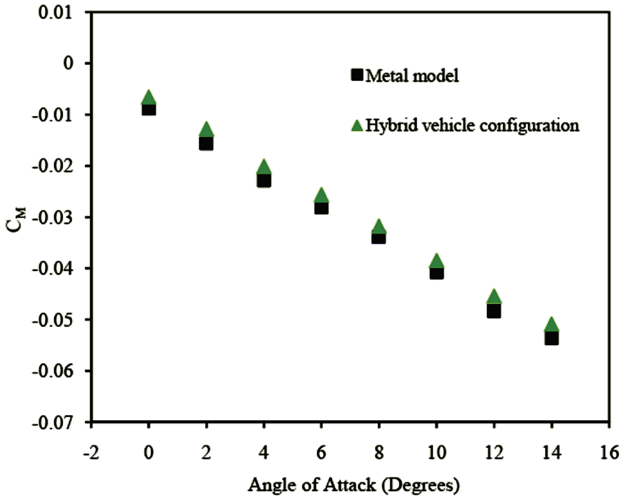

Figure 18 Pitching moment coefficient at Mach 0,3

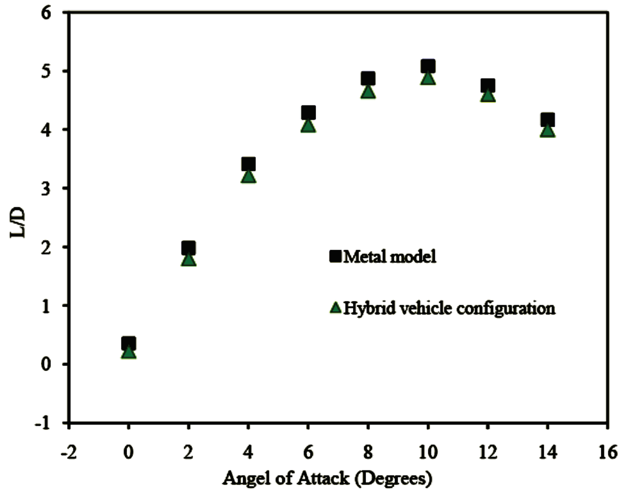

Figure 19 Lift over drag at Mach 0,3

8 Accuracy of the Results

The data accuracy resulting from the precursor test can be divided into two sources of error or uncertainty: (1) the model configuration and (2) the data acquisition system [10]. Each of these factors will be considered separately. Model configuration consists of its dimensional accuracy, surface roughness, and strength of constructing material. Dimensional accuracy depends upon layer thickness and constructing axes being chosen. Maintaining the model's length along the *X* axis and aiming at minimum layer thickness results in increased dimensional accuracy of the model. First, the dimensional accuracy of each model must be compared. Also the contours of the models used in this test were measured at two wing sections, vehicle stations, tail sections, and the *XY* and *XZ* planes. Two sectional cuts were made on each wing, left and right; two on the body; two on the vertical tail, and one cut in the *XY* and *XZ* planes. This shows a representation of the maximum discrepancy in model dimensions relative to the baseline CAD model used to construct all the models at each given station. The comparing dimensions for this configuration are shown in Tab. 2. Other parameter affecting accuracy is the surface roughness. Surface roughness is an important parameter in wind tunnel testing model fabrication. Some of the main causes of roughness on RM parts are layer thickness, part orientation, the layer build process employed by the particular RM system, presence of support structures. For the FDM technique, the optimum surface roughness is achieved by setting the layer thickness to 0,127 mm, the minimum feasible value until now. The average surface roughness for hybrid vehicle configuration, AGARD hybrid model and metal models are shown in Tab. 3. Another parameter affecting accuracy is the strength of materials. Along with velocity increase in the wind tunnel, deformations of body and wings increase and this affects the aerodynamic coefficients. To reduce deformations in RM models, metal inserts can be used. Material properties of ABS-M30, Zp150 and metal model are shown in Tabs. 4, 5 and 6. Balance displacement in the models and relative rotation of the assembled parts is another parameter affecting aerodynamic coefficients.

Table 2 Comparisons dimensions

		AGARD model			Nose-body-tail configuration		
Reference dimensions	Units	CAD model	Hybrid model	Machined model	CAD model	Hybrid model	Machined model
Length (L_{ref})	mm	282,2	282,33	282,28	521	521,12	521,08
Diameter (S_{ref})	mm	33,2	33,29	33,25	80	80,14	80,06
Tail-*XY* plane	mm	132,8	132,9	132,85	140	140,07	140,04
Nose-*XY* plane	mm	33,2	33,29	33,24	73	73,03	73,05
Tail-*XZ* plane	mm	33,2	-	33,24	85	85,06	85,03
Nose-*XZ* plane	mm	33,2	33,26	33,24	73	73,05	73,03

Table 3 Surface roughness

Surface roughness	*Ra* / µm
Hybrid vehicle configuration (FDM)	16
Metal vehicle configuration	0,430
AGARD hybrid model (3DP)	8
AGARD metal model	0,410

Table 4 Material properties of ABS-M30

Mechanical properties	Units	ABS-M30
Tensile strength	MPa	36
Tensile modulus	MPa	2,413
Tensile elongation	%	4
Flexural stress	MPa	61
Flexural modulus	MPa	2,317
Flexural elongation	%	52
Hardness Rockwell, HRC	-	109,5

Table 5 Material properties of zp150

Mechanical Properties	Units	zp150
Tensile strength	MPa	62
Tensile elongation	%	0,2
Flexural strength	MPa	44
Flexural modulus	MPa	10,680
Compression strength	MPa	98
Shore hardness, HV	-	87 D

Table 6 Material properties of steel (AISI 1045H)

Mechanical properties	Units	AISI 1045H
Tensile strength, ultimate	MPa	565
Tensile strength, yield	MPa	310
Elongation at break	%	16
Modulus of elasticity	GPa	200
Bulk modulus	GPa	140
Shear modulus	GPa	80
Hardness Brinell, HB	-	163

9 Costs and time

The cost and time requirements for the various hybrid models and the metal model are shown in Tab. 7. The hybrid model for this test cost about 350 $ and took between 3 days to 1 week to construct, while the metal model cost about 1050 $ and took one month to design and fabricate. It should be noted that the latest quote for the conversion of an RM model to wind tunnel model is 500 ÷ 100 $ for the balance adapter.

Table 7 Wind tunnel model time and cost summary

Models	Cost / $	Time
Metal vehicle configuration	1300	5 weeks
AGARD metal model	800	3 weeks
Hybrid vehicle configuration	500	1 weeks
AGARD hybrid model	200	3 days

10 Conclusion

This research investigates wind tunnel test results obtained from the AGARD model and the nose-body-tail model constructed by rapid manufacturing methods. Rapid manufacturing methods being implemented were the FDM and the 3DP. The AGARD model was fabricated by the 3DP method and the nose-body-tail model was fabricated by the FDM method. Analysis of results shows good conformity between the metal model and RM models. The maximum deviation observed is due to axial force coefficient and drag force coefficient. Enlarging the angle of attack, causes the applied moment loaded upon the models to increase and this in turn increases data deviation. The minor deviation present is due to the strength, the stiffness, surface roughness, and dimensional tolerance of the models. It can be concluded from this study that wind tunnel models constructed using rapid manufacturing methods can be used in subsonic and transonic wind tunnel testing for aerodynamic database development. The use of RM models will provide a rapid capability in the determination of the aerodynamic characteristics of preliminary designs over a large Mach range. Cost savings and model design/fabrication time reductions of over a factor of 4 have been realized for RM techniques as compared to current standard model design/fabrication practices. By using metal inserts inside the model, also, choosing the least layer thickness, and constructing the model horizontally, the least data deviation can be achieved.

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Symbols and abbreviations

AOA – angle-of-attack
C_A – axial force coefficient
C_N – normal force coefficient
C_M – pitching moment coefficient
C_X – drag force coefficient
C_Z – lift force coefficient
L/D – lift over drag ratio
RM – rapid manufacturing
RP – rapid prototyping.

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