The Effect of Layer Thickness on Aerodynamic Characteristics of Wind Tunnel RP Models*

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Abstract
Nowadays, rapid prototyping (RP) methods are widely used to produce wind tunnel testing models. Layer thickness is an important parameter that affects aerodynamic characteristics of wind tunnel models. This paper describes the effects of Layer thickness, using rapid prototyping, on aerodynamic coefficients to construct wind tunnel testing models. Three models were evaluated. These models were fabricated from ABSi by fused deposition method (FDM). The layer thickness was 0.178mm, 0.254mm and 0.33mm. The surface roughness for each model was 25µm, 63µm and 160µm (Rz) determined by PERTHOMETER2. A wing-body-tail configuration was chosen for the actual study. Testing covered the Mach no. range of Mach 0.3 to Mach 1.2 at an angle-of-attack range of -4° to +16° at zero sideslip. Coefficients of normal force, axial force, pitching moment, and lift over drag are shown at each of these mach numbers. Results from this study show that layer thickness does have effect on the aerodynamic characteristics; in general the difference between the data extracted from three models is less than 6 percent. The layer thickness does have more effect on the aerodynamic characteristics when mach number is decreased and has the most effect on the aerodynamic characteristics of axial force and its derivative coefficients.

Key words: Rapid Prototyping, Wind Tunnel Testing, Aerodynamic Characteristics, Surface Roughness, Fused Deposition Method, Layer Thickness

1. Introduction

Traditional wind tunnel models are meticulously machined from metal in a process that can take several months. Where design feasibility studies are concerned, manufacturing the product, though being precise, is very time consuming and takes a long time (1). We were looking for a way to generate experimental data quickly to verify computational fluid dynamics results. The CFD researchers generate solutions in a matter of days or even hours, and they wanted to verify their solutions with experimental data from the wind tunnels (2). Rapid prototyping technology makes this concurrent study of air vehicle concepts via computer simulation and in the wind tunnel possible. It produces a model in days or hours, depending upon model complexity. RP is cost-effective and affordable because it produces models in less time (3). Engineers created these models using stereolithography (SLA), laser sintering (SLS) and fused deposition method (FDM) (4). Stereolithography uses a laser beam to trace a form on the surface of a container of liquid photopolymer. The process then builds plastic parts layer by layer. Laser sintering, used in the strike tanker model, uses a
high-powered laser to fuse together small particles of plastic, metal or ceramic powders into a three-dimensional form. The fused deposition method (FDM) involves the layering of molten beaded ABS plastic material via a movable nozzle in thin layers (5). The layer thickness is an important parameter in model fabrication because in rapid prototyping methods each model is produced by many thin layers. In this study the effect of thickness layers and thereby effect of surface roughness on aerodynamic characteristic RP model is evaluated. Often product quality is associated with surface roughness and a smooth surface is usually expensive to make. Each process can be expected to produce roughness values within a given range. A study has been undertaken to determine the suitability of models constructed using fused deposition method (FDM) with various layer thickness for use in subsonic, transonic wind tunnel testing. Surface roughness is an important parameter in wind tunnel testing models fabrication (6). In this study, the effect of layer thickness on the aerodynamic characteristics is determined and the required surface roughness for wind tunnel testing models is evaluated. Three models are constructed using three layer thickness and the aerodynamic characteristics are determined and compared to each other. A wing-body-tail configuration was chosen for the actual study. Three ABSi models are prepared and produced at various conditions for testing wind tunnel and determining the aerodynamics coefficients. The surface roughness for each model was 25 µm, 63µm and 160µm that determined by PERTHOMETER2 with 0.8 mm wavelength. Testing was done over the Mach no. range of 0.3 to 1.2. All models were tested at angle-of-attack ranges from -4 degrees to +16 degrees at zero sideslip. Coefficients of normal force, axial force, pitching moment, and lift over drag are shown at each of these mach numbers.

Nomenclature

RP: Rapid Prototyping           CFD: Computational Fluid Dynamics
FDM: Fused Deposition Method   C_{\text{CM}}: Pitching Moment Coefficient
ABSi: Acrylonitrile Butadiene Styrene   L/D: lift over drag ratio
\alpha: Angle-of-Attack            D_{\text{ref}}: Reference Diameter
C_A: Axial Force Coefficient    L_{\text{ref}}: Reference Length
C_N: Normal Force Coefficient

2. Fabrication of Wind Tunnel Model

In this study wind tunnel model was constructed using fused deposition method (FDM). FDM involves the extrusion of thermoplastic just above its melting point using a computer controlled deposition head. The FDM process constructs three dimensional objects directly from 3D CAD data (7). The key components of the FDM system are shown in Fig. 1. A temperature controlled extrusion head is fed with a spool of thermoplastic modeling material that is heated to a semi liquid state. The head extrudes and directs the material with precision in thin layers onto a fixtureless base. The result of the solidified material laminating to the preceding layer is a plastic 3D model built up one strand at a time. Once the part is completed the support columns are removed and the surface is finished. The materials for all FDM machines are ABS, ABSi, Polycarbonate, Polycarbonate-ABS blend and Polyphenylsulfone filament. The wing-body-tail configuration was constructed using the fused deposition method using Acrylonitrile Butadiene Styrene (ABSi). ABSi is a durable engineering grade plastic with higher impact strength than normal ABS. This material is also differentiated from normal ABS in that it comes in a variety of translucent colors. ABSi comes in translucent red, amber, and white. It is also available as a colorless plastic (8). Fig. 2 show the model tested FDM .The material properties of ABSi is shown in Table 1(9).
3. Geometry

A wing-body-tail configuration was chosen for the actual study. First, this configuration would indicate possible deflections in the wings or tail due to loads and whether the manufacturing accuracy of the airfoil sections would adversely affect the aerodynamic data obtained through tests. Secondly, it would be made clear, whether the model would be able to withstand the starting, stopping and operating loads in a blow down wind tunnel. Three models were fabrication. The layer thickness was 0.178mm, 0.254mm and 0.33mm. The surface roughness for each model was 25 µm, 63µm and 160µm determined by PERTHOMETER2. The reference dimensions for this configuration are as follows.

\[ D_{ref} = 80 \text{ [mm]} \quad L_{ref} = 200 \text{ [mm]} \quad X_{MPH} = 150 \text{ [mm after of nose]} \]

4. Wind Tunnel

Transonic Wind Tunnel is an intermittent blow down tunnel, which operates by high-pressure air flowing from storage to either vacuum or atmosphere conditions. The transonic test section provides a Mach number range from 0.2 to 2.0. Mach numbers between 0.2 and 0.9 are obtained by using a controllable diffuser. The Mach no. range from 0.95 to 1.2 is achieved through the use of plenum suction and perforated walls. Each Mach number above 1.2 requires a specific set of two-dimensional contoured nozzle blocks. The tunnel flow is established and controlled with a servo-actuated gate valve. The air then passes through the test section which contains the nozzle blocks and test region. Downstream of the test section is a hydraulically controlled pitch sector that provides the capability of testing angles-of-attack ranging from –10 to +10 degrees during each run.
diffuser section has movable floor and ceiling panels, which are the primary means of controlling. As shown, table 2 shown lists the relation between Mach number, dynamic pressure, and Reynolds number per meter. The means of collecting pressure data, as well as the data collected, varies widely from test to test. 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. Also, a boundary layer mouse can be employed to determine the boundary layer characteristics. Test section dimensions are 1.1 m wide by 0.8 m high by 1.2 m. long Force and moment data refers to the three forces (lift, drag, and side force) and three moments (roll, pitch, and yaw moment) that the wind applies to the test subject. Force and Moment data is usually measured by the external balance or by an internal balance. Force and moment data is the most commonly collected data type at the Wind Tunnel.

### Table 2. Wind Tunnel Operating Conditions

<table>
<thead>
<tr>
<th>Mach number</th>
<th>Dynamic pressure</th>
<th>Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>8.96 kPa</td>
<td>9.18×10⁴</td>
</tr>
<tr>
<td>0.8</td>
<td>44.58</td>
<td>18.03</td>
</tr>
<tr>
<td>1.15</td>
<td>61.94</td>
<td>20.32</td>
</tr>
<tr>
<td>1.2</td>
<td>64.14</td>
<td>20.32</td>
</tr>
</tbody>
</table>

5. Aerodynamic characteristics

The aerodynamic loads are presented in a non dimensional form. In the case of the force coefficients where F is either lift, drag, or slide force the corresponding coefficient will have the form

\[
C_F = \frac{F}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref}}
\]

Where \(S_{ref}\) is a reference area (wing plan form area for wings), \(\rho\) is the density of the free stream and \(Q_\infty\) is the speed of the free stream. Thus:

\[
C_A = \frac{Axial \ force}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref}}
\]

\[
C_N = \frac{Normal \ force}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref}}
\]

\[
C_Y = \frac{Side \ force}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref}}
\]

Here, \(C_A\), \(C_N\) and \(C_Y\) are axial force coefficient, normal force coefficient and side force coefficient, respectively. Similarly the non dimensional moment coefficient becomes:

\[
C_M = \frac{M}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref} b}
\]

Here, again M can be a moment about any arbitrary axis and \(b\) is a reference moment arm (e.g., wing span). Thus:

\[
C_M = \frac{Pitching \ moment}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref} c}
\]

\[
C_{YN} = \frac{Yawing \ moment}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref} b}
\]

\[
C_{\beta_0} = \frac{Rolling \ moment}{\frac{1}{2} \rho \overline{Q}_\infty^2 S_{ref} b}
\]

Here, \(C_M\), \(C_{YN}\) and \(C_{\beta_0}\) are pitching moment coefficient, yawing moment coefficient and rolling moment coefficient, respectively.
6. Comparison between RP Model and Steel Model

Nowadays, there are various RP methods but the most applicable and prevalent methods for developing wind tunnel testing models are FDM, SLA and SLS (12). In this study, rapid prototyping model constructed of FDM technologies using ABSi (Acrylonitrile Butadiene Styrene) was compared to that of a standard machined steel model. AISI 1045H (CK45) was chosen as the material for the machined metal model. The material property of steel model is shown in Table 3 (8). The aerodynamic characteristics of a conventional machined model, and RP model were evaluated. Testing covered the Mach no. range of Mach 0.3 to Mach 1.2 at an angle-of-attack range of + 4° to +26°. The study revealed that between Mach numbers of 0.3 to 1.2 the longitudinal aerodynamic data or data in the pitch plane showed approximately a 1.3-degree shift in the data between the FDM and metal model for the normal force (Figs. 3 and 6) and approximately a 0.8-degree data shift for the pitching moment (Figs. 4 and 7). The total axial force was slightly lower for the FDM model than the metal model (Figs. 5 and 8). Part of the noted offset is due to the approximation for a weight tare correction. In general, it can be said that the longitudinal aerodynamic data for each model is within 3 percent.

Table 3. Material Properties of AISI 1045H

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Units</th>
<th>AISI 1045H (CK45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>Mpa</td>
<td>310</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Mpa</td>
<td>565</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>Percent</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 3 Comparison of normal force coefficient at Mach 0.3

Fig. 4 Comparison of pitching moment coefficient at Mach 0.3

Fig. 5 Comparison of total axial force coefficient at Mach 0.3

Fig. 6 Comparison of normal force coefficient at Mach 0.9
7. Investigation of Layer Thickness

The effects of layer thickness and surface roughness on the aerodynamic characteristics of the models were determined. A wind tunnel test over a range of Mach numbers from 0.3 to 1.2 was undertaken to determine the aerodynamic characteristics of the three models. The surface roughness for each model was 25 µm, 63 µm and 160 µm and layer thickness for each model was 0.178 mm, 0.254 mm and 0.33 mm. A wing-body-tail launch vehicle configuration was chosen to test RP processes ability to produce accurate airfoil sections, and to determine the material property effects related to the bending of the wing and tail under loading (13). The model construction was analyzed to determine the applicability of the layer thickness and surface roughness to the design of wind tunnel models. Testing was done over the Mach no. range of 0.3 to 1.2 at 6 selected numbers. These Mach numbers were 0.30, 0.80, 0.90, 1.05, 1.15 and 1.20. All models were tested at angle-of-attack ranges from –4 degrees to +16 degrees. The reference aerodynamic axis system and reference parameters for the baseline study are shown in fig. 9.

8. Results

The effects of layer thickness and surface roughness on the aerodynamic characteristics of the models were determined. The FDM models did not have as smooth a finish as did the metal models, so runs were made to determine if the difference in this surface roughness would affect the aerodynamic characteristics. A surface roughness was simulated on the models by various layer thicknesses. The study revealed that between Mach numbers of 0.3 to 1.2, the longitudinal aerodynamic data or data in the pitch plane showed approximately a 2-degree shift in the data between the model with surface finish 25 µm and other models for the pitching moment (figs. 10 and 14), and Between Mach numbers of 0.3 to 1.2 all the models showed good agreement in normal force (figs. 11 and 15). The greatest difference in the aerodynamic data between the models at Mach numbers of 0.3 to 1.2 was in total axial force (figs. 12 and 16). Between three models 25 µm, 63 µm and 160 µm only a small shift...
in the data was noticed, at lift over drag (figs. 13 and 17). In general, it can be said that longitudinal aerodynamic data at subsonic Mach numbers showed a slight divergence at higher angles-of-attack. At transonic Mach numbers the majority of the configurations started diverging at about 10 to 12 degrees angle-of-attack due to the higher loads encountered by the models.
9. Costs and Time

The FDM model with 25 µm surface roughness cost about $800 and took 14 days to design and fabricate, the model with 63 µm 10 days, and the model with 160 µm surface roughness, cost about $650 and took 8 days. The cost and time requirements for the FDM models are shown in table 4.

<table>
<thead>
<tr>
<th>Model with surface roughness</th>
<th>Cost</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 µm</td>
<td>$800</td>
<td>14 days</td>
</tr>
<tr>
<td>63 µm</td>
<td>$700</td>
<td>10 days</td>
</tr>
<tr>
<td>160 µm</td>
<td>$650</td>
<td>8 days</td>
</tr>
</tbody>
</table>

10. Accuracy

The data accuracy results from this test are from dimensions of each model. The dimensions of models must be compared with CAD model. 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. A comparison of model dimensions is shown in table 5. 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 standard model tolerance is 0.14 mm.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Wing L1</th>
<th>Wing L2</th>
<th>Wing R1</th>
<th>Wing R2</th>
<th>Body 1</th>
<th>Body 2</th>
<th>Tail 1</th>
<th>Tail 2</th>
<th>XY plane</th>
<th>XZ plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface finish</td>
<td>0.214</td>
<td>0.120</td>
<td>0.115</td>
<td>0.110</td>
<td>0.130</td>
<td>0.028</td>
<td>0.012</td>
<td>0.041</td>
<td>0.015</td>
<td>0.041</td>
</tr>
<tr>
<td>Surface finish</td>
<td>0.256</td>
<td>0.169</td>
<td>0.146</td>
<td>0.157</td>
<td>0.167</td>
<td>0.048</td>
<td>0.038</td>
<td>0.050</td>
<td>0.060</td>
<td>0.076</td>
</tr>
<tr>
<td>Surface finish</td>
<td>0.261</td>
<td>0.175</td>
<td>0.150</td>
<td>0.159</td>
<td>0.168</td>
<td>0.061</td>
<td>0.092</td>
<td>0.063</td>
<td>0.063</td>
<td>0.092</td>
</tr>
<tr>
<td>Dimensions of CAD model</td>
<td>65</td>
<td>-</td>
<td>65</td>
<td>-</td>
<td>80</td>
<td>-</td>
<td>60</td>
<td>-</td>
<td>190</td>
<td>130</td>
</tr>
</tbody>
</table>

11. Conclusions

It can be concluded from this precursor test that layer thickness does have an effect on the Aerodynamic characteristics in high Mach number speeds where the effect is less drastic than at lower Mach numbers. The layer thickness had little effect on the aerodynamic characteristics except for axial force and lift over drag and its derivative coefficients. In general, it can be said that the longitudinal aerodynamic data for each model is within 5 percent. The wind tunnel models are constructed with any layer thickness using subsonic, transonic wind tunnel testing for initial baseline aerodynamic database development. At transonic Mach number the majority of the configurations started diverging at about 10 to 12 degrees angle-of-attack due to the higher loads encountered by the models. The accuracy of the data is lower for models that have less surface roughness but is quite accurate for this level of testing. The aerodynamic data obtained from the three models, with a difference
range, less than three percent is acceptable for this level of preliminary design or phase studies. The models used with low surface roughness will provide a rapid capability in the determination of the aerodynamic characteristics of preliminary designs over a large Mach no. range. This range covers the transonic regime, a regime in which analytical and empirical capabilities sometimes fall short. The cost and time for models constructed with low surface roughness is less than those with high surface roughness accordingly, however models with less surface roughness are suitable for preliminary design or phase studies.

References

(8) http://www.matweb.com