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Evaluating Aerodynamic Characteristics of Wind-Tunnel Models Produced by Rapid Prototyping Methods

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Initial studies of the aerodynamic characteristics of proposed launch vehicles can be made more accurately if lower-cost, high-fidelity aerodynamic models are available for wind-tunnel testing early in the development phase. The results of a study undertaken at NASA Marshall Space Flight Center are discussed to determine whether four rapid prototyping methods using a variety of materials are suitable for the design and manufacture of high-speed wind-tunnel models in direct testing applications. Also presented is an analysis of whether these materials and processes are of sufficient strength and fidelity to withstand the testing environment. In addition to test data, costs and turnaround times for the various models are given. On the basis of this study's results, one can conclude that rapid prototyping models show promise in limited, direct application for preliminary aerodynamic development studies at subsonic, transonic, and supersonic speeds.

Nomenclature

C_A = axial force coefficient
C_M = pitching moment coefficient
C_N = normal force coefficient
C_Y = side force coefficient
C_{YN} = yawing moment coefficient
CLB = rolling moment coefficient
L_{ref} = reference length
L/D = lift over drag
S_{ref} = reference area
X_{MRP} = moment reference point
α = angle of attack
β = angle of sideslip

Introduction

A STUDY funded through a NASA Marshall Space Flight Center (MSFC) Center Director's Discretionary Fund project was undertaken to determine the feasibility of using models constructed from rapid prototyping (RP) materials and methods for preliminary aerodynamic assessment of future launch vehicle configurations. Five pertinent questions were investigated.

1) Can RP methods be used to produce a detailed scale model within required dimensional tolerances?

2) Do current RP materials have the mechanical characteristics to retain shape during required wind-tunnel testing (subsonic, transonic, and supersonic speeds)?

3) Which RP process, or processes, and materials produce the best results?

4) What steps and methods are required to convert an RP model to a wind-tunnel model, i.e., fitting a balance adapter into an RP model and attaching the model parts together?

5) What are the costs and time requirements for the various RP methods as compared with those of a standard machined-metal model?

This study was planned to answer these questions by comparing RP models constructed using four methods and six materials with a standard machined-metal model. The RP processes used were the fused deposition method (FDM) with materials of both acrylonitrile butadine styrene (ABS) plastic and poly ether ether ketone (PEEK); stereolithography (SLA) with a photopolymer resin of STL-5170 as the material; selective laser sintering (SLS) with glass-reinforced nylon as the material; and laminated object manufacturing (LOM) using plastic reinforced with glass fibers and "paper" as materials. Aluminum (Al) was chosen as the material for the machined-metal model. An aluminum model, although not as desirable as a steel model, is a more conservative baseline model because it costs less and requires less time to construct.

It can be stated initially that machined-metal models cannot now be replaced by RP models for all required aspects of wind-tunnel testing. This study focused on a small aspect of wind-tunnel testing: that of determining the static-stability aerodynamic characteristics of a vehicle with respect to preliminary vehicle configuration design.

Although some RP methods and processes have reached a mature level of development—such as SLA, LOM using paper, and FDM using ABS plastic—others are still in the development phase, or new materials that promise greater material properties or higher-fidelity part definition are being tried. For this test, some of the materials and processes still in the development phase were evaluated. Some of these models did not meet visual quality standards and were not converted into wind-tunnel models. Two of these methods and materials were FDM using PEEK, and LOM using a plastic reinforced with glass fibers. The FDM is now a standard RP technique, but using PEEK as a material is still in the early testing phases. Although PEEK provides models with much greater strength, the surface finish and tolerances on the models are presently unacceptable. The LOM is a new approach in which paper is normally used to construct a model, but this paper has low material properties, i.e., it is likely to break under the expected testing loads. A new LOM material, plastic, which was higher material properties, is being tested. At present, this material shrinks 3% during curing. From the model received, this 3% was not consistent over the model because it was warped and pitted. Given these defects, this model was not converted to a wind-tunnel test article. The LOM paper model was converted into a wind-tunnel model, but the material delaminated during the process owing to the loads experienced by the model during the machining of the bore hole and the installation of the balance adapter. The other three RP methods (SLA, SLS, and FDM–ABS) were wind-tunnel tested.

Geometry

A wing–body–tail configuration launch vehicle model was chosen for the actual study. First, this configuration was expected to indicate whether possible deflections of the wings or tail caused by loading occurred or whether the manufacturing accuracy of the airfoil sections would adversely affect the aerodynamic test data. Second, this configuration was expected to help answer the question of whether the model would be able to withstand the starting, stopping, and operating loads in a blowdown wind tunnel. Figure 1 is a photograph of the SLA wing–body model mounted in the transonic test section of the NASA MSFC 14-Inch Trisonic Wind Tunnel (TWT).

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Fig. 1 SLA wing–body model mounted in the wind tunnel.

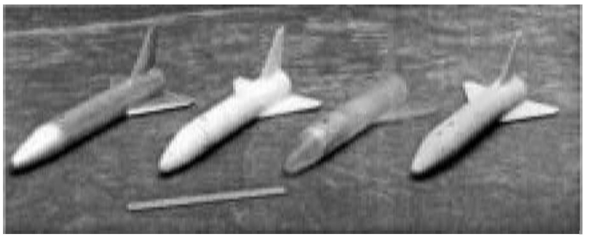

Fig. 2 Models tested (from left): aluminum, FDM–ABS, SLA, and SLS.

The reference dimensions for this configuration are as follows: $S_{\rm ref} = 8.68\,\text{in.}^2$, $L_{\rm ref} = 8.922\,\text{in.}$, and $X_{\rm MRP} = 6.2454\,\text{in.}$ aft of nose.

Model Construction

The RP processes and materials selected for the baseline study were 1) FDM–ABS using ABS plastic and FDM–PEEK using carbon-fiber-reinforced PEEK, 2) SLA using SLA-5170, 3) SLS using glass-reinforced nylon, and 4) LOM using glass-reinforced plastic and wood. The RP models were constructed using these materials and processes and are shown in Fig. 2.

The FDM process involves the layering of the molten beaded ABS plastic material via a movable nozzle in 0.01-in.-thick layers. The ABS material is supplied in rolls of thin ABS line resembling weed trimmer line. The material is heated and extruded through a nozzle similar to that of a hot glue gun and is deposited in rows and layered to form the part from numerically controlled data. The PEEK material is currently being studied for the FDM process.

Stereolithography uses a vat of photopolymer epoxy resin. Illumination of the vat by an ultraviolet laser solidifies the resin. The laser solidifies each layer; then the tray is lowered and the next layer is solidified. This continues until the part is complete.

Selective laser sintering uses a laser to fuse, or sinter, powdered glass and nylon particles or granules in layers, which are fused on top of each other, as with the other processes.

The LOM presently uses rolls of paper that are rolled onto the machines, where a laser cuts the pattern out of the sheet for that layer. The next sheet is rolled on top of the previous one and also is cut. The sheets have epoxy on one side, which, when heated, fuses them. This is done by a hot roller after each sheet is cut, and the model is built up in this way. Currently, plastic is being tested as a material to replace the paper or wood because of its better material properties. The material properties for SLA, FDM–ABS, and SLS are shown in Table 1, and aluminum properties are shown in Table 2. More detailed analyses of the processes are available.[1]

Each of the RP models was constructed as a single part. The nose section was separated from the core, and a 0.75-in. hole was drilled and reamed through the center of the body for placement of the aluminum balance adapter, which was then epoxied and pinned into place. The nose was fastened to the core body via two screws that were attached through the nose to the balance adapter. An FDM model as built directly from the machine still on the stand, a finished model with its nose removed, and an aluminum balance as used in the models are shown in Fig. 3.

Table 1 Material properties of SLA, FDM–ABS, and SLS

Property	Unit	SLA SL-5170	SLS Protoform	FDM–ABS
Tensile strength	psi	8,700	7,100	5,000
Tensile modulus	ksi	575	408	360
Elongation at break	%	12	6	50
Flexural strength	psi	15,600	——	9,500
Flexural modulus	ksi	429	625	380
Impact strength	ft-lb/in.	0.6	1.25	2
Hardness	(Shore D)	85	——	105

Table 2 Material properties of aluminum

Property	2024-T4	5086-H32
Yield strength, ksi	40	28
Tensile strength, ksi	62	40

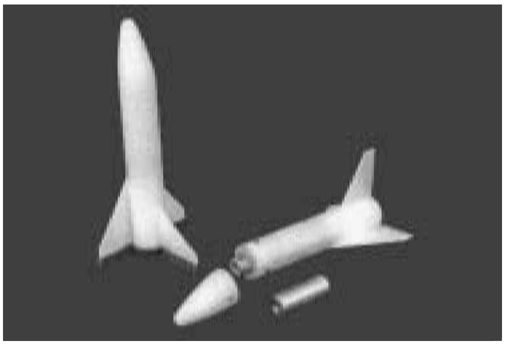

Fig. 3 FDM models (from left): as built from the machine (still on the stand), finished (with nose removed), and an aluminum balance adapter.

Facility

The MSFC 14 × 14 in. TWT is an intermittent blowdown tunnel that operates by high-pressure air flowing from storage to either vacuum or atmospheric 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 range from 0.95 to 1.3 is achieved using the plenum suction and perforated walls. Each Mach number above 1.30 requires a specific set of two-dimensional contoured nozzle blocks. A solid-wall supersonic test section provides the entire range from 2.74 to 5.0 with one set of movable fixed-contour nozzle blocks.

Downstream of the test section is a hydraulically controlled pitch sector that makes it possible to test up to 20 angles of attack from −10 to +10 deg during each run. Sting offsets are available from obtaining various maximum angles of attack up to 90 deg.

The MSFC 14-Inch TWT, because it is an intermittent blowdown-type tunnel, experiences large starting and stopping loads. These loads, along with the high dynamic pressures encountered through the Mach range, require models that can withstand these forces. It is generally assumed that the starting and stopping loads are 1.5 times the operating loads and are within the safety factor of 4 required for wind-tunnel models. The most severe starting loads occur at Mach 2.74, whereas the highest dynamic pressure of 11 psi is encountered at Mach 1.96. Table 3 lists the relations between Mach number, Reynolds number per foot, and dynamic pressure for the 14-Inch TWT.

Test

A wind-tunnel test over a range of Mach numbers from 0.3 to 5.0 was conducted in which each of the four models was tested to determine its aerodynamic characteristics. Three of the four models were constructed using RP methods, and the fourth, a standard machined aluminum metal model, acted as a control. A wing–body–tail launch vehicle configuration was chosen as the test configuration to test the 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. The methods of model construction

Table 3 Wind-tunnel operating conditions

Mach number	Reynolds number, $\times 10^6$/ft	Dynamic pressure, lb/in.^{2}
0.20	1.98	0.60
0.30	2.8	1.30
0.60	4.7	4.36
0.80	5.5	6.47
0.90	5.9	7.36
0.95	6.2	7.76
1.05	6.1	8.48
1.10	6.2	8.76
1.15	6.2	8.99
1.25	6.2	9.31
1.46	6.0	9.49
1.96	7.2	11.00
2.74	4.7	6.38
3.48	4.8	5.15
4.96	4.4	2.73

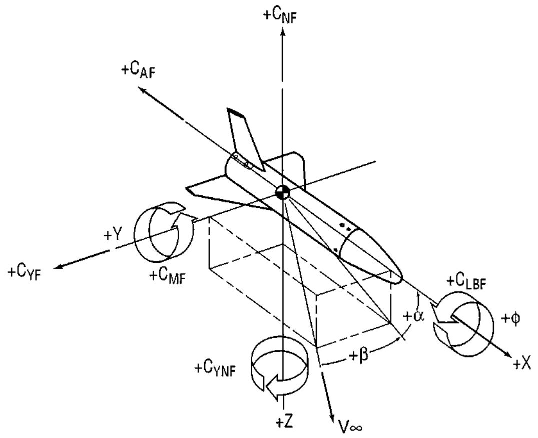

Fig. 4 Reference aerodynamic axis system.

were analyzed to determine the applicability of the RP processes to the design of wind-tunnel models, and the various RP methods were compared to determine which, if any, of these processes would be best suited to produce a wind-tunnel model.

Testing was done over the Mach range of 0.3 to 5.0 at 13 selected Mach numbers. These Mach numbers were 0.3, 0.60, 0.80, 0.90, 0.95, 1.05, 1.10, 1.15, 1.20, 1.46, 2.74, 3.48, and 4.96. All models were tested at angle-of-attack ranges from −4 to +16 deg at zero sideslip and at angle-of-sideslip ranges from −8 to +8 deg at 6-deg angle of attack. The reference aerodynamic axis system is shown in Fig. 4.

Results

For all phases of the baseline study, representative Mach numbers of 0.3, 1.05, and 3.48 are presented in this report. Coefficients of pitching moment and L/D are shown at each of these Mach numbers in Figs. 5–10. Only longitudinal data are shown for this study. Additional information on this study and its results is available.[2–4]

Baseline Models

In the study, between Mach numbers of 0.3 to 1.2, the longitudinal aerodynamic data, or data in the pitch plane, showed very good agreement between the metal model and SLA model up to about 12-deg angle of attack, when the data started to diverge because of assumed bending under high loading (see Figs. 5–10). The initial SLS data for all of the coefficients do not show an accurate representation of the process because the model has a different configuration owing to postprocessing problems. The second SLS model tested showed much better agreement with the data trends from the other models but was not as good as the FDM and SLA models. The greatest difference in the aerodynamic data between the models at Mach numbers of 0.3–1.2 was in total axial force; this can be seen in the L/D plots. Between Mach numbers of 2.76 to 4.96, all of the models showed good agreement in axial force. In general, it can be

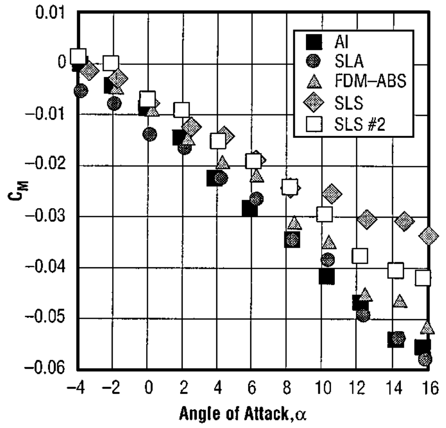

Fig. 5 Pitching moment coefficient, Mach 0.3.

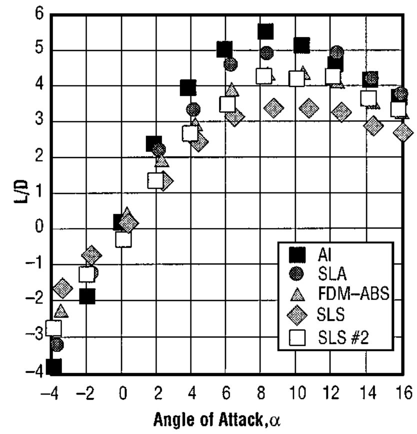

Fig. 6 Lift over drag, Mach 0.3.

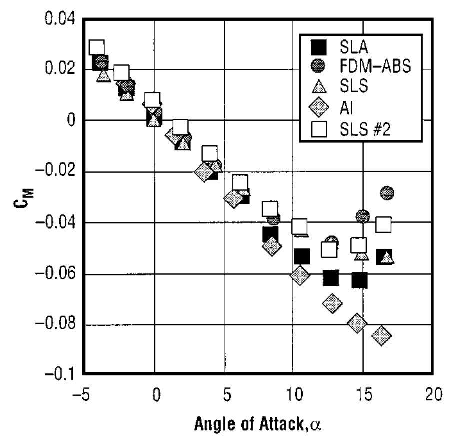

Fig. 7 Pitching moment coefficient, Mach 1.05.

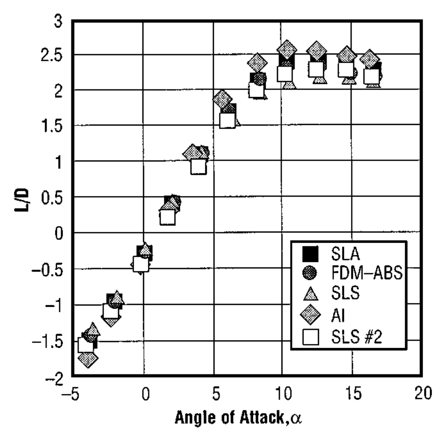

Fig. 8 Lift over drag, Mach 1.05.

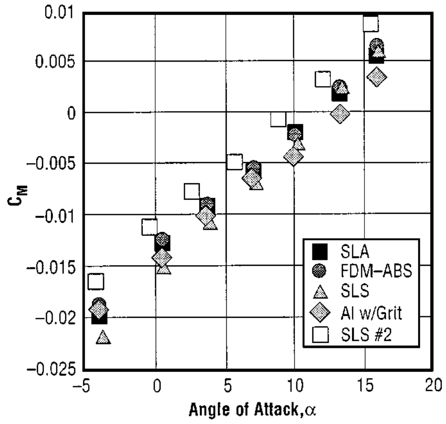

Fig. 9 Pitching moment coefficient, Mach 3.48.

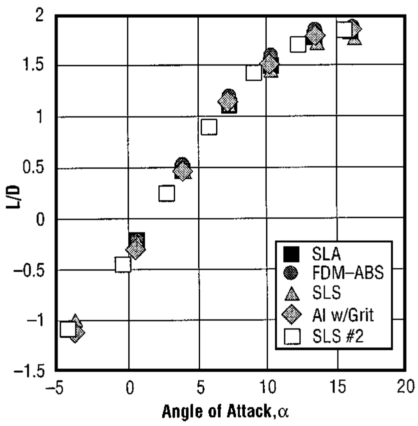

Fig. 10 Lift over drag, Mach 3.48.

said that all longitudinal aerodynamic data at subsonic Mach numbers show slight divergence at higher angle of attacks; at transonic Mach numbers most of the configurations start diverging at about 10- to 12-deg angle of attack owing to the higher loading the models encountered; and at the supersonic Mach numbers, the data show good agreement over the angle-of-attack range tested. These data are shown in Figs. 5–10. The plots of L/D show these effects. In general, the differences in L/D are due to the differences in axial force because normal force showed relatively good agreement.

Replacement Parts

Along with the baseline study, standard machined-metal model parts were replaced with RP parts. In the study, between Mach numbers of 0.3 and 1.2, the longitudinal aerodynamic data showed very good agreement between the metal model and the metal model with the replacement FDM–ABS nose and SLA nose. The supersonic data showed a slight divergence between models, but the trends are consistent. Pitching-moment-coefficient and lift-over-drag data at Mach 1.05 are shown in Figs. 11 and 12.

Cost and Time

The RP models for this test cost between \$3000 and \$3500 and took between 2 and 3 weeks to construct, whereas the metal or aluminum model cost about \$15,000 and took 3.5 months to design and fabricate. Rapid prototyping fabrication costs for each model were between \$1000 and \$1500, conversion to a wind-tunnel model cost about \$2000, and the cost of a balance adapter was \$100. At the time of this study, MSFC had in-house capabilities to produce FDM and SLA models, and these capabilities were utilized. The given costs are from quotes made by various secondary sources that specialize in RP part fabrication. Note that the latest quote for the conversion of an RP model to a wind-tunnel model in two working days was for \$600 (\$100 for the balance adapter and \$500 for parts and labor to convert the model). Along with the standard three days for RP model fabrication, a wind-tunnel model could be

Table 4 Model dimensions off theoretical

Section	Δ Wing–body model dimensions, in.				
	Al[a]	SLA	SLS[b]	FDM	SLS 2
Wing L1	0.003	0.09	0.013	0.002	0.025
Wing L2	0.004	0.01	0.02	0.005	0.015
Wing R1	0.004	0.009	0.01	0.005	0.01
Wing R2	0.003	0.009	0.012	0.010	0.018
Body 1	0.010	0.002	0.002	0.020	0.007
Body 2	0.0005	0.002	0.012	0.006	0.015
Tail 1	0.002	0.002	0.014	0.001	0.009
Tail 2	0.001	0.002	0.014	0.002	0.015
XY plane	0.001	0.015	0.016	0.006	0.014
XZ plane	0.009	0.010	0.017	0.013	0.02

[a]Aluminum. [b]Postprocessing problem with wing and tail.

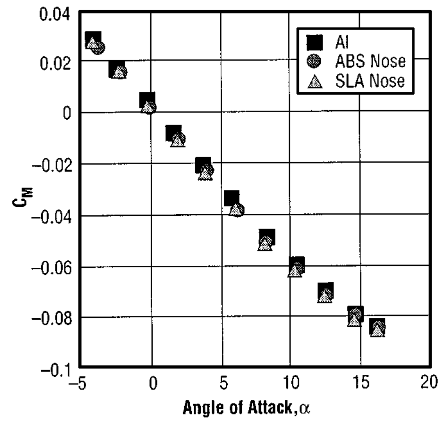

Fig. 11 Pitching moment coefficient for replacement noses, Mach 1.05.

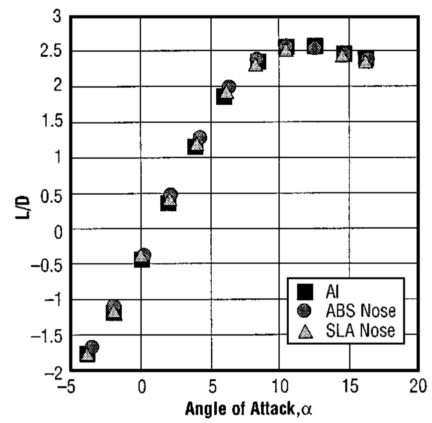

Fig. 12 Lift over drag for replacement nose, Mach 1.05.

constructed in under a week. The total cost for an RP model using in-house sources would be about \$1100 if \$500 is assumed for RP material. Presently MSFC has the in-house capability to construct models using all of the RP processes reported in this paper.

Accuracy

The data accuracy results from this test can be divided into two sources of error: 1) the model and 2) the data acquisition system. Each of these factors will be considered separately.

First, the dimensions of each model must be compared. Difficulty arose in the interface between the nose and core body for the RP models, as well as with the roll of the balance adapter in the models. Also, the contours of the models used in this test were measured at two wing sections, two vehicle stations, two tail sections, and the XY and XZ planes. Model dimensions are compared in Table 4, which shows the maximum discrepancy in model dimensions relative to the baseline computer-assisted design model used to construct all of the models at each station. The standard model tolerance is 0.005 in.

Table 5 Balance adapter roll angle installed in model

Model	Adapter roll angle, deg
Al	0.95
SLA	2.25
SLS	1.05
FDM–ABS	1.57
SLS no. 2	1.20

Table 6 Effect of balance adapter roll on aerodynamic coefficients

Roll angle, deg	C_N	C_Y
0.5	0.9999	0.0087
1.0	0.9998	0.0175
1.5	0.9997	0.0262
2.0	0.9994	0.0349
2.5	0.9990	0.0436
		(Factor of C_N)

Table 7 Balance capacity and accuracy

	Strain gauge balance 250	
Coefficient	Capacity	Accuracy
Normal force	200 lb	±0.20 lb
Side force	107 lb	±0.50 lb
Axial force	75 lb	±0.25 lb
Pitching moment	200 in.-lb	±0.20 in.-lb
Rolling moment	50 in.-lb	±0.25 in.-lb
Yawing moment	107 in.-lb	±0.50 in.-lb

The metal models' balance adapter was rolled approximately 1 deg starboard wing down, whereas the RP models were rolled from 1 to 2.25 deg starboard wing down, which resulted in a difference of about 0 to 1.25 deg between the two models. This resulted in a small error in all of the coefficients because the model was installed level in the tunnel. The installation of roll angles of the balance adapter in the metal and RP models is given in Table 5. The effect of the balance adapters' roll on the normal-force and side-force aerodynamic coefficients is shown in Table 6.

Second, the repeatability of the data can be considered to be within the symbol size on the plots. The capacity and accuracy for the six-component strain gauge balance used during this test are given in Table 7.

Conclusions

Rapid prototyping methods have been shown to be feasible in limited direct application to wind-tunnel testing for producing preliminary aerodynamic databases. Cost savings and model design and fabrication time reductions greater than a factor of 4 have been realized for RP techniques as compared with current standard model design and fabrication practices. This makes wind-tunnel testing more affordable for small programs with low budgets and for educational purposes. At this time, RP methods and materials can be used only for preliminary design studies and limited configurations because of the RP material properties that allow bending of model components under high loading conditions and the tolerance on the fabrication processes.

This study initially indicated that two of the RP methods were not mature enough to produce an adequate model. These methods were FDM using PEEK and LOM using plastic. The paper LOM model did not have sufficiently high material properties to withstand the conversion process to a wind-tunnel model. The other three processes and materials produced satisfactory models that were successfully tested. The initial SLS model did not produce good results because of postprocessing problems, but these were corrected in the second model, which yielded satisfactory results, although not as good as those for FDM or SLA.

The FMS–ABS and SLA methods produced very good results for model replacement parts. The data resulting from the FDM–ABS model diverged at higher loading conditions and produced satisfactory results only for limited test conditions. Note that the FDM–ABS process produced satisfactory results over the full range of test conditions for a vertical-lander configuration tested in a precursor study. The SLA method was shown to be the best RP process, for it had satisfactory results for the majority of test conditions. The differences in the configuration data can be attributed to multiple factors such as surface finish, structural deflection, and tolerances on the fabrication of the models when they are "grown."

One can conclude from this study that wind-tunnel models constructed using RP methods and materials can be used in subsonic, transonic, and supersonic wind-tunnel testing for initial baseline aerodynamic database development. The accuracy of the data is lower than that of a metal model because of surface finish and dimensional tolerances but is quite accurate enough for this level of testing. The difference in the aerodynamic data between the metal and RP models' aerodynamics is acceptable for this level of preliminary design or phase A/B studies. The use of RP models will provide a rapid capability to determine designs over a large Mach range. This range covers the transonic regime, where analytical and empirical capabilities sometimes fall short.

At this time, replacing machined-metal models with RP models for detailed parametric aerodynamic and control surface effectiveness studies is not considered practical because of the high configuration fidelity required and the loads that deflected control surfaces must withstand. The current plastic materials of RP models may not provide the structural integrity necessary for survival of thin section parts such as tip fins and control surfaces. Consequently, although this test validated that RP models can be used for obtaining preliminary aerodynamic databases, further investigations will be required to prove that RP models are adequate for detailed parametric aerodynamic studies that require deflected control surfaces and delicate or fragile fins.

Acknowledgments

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