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Investigation of Layer Thickness and Surface Roughness on Aerodynamic Coefficients of Wind Tunnel RP Models

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***Abstract*—**Traditional wind tunnel models are meticulously machined from metal in a process that can take several months. While very precise, the manufacturing process is too slow to assess a new design's feasibility quickly. Rapid prototyping technology makes this concurrent study of air vehicle concepts via computer simulation and in the wind tunnel possible. This paper described the Affects layer thickness models product with rapid prototyping on Aerodynamic Coefficients for Constructed wind tunnel testing models. Three models were evaluated. The first model was a 0.05mm layer thickness and Horizontal plane 0.1µm (Ra) second model was a 0.125mm layer thickness and Horizontal plane 0.22µm (Ra) third model was a 0.15mm layer thickness and Horizontal plane 4.6µm (Ra). These models were fabricated from somos 18420 by a stereolithography (SLA). A wing-body-tail configuration was chosen for the actual study. Testing covered the Mach range of Mach 0.3 to Mach 0.9 at an angle-of-attack range of -2° to +12° 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 an effect on the aerodynamic characteristics in general; the data differ between the three models by fewer than 5%. The layer thickness does have more effect on the aerodynamic characteristics when Mach number is decreased and had most effect on the aerodynamic characteristics of axial force and its derivative coefficients.

***Keywords*—**Aerodynamic characteristics, stereolithography, layer thickness, Rapid prototyping, surface finish.

I. INTRODUCTION

RAPID Prototyping (RP) can be defined as a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data. Rapid prototyping has also been referred to as solid free-form manufacturing; computer automated manufacturing, and layered manufacturing [1].RP has obvious use as a vehicle for visualization. RP models can be used for testing, such as when an airfoil shape is put into a wind tunnel [2]. RP models can be used to create male models for tooling, such as silicone rubber molds and investment casts. In some cases, the RP part can be the final part, but typically the RP material is not strong or accurate enough [3]. When the RP material is suitable, highly convoluted shapes (including parts nested within parts) can be produced because of the nature of RP. There is a multitude of experimental RP methodologies either in development or used by small groups of individuals. This section will focus on RP techniques that are currently commercially available, including Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), and Ink Jet printing techniques[4]. 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 (computational fluid dynamics) 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 model is allowing the Air Force to conduct a series of tests, based on the design, 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 [5]. It's also allowing them to investigate experimental measurement techniques for inexpensively and accurately measuring pressure and flow velocities over an entire model during testing. The layer thickness is an important parameter in model fabrication because in rapid prototyping method each model is produced by many thin layers [6]. Often product quality is associated with smooth surface is usually expensive to make. Each process can be expected to produce roughness values within a given range. In this spirit, a study has been undertaken to determine the suitability of models constructed using stereolithography (SLA) with various layer thickness for use in subsonic, transonic, wind tunnel testing. Surface finish is an important parameter in wind tunnel testing models fabrication [7].In this study, the effects of layer thickness on the aerodynamic characteristics are determined and required surface finish for wind tunnel testing models is evaluated. Three models constructed using three layer thickness and the aerodynamic characteristics are determined and compared to each other. The first model produced an aerodynamically smooth surface finish. The Second and third model produced a

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surface finishes with a noticeable distributed roughness as well as low chord wise ridges due resining over cure in at the build layer interfaces. Wind tunnel tests were performed to assess the effects of surface finish on aerodynamic performance. A wing-body-tail configuration was chosen for the actual study. Three models are prepared and produced at various conditions for testing in wind tunnel and determining the aerodynamics coefficients. The horizontal plane roughness for each model was 0.1µm Ra, 0.22µm Ra and 4.6µm Ra that determined by perthometer2 with 0.8 mm wavelength. Wind Tunnel is an intermittent blow down tunnel, which operates by High-pressure air flowing from storage to either vacuum or atmosphere Conditions. Testing was done over the Mach range of 0.3 to 0.9. All models were tested at angle-of-attack ranges from -2 degrees to +12 degrees at zero sideslip. Coefficients of normal force, axial force, pitching moment, and lift over drag are shown at each of these Mach numbers.

II. Nomenclature

RP: rapid prototyping
SLA: Stereolithography
α: angle-of-attack
C_A: axial force coefficient
C_N: normal force coefficient
C_M: pitching moment coefficient
L_{ref}: reference length
D_{ref}: reference diameter
L/D: lift over drag ratio
X_{MRP}: moment reference point

III. Wind Tunnel Model

Wind tunnel models were constructed using Stereolithography (SLA). SLA is the most widely used rapid prototyping technology. SLA builds plastic parts or objects a layer at a time by tracing a laser beam on the surface of a vat of liquid photopolymer [8]. This class of materials originally developed for the printing and packaging industries, quickly solidifies wherever the laser beam strikes the surface of the liquid. Once one layer is completely traced, it's lowered a small distance into the vat and a second layer is traced right on top of the first Fig. 1. The self-adhesive property of the material causes the layers to bond to one another and eventually form a complete, three-dimensional object after many such layers are formed [9]. Stereolithography generally is considered to provide the greatest accuracy and best surface finish of any rapid prototyping technology [10]. The RP models were constructed using the 18420 ProtoGen™ materials. The 18420 material is a high-temperature, chemical-resistant polymer that can be used in creating three-dimensional parts. The material offers less shrink, which will allow for more accurate parts and offers a higher heat-deflection, which will allow for humidity and temperature tolerant parts. Parts made from the 18420 material can be drilled and tapped without breakage, allowing for greater flexibility during post-machining and in a prototype's testing stages. The material is also easy to sand, and will allow Laser Reproduction's detailers to work more efficiently. Fig. 2 shows the model tested. The material properties of 18420 ProtoGen™ is shown in Table I [11].

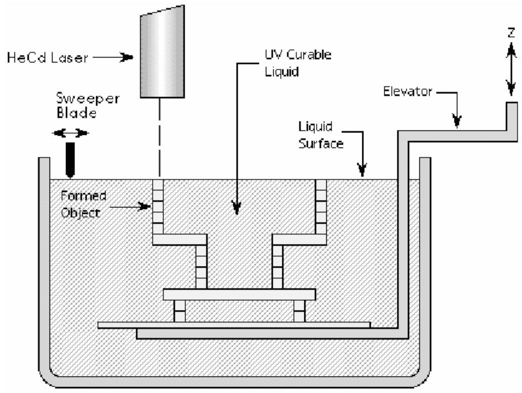

Fig. 1 The Stereolithography (SLA) process

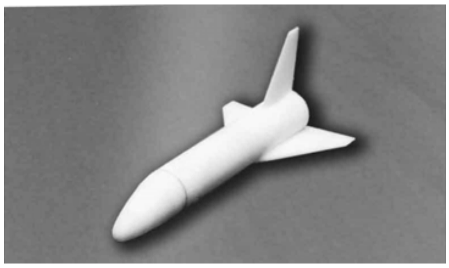

Fig. 2 Model tested

TABLE I
Material Properties of Somos 18420

ASTM Method	Description	Unit	Somos 18420
D638M	Tensile strength	MPa	42.2-43.8
D638M	Tensile modulus	MPa	2.180-2.310
D638M	Elongation at break	Percent	8-16%
D790M	Flexural strength	MPa	66.9-70.5
D790M	Flexural Modulus	MPa	1.990-2.130
D2240	Hardness	(shore D)	86-88

IV. Surface Roughness and 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 that resulted during testing. Secondly, will the model be able to withstand the starting, stopping and operating loads in a blow down wind tunnel [12]. The layer thickness was 0.05mm, 0.125mm and 0.15mm. The roughness of surfaces for each model in horizontal plane was 0.1 µm, 0.22µm and 4.6µm (Ra) that determined by perthometer2.The reference dimensions for this configuration is as Follows [13].

D_{ref} =90 [mm] L_{ref} =220[mm] X_{MRP}=150[mm after of nose]

Three models were fabricated. The first model was a 0.05mm layer thickness and surface roughness in horizontal plane 0.1µm (Ra), Vertical plane 2.2µm (Ra) and 45° plane 10µm (Ra). Second model was a 0.125mm layer thickness and surface roughness in horizontal plane 0.22µm (Ra), Vertical plane 4.2µm (Ra) and 45° plane 24µm (Ra). Third model was a 0.15mm layer thickness and surface roughness in horizontal plane 4.6µm (Ra), Vertical plane 8.34µm (Ra) and 45° plane 37.1µm (Ra). Fig. 3 shows roughness in 0.125mm layers.

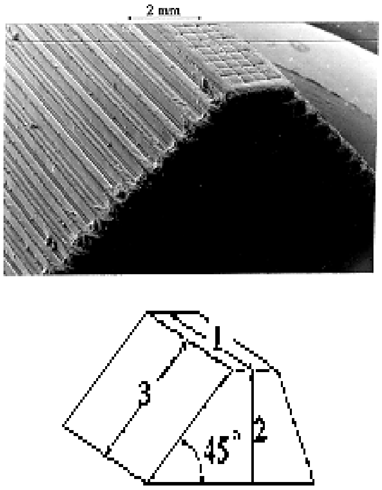

Fig. 3 Sample with 0.125mm layers
1. Horizontal plane 0.22µm Ra
2. Vertical plane 4.2µm Ra
3. 45° plane 24µm Ra

V. Wind Tunnel Operating Characteristics

The transonic wind tunnel is designed to investigate aerodynamic characteristics of aircraft models and their components. 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 0.15 to 1.2. Mach numbers between 0.15 and 0.9 are obtained by using a controllable diffuser. The Mach range from 0.95 to 1.2is 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. The diffuser section has movable floor and ceiling panels, which are the primary means of controlling. Table II shown lists the relation between Mach number, dynamic pressure, and Reynolds number per meter.

TABLE II
Wind Tunnel Operating Conditions

Mach number	Dynamic pressure	Reynolds number
0.3	8.96 kPa	9.18×10^4
0.5	25.53	12.04×10^4
0.75	30.42	15.52×10^4
0.9	45.14	18.12×10^4

VI. Aerodynamic Tests

Testing was done over the Mach range of 0.3 to 0.9 at 4 selected numbers for the study. These Mach numbers were 0.30, 0.50, 0.75 and 0.90. Models were tested at angle-of-attack ranges from -2 degrees to +12 degrees at zero sideslip. The reference aerodynamic axis system and reference parameters for the precursor study are shown in Fig. 4[14]. A wing-body-tail launch vehicle configuration was chosen to test RP processes ability to produce accurate airfoil sections, and to determine the surface finish effects related to the wing and tail under loading [15]. From a survey of past, current, and future launch vehicle concepts, it was determined that a wing-body-tail configuration was typical for the majority of configurations which would be tested. The methods of model construction were analyzed to determine the applicability of the RP processes to the design of wind tunnel models.

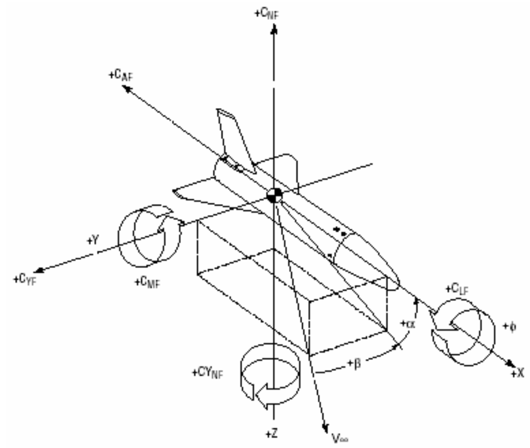

Fig. 4 Aerodynamic axis system

VII. Results

The effects of layer thickness on the aerodynamic characteristics of the models were determined. The study showed that between Mach numbers of 0.3 to 0.9, the longitudinal aerodynamic data or data in the pitch plane showed approximately a 1-degree shift in the data between the RP models for the normal force (Figs. 5, 9 and 13)and approximately a 3-degree data shift for the pitching moment (Figs. 6, 10 and 14). Except for these shifts, the data trends for each model type were consistent with each other. The total axial force was lower for the third model than other models (Figs. 7, 11 and 15). Between Mach numbers 0.3 to 0.9 only a very small shift in the data was noticed, mostly at the higher angles of attack (Figs. 5 through 16). Between three models 0.1 μm, 0.22 μm and 4.6 μm small shift in the data was noticed, at lift over drag (Figs. 8, 12 and 16).The lateral directional aerodynamic data show some discrepancies between the models types. 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.

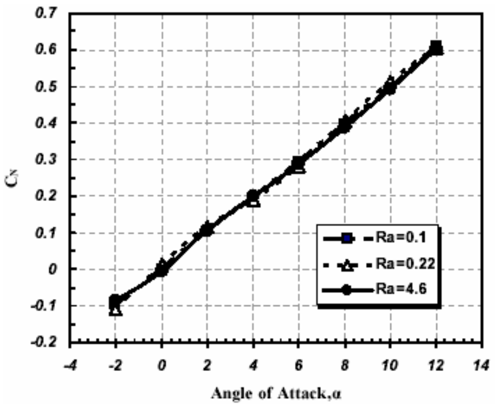

Fig. 5 Comparison of normal force Coefficient at Mach 0.3

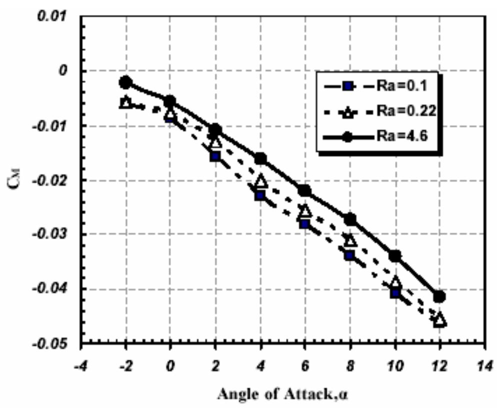

Fig. 6 Comparison of pitching moment Coefficient at Mach 0.3

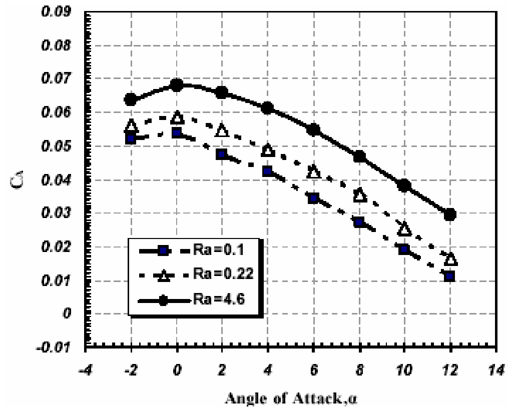

Fig. 7 Comparison of axial force at Mach 0.3

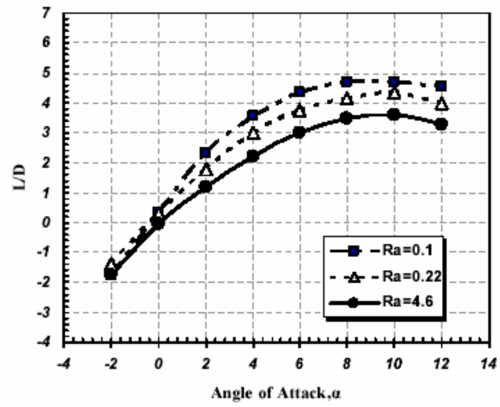

Fig. 8 Comparison of lift over drag at Mach 0.3

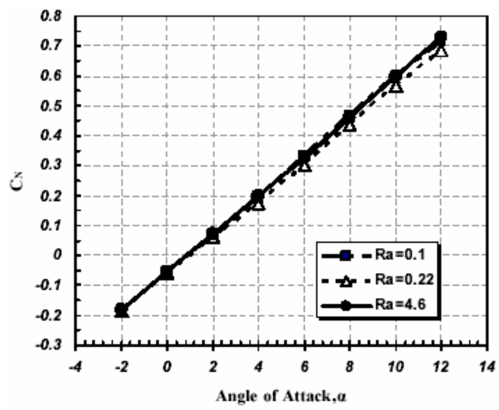

Fig. 9 Comparison of normal force Coefficient at Mach 0.75

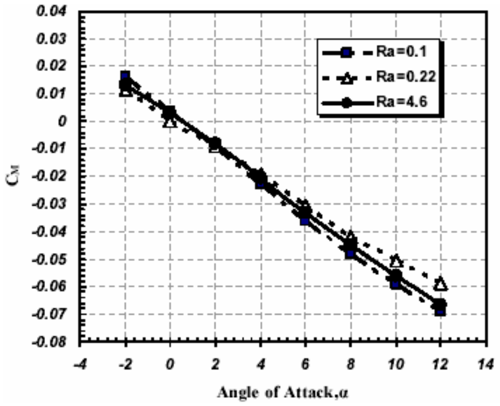

Fig. 10 Comparison of pitching moment Coefficient at Mach 0.75

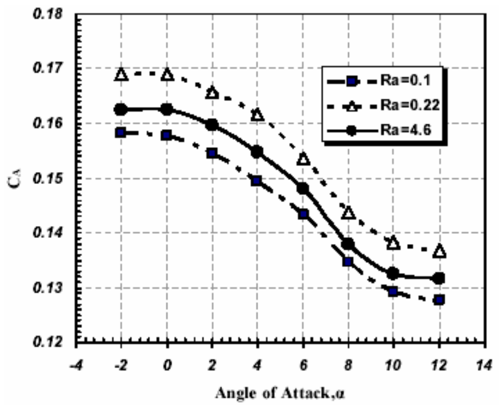

Fig. 11 Comparison of axial force Coefficient at Mach 0.75

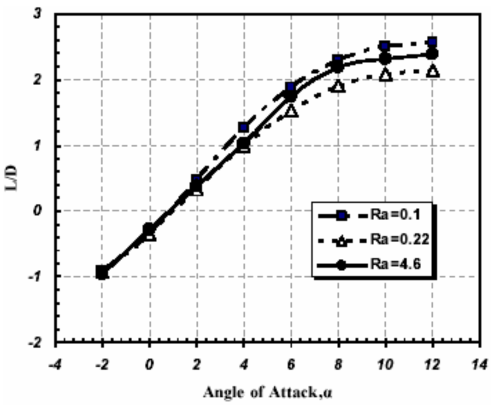

Fig. 12 Comparison of lift over drag at Mach 0.75

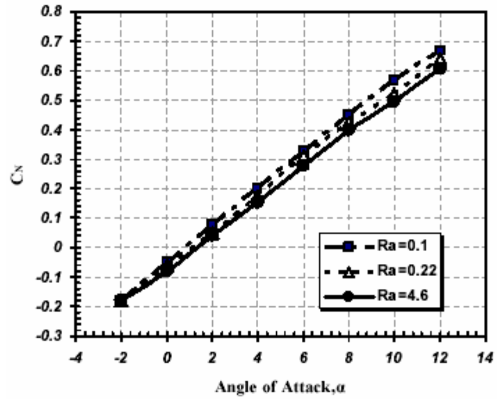

Fig. 13 Comparison of normal force Coefficient at Mach 0.9

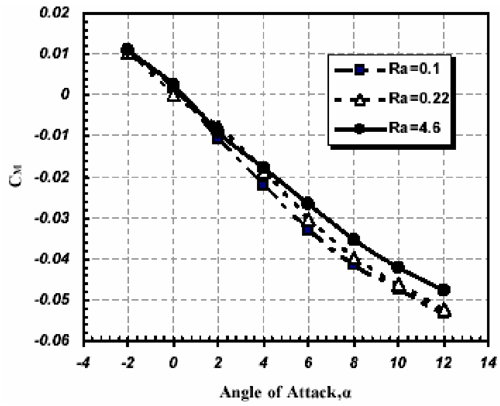

Fig. 14 Comparison of pitching moment Coefficient at Mach 0.9

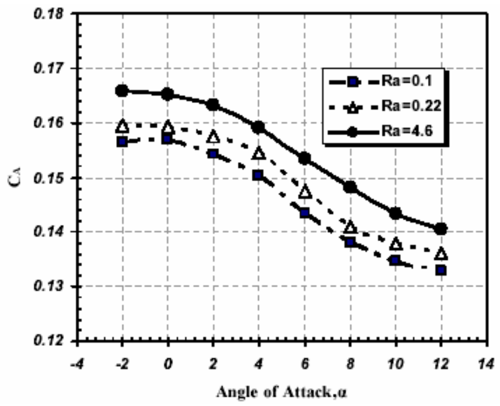

Fig. 15 Comparison of axial force Coefficient at Mach 0.9

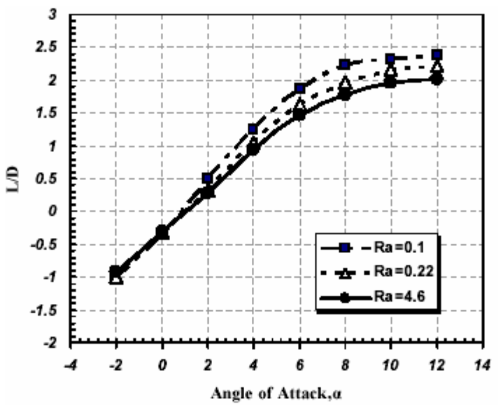

Fig. 16 Comparison of lift over drag at Mach 0.9

VIII. Costs and Time

The cost and time requirements for the SLA models are shown in Table III. The first model with 0.05mm layer thickness for this test cost about $900 and took 2 weeks to construct, while the second model with 0.125mm layer thickness cost about $700 and took 10 days and third model with 0.15mm layer thickness cost about $500 and took 7 days to design and fabricate.

TABLE III
Wind Tunnel Model Time and Cost Summary

	COST	TIME
model with 16 μm surface finishes	$900	14 days
model with 63 μm surface finishes	$700	10 days
model with 160 μm surface finishes	$500	7 days

IX. Conclusion

The RP models did not have as smooth a finish as did the metal model, so runs were made to determine if the difference in these surface finishes would affect the aerodynamic characteristics. A rough surface finish was simulated with three layer thickness. In this paper it can be seen that surface finish does have an effect on the aerodynamic characteristics up to transonic 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 its derivative coefficients. The differences between the configurations data can be attributed to multiple factors such as surface finish, structural deflection, and tolerances on the fabrication of the models. It can be concluded from this study that wind tunnel models constructed using rapid prototyping methods with low surface finish can be used in subsonic, transonic, and supersonic 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 in model with low surface finish is lower than that of a model with high surface finish, but is quite accurate for this level of testing. The difference in the aerodynamic data between the three model aerodynamics is acceptable for this level of preliminary design or studies. The use of RP models with low surface finish will provide a rapid capability in the determination of the aerodynamic characteristics of preliminary designs over a large Mach range. This range covers the transonic regime, a regime in which analytical and empirical capabilities sometimes fall short. The cost and time for models that constructed with low surface finish is less than models with high surface finish accordingly, however models with less surface finish are suitable for preliminary design or phase studies.

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