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Investigation of Surface Roughness on Aerodynamics Properties

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This paper describes the effects of surface finish models on aerodynamic coefficients for constructed wind-tunnel testing models. Three models were evaluated. These models were fabricated from aluminum 2024-T4 by computer numerical control (CNC) machining. The roughness of surfaces for each model was 6.3, 60, and 150 μm, which was determined by PERTHOMETER2. A wing-body-tail configuration was chosen for the actual study. Testing covered the Mach range of Mach 0.3 to 1.2 at an angle-of-attack range of +6 to +26 deg at zero sideslip and an angle-of-sideslip range of −8 to +8 deg at a 16-deg angle of attack; the 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 surface finish does have an effect on the aerodynamic characteristics in general; the data differ between the three models by less than 5%. The surface finish does have more effect on the aerodynamic characteristics when the Mach number is decreased and has the most effect on the aerodynamic characteristics of axial force and its derivative coefficients.

Nomenclature

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

Introduction

IN A time when "better, faster, and cheaper" are the words to live by, new technologies must be employed to try to live up to these axioms. In this spirit, a study was undertaken to determine the suitability of models constructed using CNC machining with various surface finishes for use in subsonic, transonic, and wind-tunnel testing. Surface finish is an important parameter in wind-tunnel testing models fabrication [1]. Various cutting conditions and machining tool properties have an effect on the surface finish [2]. The cutting speed, tool feed, depth of cut, tool material, and rake angle have the most effects on the surface quality, and time and costs are usually increased for the optimization of these parameters [3]. In this study, the effects of surface finish on the aerodynamic characteristics are determined, and required surface finish for wind-tunnel testing models is evaluated. Models were constructed using three different surface finishes, and the aerodynamic characteristics were determined and compared with each other. A wing-body-tail configuration was chosen for the actual study [4]. An aluminum model, although not as preferred as a steel model, costs less and requires less time to construct than would providing a more conservative baseline model. Three aluminum models were prepared and machined at various conditions for testing in a wind tunnel and determining the aerodynamics coefficients. The roughness of surfaces for each model was 6.3, 60, and 150 μm, which was determined by PERTHOMETER2, with flowing from storage to either vacuum or atmosphere conditions. Testing was done over the Mach number range of 0.3 to 1.2. 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 a 6-deg angle of attack. Coefficients of normal force, axial force, pitching moment, and lift over drag are shown at each of these Mach numbers.

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 effect the aerodynamic data that resulted during testing [5]. Second, it would indicate whether the model would be able to withstand the starting, stopping, and operating loads in a blowdown wind tunnel [6]. The wing-body-tail configuration is shown in Fig. 1. The reference dimensions for this configuration are as follows: $S_{\text{ref}} = 56.02$ cm^2, $L_{\text{ref}} = 226.61$ mm, and $X_{\text{MRP}} = 158.63$ mm, aft of the nose.

Model Construction

The precursor study of the wing-body configuration was constructed using the CNC machining method. Each of the models was constructed as a single part. The nose section was separated from the core, and a 19-mm hole was drilled and reamed through the center of the body for placement of the aluminum balance adapter. The nose was attached to the core body with two screws that were attached through the nose to the balance adapter. Figure 2 is a close-up of an aluminum balance adapter. The material properties of aluminum are shown in Table 1 [7]. The roughness of surfaces for each model was

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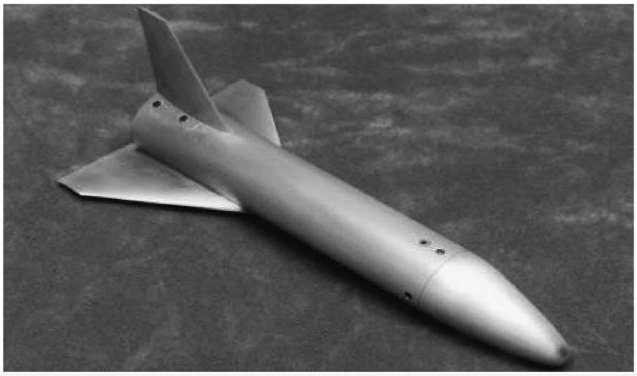

Fig. 1 Wing-body-tail configuration.

Fig. 2 Aluminum balance adapter used in the model.

6.3, 60, and 150 μm, which was determined by PERTHOMETER2 with a 0.8-mm wavelength.

Wind Tunnel

A transonic wind tunnel is an intermittent blowdown 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 were obtained by using a controllable diffuser.

Table 1 Material properties of AL

Property	Aluminum 2024-T4
Yield strength, MPa	275.6
Tensile strength MPa	427.18

Table 2 Wind-tunnel operating conditions

Mach number	Reynolds number	Dynamic pressure
0.3	$9.18 \times 104/\text{m}$	8.96 KPa
0.8	18.03	44.58
0.9	19.34	50.71
1.05	20	58.43
1.15	20.32	61.94
1.2	20.32	64.14

The Mach range from 0.95 to 1.2 was achieved through the use of a plenum suction and perforated walls [8]. Each Mach number above 1.2 requires a specific set of two-dimensional contoured nozzle blocks. The tunnel flow was established and controlled with a servo-actuated gate valve. The air then passes through the test section that 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 $+10$ deg during each run. Sting offsets are available for obtaining various maximum angles of attack up to 90 deg. The diffuser section has movable floor and ceiling panels, which are the primary means of control. Table 2 lists the relation between Mach number, dynamic pressure, and Reynolds number per meter.

Test Models

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 roughness of surfaces for each model was 6.3, 60, and 150 μm. A wing-body-tail launch-vehicle configuration was chosen to test the ability to produce accurate airfoil sections and to determine the material property effects related to the bending of the wing and tail under loading [9]. The model construction was analyzed to determine the applicability of the surface finish to the design of wind-tunnel models. Testing was done over the Mach range of 0.3 to 1.2 at six selected numbers. These Mach numbers

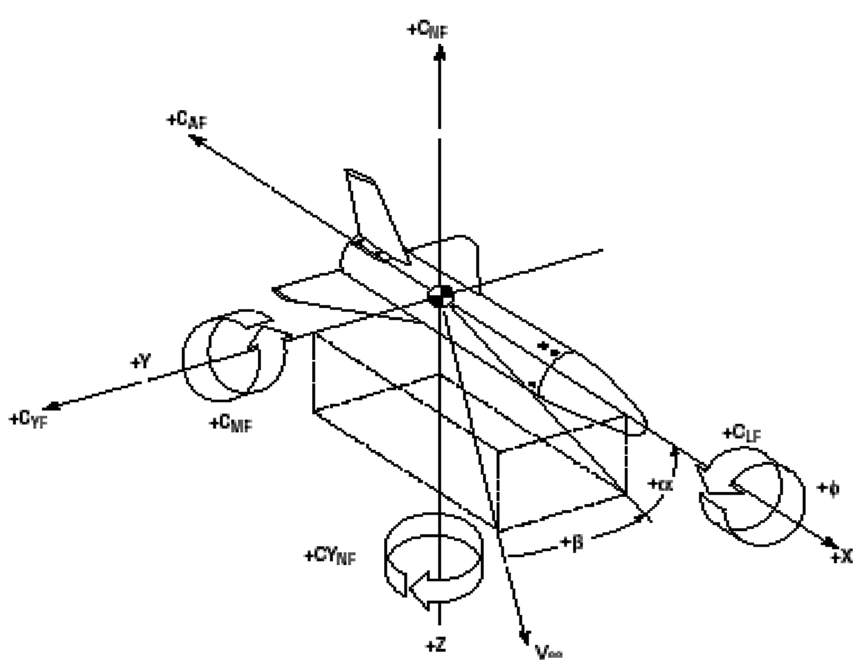

Fig. 3 Wing-body aerodynamic axis system.

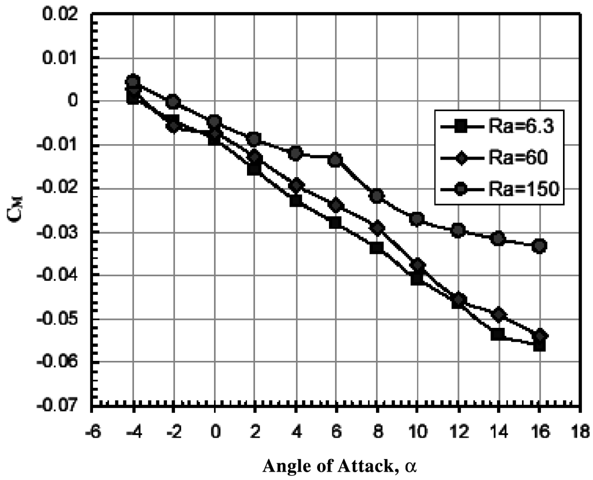

Fig. 4 Comparison of pitching moment coefficient at $M = 0.3$.

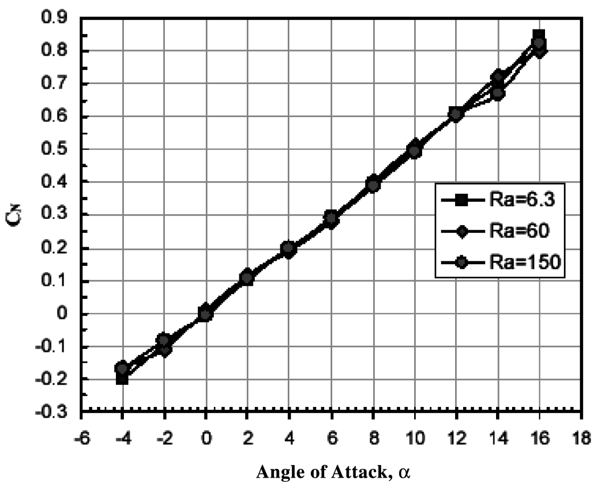

Fig. 5 Comparison of normal force coefficient at $M = 0.3$.

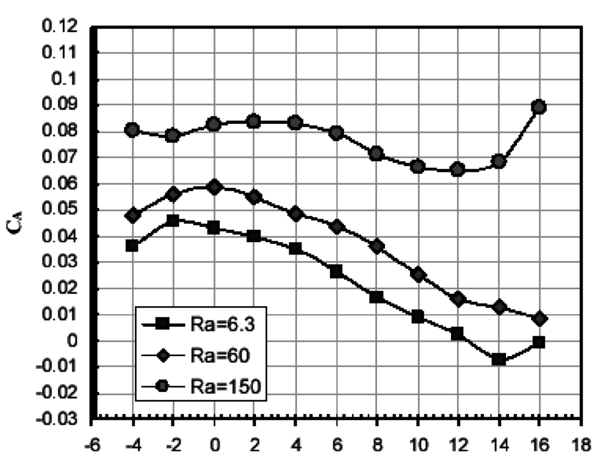

Fig. 6 Comparison of axial force coefficient at $M = 0.3$.

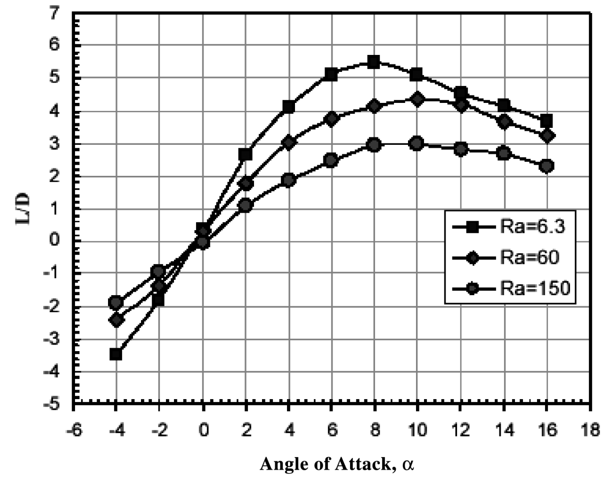

Fig. 7 Comparison of lift over drag at $M = 0.3$.

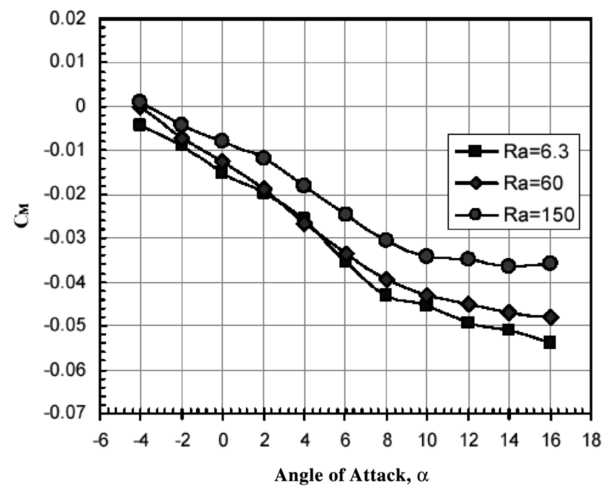

Fig. 8 Comparison of pitching moment coefficient at $M = 0.8$.

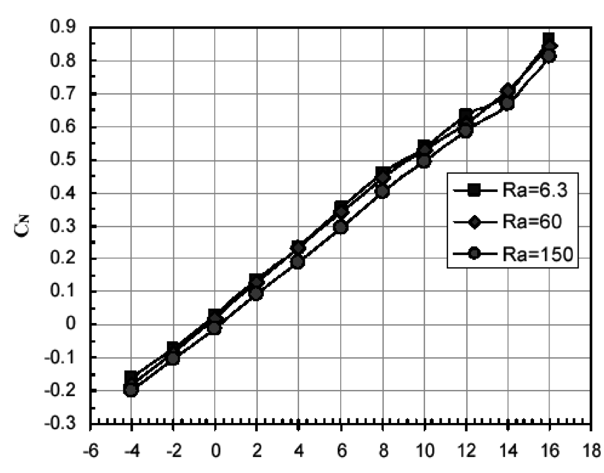

Fig. 9 Comparison of normal force coefficient at $M = 0.8$.

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 to +16 deg at zero sideslip and at angle-of-sideslip ranges from −8 to +8 deg at a 6-deg angle of attack. The reference aerodynamic axis system and reference parameters for the baseline study are shown in Fig. 3.

Results

The effects of surface finish on the aerodynamic characteristics of the models were determined. The 150-μm model did not have as smooth of a finish as the 6.3-μm models, and so runs were made to

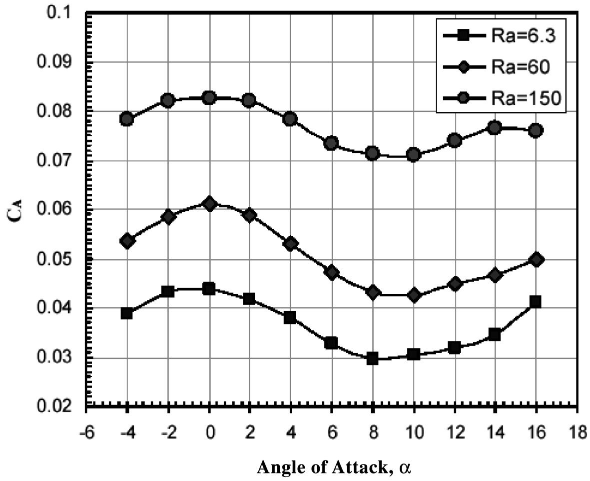

Fig. 10 Comparison of axial force coefficient at $M = 0.8$.

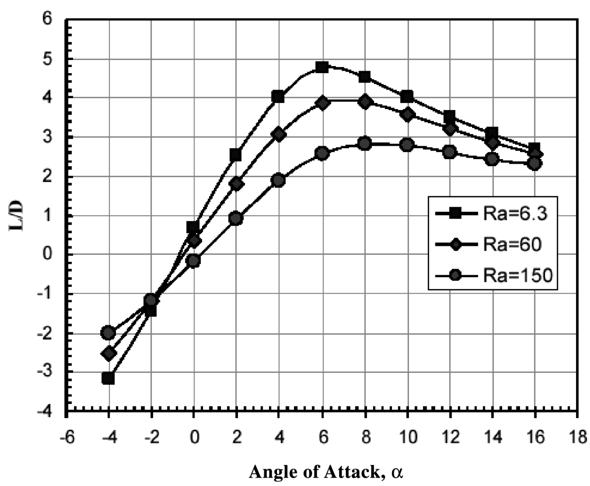

Fig. 11 Comparison of lift over drag at $M = 0.8$.

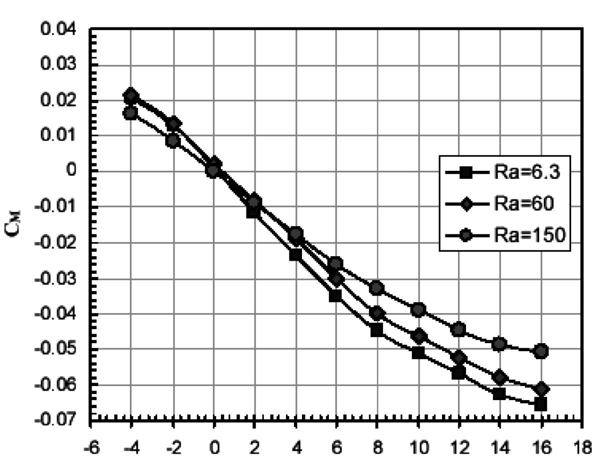

Fig. 12 Comparison of pitching moment coefficient at $M = 1.2$.

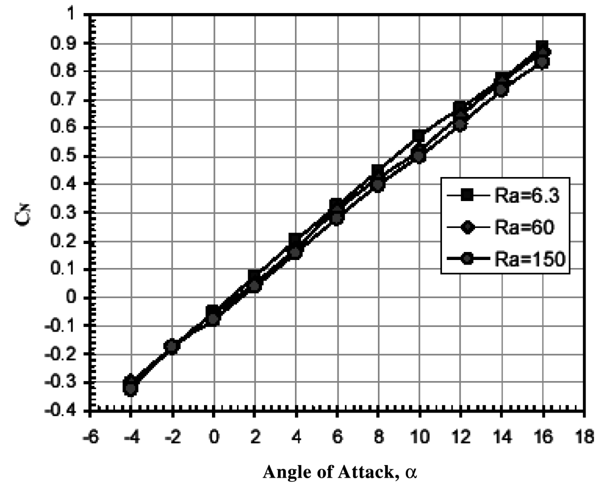

Fig. 13 Comparison of normal force coefficient at $M = 1.2$.

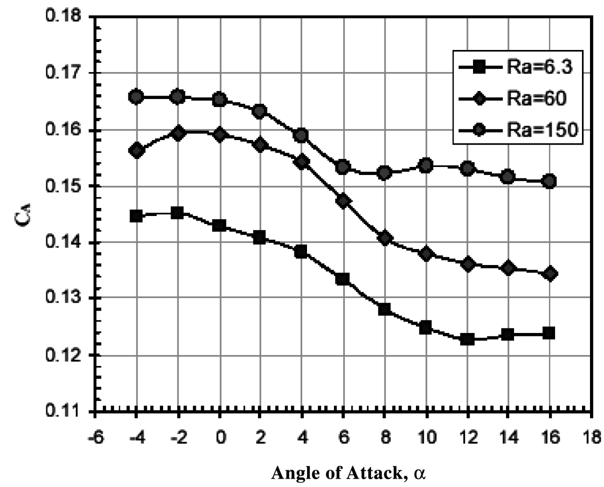

Fig. 14 Comparison of axial force coefficient at $M = 1.2$.

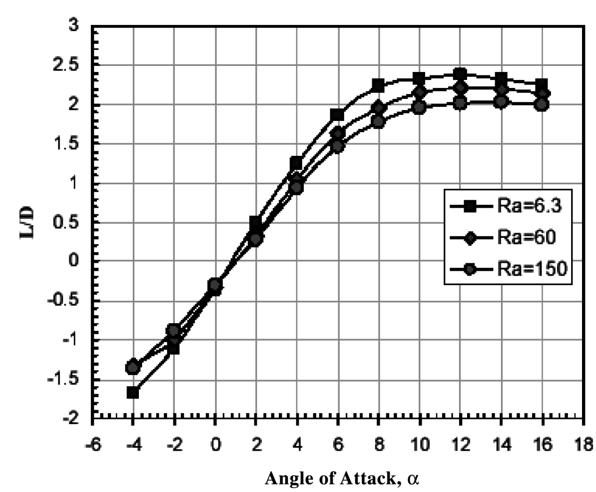

Fig. 15 Comparison of lift over drag at $M = 1.2$.

determine if the difference in these surface finishes would affect the aerodynamic characteristics. Roughening the surface simulates a higher Reynolds number than the actual wind-tunnel Reynolds number. The effect of these changes is shown in Figs. 4–15. In these graphs, it can be seen that surface finish does have an effect on the aerodynamic characteristics up to supersonic speeds, but the effect is less drastic than at lower Mach numbers. The application of surface finish had little effect on the aerodynamic characteristics, except for axial force and its derivative coefficients.

Costs and Time

The aluminum model with a 150-μm surface finish cost about \$10,000 and took two months to design and fabricate, and the model

Table 3 Wind-tunnel model time and cost summary

Aluminum	Cost	Time
Model 6.3 μm	\$12,000	3.5 months
Model 60 μm	\$11,000	3 months
Model 150 μm	\$10,000	2 months

Table 4 Model dimensions compared, mm

Dimensions	Model with surface finish 6.3 μm	Model with surface finish 60 μm	Model with surface finish 150 μm
Wing L1	0.204	0.246	0.251
Wing L2	0.890	0.109	0.115
Wing R1	0.895	0.106	0.110
Wing R2	0.120	0.137	0.140
Body 1	0.140	0.177	0.178
Body 2	0.038	0.048	0.051
Tail 1	0.072	0.078	0.082
Tail 2	0.051	0.050	0.053
X–Y plane	0.025	0.030	0.042
X–Z plane	0.061	0.076	0.082

Table 5 Balance adapter roll angle installed in the model

Model	Adapter roll angle
Model 6.3 μm	0.95
Model 60 μm	0.90
Model 150 μm	0.89

with a 6.3-μm surface finish cost about \$12,000 and took three-and-a-half months. The cost and time requirements for the aluminum models are shown in Table 3.

Accuracy

The data accuracy results from this test can be divided into two sources of error or uncertainty: a) the model and b) the data acquisition system [10]. Each of these factors will be considered separately. First, the dimensions of the models must be compared with the CAD model. Difficulty arose in the interface between the nose and core body for the models, along 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, vehicle stations, tail sections, and the X–Y and X–Z planes. A comparison of model dimensions is shown in Table 4. 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 X–Y and X–Z 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 0.12 mm. The installation of the balance adapter in the models was not at 0-deg roll (noted in Table 5). The balance adapter was rolled approximately 1-deg, starboard wing down. This resulted in a small error in all the coefficients, because the model was installed in the tunnel level. The effect of the balance adapter's roll on the normal force and side force aerodynamic coefficients is shown in Table 6. Second, the repeatability of the data can be expected to be within the symbol size on the plots.

Table 6 Effect of balance adapter roll on aerodynamic coefficients

Roll angle	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

Conclusions

It can be concluded from this precursor test that surface finish does have an effect on the aerodynamic characteristics at high Mach number speeds, but the effect is less drastic than at lower Mach numbers. The surface finish had little effect on the aerodynamic characteristics, except for axial force and its derivative coefficients. The wind-tunnel models were constructed with different surface finishes, using subsonic and transonic wind-tunnel testing for initial baseline aerodynamic database development. The accuracy of the data is lower for models that have less surface finish but is quite accurate for this level of testing. Less than 3% change in the aerodynamic data between the models aerodynamics is acceptable for this level of preliminary design or phase studies.

The use of models with low surface finish will allow the rapid 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 are constructed with low surface finish are less than for models with high surface finish. However, models with less surface finish are suitable for preliminary design or phase studies.

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