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Integration of Three-Dimensional Printing Technology for Wind-Tunnel Model Fabrication

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Nowadays, rapid manufacturing techniques have opened a new era in aerospace industry. Wind-tunnel testing models have the most application in this industry, and different manufacturing techniques are used for production purposes. For the purpose of aerodynamics experiments, a number of different testing models may be needed to be manufactured. Airfoils are such parts that are complex and time consuming from a manufacturing point of view. At present, a new manufacturing technique has facilitated manufactures with a complex geometry, and it is now possible to replace traditional methods by this technology. In this research an airfoil model, which belongs to a missile, has been manufactured using a three-dimensional printing technology, and has been compared with a model which has been manufactured using traditional methods. The comparison is made from such aspects as the surface quality, dimensional accuracy and aerodynamics coefficients. Results reveal difference between the fabrication airfoil and the metal model due to the fact that the fabrication airfoil is different with respect to the surface quality and dimensional accuracy. Therefore, a significant difference in some of the aerodynamics coefficients can be observed. It can be concluded from this research that, the manufactured models using a three-dimensional printing method can be used for primary tests, being less expensive and requiring significantly less time to build.

Nomenclature

C_A = axial force coefficient
C_N = normal force coefficient
C_M = pitching moment coefficient
L/D = lift over drag ratio
α = angle of attack

I. Introduction

WIND-TUNNEL models are generally supported in a wind tunnel by a positioning device that is often referred to as a sting. The rear portion of a model is usually hollow to allow the sting to penetrate the model body without affecting the aerodynamic properties of the model. A force transducer called a balance is attached to the inside of the model to measure forces and moments acting on the model (often measuring all 6 degrees of freedom: drag, side force, lift, roll, pitch, and yaw). The sting is rigidly fixed to the balance and all lead wires from the balance and any other control lines or strain gage leads from the model are routed inside or along the sting and back to the control room of the wind-tunnel facility. The cost of fabricating and instrument a typical wind-tunnel model is expensive [1]. Because of the high costs of building a model, program managers often rely heavily on analytical tools, such as CFD (computational fluid dynamics), to predict how a missile system might perform. Although CFD can provide valuable data, it typically requires more time to produce final results and has limitations providing data over a full range of flight conditions. Rapid prototyping (RP) is becoming an increasingly important tool for manufacturing engineers in producing concept models, functional prototypes, and master patterns for tooling, injection molding, and casting [2]. RP allows multiple iterations of designs more testing, more feedback to reach a way to make a part with less cost and in less time than traditional model-making and machining methods. Rapid prototyping methods currently in use include Stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), and three-dimensional printing (3DP), all of which can help shorten the design cycle and bring products to market faster [3]. Under the right test conditions, a rapid prototype part could be tested in a wind tunnel [4]. It is clear that increased use of RP components in wind-tunnel models could dramatically reduce the cost and time associated with wind-tunnel model fabrication [5]. There is therefore a need for novel wind-tunnel model design techniques that overcome some of the difficulties and deficiencies involving the use of RP components. RP parts can generally be made much more rapidly and less expensively than conventional machined parts. RP manufacturing is a field of high technology concerning the generation of three-dimensional solids using particles or layers of mostly polymeric materials. Reentry models for use in wind-tunnel tests were fabricated using a stereolithography apparatus. These models were produced in one day or less, which is a significant time savings compared with the manufacture of ceramic or metal models. Most of the models did not survive repeated tests in the tunnel, and several failure modes of the models were identified [6]. Steel wind-tunnel model are relatively expensive and typical take months to manufacture. Ceramic wind-tunnel models are generally rally less expensive but still takes weeks to produce [7].

Wind-tunnel models, used to provide performance test, can be produced at lower cost than traditional methods [8]. Rapid prototyping technologies being developed for the space program have many uses in the commercial industry [9]. The purpose of this paper is to demonstrate the use of three-dimensional printing (3DP) process for rapid manufacturing of wind-tunnel testing. Two models are prepared and produced at various conditions for testing in wind tunnel and determining the aerodynamics coefficients. RP model constructed using 3DP with zp150 as a material. AISI 1045H (CK45) was chosen as the material for the machined metal model. The layer thickness for 3DP model was 0.089 mm. The wind tunnel is an intermittent blowdown tunnel, which operates by high-pressure air flowing from storage to atmosphere conditions. Testing covered the

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Mach range of Mach 0.1–0.4. All models were tested at the angle-of-attack ranges from 4 to +22 deg at zero sideslip. Coefficients of normal force, axial force, pitching moment, and lift over drag are shown at each of these Mach numbers. The results from this study show, under the right test conditions, a 3DP models could be tested in a wind tunnel and use of 3DP to rapidly build wind-tunnel test articles and can potentially shorten the design cycle for future vehicles.

II. Rapid Prototyping and 3DP

Rapid prototyping technologies can create the physical part directly from the digital model by accumulating layers of a given material [10]. Rapid prototyping has become a widely used tool for the fabrication and evaluation of physical prototypes during the product development cycle. RP is used because it can produce prototypes with arbitrary shapes quickly with a lower cost than traditional prototyping techniques [11]. Recently RP has also been investigated regarding its ability to replace traditional mass manufacturing processes in applications where only one or a small number of individually shaped parts are required [12]. Today there are many different rapid prototyping technologies available. Three of the most popular RP techniques are stereolithography (SLA), fused deposition modeling (FDM) and selective laser sintering (SLS) [13]. Each RP technology has its limitations and strengths. Stereolithography uses a vat of liquid polymer plastic which is hardened in layers with laser to create a solid plastic object. SLA offers good detail, accuracy, and surface finish, but falls short in strength and toughness. The liquid material is a very expensive item, it process very slow, and it needs a controlled environment room. Selective laser sintering, on the other hand, offers durability and toughness while losing some accuracy and detail. Fused deposition modeling and SLS surfaces are said to exhibit rougher finishes than those with SLA. These parts can be smoothed with postprocessing, such as sanding or use of solvents or adhesives. Stereolithography requires adding support structure thin ribs placed at 0.25-in. intervals for mounting the part while building it. After the build, the operator removes the supports, then hand finishes. Fused deposition modeling, likewise, requires a support structure to mount the part. Many other technologies followed, usually offering faster and cheaper operation. All processes have their advantages and disadvantages and those that have stood the test of time have some particular characteristic that gives them a market niche.

All systems are based on the idea of taking a computer 3-D model and calculating paper-thin slices through it, so the data represents a laminated model. These laminated-model data are then output layer-by-layer to the machine to solidify, fuse or cut material for each lamination. A standard now exists for the lamination model data, the STL file format, and virtually all 3-D manufacturing CAD systems can now generate STL files. This makes it easier for designers to interface with a variety of machine systems with was the case in the early days of rapid prototyping. A U.S. company, Z-Corporation, has developed a rapid prototyping machine that offers a very attractive combination of features. It uses extremely cheap material, operates very quickly and does not need elaborate special environments [14]. The only downside aspect of the machine is that the models produced are not as strong as some other systems. Although they cannot serve as short-term mechanical working components, they do provide very good quality, highly detailed objects that are ideal for design-team and client evaluation. They can be handled quite roughly, and can be finished to a good surface and receive paint and other coloring treatments. Three dimensional printing starts by depositing a layer of powder object material at the top of a fabrication chamber. To accomplish this, a measured quantity of powder is first dispensed from a similar supply chamber by moving a piston upward incrementally (Fig. 1). The roller then distributes and compresses the powder at the top of the fabrication chamber. The multichannel jetting head subsequently deposits a liquid adhesive in a two dimensional pattern onto the layer of the powder which becomes bonded in the areas where the adhesive is deposited, to form a layer of the object. Once a layer is completed, the fabrication piston moves down by the thickness of a layer, and the process is repeated until the entire object is formed within the powder bed. After completion, the object is elevated and the extra powder brushed away leaving a green object. No external supports are required during fabrication because the powder bed supports overhangs [15]. Three dimensional printing offers advantages for a fast fabrication and low material cost. In fact, it is probably the fastest of all RP methods. Color output is also available; however there are limitations on resolution, surface finish, part fragility and available materials.

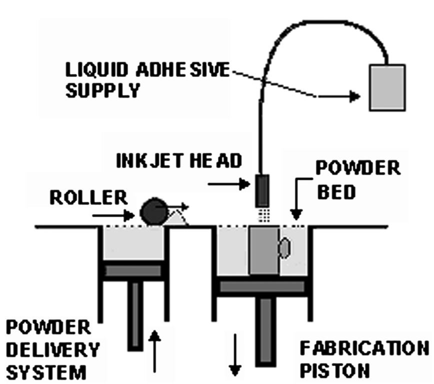

Fig. 1 3DP process.

III. Material Selection

Selecting a product material is one of the most important decisions that an engineer can make in the development of a new product. The RP process was three -dimensional printing (3DP) with a zprinter450 and using material of zp150. The zprinter450 creates physical models directly from digital data in hours instead of days. It is fast, versatile and simple, allowing engineers to produce a range of concept models and functional test parts quickly and inexpensively. The layer thickness was 0.089 mm. High-performance composite material makes strong, high-definition parts and is the material of choice for printing color parts. Fine resolution on small features and excellent strength make this material suitable for applications ranging from concept modeling. It consists of a heavily engineered plaster material with numerous additives that maximize surface finish, feature resolution, and part strength. Zp150 is the best powder system available on Z Corporation 3-D printers. It provides significant improvements over previous materials in both appearance and strength and offers the versatility to be the new standard in 3-D printing materials. Zp150 offers a range of finishing options to meet your needs, from infiltrating parts with resin for ultrastrong functional prototypes to simply spraying water on parts to create concept models quickly, safely, and very affordably. AISI 1045H

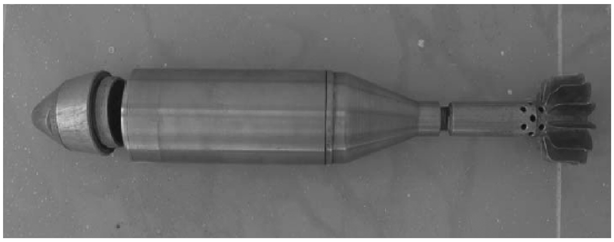

Fig. 2 Steel model configurations.

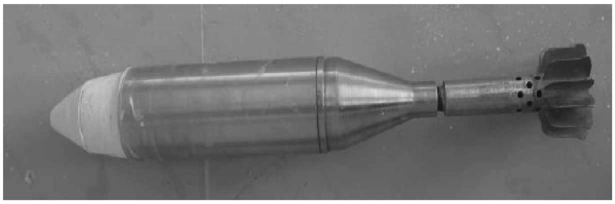

Fig. 3 Steel model with 3DP nose.

Table 1 Surfaces roughness (metric)

	3DP nose	Steel nose
Lt	5.600 mm	5.600 mm
Lc	0.800 mm	0.800 mm
Ra	0.742 μm	0.410 m
Rz	3.450 μm	2.580 μm
Rmax	6.940 μm	2.980 μm

Table 2 Wind-tunnel test section characteristics

Maximum speed, m/s	150
Minimum speed, m/s	2
Mach number rang	0–0.5

(CK45) was chosen as the material for the machined metal model [16].

IV. Wind-Tunnel Model

The dimensions for the scaled model of the missile are 52 cm × 8 cm × 8 cm. The model was built in several pieces and then assembled. Two models were fabricated. The first model was constructed using steel in three parts, a nose, body and tail as shown in Fig. 2. The second model was manufactured using a RP nose attached to a cylindrical steel and tail as depicted in Fig. 3. The cylindrical steel provides strength and rigidity to the plastic model and also allows larger scale models to be built. The cylindrical steel, fabricated from AISI 1045H (CK45), is a 30 cm long cylinder with a 8 cm outer diameter and a 7 cm inner diameter. The surface of the cylinder has a surface finish of a 0.315 μm (Ra).The inside forward end of the cylindrical steel was machined to a 6 cm diameter and threaded for attachment of the RP nose. The RP nose was manufactured using a Zp150. The RP part was designed with the solid geometry models that were created using CATIA software and output as a stl file. The roughness of surfaces for RP and steel nose was 0.742 μm (Ra) and 0.410 μm (Ra) that determine by perthometer M1 and shown in Table 1.

V. Wind Tunnel

To verify the engineers' calculations during the preparation of a model, aerodynamic tests are carried out starting from wind-tunnel conditions and ending to surrounding conditions. Forces and moments measurement is the most important parameter of the wind-tunnel test [17]. The wind tunnel is an intermittent blowdown tunnel, which operates by high-pressure air flowing from storage to atmosphere conditions. This will be used for characterizing power plant at different wind-tunnel speed. This wind tunnel will also be used for the measurement of aerodynamic characteristics of the aircraft. The size of the wind tunnel is 0.6 m × 0.6 m × 1 m and the maximum

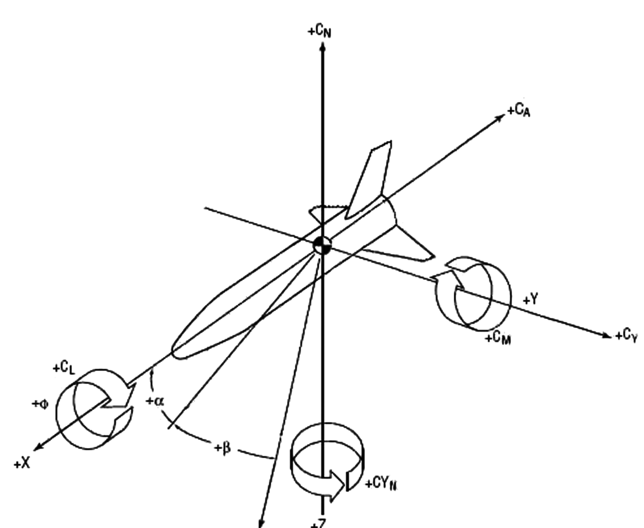

Fig. 4 Reference aerodynamic axis system.

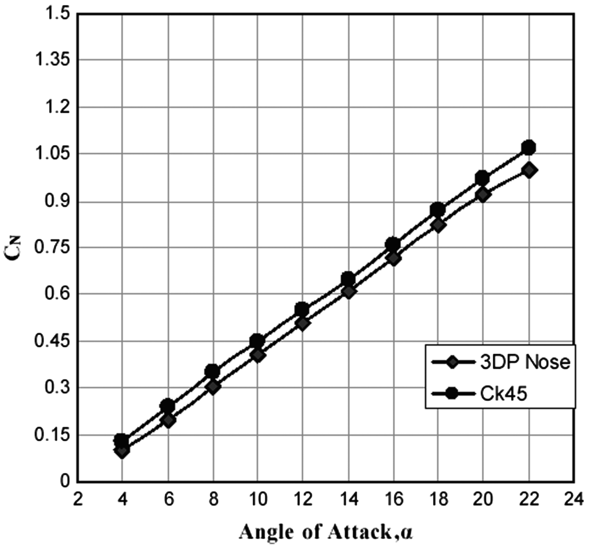

Fig. 5 Comparison of normal force coefficient at Mach 0.1.

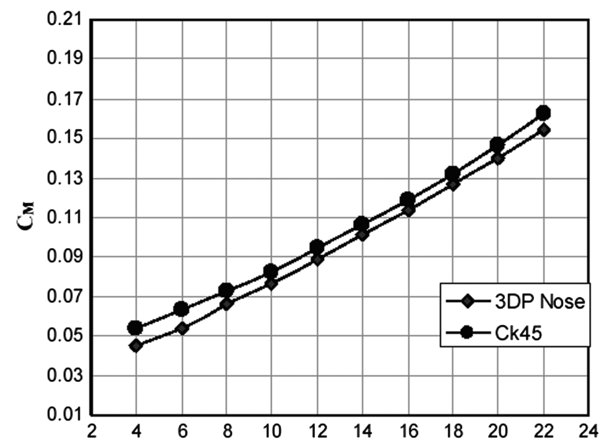

Fig. 6 Comparison of pitching moment coefficient at Mach 0.1.

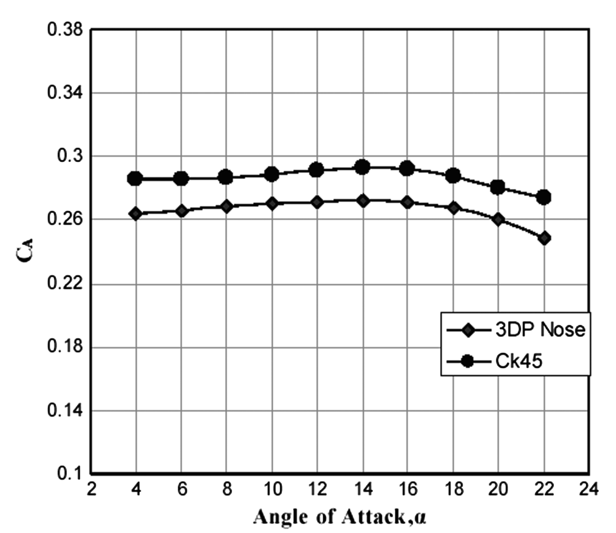

Fig. 7 Comparison of total axial force coefficient at Mach 0.1.

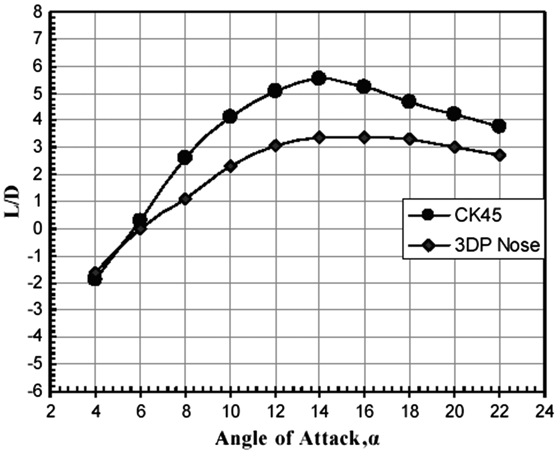

Fig. 8 Comparison of lift over drag at Mach 0.1.

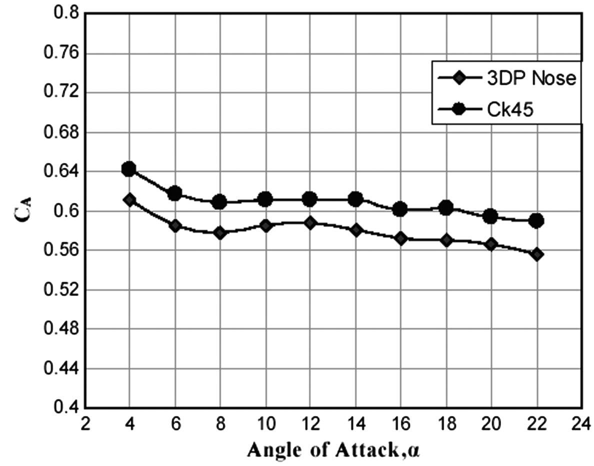

Fig. 11 Comparison of total axial force coefficient at Mach 0.3.

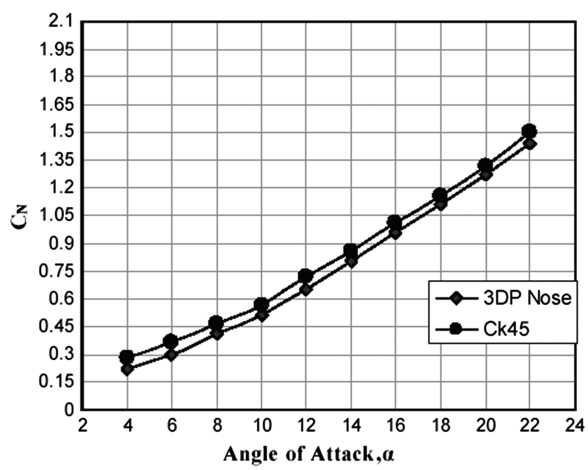

Fig. 9 Comparison of normal force coefficient at Mach 0.3.

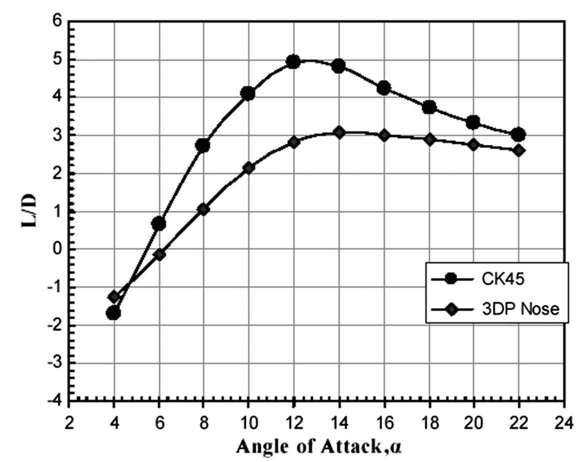

Fig. 12 Comparison of lift over drag at Mach 0.3.

tunnel speed was 150 m/s. For a small load measurement torque sensor is used and the arm of the torque sensor works as a mechanical amplifier. Test section provides a Mach number range from 0.10 to 0.50. Each Mach number above 0.5 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 −5 to +25 deg during each run. The diffuser section has movable floor and ceiling panels, which are the primary means of controlling. Table 2 shows the wind-tunnel test section characteristics. A six-hole probe or a wake rake can be used to determine the wake characteristics of a test subject. Pilot 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 analysis can be applied to determine the

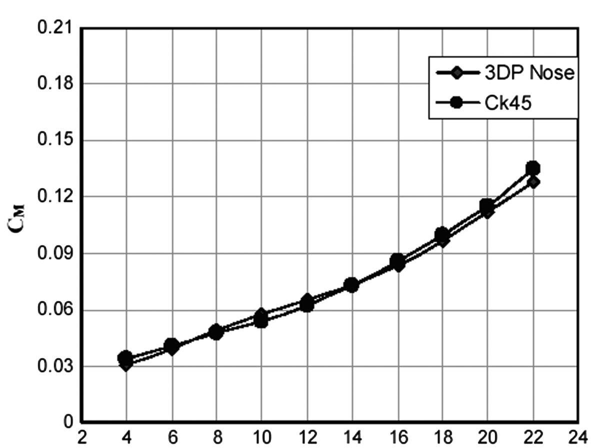

Fig. 10 Comparison of pitching moment coefficient at Mach 0.3.

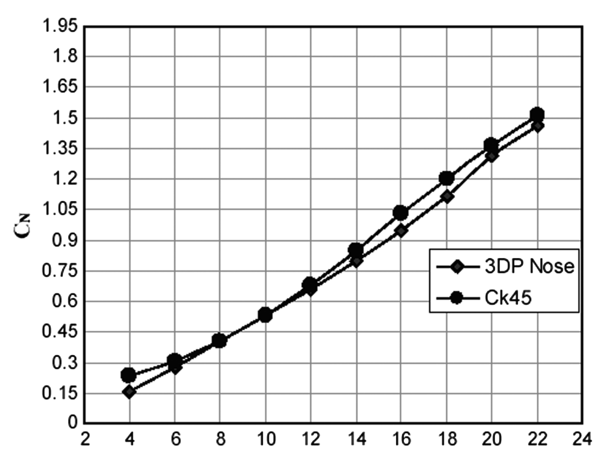

Fig. 13 Comparison of normal force coefficient at Mach 0.4.

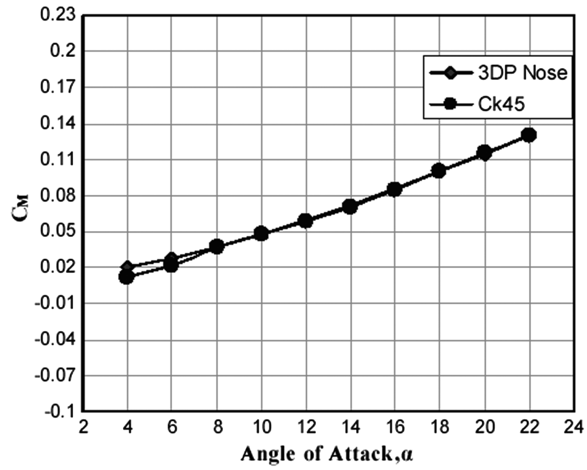

Fig. 14 Comparison of pitching moment coefficient at Mach 0.4.

boundary-layer characteristics. Longitudinal forces and moment's data refer 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.

VI. Test Parameters

A wind-tunnel test operating over Mach numbers ranging from 0.1 to 0.50 was undertaken to determine the aerodynamic characteristics of the models at 3 selected numbers for the precursor study. These Mach numbers were 0.10, 0.30, and 0.40 and the models were tested at the angle-of-attack ranges from 4 to +22° at zero sideslip. The reference aerodynamic axis system and reference parameters for the precursor study are shown in Fig. 4 [18]. Coefficients of pitching moment; normal force, axial force, and lift over drag are shown at each of these Mach numbers.

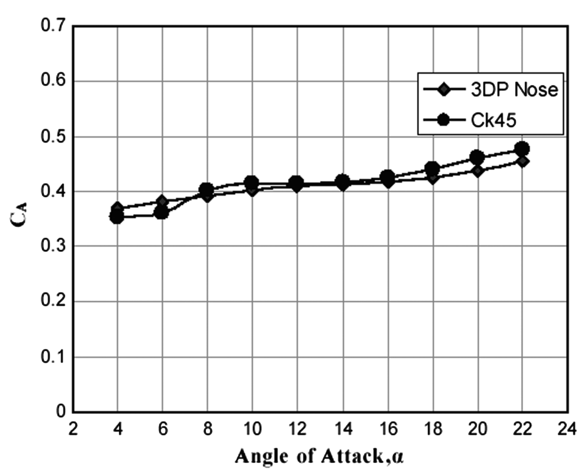

Fig. 15 Comparison of total axial force coefficient at Mach 0.4.

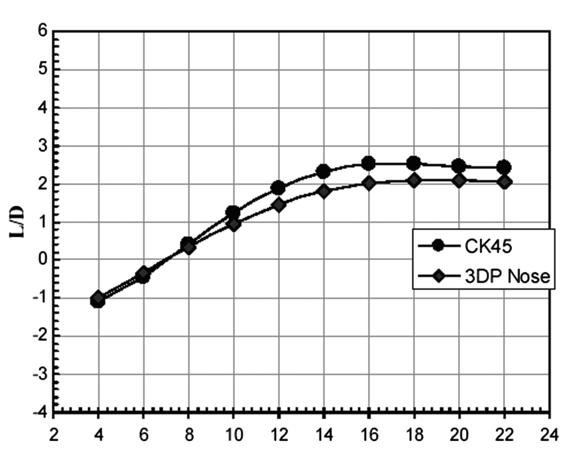

Fig. 16 Comparison of lift over drag at Mach 0.4.

VII. Results

The study showed that between Mach numbers 0.1–0.4, the longitudinal aerodynamic data shows significant agreement between the metal model and the metal model with the 3DP nose replacement. The subsonic data showed a slight divergence between the data, but the data trends were consistent. The data from the replacement part phase of the test is plotted in Figs. 5–16. The greatest difference in the aerodynamic data between the models at Mach numbers 0.1–0.5 was in total axial force and lift over drag. All the models showed significant compatibility in normal force (Figs. 5, 9, and 13). In general, it can be said that metal model with the r3DP nose longitudinal aerodynamic data replacement shows a slight divergence at higher angles-of attack when compared with the metal model data. The longitudinal aerodynamic data shows approximately a 2-deg shift in the data between the metal model with the 3DP nose replacement and the metal model for the total axial force (Figs. 7, 11, and 15), and approximately a 2.5-deg data shift for the lift over drag (Figs. 8, 12, and 16).

VIII. Conclusions

It can be concluded from this study that wind-tunnel model design that may incorporate both RP components and conventional metal components can be used in wind-tunnel testing for initial baseline aerodynamic database development. A typical aircraft development program usually needs at least four to five wind-tunnel models to adequately test the aerodynamics for a new airframe. Rapid prototype materials and methods have been considered as a potential source of improvement for conventional wind-tunnel models. The use of RP models will provide a rapid capability in the determination of the aerodynamic characteristics of preliminary designs over a large Mach range. The aerodynamic data shows some small discrepancies between the two model types. In these graphs it can be seen that RP nose has an effect on the aerodynamic characteristics up to high speeds where the effect is less drastic than at lower Mach numbers. Advantages of the precursor test include wind-tunnel model designs that are less expensive and require significantly less time to build than conventional designs associated with the prior art. According to the present test designs may incorporate RP components and conventional metal components, to optimize cost, construction time, and strength issues. The accuracy of the data is lower than that of a metal model due to its surface finish and its dimensional tolerances, but is quite accurate for this level of testing.

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