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Ground experimentation with 3D printed scramjet inlet models at hypervelocities

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ABSTRACT

3D printing technologies have gained acceptance by aerospace engineers as an alternative way for manufacturing models for experimentation in wind tunnels. This paper addresses ground experimentations with polymer-based 3D printed models of a single ramp scramjet inlet at Mach number near to 7.5 done in the T2 impulse hypersonic wind tunnel at IEAv. CAD models, shock wave theory, CFD simulations, and FEA predictions were all employed in synergy prior to fabrication of models by FDM and PolyJet 3D printing technologies. This methodology is shown in details herein. Based on high-speed schlieren imaging of the interaction between the 3D printed scramjet inlet and the hypersonic airflow, these 3D printed models have yielded satisfactory aerodynamic performance, showing reasonable thermal and structural survivability under dynamic pressure around 58,6 MPa. Also, the 3D printed scramjet inlets tested herein have shown remarkable versatility in terms of fabrication cost, elapsed time and model handling.

1. Introduction

With the advent of the 3D rapid prototyping techniques [1,2] such as stereolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM) and PolyJet around two decade ago, the use of 3D printed models by experimentalists for aerodynamic studies in wind tunnel facilities has became more usual as the 3D printing has proven to be a success in fabricating physical models for ground-tests directly from a CAD model in an additive, layer-by-layer way, while saving time and money [3–8]. The majority of papers published in the literature about the application of 3D printed models in wind tunnel tests, concerns mainly about subsonic and supersonics, and a few of them about hypersonic. Thus, there is a lack of works involving 3D printing technologies in hypersonic ground-tests, demanding more experimental investigations.

In 2006, the Laboratory of Aerothermodynamics and Hypersonics Prof. Henry T. Nagamatsu at the Institute for Advanced Studies (IEAv) in São José dos Campos, Brazil, initiated research and development on aerothermodynamics and hypersonic oriented towards the 14-X project, an unmanned scramjet-powered hypersonic aerospacecraft designed to fly at Mach 10 or 3017 m/s at about 30 km of altitude [9,10]. The 14-X project has been the result of a continuous effort by the Brazilian Air Force High Command for alternative hypersonic technologies for safe, cheap and eco-friendly access to space.

Currently, the laboratory has used machining metallic models for scramjet experimentation in the IEAv impulse hypersonic wind tunnels. In order to reduce the elapsed time or test cycle from the execution of the CAD model to the acquisition of the experimental data as well as the fabrication costs, the laboratory is now investing in 3D rapid prototyping technologies for production of airframe-integrated scramjet engine models for hypersonic ground-tests, aiming to benefit from the following advantages:

- Thermoplastic models lighter than steel and even aluminum ones, allowing them to be easily handled for instrumentation and installation in the test section of the hypersonic facility;
- Geometrical complexity superior to that offered by the conventional computer numerical control (CNC) machining, which

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Table 1
Comparison between FDM and PolyJet printers [11].

	Fortus 900 printer (FDM)	Object 500 Connex 2 printer (PolyJet)
Operation		
Process time	Slower build speeds	Faster build speeds
Pre-process	Simplicity of file setup (less than 5 min)	Easy file setup plus user control
Post-process	Faster manual model cleaning	Longer automated model cleaning
Operating expenses	Material cost per cm^3 is less	A bit higher because of consumables
Model characteristics		
Surface finish	Visible layer lines and “tool paths”	Smooth, glossy surface
Feature detail	Not so small features	High resolution and fine features
Stability	More stable over time and under load	Similar from the date of manufacture
Size	Comparable mid- and large-sizes	Comparable mid- and large-sizes
Materials		
Rigid	Similar rigidity	Similar rigidity
Flexible	No rubber-like options	Rubber-like options
Durable	More durable thermoplastics	Poor durability
Transparency	Opaque only	Either opaque or transparent

allows the model to be manufactured with internal passages for instrumentation and curved-surface parts in an uncomplicated fashion;

- Dimensional accuracy (in length, width and height) equivalent to that obtained by CNC machining, allowing the 3D printing of models with small parts and fine details;
- See-through models made of translucent thermoplastics in contrast with the opacity of steel and aluminum, which is ideal for visualization of the flow pattern;
- Smooth surface finish similar to that obtained by CNC techniques, which is desirable to mitigate the effect of roughness on the boundary layer transition over the 3D printed model;
- Thermoplastic models with mechanical and thermal characteristics that may allow them to with stand the transient loads imposed by impulse hypersonic wind tunnels.

This paper describes in details the methodology of using 3D printers running on FDM and PolyJet technologies in synergy with CAD models, CFD and FEA simulations for design and manufacture of 3D printed models of a planar single-ramp scramjet inlet, followed by a brief overview of the experimental set-up such as the T2 impulse hypersonic wind tunnel and the high-speed schilirien imagery technique. Next, discussions are presented regarding the initial experimental results about the airflow behavior over the 3D printed scramjet inlet model at Mach number near to 7.5, and the thermal–structural response of the 3D printed model under dynamic pressure of around 58,6 kPa. Finally, the experience and lessons learned from the use of such 3D printed models in hypersonic are outlined.

2. Methodology

2.1. FDM & PolyJet 3D printers

Fortus 900 and Object 500 Connex 2 3D printers, two of the most advanced additive manufacturing (AM) technologies nowadays, have been utilized for FDM and PolyJet printing, respectively, of the scramjet inlet models investigated herein. Both printers are from Stratasys Company [11]. The application of both printers to manufacture the scramjet inlet models has allowed us to investigate each printing technology in terms of operation, model characteristics and material options, as listed in Table 1. Basically, in the FDM printing technology, a thermoplastic filament under high pressure feeds a heated chamber, where the extrusion process occurs continuously such that a thermoplastic layer is formed. Such a process repeats until the scramjet inlet model is manufactured layer-by-layer from bottom to top. On the other hand, in the PolyJet printing technology, a carriage containing various inkjet heads and ultraviolet (UV) lamps crosses over the work space while depositing tiny droplets of photopolymers that solidify when exposed to the UV light, thereby forming a thin layer of material. This layering process repeats to form the scramjet inlet model.

Table 2
Properties of Ultem 9085 thermoplastic and RGD535 photosensitive polymer [11].

Physical properties	Ultem 9085	RGD535
Ultimate strenght [MPa]	71.6	55–60
Elongation at break [%]	6	25–40
Modulus of elasticity [MPa]	2200	2600–3000
Flexural strength [MPa]	115.1	65–75
Flexural modulus [MPa]	2500	1700–2200
Heat deflection temperature [°C]	153 @ 1.8 MPa	58–68 @ 0.45 MPa
Izod notched impact [J/m]	106	65–80
Shore hardness (D)	–	85–87
Rockwell hardness (M)	–	67–69
Density [g/cm^3]	1.34	1.18

2.2. Thermoplastic & photopolymers materials

Two types of materials were used for 3D printing of the scramjet inlet models: Ultem 9085 thermoplastic and RGD535 Green photopolymer from the Digital ABS family, where the Fortus 900 3D printer employs Ultem 9085 filament while the Object 500 Connex 2 3D printer uses RGD535 liquid resin. The selection of such materials considered their physical properties as summarized in Table 2. The scramjet inlet models that were manufactured with Ultem 9085 were printed in a longitudinal – as well as in a transverse-layered manner in order to investigate the influence of the layer orientation not only on the physical properties of the models but also on the airflow characteristics over them.

2.3. Softwares (CAD, HAP, CFD, and FEA) and hardware

The INVENTOR® software from AUTODESK was used to produce a computer-aided design (CAD) model of the scramjet inlet whose geometry was based on the oblique shock wave theory written in the Hypersonic Airbreathing Propulsion (HAP) computer program developed by Heiser and Pratt [12]. Once the CAD model of the scramjet inlet was sketched, it was then exported as a STEP file to the FLUENT® software from ANSYS for computational-fluid dynamics (CFD) simulations, where the aerodynamic loads on the model at hypersonic speeds were numerically predicted. The same STEP file is then feeded into the ANSYS® software for deformation and failure predictions via Finite Element Analysis (FEA) for the CAD model under aerodynamic load. Finally, an STL file of the original CAD model is then exported to both 3D printers, where the CAD