Application of 3D printing technology in aerodynamic study

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Application of 3D printing technology in aerodynamic study

K Olasek and P Wiklak
Łódź University of Technology, Institute of Turbomachinery, Wólczańska 219/223, 90-924 Łódź, Poland
E-mail: krzysztof.olasek@p.lodz.pl

Abstract. 3D printing, as an additive process, offers much more than traditional machining techniques in terms of achievable complexity of a model shape. That fact was a motivation to adapt discussed technology as a method for creating objects purposed for aerodynamic testing. The following paper provides an overview of various 3D printing techniques. Four models of a standard NACA0018 aerofoil were manufactured in different materials and methods: Multi-Jet Modelling (MJM), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). Various parameters of the models have been included in the analysis: surface roughness, strength, details quality, surface imperfections and irregularities as well as thermal properties.

1. Introduction
Preparation of an appropriate model to conduct experiments is a crucial aspect of every science investigation. Usually, apart from the requirement to achieve a desired level of a model quality, it is also very important to keep in mind the costs and time of its manufacturing. Recently, development of technologies made the production of even very complicated objects simpler, cheaper and less time consuming. One of such techniques that can simplify life of every researcher seems to be a 3D printing (an example of additive manufacturing). This method of fabrication is a process of making a three-dimensional solid objects from a digital model. 3D printing is an additive process, where successive layers of material are laid down in controlled way in order to achieve desired shape. 3D printing is often put in opposition to traditional machining techniques, which mostly rely on the removal of material by methods such as drilling, turning, milling or cutting.

A 3D printer is a limited type of industrial robot that is capable of carrying out an additive process under computer control. The first working 3D printer was created in 1984 by Chuck Hull of 3D Systems Corp. From that point, various additive manufacturing processes, techniques and systems have been developing constantly. The 3D printing has begun to exhibit great applications potential and advantages in the aerospace, construction, architecture, automotive, power engineering, dental and medical industries, biotech (human tissue replacement), education and many other fields providing a cost-effective and time-efficient way to produce low-volume, customized products with complicated geometries and advanced material properties. Objects that are manufactured additively can be used anywhere throughout the product life cycle, from pre-production (i.e. rapid prototyping) to full-scale production (i.e. rapid manufacturing), in addition to tooling applications and post-production customization [1].

1 To whom any correspondence should be addressed.
Drop in prices of these devices in recent years effects in increase of their accessibility. Traditional models for tests performed in the wind tunnel are fabricated of light wood, aluminum (and other metals) or various plastics. Most of the models are manufactured with computerized numerical control (CNC) milling machines. That is why processing of these materials is not very difficult, but in most cases due to the complicated shape desired several machining processes are required. Due to this fact, operator’s skills, appropriate equipment and a lot of time is needed. It happens that for simple testing or classes (study cases) with students it is a much too big expense. Summarising all above, lower prices of 3D printers may become an opportunity for a more practical and accessible knowledge for students and more efficient aerodynamic investigations for researchers. However, not everything is so perfect. In aerodynamic experiment a crucial factor is proper preparation of tested elements surface. Various 3D printing techniques provides different quality and surface finish which is not always acceptable for certain application [2]. The following paper attempts to review chosen properties of rough 3D printouts and analyse them.

2. 3D printing technologies and materials
Aim of the research carried out was to evaluate the utility of most common 3D printing techniques for aerodynamic study. Similar field has been already explored by various research centres (e.g. [3], [4]). In order to perform a reliable comparison of most common 3D printing methods, four models of standard NACA0018 aerofoil have been created in various materials and technologies: Multi-Jet Modelling (MJM), Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM). Each of them is described briefly in table 1. The most crucial factor defining the 3D printing technology and influencing the properties of final product manufactured is the type of bulk material used. Depending on the fact whether a solid filament is extruded (FDM), fine powder is laser-sintered (SLS) or liquid is solidified by means of UV light curing (MJM), models of various quality and properties are obtained.

Table 1. The overview of the most popular printing techniques and materials.

<table>
<thead>
<tr>
<th>Type</th>
<th>Technology</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>Fused deposition modeling (FDM)</td>
<td>Thermoplastics: PLA, ABS, nylon</td>
</tr>
<tr>
<td>Granular</td>
<td>Selective laser sintering (SLS)</td>
<td>Thermoplastics, metal powders, ceramic powders</td>
</tr>
<tr>
<td>Liquid</td>
<td>Multi Jet Modeling (MJM)</td>
<td>Acrylic Plastic</td>
</tr>
</tbody>
</table>

Below a description of materials used for printing models discussed in this paper are presented.

ABS - Acrylonitrile Butadiene Styrene is a very popular material used in the industry. Most popular applications are the production of housings for electronic equipment, household appliances, automotive interior parts, sports equipment, and furniture. ABS is known as material to production of LEGO bricks.

Nylon - invented and developed by DuPont Company in 1935 is a synthetic polymer used to create fibres having high tensile strength. It is used, among others, in the production of textiles, ropes and veins as well as gears, bearings etc.

Alumide - The material formed in the sintering process blend of nylon and aluminium dust. It has medium strength and fidelity of detail. It can be polished. Suitable for printouts related to jewellery. Objects printed with alumide are not suitable for recycling.

UV Curable Acrylic Plastic – material used in MJM 3D printing technology. Models prepared from a liquid plastic, which is distributed on the platform by a number of nozzles of the printer, and then UV-cured. This type of material and technology are ideal for printing very fine details, or thin walls.

Table 2 presents the most significant parameters of discussed materials and 3D printing techniques [5], [6], [7].
Table 2. 3D printing materials data.

<table>
<thead>
<tr>
<th></th>
<th>Alumide®</th>
<th>PA 2200 (nylon)</th>
<th>UV curable acrylic plastic</th>
<th>ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D printing technology</strong></td>
<td>SLS</td>
<td>SLS</td>
<td>MJM</td>
<td>FDM</td>
</tr>
<tr>
<td><strong>accuracy</strong></td>
<td>±0.15mm</td>
<td>±0.15mm</td>
<td>±0.025-0.05mm</td>
<td>-</td>
</tr>
<tr>
<td><strong>min. wall thickness</strong></td>
<td>0.8mm</td>
<td>0.7mm</td>
<td>0.3mm</td>
<td>-</td>
</tr>
<tr>
<td><strong>density</strong></td>
<td>1.36g/cm³</td>
<td>0.93g/cm³</td>
<td>0.45g/cm³</td>
<td>1.02g/cm³</td>
</tr>
<tr>
<td><strong>tensile modulus</strong></td>
<td>3800MPa</td>
<td>1700MPa</td>
<td>26.2MPa</td>
<td>1627MPa</td>
</tr>
<tr>
<td><strong>tensile Strength</strong></td>
<td>48MPa</td>
<td>48MPa</td>
<td>22MPa</td>
<td></td>
</tr>
<tr>
<td><strong>flexural modulus</strong></td>
<td>3600MPa</td>
<td>1500MPa</td>
<td>n/d</td>
<td>1834MPa</td>
</tr>
<tr>
<td><strong>flexural strength</strong></td>
<td>72MPa</td>
<td>58MPa</td>
<td>41MPa</td>
<td></td>
</tr>
<tr>
<td><strong>elongation at break</strong></td>
<td>4%</td>
<td>24%</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td><strong>shore D - hardness</strong></td>
<td>76</td>
<td>75</td>
<td>n/d</td>
<td>n/d</td>
</tr>
<tr>
<td><strong>thermal properties</strong></td>
<td>172-180°C (melting point)</td>
<td>46°C (heat distortion temp. at 0.45 MPa)</td>
<td>190-240°C (melting point)</td>
<td></td>
</tr>
<tr>
<td><strong>recycling</strong></td>
<td>non recyclable</td>
<td>recyclable</td>
<td>most recyclable</td>
<td>recyclable</td>
</tr>
</tbody>
</table>

*a FDM accuracy depends on filament thickness and layer structure [8], [9]. b laser-sintered part density, c bulk density

3. Manufactured models
Aerofoil with complex structure adapted for aerodynamic study has been designed and printed in 4 different materials described in previous section. Model dimensions are 100mm chord and 170mm span. Due to costs reduction and material saving aerofoil is empty inside. Two ribs with holes improve model’s rigidity and enable easy mounting in the test section of the wind tunnel. Additionally two side segments have been manufactured with MJM technique. Segments assembled with the aerofoil extend its span to 300mm (see Figure 1). As only central part of the assembly is used for measurements, side segments were printed in one technology and can be applied with all 4 testing models. Aerofoil wall thickness along its circumference is constant and equals 4mm. Design details are presented in the Figure 2.

![Figure 1. Full aerofoil assembly with mounting system for wind tunnel testing - black SLS model & two MJM side segments.](image-url)
In order to allow static pressure measurements at the aerofoil surface a unique design was proposed. 48 channels with diameter of 1.5mm and 0.4mm are hidden in the shell. 1.5mm diameter channels are distributed in aerofoil's transverse direction along 55% length of its span (ca. 95mm). It gives a very large length to diameter ratio l/d=60. Such a solution is practically impossible to be fabricated using any other manufacturing method than 3D printing. Small measurement holes of diameter equal 0.4mm normal to aerofoil surface are evenly distributed along the aerofoil cross-section circumference.

Apart from pneumatic measurements, designed aerofoil was considered for Particle Image Velocimetry (PIV) experiment, thus, models should be black in order to reduce excessive light reflections. One of the SLS printout as well as the FDM one are originally made of black bulk material and do not require further processing. Acrylic plastic and alumide models could require darkening of the surface for wind tunnel testing if problems with proper quality of PIV measurements occurred. In Figure 1 MJM side segments and mounting shanks painted in black are shown.

![Figure 1 MJM side segments and mounting shanks painted in black](image1)

3D printed models vary in materials used for manufacturing. In the Figure 3 it is clearly visible how printed aerofoils differs from each other. A more specific comparison however, can be made after more detailed analysis of prepared models. Most findings and observations are listed in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>MJM</th>
<th>SLS</th>
<th>SLS (alumide)</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>color/opacity</td>
<td>translucent</td>
<td>black</td>
<td>silver (shiny)</td>
<td>black</td>
</tr>
<tr>
<td>surface roughness</td>
<td>low</td>
<td>moderate</td>
<td>moderate</td>
<td>high</td>
</tr>
<tr>
<td>surface irregularities direction</td>
<td>transverse</td>
<td>uniform</td>
<td>uniform</td>
<td>longitudinal</td>
</tr>
<tr>
<td>ϕ 1.5mm holes quality</td>
<td>most open</td>
<td>blocked</td>
<td>most open</td>
<td>excluded from design</td>
</tr>
<tr>
<td>ϕ 0.4mm holes quality</td>
<td>most open</td>
<td>blocked</td>
<td>blocked</td>
<td>excluded from design</td>
</tr>
</tbody>
</table>

4. PIV measurements

One of the experimental techniques used for measurements of printed aerofoil was Particle Image Velocimetry (PIV). Results presented in this paper are of the preliminary character and concern only black SLS model. Rest of the aerofoils are scheduled to be tested later.

PIV results are presented in the form of velocity field around the aerofoil. It gives a full information about the 2D flow velocity components in the proximity of the model. Aim of the experiment carried out was to obtain results for various angle of attack settings. Choice of the measurement plane aligned with the flow and perpendicular to the aerofoil allows to obtain full image of the flow around the aerofoil. Flow structures like separation bubble with reverse flow can be easily detected therefore while increasing the angle of attack. Such a procedure was applied to identify the moment of static stall and find the critical angle.
Figure 3. Examples of 3D printed NACA0018 aerofoil models in (a) SLS (black PA2200), (b) SLS (alumide), (c) MJM, (d) FDM technology.

A 2D measurement method was chosen, i.e. each camera pointing at different flow region (with slight overlapping enabling merging results). Cameras were placed in a vertical arrangement observing top and bottom surface of the aerofoil. Laser sheet optics was illuminating observed area from the top creating a plane parallel to the flow. Mirror located at the bottom of test section was used to reflect laser sheet in order to illuminate bottom of the aerofoil.

Experimental setup consisted of the following main components:

- double-pulse Nd:YAG laser from Litron (1200mJ max output, 4ns pulse duration, 1064/532nm wavelength),
- arm with optical system redirecting laser beam to desired position,
- laser sheet optics (cylindrical lens f=-20),
- two PIV cameras Imager pro x 4M from LaVision (2048x2048 pixels),
- Nikkor camera lenses (24-85mm, f2.8),
- mirror (reflectance R=100%) for illuminating bottom part of the aerofoil.

Flow images were captured by two cameras in a double frame mode (giving 4 images per one measurement). Maximum available frame rate of 7.26Hz was used for image acquisition. 100 instantaneous measurements were taken and then averaged to obtain mean velocity fields.

NACA0018 aerofoil model was mounted in the open test section of the subsonic wind tunnel at the Institute of Turbomachinery at the Lodz University of Technology [10]. For the aerofoil chosen (chord c=0.1m) and average flow velocity v=11m/s Reynolds number Re≈75000. Range of the angle of attack investigated was ±20° with 1° increment. Exemplary results are presented in the Figure 4. Basing on the following velocity fields critical angle has been defined to appear between 15° and 16° angle of attack. The same procedure is planned to be repeated for the rest of 3D printed models. The most crucial observation expected is to determine the influence of printouts surface quality (roughness, imperfections, etc.) on the separation layer formation.
Figure 4. Exemplary PIV results of NACA0018 aerofoil SLS 3D printed model for (a) +15°, (b) +16°, (c) -15°, (d) -16° angle of attack.

5. Further development and perspectives

Results and observations presented in this paper are only the beginning for larger research campaign that includes for instance:

- continuation of PIV measurements,
- performing pneumatic measurements by means of designed system of channels,
- direct lift and drag force measurements with the use of aerodynamic balance,
- lift and drag force measurements basing on PIV measurements [11],
- determination of roughness influence and printouts quality on aerodynamic characteristic of the aerofoils,
- investigation of embossed and engraved artefacts induced by 3D printing technology as a vortex generation modifying the flow,
• determination of influence of the channels inside the aerofoil’s shell on flow parameters,
• study aimed at comparison of untreated 3D printed aerofoils and models after surface smoothing process.

6. Conclusions
As for the summary of presented study following observation and conclusions can be drawn:

• 3D printing is a quick, simple and relatively cheap method for production of models for aerodynamic testing.
• As it was presents a wide range of materials and technologies with various features and parameters are available (scope presented in the following paper is very limited as a choice of representative popular technologies only). This enables a potential researcher to choose the right technology fitting exactly his needs and fulfilling the requirements of prepared experiment.
• Thin-walled and tough models have been successfully manufactured.
• It is possible to 3D print holes of very high length to diameter ratio as well as very small objects (like measurement holes of 0.4mm diameter). Still however not all of presented 3D printing technologies give perfect results. Quality strictly depends on method and material chosen.
• Certain 3D printed models are suitable for only limited temperature range. Otherwise they can soften, deflect, deform, etc.

References

[9] Ebel E and Sinnemann T 2014 Fabrication of FDM 3D objects with ABS and PLA and determination of their mechanical properties RTezjournal