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ADVANCEMNETS IN 3D PRINTING TEHNICQUES FOR LOW-SPEED AERODYNAMICS IN VEHICLE VENTILATION – PART 2

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Abstract: *This study investigates 3D printing advancements for low-speed aerodynamics in vehicle ventilation, focusing on accuracy and precision. Surface rugosity and dimensional measurements of 3D-printed air diffusers were conducted using advanced technologies. Surface roughness parameters were evaluated, revealing variations among printing techniques. 3D scanning was used for comparing the dimensional data, highlighting inconsistencies in FDM, SLS, and DLP methods, while SLA exhibited superior accuracy. Notably, SLA printing demonstrated minimal deviations, emphasizing its potential to enhance aerodynamic performance. This research underscores the significance of precision in 3D printing for optimizing vehicle ventilation and air quality. The findings suggest that SLA technology holds promise for revolutionizing automotive ventilation systems, offering improved functionality and driving experience.*
Keywords*: 3D printing, Air diffusers vehicles, HVAC, SLA, SLS, DLP, FDM*

1. INTRODUCTION

As shown in the first part of this study, we know that 3D printing has brought a transformation to the manufacturing sector, opening new avenues for creating intricate and personalized components in various domains, like aerospace, medicine, and automotive engineering [1].

Effective air distribution within a vehicle plays a decisive role in ensuring an optimal indoor environmental quality (IEQ) across diverse vehicle types, from automobiles and trains to buses and airplanes [2-4], or even in enclosed spaces like the cabin of an International Space Station [5, 6]. In these confined spaces, air quality exerts a significant impact on the well-being and physical health of both passengers and crew members.

The vehicle's HVAC (Heating, Ventilation, and Air Conditioning) system plays a crucial role in ensuring an uninterrupted flow of fresh air while efficiently removing pollutants from the surroundings through dilution. High-induction air diffusers equipped with lobed apertures have emerged as a promising solution for enhancing the indoor environmental quality (IEQ) within vehicles [7]. This discovery is also validated in. .[8], who emphasize the effectiveness of these air diffusers in supplying enclosed spaces with fresh air and encouraging its mixture with ambient air. This is not a novel idea. In fact, prior investigations conducted in [9-16] demonstrated significant improvements in thermal comfort when lobed diffusers were used, without causing detrimental effects on pressure drop or sound pressure levels. More research on this subject has been caried out in [17, 18] greater air induction rate devices being developed.

Producing innovative shapes for air diffusers presents a major challenge due to intricate geometries. 3D printing offers a compelling solution [19], enabling engineers to craft complex designs, lightweight structures, and functional prototypes with remarkable precision.

Several key 3D printing techniques have emerged for vehicle ventilation components. Stereolithography (SLA), Digital Light Processing (DLP), and Selective Laser Sintering (SLS) are noteworthy methods lauded for their versatility and capabilities.

SLA, known for excellent resolution and surface finish, produces high-quality detailed parts. Engineers leverage SLA for intricate ventilation ducts, optimized diffusers, and precisely designed grilles that ensure smooth airflow.

DLP, an SLA alternative, offers faster speeds by curing entire layers at once. While its resolution may not match SLA's due to light bleeding, DLP-based 3D printing creates complex geometries and functional prototypes, suitable for rapid prototyping and iterative design optimization.

SLS employs laser sintering to fuse powdered materials, crafting functional prototypes and end-use parts from diverse materials, some with impressive mechanical properties.

In this article, we explore the subject of 3D printing advancements for low-speed aerodynamics in vehicle ventilation from the lens of accuracy and precision. To this end, we will measure the intricately shaped innovative diffuser's surface roughness and the dimensions of the 3D-printed piece using a state-of-the-art 3D scanning technique.

2. MATERIAL AND METHOD

2.1. Surface roughness measurement

For the roughness measurement the MarSurf PS1 equipment was used (Fig. 1). MarSurf PS1 is an advanced surface measurement equipment developed by Mahr, a leading company in high-precision measuring technology.

Figure 1. MarSurf PS1 equipment

The device's purpose is to offer precise and reliable solutions for evaluating surface roughness. Equipped with state-of-the-art technology, the MarSurf PS1 can measure various roughness parameters, such as the arithmetic mean of the profile (Ra), the profile peak height (Rz), and other relevant indicators.

The Ra parameter, also known as the arithmetic mean of the profile, is a fundamental aspect of surface roughness measurement. It represents the average height deviation of the roughness profile from the mean line within a sampling length.

The measurement process involves recording the surface profile using MarSurf PS1 equipment, and then calculating the deviations between the actual profile and a median line that passes through all the profile points. The absolute values of these deviations are then averaged to obtain the Ra value. The significance of Ra lies in its ability to provide valuable information about the overall roughness and texture of a surface. Industries such as automotive, aerospace, and precision manufacturing rely on Ra measurements to ensure the quality and functionality of their products, as well as to meet specific design and engineering requirements.

The Rz parameter, known as the peak-to-valley height of the profile, is another critical aspect of surface roughness evaluation. It represents the maximum vertical distance between the highest peak and the lowest valley within a specified sampling length. The measurement procedure for Rz is similar to that of Ra, where the surface profile is recorded using MarSurf PS1 equipment, and the maximum peak-to-valley height is determined.

The importance of Rz lies in its ability to provide crucial insights into the depth of surface irregularities. Industries that deal with sealing applications, friction, and wear, such as automotive, hydraulic systems, and metalworking, rely heavily on Rz measurements to ensure optimal performance and longevity of their products. Additionally, Rz plays a vital role in determining the suitability of surfaces for specific functional requirements, such as adhesion and coating applications.

2.2. Dimensions measurement

For the dimensional measurement, we used the surface 3D scanning method. There are a lot of companies that produce 3D scanners, but the one we used was the HandyScan 700 Silver Series from Creaform 3D (Fig. 2). They are the leading manufacturers of 3D scanners now, having many scanner types, from simple and easy to use handy scanners, to the ones operated with numerical coding by 7 axis robot arms. We used VXelements software to connect the scanner and insert all the needed characteristics, the software being able to accept all the accuracy characteristics that the scanner can give. The way that this device is normally used is by scanning the surfaces of an object and then refining the 3D surfaces in order to be able to have it as a 3D model.

Figure 2. HandyScan 700 Silver Series, Creaform 3D equipment

The 3D scanner is capturing the shape and appearance of real-world objects and it's converting them into digital 3D models. The way that the scanner captures data is by emitting some form of energy, such as laser light or structured patterns onto the object surface. The interaction between the emitted energy and the object's surface provides information about the object's shape and geometry. As the emitting energy interacts with the surface, the scanner's sensors measure the distance and depth of the surface points. The process is known as surface measurements or point cloud acquisition. This data represents a set of tree-dimensional points in space, and this collection of points is called "point cloud", because each point in the cloud represents a specific coordinate (x, y, z) and may also store additional information such as color or intensity. Once the point cloud is generated, it undergoes various post-processing steps to clean up noise, remove outlines, and enhance the overall quality of data. This step is called "Data processing" and is crucial to obtain an accurate representation of the scanned object. After this, the mesh generation moment comes, where the point cloud is used to create a digital mesh representation of the object's surface. The final step is the 3D model creation/generation, where the mesh is taken and used as reference in order to have the perfectly measured points or surfaces, helping the engineer with all the data needed for the 3D model generation. The scanner is capable of delivering high accuracy surfaces as long as the person that is operating the scanner has a long experience in using the device. For a good scan, the person has to have really steady hands who don't tremble, and good muscle training in order to have smooth transitions when is going around or changing the proximity towards the object that is scanned.

In terms of technical specifications, the scanner is capable of delivering a surface accuracy up to 0.030 mm and a volumic accuracy of 0.020 + 0.060 mm, based on the part size. The scanner is capable of reproducing mesh resolutions of 0.200 mm at a measurement rate of 480,000 measurements/second. The recommended stand-of distance is somewhere around 300 mm, and the optimal depth of field is 250 mm. The ideal operating temperature range is 5 to 40 °C and the relative humidity range 10 to 90%. In our case the scan was performed at 22°C and 55% relative humidity.

3. RESULTS AND DISCUSSIONS

3.1. Surface rugosity measurement

The MarSurf PS1 equipment, with its advanced capabilities, played a pivotal role in accurately measuring surface roughness parameters like Ra and Rz. These parameters offer valuable information about the surface texture, helping us to evaluate the quality, performance, and compliance with design specifications.

Figure 3. a. Positioning of the printed diffuser in other to take the roughness measurements; b Positioning of the MarSurf PS1 equipment; c. Ra parameter measurement; d. Rz parameter measurement.

Measured absolute roughness and relative deviation for Ra and Rz parameters, for the printed air diffusers (Fig. 3), are presented in Table 1.

Table 1

Absolut rugosity and relative deviation for Ra and Rz rugosity parameters

Printing technology	Ra [μm]	Ra relative deviation [%]	Rz [μm]	Rz relative deviation [%]
FDM	16.43	487%	78.3	444%
SLS	12.1	332%	57.1	297%
DLP	3.254	16%	14.4	0%
SLA	2.801	0%	15.6	8%

The roughness measurements revealed, as expected, that FDM and SLS printed air diffusers exhibited the highest roughness. However, the differences in roughness between DLP and SLS printed air diffusers were relatively small.

The relative deviation between these two parameters indicated a certain level of equivalence in terms of roughness, with a slight advantage observed for the SLA method.

3.2. Dimensions measurement

Based on the 3D scanning data, there are going to be comparisons made between the 3D model that was given to be printed, and the printed object itself (Fig. 4). In order to do such an operation, the surface obtained from the 3D scanning procedure must overlap perfectly with the 3D model. For this operation we used PolyWorks Inspector, software made and sold by Innovmetric company.

The measurements for every model had to be made from two sides. The reason being that the signal sent by the scanner was not able to reach to the other side because the lobes and the blades/rings inside the model were in the way.

As mentioned before, the software used for the 3D scanning procedure was VXelements and in this program, the boundary conditions for the scanner were set, they are presented in Table 2.

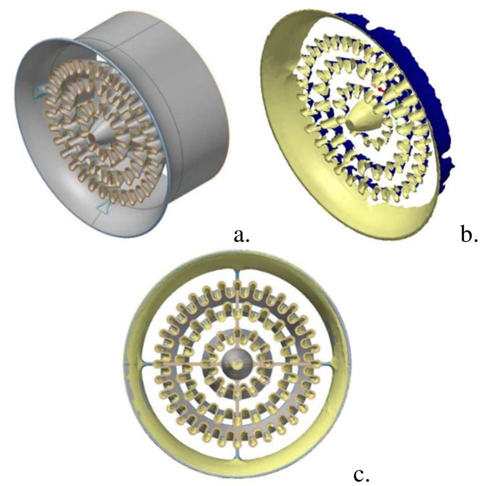

Figure 4. a. Original 3D model; b. Scanned 3D model as surfaces; c. The overlapped scan with the 3D model

Table 2

Scanner settings in VXelements

Scanner Parameters	Values
Resolution	0.40 mm
Optimize Scan Mesh	50 %
Decimate Scan Mesh	40 %
Boundaries Optimization	50 %
Auto-Fil Holes	0 %
Remove Isolated Patches	0 %
Use Clipping Planes	Negative
Fill Positioning Targets	Positive

3.2.1. FDM technique measurements

The 3D printed model was not in the range of good quality ones, having multiple small wires of plastic in between the lobes and the rings, Figure 5.

Due to this fact, the 3D scanning procedure was complicated, having some trouble when the mesh surface was generated, causing the effect of super layering.

The explanation for this effect is complicated, because the scanner receives a signal back from the surface and understands this signal as a shadow, the reason being that the objects, in our case plastic strings, are thinner than the minimal resolution capable to be seen, for our 3D scanner 0.2 mm of mesh resolution. This meant that the operation of cleaning the mesh took more time to finish.

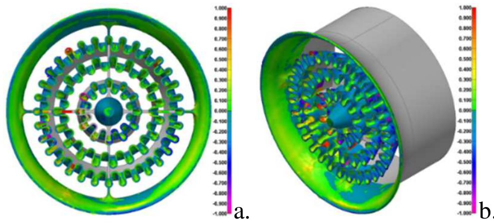

Figure 5. FDM Measurements: a. Front side view; b. Top left

As was mentioned before, the FDM technique for this case had a poor printing quality. Looking at Figure 5, there are large spots on the outer shell where the dimensions are positive and negative at the same time. Values such as +0.28mm and -0.26mm are easy to be seen, but that is not all, because there are a lot of small spots where the dimensions are going from +0.7mm to -0.65mm.

In the following figure a sectioned view is presented, where it's easier to be seen the fact that there are so many areas where the instability in printing is easily noticeable.

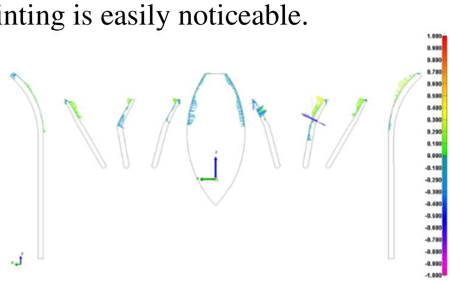

Figure 6. Sectioned view of the FDM front side measurements

For the back side, the dimensions are not looking great at all. This is crucial when the process of overlapping is started, causing multiple tries for the procedure usually resulting in failure of having a prefect overlaying of the two parts (the scanned model and the 3D model).

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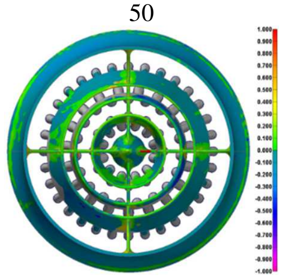

Figure 7. FDM Measurements - Back side view

The main concern for this model was if the printer is able to reproduce the lobed area, the three blades and the streamlined body in the middle. In Figure 5 it easy to see that the lobed area had many spots where the dimensions are going from +1mm to -1mm. As it can be seen in Figure 7, the inner rings have a large persistence of -0.25mm and +0.2mm areas. Although, one of the rings is mostly off centered suffering values of -0.6mm.

On the largest perimeter of the outside walls, there is a value of -0.25mm. It's clearly seen that there are even smaller values where the dimensions are going even to -0.6m, but these zones don't have a big influence of the phenomenon that is happening on the inner part of the walls where the values are going from +0.2mm to -0.3mm.

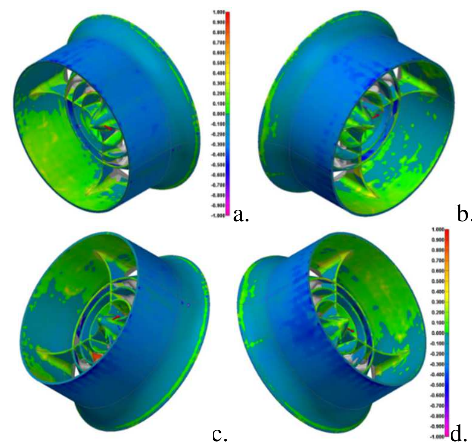

Figure 8. Four views of the FDM back side perspective: a. Top right; b. Top left; c. Bottom right; d. Bottom left

In conclusion, there is no reason why there are so many instabilities in the printed part. The process had no problems from start to finish, the axis speeds had a good consistency, and the nozzle temperatures were unchanged. All the small and large defects that the model has are a huge problem for the airflow that has to go through the model because this can affect the air performance of the design.

3.2.2. SLS technique measurements

The overall quality of the 3D printed part looked poor but wasn't as bad as the one obtained from the FDM technique. The plastic strings that previously were found in between the lobed area and in between the blades, for this model they were no longer to be found.

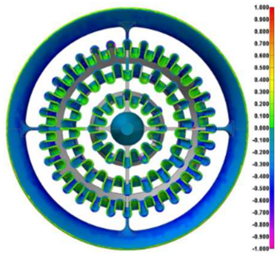

Figure 9. SLS measurements - Front side view

For this method, the problem appeared in the form of low thickness for all the dimensions. It can be seen in Figure 9 and Figure 10, where the inner part of the outside wall has a smaller thickness than the ideal model with -0.52mm.

The lobed area was affected as well, the model having a different shape for the radius of most of the lobes. The continuous radius was printed in a squared form, this coupled with the fact that all the dimensions had a smaller thickens than the corect model, led to dimension offsets of -0.64mm, and in some zones even -1mm. The plus side didn't look good either, having dimensions offsets of +0.26mm or +0.30mm.

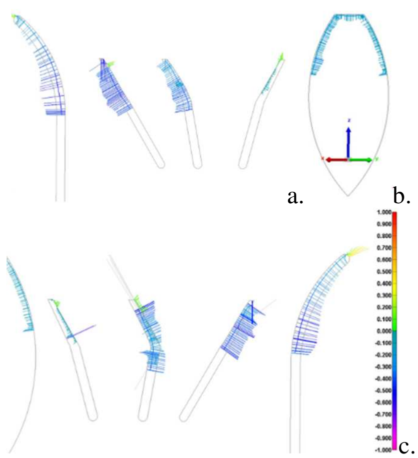

Figure 10. SLS measurements: a. Left side; b. Middle side; c. Right side

The thickening material continued for the back side as well, having smaller dimensions for the inner walls of the model reaching values of -0,64mm and for the outside walls going up to +0,22mm. The outside wall had some regions where the dimensions reading was unexpected having negative values of -0.2mm, this fact leads again to more time spent for the fitting/overlapping procedure.

The inner blades are surprisingly good in a visual and structural form, but they have the same problem as the rest of the model, the walls have a smaller dimension than they should have.

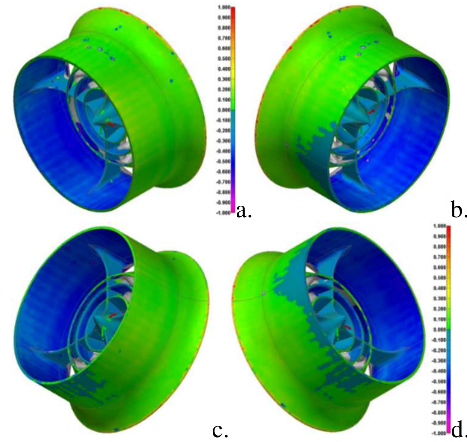

Figure 11. Four views of the SLS back side perspective: a. Top right; b. Top left; c. Bottom right; d. Bottom left

The main concern for this type of 3D printing was the lobed area where the shape of the radius surfaces was not round at all, but worse than that having a squared shape.

Regarding the thickness issue, having less material on the important structural parts of the 3D model can lead to fatal consequences of structural deformations, material cracking or complete breaking when this is used for experimental testing.

3.2.3. DLP technique measurements

In terms of quality, the front side of the printed model looks good. This was expected given the fact that the DLP technique is one of the most stable, offering precise and detailed plastic prints for various applications (Fig. 12).

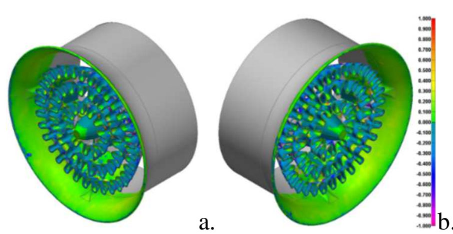

Figure 12. DLP measurements - Front side view: a. Top left; b. Top right

Although the fact that the Digital Light Processing technique is known for its precision in the 3D printing world, for our application the dimensional characteristics are not the best ones. The inner diameter for the outside wall is smaller having a decrease of -0.14mm in overall dimension.

The lobed area is better than the ones received from FDM and SLS, having deviation in dimensions of -o.48mm, but this phenomenon was found only in the bottom of the lobes, place where the connection between the lobes and the blades is made. This scenario is presented in a more detailed manner in Figure 13.

The back side of the part is not looking bad either, having small dimension offsets for the outside walls. The curved part of the outside walls has a deviation of +0.8mm, and the rest of the outside wall going inside with the deviation having a value of -0.50mm. Looking inside, the inner walls of the outside duct have some alteration for the proposed dimensions, going from -0.48mm up to +0.70mm.

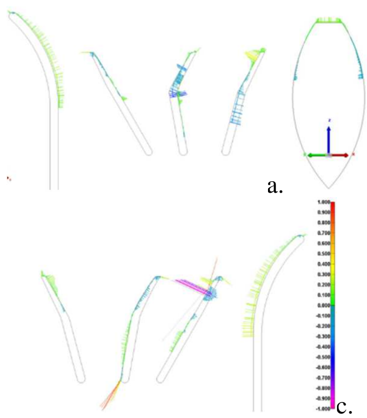

Figure 13. DLP measurements: a. Left side; b. Middle side; c. Right side

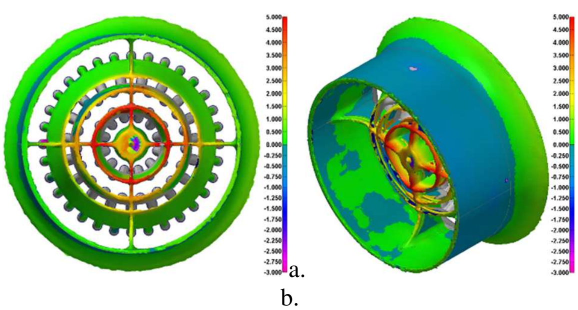

Figure 14. DLP measurements – a. Back side view; b. Top right view

Knowing the way that most 3D printers are working, we know that if the model has a section that is going to be later connected to the main part, there are a lot of automatic supports that are created in other to sustain the specific part until this one is going to meet with the main structure. In our case this phenomenon did not manage to take place. As can be seen quite clearly in Figure 15.

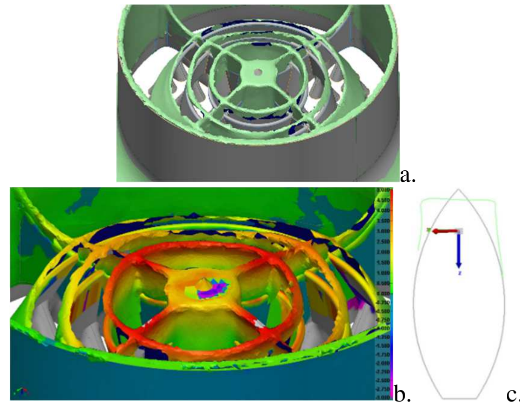

Figure 15. DLP measurements – a. Overlapped scan surface with the 3D model; b. Inner blades measurements; c. Sectioned view of the streamlined body

The whole inner section of the main part has a deviation of more than +5mm and not only that, but the edges of the blades also have a wavy shape.

This means that the supports that were needed to hold the material in place until the inner part is united with the outside part, failed to have the required that is beneficial to this kind of structure.

Although the blades angle looks particularly good, even if they are longer in some part with 5mm, the angle remained unchanged and the surface deviation of the blades, at least for the bigger inner ring was not more than +0.5mm. The other two circular blades remain true to the angle but have bigger offsets in dimension.

The anomaly that was spotted is in the middle of the part where the streamlined body is found. For our case, the pointy side of the body is flat, and the printer continued to poot material over that flat surface creating a cylindrical shape. For this to be understood better, Figure 15 c. shows a better view for the 3D printed part.

In conclusion, a 3D part like this one can bring problems for the air that has to go through all the elements inside. First of all, the streamlined body is called and looks like that because air should go over its surfaces as ideal as possible witch in this case something like that is not possible.

The blades, being longer and having a different shape than the proposed ones are going to change a lot of areas where the air should go through, meaning that the output performances of the overall diffuser are incorrect.

3.2.4. SLA technique measurements

Having a better stiffness of the material, smoother surfaces and heightened accuracy of small details, the SLA technique is by far much better and proves to have a superior quality compared to the other 3D printing methods used until now.

The lobed geometries have a good consistency of dimensions, even if there are deviations of maximum +0.4mm and minimum -0.4mm, the overall form of the lobes is improved when it is compared with the other three methods.

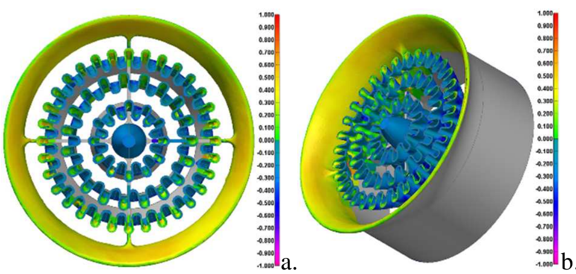

Figure 16. SLA measurements – a. Front side view; b. Bottom left view

Looking at the curved profile of the geometry, it’s obvious to see that there are some differences in dimension. The tip has a small deviation of maximum +0.1mm, but as the curvature continues to go towards the inside of the geometry, there is an increase in the offset of the printed geometry reaching the value of +0.62mm.

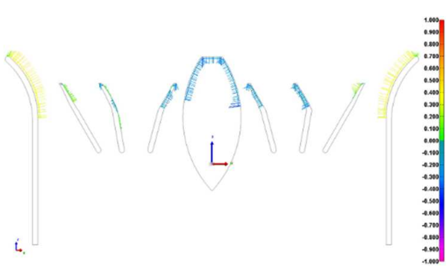

Figure 17. Sectioned view of the SLA front side measurements

The back side is not perfect either, coming with deviations of dimension from -0.5mm for the outside wall, having small spots where the dimensions are going in the region of -0,7mm. This meant that the inside surface of the wall is going to have a plus value, which is corect because there are dimensions that go outside the original geometry with an overall dimension of +0.38mm and a maximum of +0.5mm.

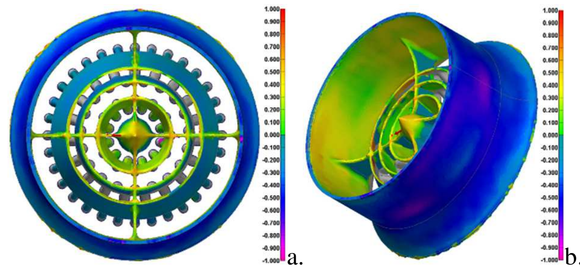

Figure 18. SLA measurements: a. Back side view; b. Bottom right view

The bigger two inside deflector blades are printed as close as possible to the expected dimensions, being only -0.02mm in deviation from the proposed geometry, even if the tip of the blades is longer with +0.3mm, the overall dimensions are close to what it should be.

The aerodynamic sphere that is positioned in the center of the 3 D model is longer than it should be but not with too much, having an overall increase in dimension of +0.5mm. The smallest blade deflector is again, with a corect angle, but the deviation is inverted compared to the other two, having a +0.18mm deviation.

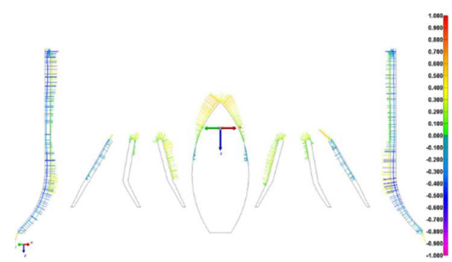

Figure 19. Sectioned view of the SLA back side measurements

In conclusion, for this application, the SLA method of 3D printing proves to be the best one. Being close to the dimensions that the imported 3D model has and being able to create all the complicated geometrical forms as close as possible. As revealed in Tab 7, the overall roughness for the SLA printed part is one of the best, meaning that the geometrical quality of the printed model is the best of the four that we used.

All these facts support the reason why an SLA type 3D printer is more expensive than an DLP, SLS or FDM type.

4. CONCLUSIONS

This article has delved into the realm of 3D printing advancements for low-speed aerodynamics in vehicle ventilation, with a specific focus on accuracy and precision. Through the utilization of state-of-the-art technologies and methodologies, we have explored the surface rugosity and dimensional measurements of 3D-printed air diffusers. The MarSurf PS1 equipment played a pivotal role in assessing surface roughness parameters like Ra and Rz, offering insights into the quality and compliance of the printed components. The data revealed variations in roughness among different 3D printing techniques, with slight advantages observed for SLA.

Furthermore, the dimensional measurements using the surface 3D scanning method, particularly the HandyScan 700 Silver Series from Creaform 3D, provided a detailed analysis of the accuracy of the printed models. The FDM technique showcased considerable inconsistencies in dimensions, with noticeable deviations affecting the airflow performance of the design. SLS exhibited improved results compared to FDM, yet still displayed issues in thickness and shape. DLP demonstrated better overall quality, but variations in dimensions persisted, affecting critical features such as the streamlined body and inner blades.

Among the techniques, the SLA method stood out for its superior accuracy, minimal deviations, and ability to replicate intricate geometrical forms closely. The high precision of SLA printing has a positive impact on the aerodynamic performance of the diffuser.

Overall, the results of this study strongly support the notion that the SLA technique stands as the superior choice for 3D printing air diffusers for HVAC systems in vehicles. The combination of precision, material versatility, complex design capabilities, dimensional stability, and efficient production make SLA the ideal solution for achieving optimal indoor environmental quality and thermal comfort in vehicles.

Thus, this study demonstrates that choosing the appropriate 3D printing technique is crucial in achieving high-quality automotive components related with fluid flow. Stereolithography (SLA) represents a superior option for attaining the desired precision and detail. The continued development of SLA technology and its application in various areas of the automotive industry will open new possibilities and contribute to advancing the production of complex and precise components.

5. ACKNOWLEDGEMENTS

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TEHNICI AVANSATE DE IMPRIMARE 3D PENTRU AERODINAMICA LA VITEZĂ REDUSĂ ÎN VENTILAȚIA VEHICULELOR – PARTEA 2

Rezumat: Acest studiu investighează tehnica actuală în imprimarea 3D asociate curgerilor la viteză redusă în domeniul ventilației vehiculelor, concentrându-se pe acuratețea imprimării 3D. Am efectuat măsurători ale rugozității suprafeței și dimensiunilor difuzoarelor de aer imprimate în 3D utilizând tehnologii avansate. Am evaluat parametrii rugozității suprafeței, dezvăluind diferențe între tehnicile de imprimare. Am folosit scanarea 3D pentru a compara datele dimensionale, evidențiind inconsistențe în metodele FDM, SLS și DLP, în timp ce SLA a prezentat o precizie superioară. În mod deosebit, imprimarea SLA a demonstrat abateri minime, evidențiind potențialul său de a îmbunătăți performanța aerodinamică în curgerea aerului. Această cercetare subliniază importanța preciziei în imprimarea 3D pentru optimizarea ventilației și calității aerului în vehicule. Concluziile sugerează că tehnologia SLA promite să revoluționeze sistemele de ventilație auto, oferind o funcționalitate îmbunătățită și o experiență de conducere mai bună.

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