REDESIGN OF A HYDRAULIC MANIFOLD IN ADDITIVE MANUFACTURING FOR APPLICATION IN A CLEANING AND INSPECTION ROBOT

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Abstract: A flexible joint riser inspection and cleaning robot needs to be small and powerful to carry out its mission. For power, hydraulic units are commonly used in submerged operations. In this context, a custom hydraulic unit was designed for a robot. Due to its complexity, the hydraulic manifold was redesigned to be manufactured by additive manufacturing. The objective was to reduce the volume and mass of the hydraulic power unit. Several computational analyzes were performed and analytical methods were used to validate the designed concept. At the end of the process, a more compact and lighter structure was obtained.

Keywords: Additive Manufacturing; Hydraulic Manifold; Selective Laser Melting; Structural Analysis; Dimensioning.

REPROJETO DE UM MANIFOLD HIDRÁULICO EM MANUFATURA ADITIVA PARA APLICAÇÃO EM UM ROBÔ DE LIMPEZA E INSPEÇÃO

Resumo: Um robô de inspeção e limpeza de juntas flexíveis de *risers* precisa ser pequeno e ter potência para executar sua missão. Para potência, unidades hidráulicas são comumente utilizadas em operações submersas. Nesse contexto, uma unidade hidráulica customizada foi projetada para um robô. Devido a sua complexidade, o *manifold* de ligação e atuação das válvulas de operação hidráulicas foi reprojetado para ser fabricado por manufatura aditiva. O objetivo foi reduzir o volume e massa da unidade hidráulica de potência. Foram realizadas diversas análises computacionais e utilizados métodos analíticos para a validação do conceito projetado. Foi obtida ao final do processo, uma estrutura mais compacta e leve.

Palavras-chave: Manufatura Aditiva; *Manifold* Hidráulico; Fusão Seletiva a Laser; Análise Estrutural; Dimensionamento.

1. INTRODUCTION

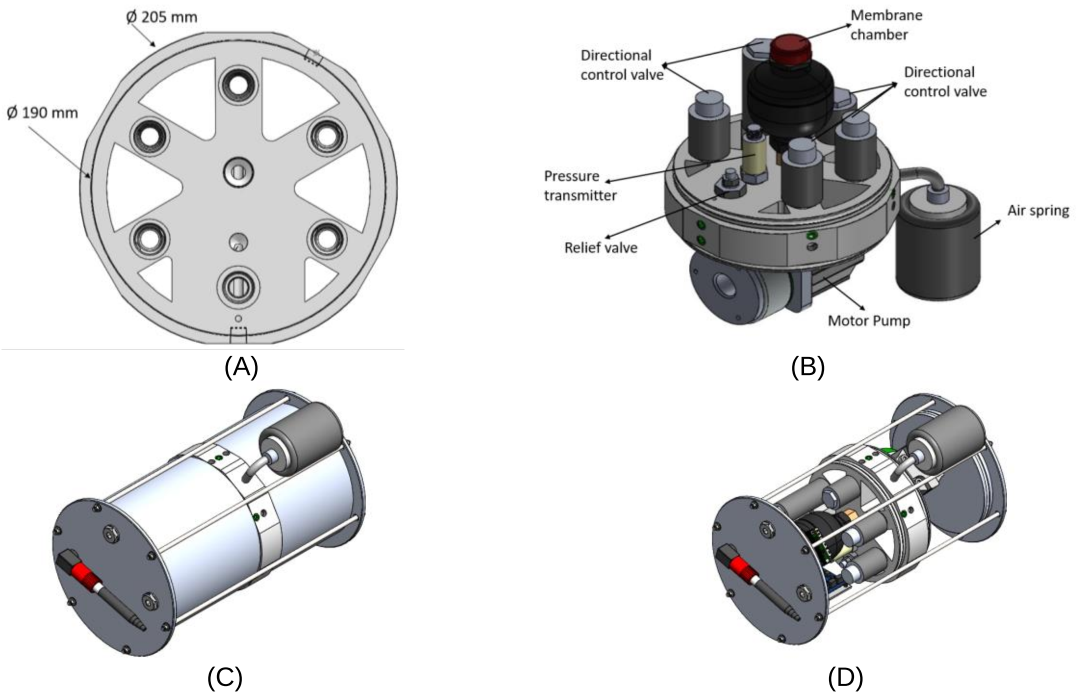
With the advance of industry 4.0, additive manufacturing (AM) started to gain more and more space, its use becoming common in several sectors. For Keller and Mendrickt (2015) [1], this is mainly due to the possibility of producing parts in complex shapes that cannot be obtained by conventional manufacturing methods.

According to Aboulkhair et al.(2019) [2] the AM process has the potential to reduce the design-to-manufacture time of the part by simplifying the production steps (often the final part is obtained without the need for manufacturing molds, machining process, among others). In addition, there is a reduction in the use of raw material, consuming only the material that will be used in the part. With this, more resistant and lighter parts are generated.

In this context, a robot is being developed by Shell Brasil, in partnership with SENAI CIMATEC, with the objective of cleaning and removing marine life from flexible joints of rigid risers on floating production platforms. One of the main components that allow the robot to perform its function is a hydraulic manifold, which is equipment whose function is to regulate the fluid flow between the pumps and actuators.

The original manifold is a multi-channel structure made of 6061-T6 aluminum and it has a mass of 3.5 kg (Fig. 1(A)). In this part are coupled five directional valves, a relief valve, a pressure transmitter, a hydraulic accumulator, a motor-pump system, and an air spring, as shown in Fig. 1(B). In addition, the structure was designed to support high loads due to the high power generated by the hydraulic system. The manifold is coupled to a more complete structure, as shown in Fig. 1(C) and (D), which has a total height of 372.7 mm and approximately 13.10 kg. The internal channels, through which the fluid flows, have a diameter of 6 mm and operate under a maximum internal pressure of 60 bar.

Figure 1. Original manifold (A); original manifold assembly (B); structures attached to the manifold (C) and view of internal components (D).



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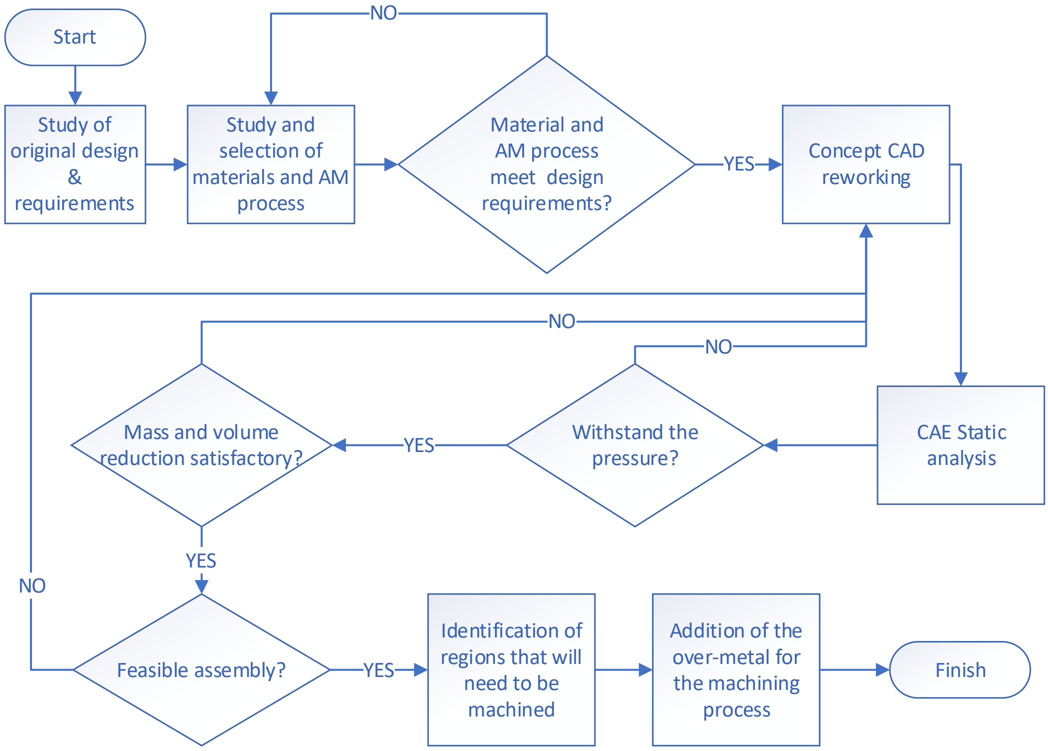
Based on this problem, this work presents the redesign of the manifold, using the benefits provided by additive manufacturing. The piece obtained is lighter and occupies a smaller volume than the original, supporting the same mechanical stresses.

2. METHODOLOGY

Figure 2 summarizes the flowchart with the activities that were carried out for the redesign of the manifold.

Figure 2. Flowchart of activities performed



An aluminum alloy with properties like the original model was adopted as a material. This choice was made based on the design requirements since the material must support stresses that would be high for a polymeric material. Thus, the selected alloy was AlSi10Mg, which has low density and good corrosion resistance, since the part will be submerged in the sea. Furthermore, according to Zygula et al. (2018)[3], this material has excellent moldability, low shrinkage, and low melting temperature, which makes it a good material to be used in additive manufacturing.

The printing method adopted was SLM (Selective Laser Melting). This process uses a high-energy laser beam to melt metal powder in a protective atmosphere, the molten metal quickly solidifies. By repeating this procedure and overlaying it layer by layer, a three-dimensional component is eventually formed. According to Zhang et al. (2018) [4], this technology is one of the most promising in the universe of additive manufacturing, as it produces parts with excellent quality and performance, in addition to being possible to reuse the metallic powder that was not cast, reducing the costs.

For the conception of the proposed concept, three software were used: Solidworks, for 3D modeling; Altair Inspire, for static analysis and topological optimization; and Ansys, also for static analysis. Analyzes were performed using two software to compare the results. The von Mises failure criterion was used to predict the onset of yielding.

After developing the concept, studies of stress concentrators and dimensional calculations were carried out. To calculate the diameter of the channels, we consulted Norton (2013) [5] and Shigley (2005) [6] to find the hoop (σ_θ) and radial (σ_r) stresses in thick-walled cylinders. ASME [7] was consulted for the maximum allowable stress.

With the concept defined, it was also necessary to think about the correct order of assembly of the components, ensuring the feasibility of the assembly.

Finally, Kamurudin et al. (2016) [8] was adopted on dimensional precision, to add the extra metal, as the final part will need to go through the machining process for threading and the surface finish required for certain regions of the part.

2.1 Material Characterization

The alloy adopted is supplied by the company SLM Solution [9] and has the following chemical composition: 9%-11% Si, 0.55% Fe, 0.05% Cu, 0.45% Mn, 0.20%-0.45% Mg, 0.10% Zn, 0.15% Ti, 0.05% Ni, 0.05% Pb, 0.05% Sn, 0.15% other substances and the remainder aluminum. Data referring to alloy particles of 60 µm and with a laser power of 700 W were used.

After printing, the manufacturer recommends performing a heat treatment to relieve residual stresses, by heating the part at 300 °C for 2 hours. Table 1 presents the mechanical properties of the alloy used. In addition, the SLM process has a print rate of 67.9 cm^3/h.

Table 1. Mechanical Properties of AlSi10Mg [9]

Information	Data
Density (g/cm^3)	2.67
Tensile Strength (MPa)	261
Yield strength (MPa)	141
Young's modulus (GPa)	59

2.2 Dimensioning of the internal manifold channels

For dimensioning the channels, the hoop (σ_θ) and radial (σ_r) stresses were calculated using the following equations [5, 6]:

$$\sigma_\theta = \frac{p_i * r_i^2 - p_o * r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 * r_o^2 * (p_i - p_o)}{r^2 * (r_o^2 - r_i^2)} \quad (1)$$

$$\sigma_r = \frac{p_i * r_i^2 - p_o * r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 * r_o^2 * (p_i - p_o)}{r^2 * (r_o^2 - r_i^2)} \quad (2)$$

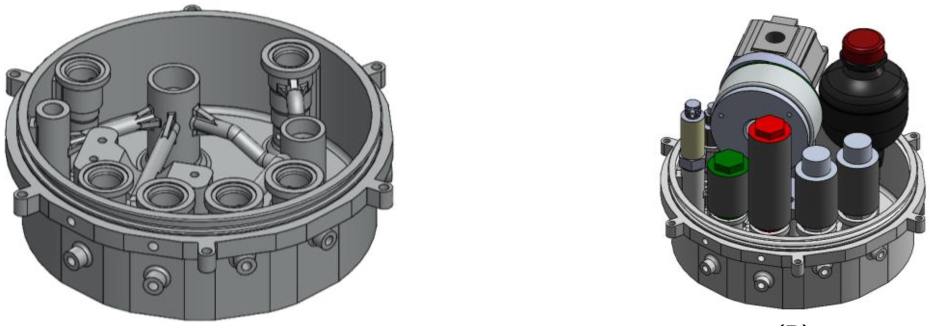
where p_i and p_o represent, respectively, the internal and external pressure, r_o is the external radius, r_i is the internal radius, and r is the radial coordinate.

3. RESULTS AND DISCUSSION

3.1 Manifold design

The redesign of the original manifold (Figure 1) sought to reduce mass as well as height. For mass reduction, the proposed structure was completely reworked. Only functional structures were kept like the internal channels through which the fluid will flow, the walls of the structure, the valve cavities, the pump support, and hydraulic actuators, as can be seen in Figure 3.

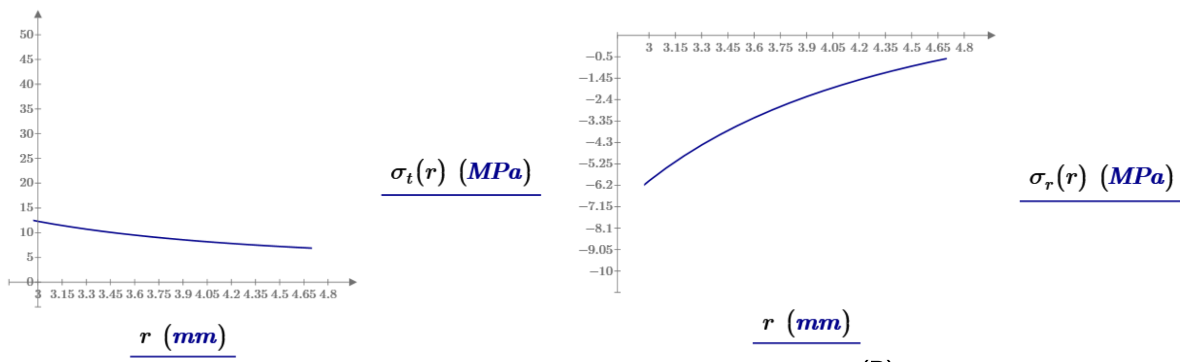
Figure 3. Proposed manifold concept (A) and its assembly with the main components (B).



(A) (B)

The stresses in the most critical inner channel, with dimensions r_i = 3 mm, r_o = 4.75 mm, with p_i = 60 bar and p_o = 5 bar were calculated according to Eqs. 1 and 2 and can be seen in Figure 4.

Figure 4. Hoop stress (A) and Radial stress (B) based in the channel radius.



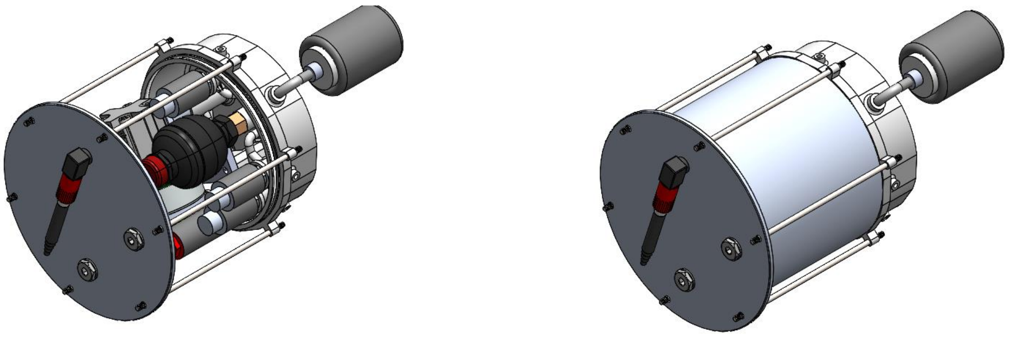
(A) (B)

The maximum von Mises stress obtained in the channels was 16 MPa. This value was compared with the allowable stress according to ASME [7] whose value is 74.5 MPa. As a result, the stresses in the channels are below the allowed limit.

In addition, to support the ducts during the printing process and also to reduce the stress concentration, the fillets suggested by Morgenbrod (Walter D. Pilkey and Deborah F. Pilkey, 2008) [10] were used in the geometry changes arising from the connections of the channels with the cavities. This type of fillet is often used on heavy shafts to avoid high stresses.

To reduce the height of the structure, there was an increase in the internal diameter of the manifold, from 190 mm to 198 mm, thus allowing a better reorganization of the components, leaving them on only one side of the structure and eliminating the lower tray and cylinder. In addition, the tie rods now connect directly to the manifold. The modifications can be seen in Figure 5.

Figure 5. New assembly structure (view of internal components) (A) and covered (B)



(A) (B)

Static analysis of the manifold was also performed, considering an operating pressure of 60 bar inside the channels. Furthermore, due to the presence of the “air spring”, whose function is to equalize the internal pressure of the manifold with the external pressure (of the water depth of 40 m), an internal and external pressure of 5 bar was adopted in the manifold. The manifold had a safety coefficient of 1.2, using von Mises as a failure criterion for the onset of yielding. Figure 6 shows the result of the static analysis.

Figure 6. Result of static analysis of the manifold (von Mises stress).

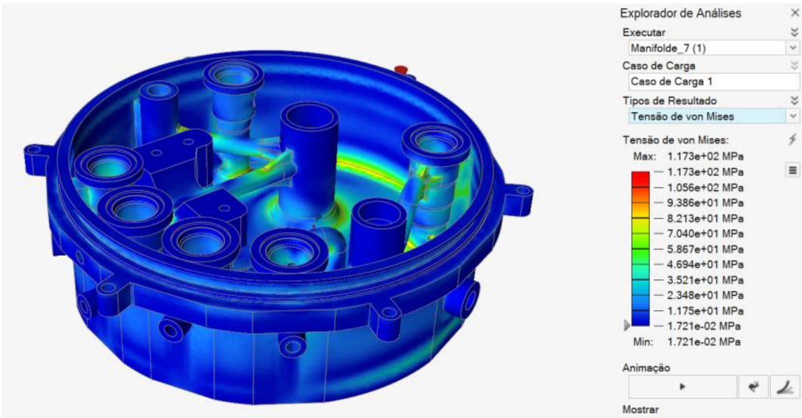


Table 2 shows a comparison between the original manifold and the manifold proposed in this work. If we consider the assembly complete, with the proposed manifold, we obtained a 30% reduction in height and a 39% reduction in mass.

Table 2. Models comparison.

Information	Original structure	New AM concept
Manifold Mass (kg)	3.5	1.76
Volume (cm^3)	Not applicable	659
Complete structure mass (kg)	13.10	8
Complete structure height (mm)	372.7	259.0
Manufacturing time (hr)	Not applicable	9.7

3.2 Machining

After printing the part, it is still necessary to carry out some machining processes to generate the necessary threads and give the recommended surface finish for each specific region. For this reason, we tried to add an over-metal in these regions.

The over-metal was calculated based on the dimensional accuracy of the SLM printing process and added a safety value, thus ensuring the existence of the amount of material needed for the part to be machined.

According to Kamurudin et al. (2016) [8], for cylinders between 10 and 5 millimeters in diameter, there is a variation between 1.3% and 2%. A 2.5% diameter surplus was then adopted in the regions that will undergo the machining process.

4. CONCLUSIONS

The new manifold withstood the operating demands well, in addition to providing a reduction in the structure's mass and making it more compact, representing a significant reduction in mass and height. In addition, the redesign reduced the number of components involved in the structure. However, the reduction of mass and volume is not that significant compared to the complete robot, but this work can be the first step to redesign other components of the structure in MA and obtain results that are more significant.

On the other hand, the assembly of the components of the new manifold became a little more complex, having to obey a certain order to guarantee the correct fixation of all the elements. This difficulty in the assembly does not represent a significant disadvantage.

Another disadvantage, this one significant, is the cost of manufacturing the structure. By the traditional method (machining), the cost per part was around 1500 dollars. With the AM, the cost is around 1500 to 2000 dollars, and it will still be necessary to carry out some machining processes for the generation of threads and surface finish.

The next steps in the project are to obtain more information about the material to perform fatigue analysis on the part, ensuring its good functioning and estimating its lifetime. Later, it is expected to print the manifold and perform tests on the prototype.

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