Design Process of a Pressure Transducer Vibration Fixture

Andrew Gilstrap
NASA KSC
Major: Mechanical Engineering
NE-L6 Fall Session
Date: 17 11 2017

Design Process of a Pressure Transducer Vibration Fixture

Andrew Gilstrap[1]
NIFS Intern, NE-L6, NASA KSC, University of Michigan – Dearborn

Abstract

This paper details the iterative design cycle of a fixture used to mount two types of pressure transducers for vibration testing which allows for functional testing without the removal of the transducers. The objective of the fixture is to prove that the pressure transducers can survive vibrations induced during launch. This would increase the Technology Readiness Level of the pressure transducers which is a requirement for the Lunar Advanced Volatile Analysis subsystem preliminary design review. During the design process, additive manufacturing is considered as a manufacturing method of the fixture as a way to investigate the use of additive manufacturing for the final flight version of the Fluid Sub System manifold. It is ultimately shown that the added ability to perform functional testing and optimization for additive manufacturing made the fixture less than ideal for vibration testing. It is determined that the best option is to design and manufacture a traditional vibration fixture without the ability to perform functional testing of components while attached and a separate part to investigate the application of additive manufacturing to the Fluid Subsystem manifold.

Nomenclature

AM	=	Additive Manufacturing
CAD	=	Computer Aided Design
C_i	=	Internal Corrosion Allowance
C_o	=	External Corrosion Allowance
COTS	=	Commercial off the Shelf
d	=	Inner Diameter of Largest Port
DMLS	=	Direct Metal Laser Sintering
ETU	=	Engineering Test Unit
FDM	=	Fused Deposition Modeling
FEA	=	Finite Element Analysis
FSS	=	Fluid Subsystem
GSS	=	Gas Supply Subsystem
LAVA	=	Lunar Advanced Volatile Analysis
LPBF	=	Laser Powder Bed Fusion
MAWP	=	Maximum Allowable Working Pressure
P	=	Maximum Allowable Pressure
PDR	=	Preliminary Design Review
PT	=	Pressure Transducer
S	=	Allowable Stress
T	=	Minimum Wall Thickness
TRL	=	Technology Readiness Level

[1] NIFS Intern, no standing with AIAA

I. Introduction

Resource Prospector is a NASA rover mission currently designed to characterize volatiles on the surface of the Moon. To accomplish this, regolith samples will be taken from a drill and baked inside of a reactor to release volatiles. The volatiles released will then be transferred to the Lunar Advanced Volatile Analysis (LAVA) subsystem to investigate the composition of the volatiles. The LAVA subsystem contains manifolds for both Fluid Subsystem (FSS) and the Gas Supply Subsystem (GSS) which utilize a variety of components to allow for the monitoring and transport of both volatiles and supply gas required to operate the mass spectrometer and gas chromatograph used for volatile analysis. As a part of the design process, the LAVA subsystem must pass a Preliminary Design Review (PDR) which requires that all of the systems in the LAVA subsystem have at least a Technology Readiness Level (TRL) of 6. TRL 6 requires that systems have a prototype demonstration in a relevant environment. All of the components on the FSS and GSS manifolds have been shown capable of operation in a vacuum, but not all of the components have been vibration tested to show that they can survive the launch environment. At the start of the internship, I was tasked with designing vibration test fixtures to test critical parts of the LAVA subsystem.

II. Design Process

A. Preliminary Design Requirements

1. Design structurally similar versions of the FSS and GSS manifolds to be used as fixtures in vibration testing.

To advance the TRL of the FSS and GSS manifolds, structurally similar fixtures were to be designed and vibration tested to prove that the manifolds would remain within vibration constraints. The rational to use structurally representative fixtures opposed to the designs being used on the next LAVA subsystem Engineering Test Unit (ETU) is twofold. The primary reason is to reduce costs. The full manifold design is complex, requires extensive machining to manufacture, and is designed to utilize a number of the same kinds of components which makes it cost prohibitive to have a dedicated unit for vibration testing. The second reason is turnaround time. The fast-approaching LAVA PDR necessitated a rapid turnaround time on vibration test validation of the manifolds. Since the designs for the manifolds being used in the next ETU are complex to machine and are expensive, a long lead time is required for purchasing and manufacturing. This makes them impractical to use for vibration testing while representative fixtures allow for quicker purchasing and manufacturing times.

2. The fixture designs must allow the mounting of various components during vibration testing.

Along with the need to advance the TRL of the manifolds in LAVA, there was a need to vibration test various components being used in the current ETU or being considered for use on the flight version of the manifold to advance the TRL of the individual components. Vibrations are a concern for the components since vibrations experienced during launch may effect individual component functionality. If any of the components on the manifolds were to fail during flight, some or all of the analytical capabilities of the LAVA subsystem would be lost. By verifying that the components will survive the vibrations experienced during flight, there can be a high degree of confidence in the accuracy of the data being recorded by the LAVA subsystem. Table 1 is a list of components that were required to be included on the fixtures or inline of a fluid line running in-between the FSS and GSS fixtures.

Required Components
TE Connectivity Pressure Transducer
Helium Tank
LG-1 Regulator
Memscap Pressure Transducer
Gland Nut Fitting
Water Drop Demo
Marotta Isolation Valve
Piezoelectric Valve

Table 1. List of required components to include on the vibration fixtures. *Although the pressure transducers and the representative manifold fixtures were the primary concern of the vibration testing, the other components listed in the table were also required.*

3. The fixtures must be able to allow functional testing of mounted components without removing the components from the fixtures.

The designs must allow for verification of proper component functionality after the vibration test. The performance of a particular component can change after removing and reattaching to the fixtures due to factors such as variable installation torque on threaded components, accidental altercations while handling, or slight changes in component loads due to changes in orientation when reattaching components. This makes it highly advantageous to perform functional testing without removing components from the test fixtures. This requires that there must be a fluid pathway in the fixtures with an inlet and outlet. To adhere to the first design requirement, a simplified internal fluid path should be used to minimize manufacturing time and cost.

As a result of the need to have an internal fluid path that will hold pressure, the fixtures must be designed so that they can be safely pressurized past the intended operating pressure range. The Maximum Allowable Working Pressure (MAWP) needed to perform functional testing on the components is 120 psi. The fixtures will be designed to safely operate at a value of 2.5x MAWP (300 psi) and will also be hydrostatically pressure tested once manufactured to ensure safe operation during functional testing.

4. A plate needs to be designed to act as an interface between both fixtures, vibration table, and additional fixtures that may be designed in the future.

Decreasing the required setup time of the test is another avenue to further reduce the cost and required time to complete the vibration testing. By using an interface plate that can mount all of the required fixtures, setup time can be reduced by decreasing the total number of required attachment points to the vibration table.

B. Design Iteration A

Iteration A of the design is a series of suggested modifications to the preexisting GSS manifold design. The FSS fixture was chosen as the first design task since it was identified as the most important manifold to replicate. Since this iteration is a series of suggested modifications developed without the aid of Computer Aided Design (CAD), there are no associated dimensions to any of the suggested changes. The suggested modifications focus on reducing the overall size of the manifold and reducing the number of times the part would need to be moved during machining. As seen in Fig. 1, the suggested modifications not only included the addition or subtraction of material to the primary structure, but also included the complete removal of small features such as bolt holes. Another suggested change was to rotate the direction of the majority of the representative valve ports so that they could be machined from a single direction. The internal fluid paths were also simplified as to only include three pressure transducers and two Commercial off the Shelf (COTS) fittings. In an effort to maintain structural similarities, the fluid path intersects three holes that represent Mindrum valve ports. To allow both hydrostatic and functional testing, COTS plugs would need to be utilized to block fluid escaping through the representative valve ports. At this stage of the design, the representative dome structure was still undetermined. The FSS manifold uses a separately-machined dome piece that is welded to the major structure of the FSS after machining. Welding parts adds a degree of complexity to the manufacturing process so alternatives were being investigated until the conclusion of Iteration A.

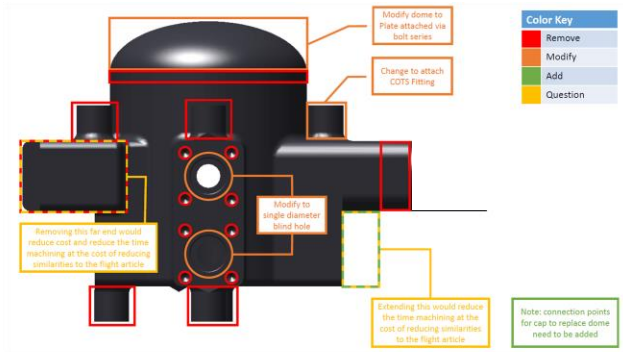

Figure 1. Primary modifications suggested for Iteration A. *This figure illustrates a majority of the suggested design alterations to the FSS manifold for use as a fixture.*

Initial feedback on the design was positive. All of the suggested modifications were deemed as appropriate simplifications, and some minor critiques were given and were addressed regarding dome implementation. However, after further review three major concerns emerged with the design requirements. One concern was that the manifold structures TRL is not a requirement for the PDR. The second concern was that regardless of the degree of modification, the fixtures response under induced vibration would be drastically different than the manifolds they represent. The last major concern was that due to the drastically different response to vibrations of the fixtures, the components that needed to be vibration tested would be subjected to vibrations that were not representative of the vibrations experienced on the manifolds.

C. Design Requirements Revision I

The feedback on the Iteration A design prompted an update to the design requirements. The first design requirement which required that two structurally representative fixtures be produced was dropped and was replaced by the requirement to design a single vibration fixture that required minimal machining. The new fixture would be required to have the ability to only test a TE connectivity Pressure Transducer (PT) and a Memscap PT simultaneously.

D. Design Iteration B

Given that the primary design requirement was significantly changed, none of the suggested modifications that were suggested for Iteration A were applicable anymore. It was advised that the new design should be simple so that the input vibrations into the PT's could be easily attainable from accelerometers during vibration testing. As a result, a basic design was developed which only required three holes and four threaded sections for the PT ports and fluid path. A section view of the design can be seen in Fig. 2. The center positions of each PT were selected to be equidistant from the nearest edges of the mount and from the other PT. This was chosen in an effort to match the vibration input experienced by each PT At the time of this iteration, the mounting holes for the fixture were not included as mounting information to the vibration table was unknown. Although the design requirements still called for the use of an interface plate, it was determined that using mounting holes on the fixture that conformed to the mounting requirements of direct attachment to the vibration table allowed the option of not using the interface plate if the requirement of using an interface plate was dropped in the future.

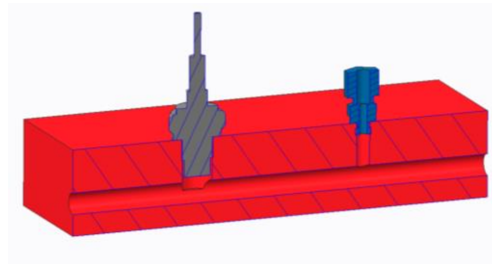

Figure 2. Section view of a design iteration B partial assembly. *The section view of the assembly clearly shows the internal fluid path used for functional testing. The B1 iteration design (red) is pictured with a TE Connectivity PT (gray) and a Beswick fitting used to mount the Memscap PT (blue). The Memscap PT and both COTS fittings are not included in this assembly.*

To ensure that the design could perform functional testing safely and that the fixture could survive hydrostatic testing to 2.5x MAWP, the fixture was analyzed using two separate methods. The first method was the ASME B31.3 standard for process piping. The B31.3 standard was previously used for analysis of the RP-15 LAVA manifolds, so it was a good baseline analysis technique. ASME B31.3-2012 Equation 35b calculates the maximum allowable internal pressure in a straight high pressure pipe and is shown below as Eq. (1).

$$P = S \cdot ln\left[\frac{d + 2(T - c_o)}{d + 2c_i}\right] \tag{1}$$

Where P is the maximum allowable pressure, S is the allowable stress in the part, C_o is the external corrosion allowance of the material, C_i is the internal corrosion allowance, d is the inner diameter of the largest port, and T is the minimum wall thickness of the fixture. Evaluating this equation using the corrosion allowances and allowable stress for 316L stainless steel, which was selected to match the material of the flight manifolds, the maximum allowable pressure was found to be 15363 psi.

CREO Simulate was used to perform Finite Element Analysis (FEA) as the second analysis method. The FEA was used to find the maximum allowable pressure by applying an internal pressure of 2.5x MAWP to the internal fluid path surfaces and then incrementing the applied pressure until the maximum internal stress value matched the max allowable stress reported by the B31.3 standard for 316L stainless steel. The results showed that an internal pressure of 5100 psi would be needed for any section of the fixture to reach the maximum allowable stress. Since the result of the FEA analysis reports a pressure that is less than that calculated by the B31.3 standard, the maximum allowed pressure of this design iteration is determined to be 5100 psi. Since 5100 psi is much higher than the 300 psi requirement, the design is determined safe for use with the expected operational pressures.

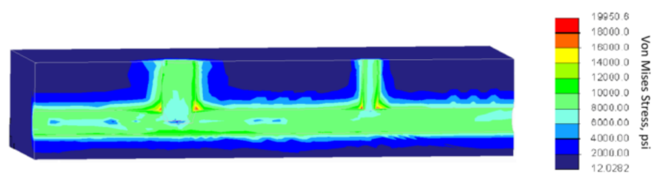

Figure 3. Stress distribution in design Iteration B at 1500 psi. *The internal stresses in the fixture first reach the maximum allowable stress when an internal pressure of 1500 psi is applied.*

E. Design Requirements Revision II

The current ETU design requires the use of both the FSS manifold along with two smaller manifolds due to the complexity of the fluid paths and practical limits of conventional machining. Additive Manufacturing (AM) is an attractive manufacturing option for the FSS manifold, since several manifolds could be included in a single unit which reduces cost and lead time for manufacturing. After the completion of design Iteration B, the LAVA project team became interested in the possibility of utilizing AM for the flight version of the FSS manifold. Thus, two more design requirements were added.

1. *The vibration fixture must be manufactured with an AM process with minimal expenses.*

Although design Iteration B could be used with the AM process, it is fairly large and thus expensive to manufacture. To reduce cost, a smaller volume would be needed which means the fluid paths and components being tested on the fixture are more condensed.

2. *The vibration fixture must include features that would be included on the flight manifold utilizing AM*

Since AM is an up-and-coming technology and is vastly different from conventional machining, a number of features that are designed for traditional manufacturing methods may not translate well to the new manufacturing process. Some features, like the dome, may need several parameters changed so that they can be manufactured, while other features, such as the fluid paths, can be manufactured by AM but are not taking advantage of the capabilities of the process.

F. Additative Manufacturing of Metals Process and Influence to Design

In recent years, AM for plastics has become common in the consumer market and thus is often the only type of AM process that many are familiar with. The AM method used by the majority of printers in the consumer market utilize a process known as Fused Deposition Modeling (FDM) which involves extruding plastic filament through a heated printer head which is moved around the print area to deposit material. Unlike the consumer markets use of FDM printers for plastic, AM methods for metals almost entirely rely on Laser Powder Bed Fusion (LPBF). LPBF does operate similarly to FDM in regards to the layered construction method. Both processes treat an object as a stacked layer of two dimensional cross sections that are created in succession to produce a final part. Figure 4 shows the typical operation of a LPBF process.

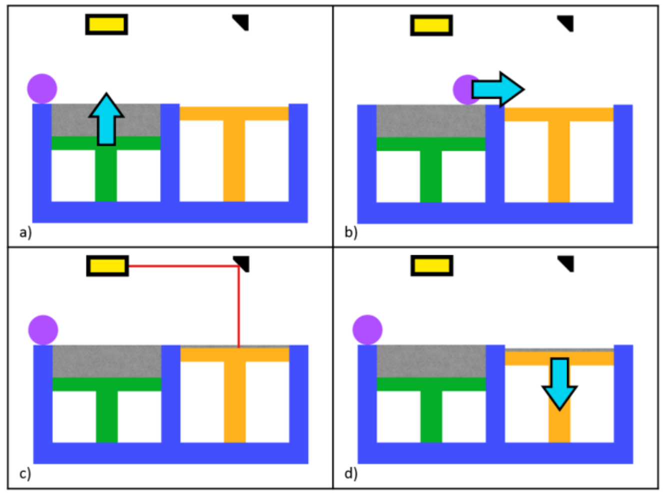

Figure 4. Typical LPBF manufacturing process. *a) A feed piston (green) rises slightly to bring metallic powder (grey) to the working surface. b) A roller (purple) moves across the newly exposed powder and evenly distributes it across the print bed (orange). c) A laser (yellow) activates and uses a series of movable reflectors to sinter a cross section of the part in the powder. d) The print bed descends, which allows for the process to repeat again until the part is complete.*

Direct Metal Laser Sintering (DMLS) is the specific type of LPBF manufacturing that is viable for the needs of the project, as DMLS is currently the only process that is mature enough and can print using a material acceptable for use in the vibration fixture or flight manifold. Several limitations are imposed on possible parts printed with the DMLS due to the printing process. One such limitation is that parts are anisotropic due to the bonding between the sintered layers, which means that a part's dimensions may need to change to account for the variance in material properties. Another is that the surface finish of parts is very poor which means that any surface of a printed part that acts as an interface to some other part must either be machined or surface finished. The poor surface finish can also reduce the fatigue life of the part if not removed from fatigue critical surfaces. The limitation that has the greatest influence on the design of the vibration fixture is the limitation on overhanging and unsupported features. This is primarily due to two separate effects, the first of which is the loads imparted by the roll when new powder is added to the print bed and the second is the lack of support provided by the un-sintered powder. Current DMLS printers that are used commercially have the ability to create unsupported features that range between 0 and 45 degrees from the vertical axis as can be seen in Ref. 1.

G. Design Iteration C

A new revision of the design was created after researching the capabilities of the DMLS process. The first and most difficult challenge of the design was determining a way to produce the dome. On the current model of the FSS manifold, the dome is a quarter ellipse revolved around a center axis. It would be possible to print the dome if printed with a series of sacrificial supports that were removed after printing. This solution presents several problems. If the dome is printed separately, the supports can be removed, however welding would be required for the final assembly. One of the enticing design options made possible by AM is the ability to print the entire fixture without the need to weld sections together, so avoiding welding is a high priority. If the dome is printed as a part of the main body of the fixture, sacrificial supports would be required and could not be removed after printing due to the supports being completely encapsulated by the fixture. This is also undesirable, since the supports are likely to break under launch conditions and the volume enclosed by the dome is a chamber that requires good flow conditions. Since it is impossible to use the dome geometry of the current FSS manifold without welding or extraneous sacrificial supports, the geometry of the dome had to change for the fixture. Out of the various alternative geometries, a hemisphere was chosen since hemispheres are self-supporting and thus can be built directly on the main body of the fixture without sacrificial supports. The diameters of both of the dome structures were selected so that the internal volumes closely matched that of the reservoirs in the FSS manifold.

The fluid paths were the next item of interest in the design. Traditionally, fluid paths in machined manifolds are often linear with occasional sharp bends. This can severely limit the ability to place components in the most logical and easy locations. With AM, fluid paths can take whatever form desired by the designer. To take advantage of this, components were arranged around the two tanks on the test fixture at locations that allowed the fixture to assume a tight form factor and also allowed for easy installation of components. Although it is entirely possible to design the fixture to mount components in any orientation desired, all ports for the components were oriented in the same vertical direction to minimize costs associated with setup time when post process machining the ports.

Although not a driving requirement, there was also a desire to include a secondary fluid path in the design so that functional testing could be performed in the first fluid path and the second could be used to mount other components being used on the FSS manifold. Although the components on the second fluid line do not need vibration testing, the exact difficulty in creating ports for those components in an AM manifold are unknown. This provides an opportunity to gain more experience using AM prior to flight. Including these components on a separate fluid line allows for functional testing of the two PTs without requiring the attachment of the secondary components or the need to perform post machining on the secondary component ports.

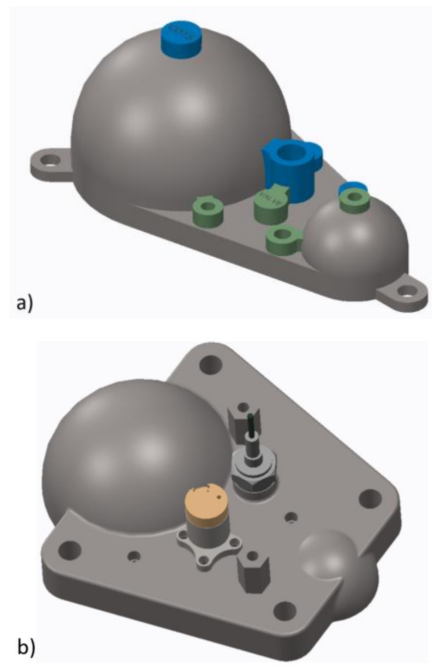

Figure 5. The preliminary and final designs of iteration C. *a) Isometric view of the preliminary version of design iteration C. The blue features are ports in the primary fluid path, and the green features are ports in the secondary fluid path. b) Isometric view of the final version of design iteration C with several components installed.*

There were two major versions of Iteration C that utilized this AM design decision, which will be referred to as the preliminary and the final versions of Iteration C. The preliminary design of iteration C displayed in Fig. 5 a) was designed for minimalism while still providing a significant degree of rigidity around ports. This was accomplished by creating a "bridge" between the two reservoirs with embedded fluid paths. Ports were extruded from this bridge to the minimum height required to mount each individual component. To increase the rigidity of the component mounting, supports were created between nearby extruded ports and reservoirs. FEA was performed on the design and confirmed that it could safely hold 2.5x MAWP, verifying that it could be used for functional testing.

There were concerns that the bridge and mounting points of the preliminary design were still too flexible for use as a vibration fixture, so the design was modified to the final version of Iteration C as shown in Fig. 5 b). Instead of determining the bridge thickness independent of the components, the bridge thickness was determined by the required depth of the ports. All ports, excluding the port for the TE Connectivity PT, were completely contained within the bridge. The bridge was not increased in thickness to encompass the TE Connectivity PT as a cost-saving measure. The mounting points were also changed significantly. In the preliminary version, there were three mounting tabs that were add as additional features external to the bridge feature. On the final version, the rigidity of the mounting points was significantly increased by extending the bridge to include four mounting points. In addition to these changes, it was discovered that the Mindrum valve required a port with a high and low fluid path to function. Thus, a higher fluid path was added as a part of the secondary fluid path to accommodate the valve's requirements. FEA was performed on the design and confirmed that it could safely hold 2.5x MAWP, verifying that it could be used for functional testing.

After an in-depth review of the final version of Iteration C, it was determined that the current design requirements were producing a part with poor qualities in multiple areas. Although the final version significantly increased rigidity over the preliminary version, the dense concentration of components, minimal build volume, and large hollow features would prove difficult to extract useful vibration testing data on the PTs. The density of components and minimal volume ensured that each port would affect the vibration experienced in neighboring ports. The large hollow features would have vastly different responses under vibration and would further complicate the analysis. During physical vibration testing, vibrations can only be evaluated at select locations due to the limitation on practical sensor application and monitoring. Due to this limitation, correlating data from the physical vibration test to the computational analysis of the fixture would be exceedingly difficult. This means that regardless of whether a component passes the physical test, it would ultimately be impossible to be sure that the vibrations experienced on the fixture are as harsh as or harsher than those expected to be experienced during flight. The final version of Iteration C also doubled the cost of production due to the increase in bridge material, making it even less attractive option.

H. Design Requirements Revision III

As a result of the review of the final version of iteration C, it was determined that the design requirements should be divided and applied to two separate parts. The requirements used to design Iteration B were assigned to a vibration fixture created from conventional machining practices excluding the requirements for functional testing in the mount. Although functional testing of the PT's is valuable, the desire to have a vibration fixture that provides a simple vibration environment for the PT's being tested proved to be the more important requirement.

The second part would act as a technology demonstration of DMLS manufacturing in regards to manifold design and construction. This new part would only exist as a way to learn as much as possible about possible issues with critical features and also a way to investigate validation and vendor requirements associated with LPBF-produced parts used at NASA.

III. Conclusion

As a result of the continuous design, evaluation, and requirement updates, the LAVA team has learned valuable information regarding the design and implementation of both vibration fixtures and an AM FSS manifold. Additionally, two new parts have entered into the initial stages of design and analysis to continue the design process. Figure 6 shows the current design of the vibration fixture, and Fig. 7 shows the initial design of the new DMLS test part. After the vibration fixture design is completed, designs will begin on the interface plate.

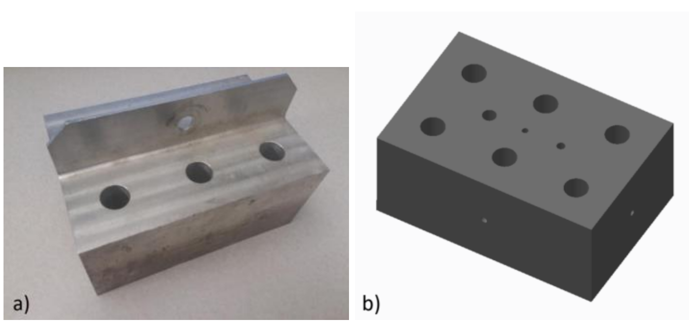

Figure 6. Preliminary vibration fixture. *a) A reclaimed vibration mount being used for the new vibration mount. b) An isometric view of the CAD model of the preliminary alterations to the reclaimed vibration mount to allow the vibration testing of both the TE Connectivity PT and Memscap PT*

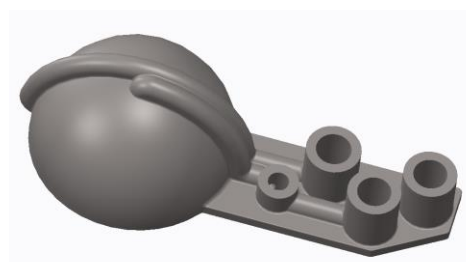

Figure 7. Preliminary design for the DMLS test part. *The preliminary CAD model of the new DMLS test part. Currently, there are only ports for the TE Connectivity PT, Memscap PT and two Swagelok fittings.*

References

[1]Dana, M., Hanzl, P., and Zeetkova, I., "Need for Support Structures Depending on Overhang Size" Faculty Paper, Mechanical Engineering Dept., Regional Technological Institute., Pilsen, Czech Republic, 2016.