Ultrasonic Vibration of Optics in Laser Materials Processing

Team 7

December 12, 2023

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Abstract

Using ultrasonic vibrations in conjunction with lasers to process materials has become a popular choice due to its versatility and efficiency. Currently, this is done by vibrating the workpiece, but since each workpiece is different, each must be vibrated at a different resonant frequency. To mitigate this, preliminary research has indicated vibrating the laser optics instead, though this has only been explored with vertical vibrations along the axis of the laser beam. Here, a novel solution is developed to induce laser vibrations transverse to the axis of the laser beam through the use of piezoelectric transducers and a booster.

Table of Contents

Abstract 1
Table of Contents 1
Introduction and Problem Context 2
Design Process 5
Stakeholder Analysis and Ecosystem Map 7
Intellectual property 9
Information Sources 9
User Requirements and Engineering Specifications 9
Concept Generation 11
Concept Selection Process 13
Problem Analysis 19
Engineering Analysis 20
Final Design Description 22
Verification and Validation Plans 33
Discussion 38
Reflection 39
Recommendations 43
Conclusions 43
Acknowledgements 45
References 46
Author Biographies 48
Appendices 50
1.A - Kevin Ho's Concepts 50
1.B - Jonathan Kazelskis's Concepts 55
1.C - Eashan Prabhu's Concepts 56
1.D - Nick Ventresca's Concepts 58
1.E - Other Concepts 59
2 - Transmission Intensity Coefficient Calculations 60
3 - Bill of Materials 61
4 - Manufacturing Plans 62
5 - Assembly and Fabrication Plan 63

Introduction and Problem Context

A thorough literature review of vibration assisted laser manufacturing was conducted to better understand the context of the design problem. Laser use in manufacturing is rapidly increasing over time due to its numerous advantages over traditional mechanical manufacturing. It is extremely fast, versatile, energy efficient, and able to be automated - making it an attractive alternative [30]. Lasers are useful for a number of different processes in both subtractive and additive manufacturing, such as cutting, welding, joining, cladding, cleaning, casting, deposition, etc [15,18]. Fig. 1 below contains a schematic of a typical laser manufacturing machine; a laser beam is pointed to a mirror that reflects the light downwards into a lens that focuses the beam into a spot on the workpiece [15,18,30]. Due to optical radiation hazards, there are a number of international safety standards regarding laser processing machines, most notably ISO 11553-1:2020 [25]. This standard also references IEC 60825-4:2006 for safety guidelines regarding the laser beam delivery system, which is the subsystem of "all optical beam components….and their enclosures" [24] - these components are represented in blue in Fig. 1.

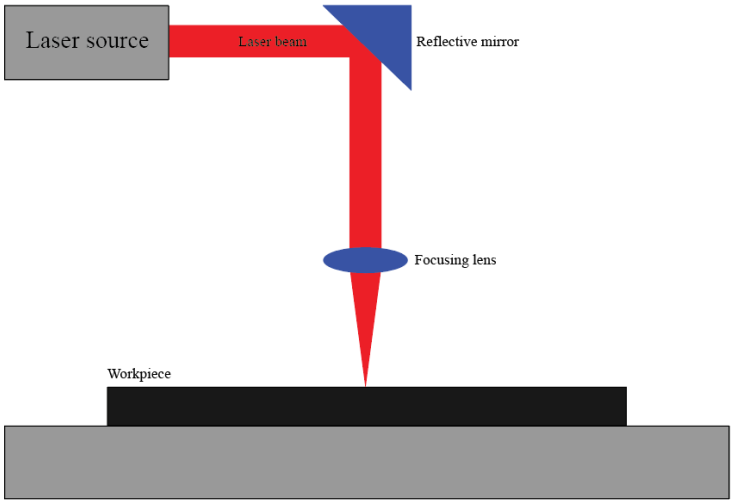


Figure 1: Schematic of a commonly used laser manufacturing machine. The components of the laser beam delivery system are shown in the color blue.

A large amount of research has been conducted into vibration assisted manufacturing. Many groups have found that vibrations introduced into various processes will greatly improve the quality of the end product. Generally, this is due to an element of randomness introduced by the vibrations propagating through the lattice of a material. This chaotic motion produces a macroscopic effect - defects become "smoothed over" and healed [15]. In laser manufacturing specifically, there are added mixing effects created in melted material that further benefit the end product quality. For the most part, this is because of cavitation, which is the formation and implosion of small vapor bubbles in the material being processed [18]. However, typically in order to reap these benefits in laser manufacturing, a high frequency vibration, in the ultrasonic range, is needed. This is because laser manufacturing often requires high linear speeds, such that the laser beam travels across the surface of the manufactured material very quickly. Therefore, for the same degree of random motion to be introduced, a higher frequency vibration is necessary [31]. Fig. 2 contains comparisons of different laser manufacturing processes with and without ultrasonic vibrations, and the improvement in end quality is vastly apparent [18].

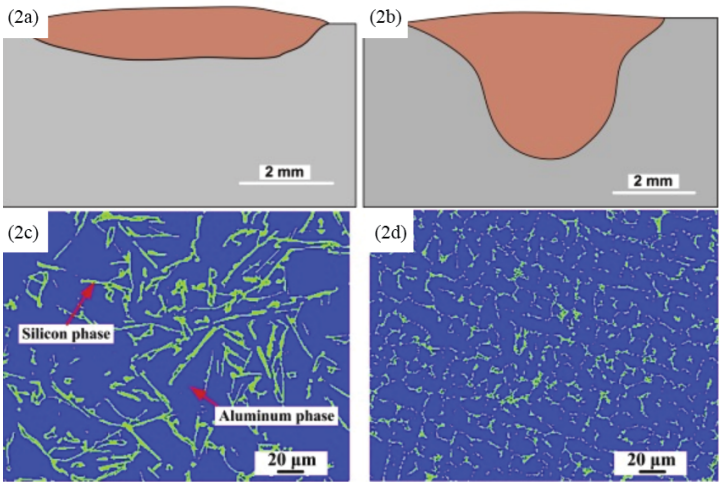


Figure 2: Various laser processes with (left) and without (right) ultrasonic vibration. Fig. 2a and 2b show the weld melt zone cross section. Fig. 2b, including ultrasonic vibration, clearly has a deeper weld melt, resulting in increased strength. Fig. 2c and 2d show the microstructures of a fabricated aluminum alloy. When ultrasonic vibration is introduced (2d), the grain structure is finer and more evenly distributed [18].

To introduce vibrations in manufacturing, the current state of the industry is to vibrate the workpiece being processed using a piezoelectric transducer (PZT) [18,30]. Piezoelectric materials, when a voltage is induced across them, exhibit a proportional strain - causing deformation. Thus, controlling the deformations of the material will allow for vibrations to be created [6,7]. Researchers at Oklahoma State University utilized this method to assist a laser atomization process, vibrating vertically at an ultrasonic frequency of 20 kHz with amplitudes of 23, 37 and 51 µm. A schematic of their experimental set up is provided in Fig. 3 [1].

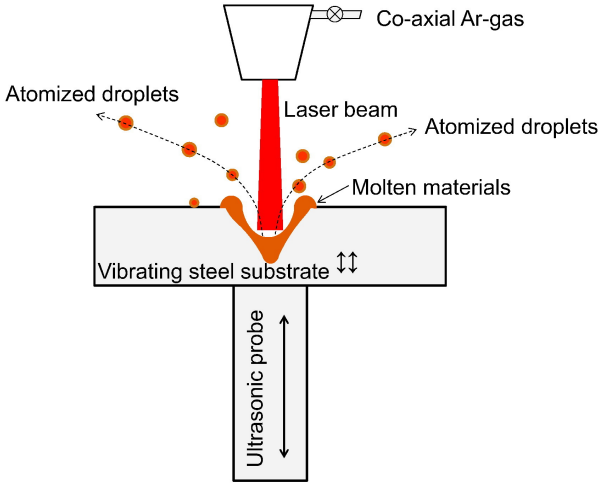


Figure 3: Experimental set up of an ultrasonic assisted laser atomization process with vibrations introduced to the workpiece [1].

Unfortunately, this methodology has a number of limitations - primarily that every workpiece has a different mass and makeup, resulting in different resonant frequencies [12]. This makes universal vibration in laser processing difficult, as the frequency of the vibrations should ideally match the resonant frequency of what is being vibrated to result in maximal power transfer [14]. One way to address this issue is by manipulating parts of the laser beam delivery system rather than the workpiece, which was explored by a group of researchers in collaboration with General Electric. They made use of General Electric's proprietary Fast Steering Mirror (FSM) module, a motorized device that precisely controls the

orientation of a mirror [22,23], rather than a traditional static mirror, to oscillate a laser beam in a circular spiral along a linear weld path at a frequency of 5.5 kHz. They tested a number of different diameters, from 45-90 μm. A figure illustrating their method for the laser beam path is provided in Fig. 4 [31].

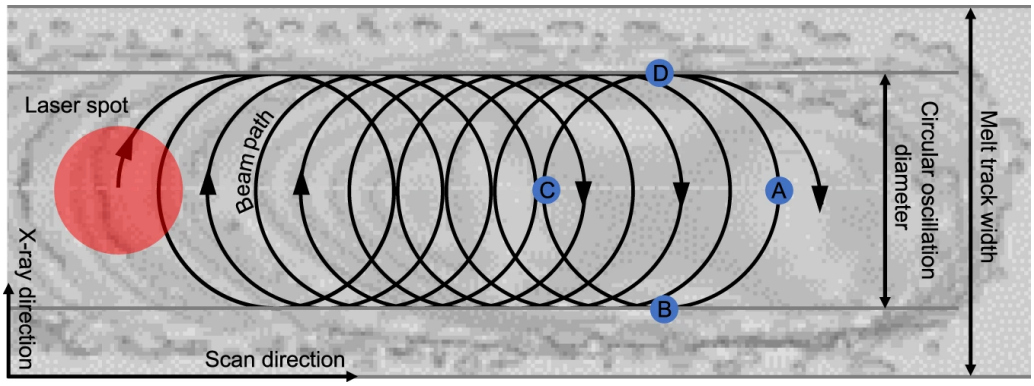


Figure 4: Plot of the laser beam path controlled by GE's FSM module [31].

While this solution achieved satisfactory results, it is a fairly inaccessible method both commercially and in research settings due to their use of proprietary technology. Therefore, most other research groups vibrating the laser beam delivery system have experimented using a PZT attached to the laser focusing lens instead. A team in collaboration with the South Korean government created a cylindrical module, composed of a compound circular flexure spring, containing a PZT and attaching to the focusing lens of a laser. Using this module, they were able to induce vibrations at a frequency of 724 Hz with an amplitude of 8 μm in the vertical (parallel to the laser axis) direction. Their module is pictured in Fig. 5 [29].

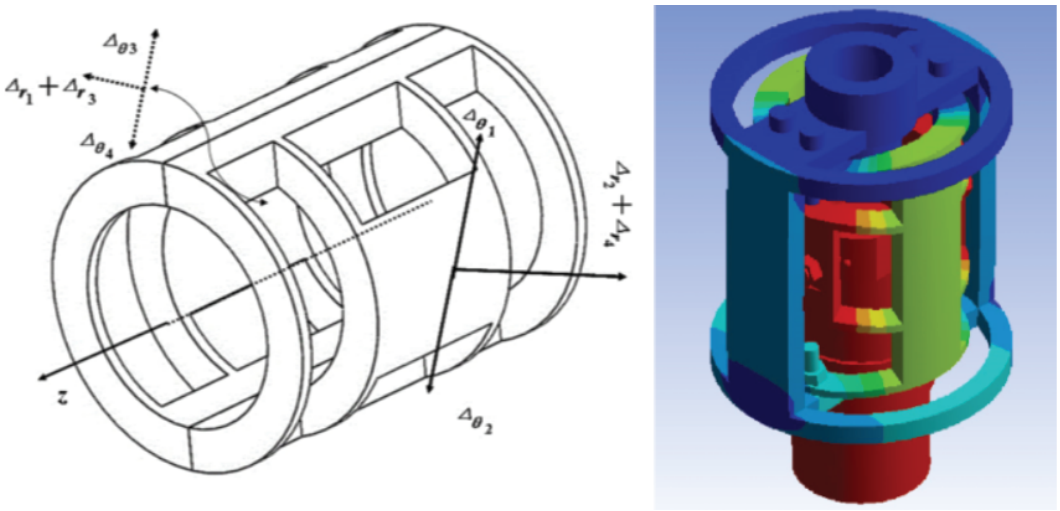


Figure 5: Geometry of the hollow vibrating module [29].

Another issue with workpiece vibration is that sensitive parts can become exposed to the thermal effects of the laser, which is not addressed by this team. To account for this, many other groups vibrating the focusing lens transmit their vibrations over a distance [18]. One of such groups based in South Korea designed a module consisting of a waveguide, a PZT actuator, and a lens. As shown in Fig. 6, the PZT actuator is attached to a top support and vibrates into the acoustic waveguide with the lens attached - which protects the lens from vibrational damage as well. Using this design, the group was able to achieve vibration at 23.56 kHz at an amplitude of 80 nm, again vertically along the axis of the laser [13].

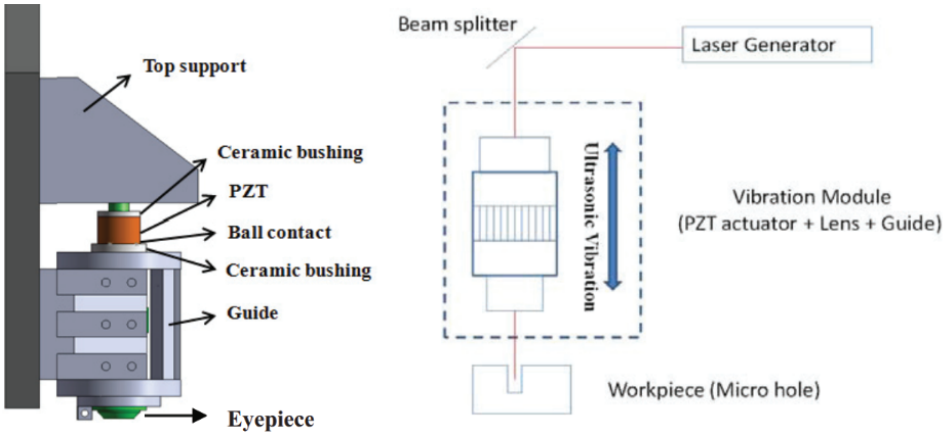


Figure 6: Side view of vibrating module with waveguide and important components labeled (left) and schematic of experimental set up (right) [13].

Another team of researchers created a similar product for use in polishing and drilling of stainless steel by developing a hollow module, consisting of two masses and a booster, vibrated at 29.703 kHz by a PZT with an amplitude of 30 μm and attached to the laser lens to vibrate along the laser axis. Instead of using a waveguide, this team transmit their ultrasonic vibrations to the lens through the physical booster itself. Their experimental schematic is shown in Fig. 7 [12].

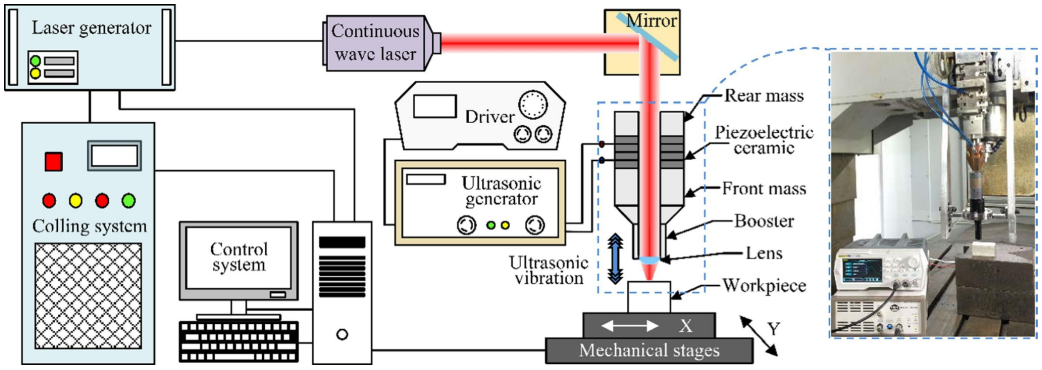


Figure 7: Experimental set up of hollow ultrasonic booster module for use in polishing and drilling stainless steel [12].

Each of these designs were successfully able to induce ultrasonic vibrations in a laser processing system. However, none fully address the needs of the sponsor of this project, Professor Wenda Tan. Professor Tan is an assistant professor with the Mechanical Engineering department at the University of Michigan. His research covers advanced manufacturing techniques, and he has a special interest in improving laser manufacturing processes. He has requested that a device be designed to induce vibrations transverse to the axis of the laser beam (i.e. horizontally) so as to study the effects on end product quality. This has not been achieved by any groups currently, other than the team in collaboration with General Electric, though, as discussed, their solution is not feasible due to the use of a proprietary FSM module. If successful, a physical, working prototype will be fabricated that is able to vibrate elements of the laser beam delivery system horizontally at an ultrasonic frequency and appropriate amplitude [30].

Design Process

During a team meeting, a customized design process model was created, informed by team sentiment regarding the models presented in the Design Process. The design process is a mixture of elements from the ME450 model and the discussion of cyclic models in the excerpt from the Clive Dym and Patrick

Little book, *Engineering Design: A Project-Based Introduction* [5]. The final model designed by the team to guide efforts in an effective and concise manner is shown below in Fig. 8.

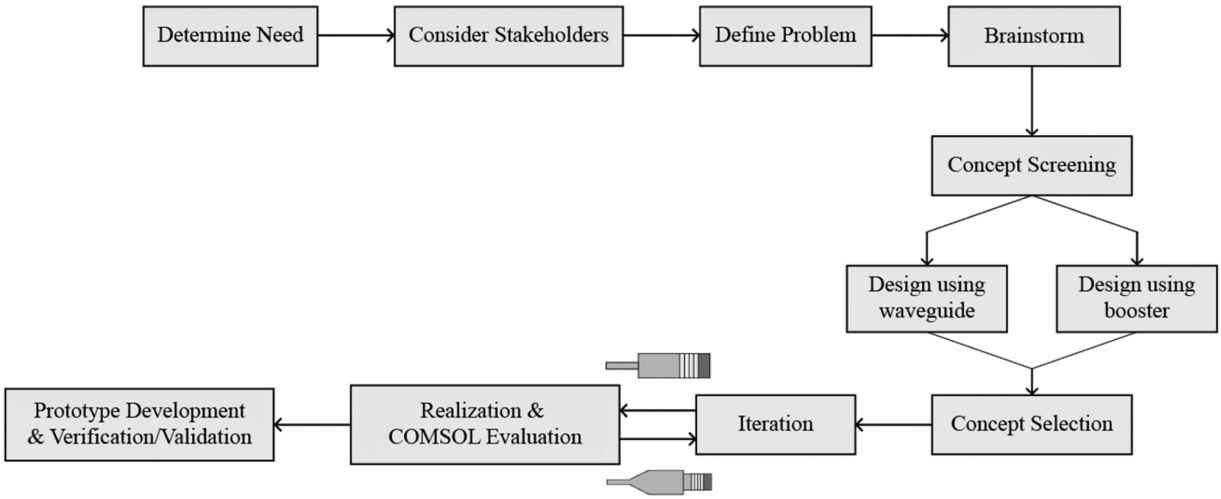


Figure 8: Team 7's customized final design process chart

Many of the models presented in Winn and Clarkson's *Models of Designing* [32] were considered in creating the custom process, as well as the ME450 model. First, the advantages and disadvantages of a stage-based model versus an activity-based model were explored. Due to the constantly evolving nature of the project, it was decided that the cyclic elements of activity-based models combined with some hard stages was best suited for the project. It was also considered if a solution-oriented or problem-oriented model was desired. Due to the emphasis on a thorough problem statement, it became clear that a problem-oriented model was needed. Then, the complete models presented in the text were examined to see if any fit the exact needs of the project or if elements could be adapted into a custom process. Some of these include the procedural cycle for systems analysis (Ehrlenspiel, 1995), Cross's model of the design process (Cross, 1994), and the design process (French, 1999). All of these models had components that fit but none of them were perfect as a whole. Thus, aspects that were helpful were incorporated into the custom model.

The most useful models were ones that were problem-oriented with aspects of both stage and activity-based models. This is because the project would benefit from designing the problem structure and generating many possible solutions, as this design is not starting with an initial proposed solution to work backwards from. In addition, the team recognized that parts of the process need to be structured and linear, while other stages require iterative elements. Combined models would therefore be most useful. Thus, the ME 450 model was useful as a starting point, but a model going more in depth on the concept exploration stage was desired. Useful models were found in Winn and Clarkson's Models of designing [32]. One such model was Cross's model of the design process (Cross, 1994), as it inspired the inclusion of iteration back from the evaluation stage to the idea generation stage. This makes sense because, after evaluating ideas, it was discussed that an idea may be found promising, but could be improved more if it was returned to idea generation. Another useful model for inspiration was French's stage based design process (French, 1999) because it laid the groundwork for the general flow of the custom process. The way the process flowed from need to problem and then conceptual design to selecting schemes was used for inspiration, and it also had feedback in key points, which was desired for the custom model.

As a result of the custom design process model being created as an amalgamation of different models, there are differences between it and the ME450 model presented in the learning block. Firstly, it was

chosen to add a step between the need determination step and the problem statement step as it was deemed necessary to take time to consider the implications of the project - whether that be stakeholders impacted, public health and safety, or a variety of other factors. By taking time to assess the impact of the project outside of the immediate team context, selecting a concept and design later down the road was easier. Secondly, a different approach was chosen because the group disliked how the ME450 model skipped over the concept screening, exploration, and evaluation phase. Thus, adding these sections in was deemed critical for the design process. Using this custom design process, the team was ready to move forward and deliver a high quality prototype design that meets and fills all the requirements and specifications set out. The design process evolved over the semester as the group learned more and things changed. The team desired to follow a systematic design process and this notion influenced the actions of the resulting design process. The chosen design process of the semester was systematic as the team moved through a clear, logical process of design.

Stakeholder Analysis and Ecosystem Map

After thorough consideration for the context of the project, the following combined stakeholder and ecosystem map in Fig. 9 below was created. Stakeholders are categorized into primary, secondary, and tertiary stakeholders based on their proximity to the possible impacts from the design solution. They are further categorized into their ecosystem map categories according to their possible roles in the project.

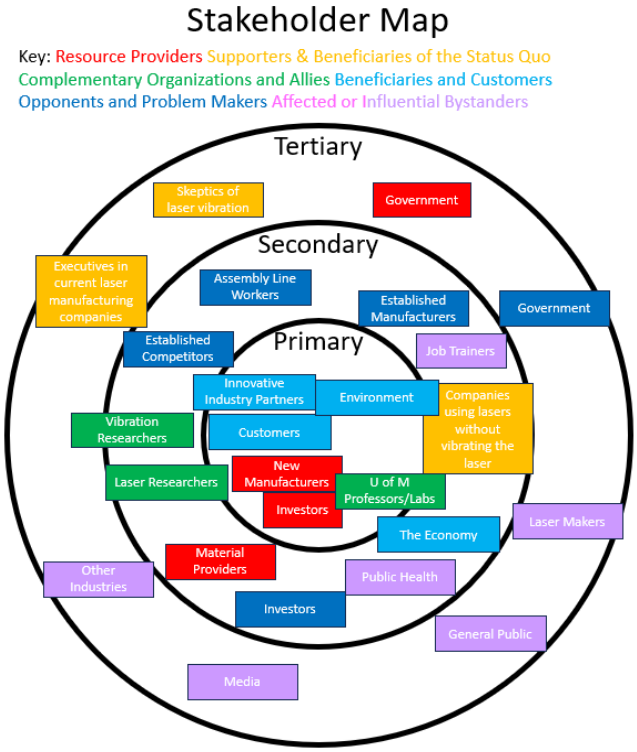


Figure 9: Stakeholder map of primary, secondary, and tertiary stakeholders for the project. A color key is provided to categorize each stakeholder into its corresponding ecosystem map category.

Since Professor Tan is the project sponsor, the main primary sponsor is the University of Michigan and its research labs. The immediate direct success of the project will impact the university since it is a university sponsored project. However, if all the stakeholders who may be impacted by the product (if it enters the market) are considered, there are many more primary, secondary, and tertiary stakeholders that are necessary to consider. Some other groups that will be directly affected by the project include potential customers, manufacturers, investors, industry partners, and the environment. Investors and industry partners may invest in the product, which will be produced through manufacturers. In addition, the

environmental burden is a notable concern as it requires a lot of energy to power laser manufacturing. However, laser manufacturing processes are much more energy efficient than conventional manufacturing processes, which justifies the energy cost. Some secondary stakeholders who are within the problem context include already established manufacturers, competitors, and workers. They will possibly be negatively affected by a mass rollout of the product, especially if it becomes the industry standard. Nevertheless, it was decided that other researchers in the manufacturing vibration field may support the group's work. The economy should be impacted from the increased efficiency and cost-cutting that results from laser manufacturing as well. Also, the vendors providing the materials for the design, such as piezoelectric ceramic producers, will be affected. Finally, tertiary stakeholders, those outside of the immediate problem context but who will influence the potential solution, were considered. For example, government officials and politicians may support or oppose the final design. The same can be said for the media, general public, and other industries. Finally, there will always be skeptics of laser vibration who doubt the feasibility of the process and if it is worth using over conventional methods.

Of the stakeholders discussed above, many will benefit from the development of this project. The most direct beneficiary will be the University of Michigan & its research labs. Other beneficiaries include manufacturers, customers, other researchers, the economy, and the environment. Laser vibration creates better quality products for businesses and manufacturers which increases customer satisfaction. It will also be a more attractive option for manufacturers who will be able to cut-costs and possibly line worker positions due to the automation available with laser manufacturing. The environment will also benefit because laser vibration mechanisms will improve laser manufacturing, causing it to be used over more energy-intensive traditional methods. This is important because the immense energy required to power traditional manufacturing methods is a burden on the environment, as this electricity is largely generated by fossil fuels. Thus, the improvement to energy efficiency will have recognisable benefits for the environment. However, there will be some stakeholders who unfortunately may be negatively impacted. Most directly, competing established manufacturers and companies already exploring laser optics vibration for use in manufacturing will be hurt by the team's work. For example, GE is already researching their own laser vibration methods, and if the group's findings are an improvement on their design, their bottom line could be negatively affected. Another core group that may suffer is assembly line factory workers who may lose their jobs if there is wide-spread distribution of the team's product. Laser manufacturing can be automated which may interest companies in replacing people with automated workers they don't need to pay a salary. These are the main social and ethical factors that were considered. It is clear that the social aspect of this design problem is the interaction between the economic and efficiency benefits of laser manufacturing, which comes at the cost of people's jobs and livelihoods. Laser manufacturing also can be dangerous if the proper safety regulations are not followed, so public health is another social concern. Nevertheless, beyond the interests of the project sponsor, the potential economic and environmental benefits with vibration in laser manufacturing are driving the project to be completed. Certainly, better quality products and energy efficiency advantages are at the core of the problem's motivation.

The project sponsor likely ranks the social impact at the same level as other key priorities, including the economic benefit, the team's education, and environmental improvements. He has mentioned that while economic benefits are a driving force due to the cost-cutting & improved efficiency of laser manufacturing, he also believes that the social impacts of better products for the public and greener energy are just as important. Due to the fact that the sponsor values all of these priorities equally, it is unlikely that the order of these priorities will affect the design significantly. Likely all factors of the project will be considered equally. However, this should positively reinforce the social impact of the project because the design will be catered to a sponsor who recognizes the social implications of the project. Since the social impact will be considered during design, the positive aspects of the project's social impact should be visible in the final product.

Intellectual property

Intellectual property rights played a respectable role in the project. The final solution is a novel one, and more simplistic than many of the solutions developed by research groups. Since the project is research through the University of Michigan, all intellectual property rights were signed over to the university. This includes patent rights, copyrights, and any inventions from the work. It is the team's responsibility to follow all the rules and regulations set by the University of Michigan. As employee-inventors of the university, the University of Michigan will control the intellectual property and will be solely responsible for pursuing any protections or commercializations of the project if they choose to. As a result, the group will not have control of what is done with the final design, whether it is sold as a commercial product or kept for research purposes only. If released to the public, the final design could potentially compete with similar technology using a fast steering mirror in development at General Electric.

Information Sources

Using the University of Michigan library databases, patents, academic journal articles, and stakeholder interviews, a comprehensive literature review of ultrasonic vibration assisted laser manufacturing was put together. Much of the research conducted by the team was individual. Each team member discovered and reviewed a number of papers related to vibration assisted manufacturing, specifically laser manufacturing, using the University of Michigan library databases. These articles and findings were then brought to the full group in team meetings in order to discuss the design context and put together the more formal literature review. This was a very effective strategy, as it allowed for a large number of unique information sources to be considered - casting a wide net to discover potential benchmarks that would be relevant to the project. However, the University of Michigan librarians were likely under-utilized by the team, which created some challenges in finding certain information, like appropriate and applicable safety standards.

User Requirements and Engineering Specifications

Once the problem was fully defined through literature review and benchmarking, a list of user requirements and the corresponding engineering specifications was developed. These requirements were created by not only interviewing the project sponsor and determining his needs for the project, but also through stakeholder analysis and consideration of the secondary and tertiary stakeholders. Some requirements and specifications were also inspired by research done into benchmarking current products. All requirements, along with their specifications and justifications, are contained in Table 1 below. They are listed in descending order of importance, which was determined by reviewing with the sponsor of the project and gathering feedback on the requirements that were necessary vs. requirements that were "wishes."

Table 1: Table of requirements and specifications for the project with justifications including the stakeholders that best benefit from each requirement

Requirements	**Specifications**	**Justifications**
Vibrate Ultrasonically	Stable vibration mode occurs at a frequency ≥ 20kHz	Fundamental requirement of the project specified by sponsor to match the high linear speed of common laser processes [30,31].
Vibrate Horizontally	Design produces vibrations in the x-y plane	Requirement specified by sponsor based on current technology available [30].
Appropriate Amplitude	Vibration displacement	Requirement specified by sponsor because an

	between 200-500 microns	amplitude outside this range will either be too small to be effective, or too large to be accurate [30].
Optimizes Power Use	The driving PZT voltage is < 500 V	Needs to be environmentally friendly and save unnecessary power costs for users. Based on operating voltages from previous benchmarks [12,13]. Also, must be able to be achieved with common lab equipment.
Safe to Use	Complies with ISO 11553 [25] and IEC 60825 [24] standards.	Guarantees safety of use for users, the general public, and the environment.
Portable	Dimensions: 50x50x200 mm	Based on dimensions from previous papers and benchmarks, affecting customers and researchers. [12,13,29]
Durable	Must operate for > 1.5*10^11 cycles without failing	Assuming an estimated usage of (8 hours/day)*(5 days/week)*(52 weeks/year)*(5 years) at 20kHz to act as a minimum use case. Durability is important for users, investors, and limiting waste towards the environment.
Easily Maintainable	Parts can be sourced from ≥ 2 vendors	Lowers maintenance costs and ease of use for users, potential job trainers, and the environment.
Manufacturable	Can be manufactured by in < 3 weeks (not including time for shipping)	Ensures that too complex of a design is not undertaken, such that a working high-quality prototype can be delivered to the sponsor at the end of the term.

The table outlines all the requirements for the project's design, the specifications that certify the requirements, and the justification for each requirement along with the stakeholder(s) it represents. The only standards that must be met for the project are the standards outlined in ISO 11553 and IEC 60825, which clarify the safety requirements and procedures that are necessary for any company or organization that works with lasers and beam delivery systems. This was included with the social consideration of public health and the environmental consideration of energy use guidelines in mind. The needs, which are the most important requirements, are the top five requirements which were outlined by the project's sponsor and the team. The whole team made sure to consider the social, economic, and environmental aspects of the project when determining the requirements. The "wants," or the requirements that would be beneficial to have but not necessary, are listed below the needs starting with portability. It was decided to list portability as the most important "want" because it was determined to be important that the project is able to be easily moved in case installation, transportation, or the discarding of the design after it has reached its cycle life. From there, the team decided to include the requirements of the product being easily maintainable and durable as well, appealing to the stakeholders of not only the users of the product but also reaching into the social aspect of the project that includes the environment, the general public, and opponents or critics of the design. During the concept generation and selection process, it was necessary for the team to add a manufacturable requirement. It was determined that this is critical in the concept

selection stage as a design that was not too complex to manufacture and could be assembled into a prototype to deliver to the sponsor at the end of the semester was desired.

Every requirement listed has been translated into engineering specifications that can easily be measured and validated once the project has been completed. The quantities of each specification were either specified by the sponsor or calculated through literature review and research. For example, the specification of the lens vibrating at at least 20 kHz was specified by the sponsor and can easily be measured when using a transducer to induce vibrations in the lens. Other specifications that were laid out by the sponsor include the vibration displacement between 200 and 500 microns and the vibrations being horizontal in the x-y plane. The requirement for the design being safe to use can be measured by whether it complies with the ISO 11553 and IEC 60825 standards or not. The measurement values for specifications not outlined by the sponsor were calculated by the team using previous research and skills from learning blocks. For example, the measurement for the durability requirement of being able to withstand more than 1.5*10^11 cycles was calculated using the knowledge from the social context assessment learning block. Similarly the requirements of portability and ease of maintenance were given specifications based on the research of the stainless steel drilling design [12], or the power requirement that was justified using research from benchmarks outlining PZT driving voltage [12,13]. The manufacturable requirement can be specified by all parts being able to be manufactured in less than a three week span due to the tight timeframe of the project and to save on cost of both money and time during the manufacturing process. All specifications given to the respective requirements are reasonable and can be validated at the end of the design process.

When justifying the requirements that were developed, it was important to include not only the primary stakeholders in the thought process but also the secondary and tertiary stakeholders. By doing this, the team ensured that the requirements of the project not only benefited the customers and users of the final solution, but also stakeholders such as the environment, job trainers, and the general public. An example of this is the easy to maintain requirement. Not only does an easily maintainable project make it easier for the user of the laser to use, but it makes it easier for job trainers to train potential employees on and limits the amount of waste that will end up affecting the environment. Putting environmental context into the requirements and specifications is extremely important, as it is necessary to ensure that whatever design is chosen is as environmentally friendly as possible. The team incorporated this by setting requirements to limit the amount of waste and the energy usage of the design, combatting materials ending up in landfills and conserving energy that would otherwise be wasted.

Concept Generation

Multiple concept generation methods were used to create solution ideas. First, forty ideas were generated individually as a part of the Concept Generation Learning Block. Kevin used divergent thinking and tried to not rule out “crazy” ideas. He spontaneously jotted down a variety of ideas while exploring numerous solutions to the design problem. He then used a morphological chart to divide the design into subsystems and create new ideas from the combinations. Additionally, he found design heuristics helpful to iterate on previous ideas. Similarly, Jonathan focused on using a morphological chart to create subsections for the project. He iterated through designs by building on, reflecting, and improving previous ideas. Eashan first started with divergent thinking, and also relied on a morphological chart for idea expansion. However, he differed from the others by utilizing the TRIZ method to overcome psychological interia. He accomplished this by researching similar solutions that have been used in other areas of industries and adapting them to apply to this project. Finally, Nick discovered many of his concepts from functional decomposition and used these ideas to create his own morphological chart. He also was a big supporter of using design heuristics to create innovative evolutions of his original ideas.

After individually brainstorming, the group came back together to compare and discuss the different concepts generated. Over the course of discussion, three major categories of generated concepts became visible - those derived from a morphological chart, from design heuristics, and from divergent thinking. The ideas within these categories could be broken down even further by determining the subfunctions of design that each related to. It was quickly discovered that many of the ideas from individual members were similar across the group and that the use of a morphological chart created as a team would be beneficial as seen in Appendix 1E. Functional decomposition was used to divide the design into four subfunctions with three solutions addressing each subfunction, of which different combinations could be selected. The first subfunction was the type of vibration method - using piezoelectric ceramic materials, a vibration motor, or an FSM module. As outlined in the background sections, piezoelectric materials are those that deform when a voltage is induced across them, so they can be used in an ultrasonic transducer. The vibrational motor would involve a motor operating with an off-axis, unbalanced mass attached. The FSM would operate similarly to the GE benchmark [31] to create oscillations instead of vibrations. The second subfunction was the method of vibration transmission. The solutions considered were using a waveguide, booster, and direct contact. A waveguide is a hollow chamber that supports transmission of vibrations through air, while a solid booster acts as both a waveguide (i.e. it supports transmission of vibrations through a solid) and an amplifier. Next, the third subfunction was the plane, or axis, of vibration. This was broken down into options along the x-y plane, z-axis, and y axis. It is important to note that these choices assume the linear direction of the laser processing is the x-axis. This subfunction was of significant importance to the sponsor, so it was ensured that multiple viable options were examined. A final subfunction was discussed detailing how the design would be mounted, that is, what part of the laser manufacturing set up shown in Fig.1 on p. 1 would be vibrated. Solution ideas were narrowed down to attaching it to the laser, the workpiece, or a component of the laser beam delivery system. Concepts were generated using different combinations from the morphological chart. Additionally, since most of the group used design heuristics in some way, it was decided that some of the best ideas from this pool should be explored as well. The team generated numerous ideas with design heuristic cards such as “Cover or Wrap”, which could incorporate an additional material to cover the workpiece while it is being vibrated (ex. Appendix 1E #2). The “Incorporate Environment” card was used to bring in existing elements of the surroundings for the product (ex. Appendix 1A iteration #7) and “Mimic Natural Mechanisms” cards were used (ex. Appendix 1A iteration #2 or Appendix 1D #23) to imagine a design that used animal noises. The “Attach Product to User" (ex. Appendix 1A iteration #3) and “Add to Existing Product” (ex. Appendix 1E #2) cards either use the employee or another worker to induce vibrations or consider modifying an existing product.

The concepts generated are distinct from each other either because they are completely unique ideas or they are variations generated from different combinations of a morphological chart. The team determined that a concept was distinct if it had a component or function/subfunction that was unique. Often, there were variations of a similar concept with one component changed due to iteration, which made the concept unique. For example, there were several concepts that used piezoelectric transducers that varied in how the transducer was attached to the design. Building on this idea, there were also several concepts that had the mechanism attached to the laser delivery system but used different means of inducing vibrations. Concepts were classified according to the subfunction or component parts in the design. For example, concepts using piezoelectric materials were grouped together and concepts with a motor were grouped together. The reasoning behind this is that it allowed for the creation of more concepts that were feasible and realistic to create as well as concepts that built off of subfunctions that addressed requirements of the project. Concepts were also classified based on the method of which they were generated. The reasoning behind this decision was that the concepts created with the morphological chart could be compared based on what subfunctions were kept the same and which ones were changed, whereas designs that were created using design heuristics were typically more creative and unique.

In the end, the morphological chart created by the group resulted in a total of 81 concepts. This, in conjunction with the concepts each group member brainstormed individually for the Design Process Learning Block and some design heuristics ideas, netted a total of 254 design concepts. These design concepts featured heavy overlap and many were extreme and unfeasible. Thus, filtering was necessary. The full list of concepts generated can be found in Appendix 2.

Concept Selection Process

To narrow down the 254 total concepts generated, convergent thinking was used to identify a few high quality concepts to investigate further. Thus, the first method of reduction was eliminating multiple instances of the same, or similar, design concepts. For example, if two group members came up with a concept involving a PZT to vibrate the focusing lens within the laser delivery system, one of the two instances would be removed. Through removing replicates, the total number was able to be filtered down to just around 165 designs. From here, the remaining designs were discussed and those that seemed to be too imprudent or ill-considered were eliminated. Many ideas fell into this category as a result of divergent thinking, leading to crazy ideas. This further narrowed down the list of concepts to just about one hundred. From here, ideas that were too expensive, too complex, or too labor intensive were filtered out to ensure a working prototype or solution could be manufactured by the end of the semester in time for the design expo while remaining within the strict six-hundred dollar budget. This second pass of filtering narrowed the list down to seven higher-quality designs, all more promising solutions. Five of these designs were from the group morphological chart, and the other two were from the “Add to Existing Product” and “Cover or Wrap” design heuristic cards. With these seven designs selected, it was apparent that some design components had similarities to the first solution concepts thought of after meeting with the sponsor for the first time when the project was assigned. The use of piezoelectric transducers to illicit vibrations was immediately attractive due to their heavy usage in industry in acoustic and vibration scenarios. Additionally, initial thoughts were focused on vibrating parts within the laser delivery system, similarly to some of the seven filtered designs. However, none of these original ideas were complete and as detailed as the final concepts. There is no evidence of fixation because the team reviewed numerous concepts and many of the final seven designs are entirely unique from the original concepts. The idea of using piezoelectric ceramics was determined to be a strong option for reasons other than its market usage. Additionally, there is nothing on the market currently where the laser delivery components are vibrated with piezoelectric materials transverse to the laser axis. It is easily justifiable that some of the current concepts have some components similar to the original concept since there are not many benchmarks or literature on vibration for laser manufacturing, but given this, other concepts were still thoroughly researched and developed before settling on a design. This involved researching mechanisms such as vibration motors or fluid induced vibration and comparing their effectiveness. Furthermore, the use of vibrations in manufacturing has long been developed, and thus, many of the technologies surrounding workpiece vibration have been optimized. It therefore makes sense to utilize current methods and adapt the effective parts in new and novel ways. Given this, there are only so many realistic and viable ways to vibrate a laser manufacturing device consistently without impeding workpiece quality. Thus, the team does not believe more concept development would result in any new breakthroughs because the best options have already been thoroughly researched and/or selected. Given this, the group was able to categorize many of the remaining ideas under one of the sub function groups in the morph chart - vibration method. Many of these ideas could meet the subfunction requirements and could be put together as a system to create a complete design. The team used the morphological chart to transform subfunctions into an overall system. This led to the classification of objects as either using piezoelectric materials, vibration motors, or a fast steering mirror module. This helped later down the line when choosing which 7 final ideas to include in the Pugh Chart as we could choose ideas that were more representative of the concepts generated.

A sketch of the first of the seven preliminary designs, created using the morphological chart, is shown below in Fig. 10 on p. 15.

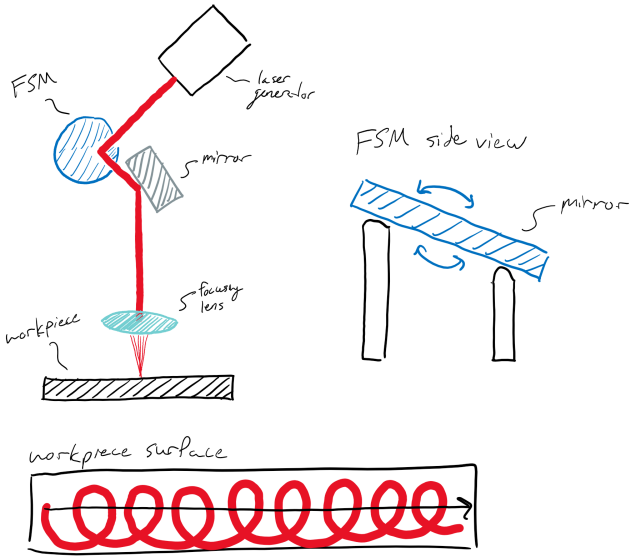


Figure 10: Concept Selection Design 1

This first design chosen in the selection process uses an FSM Module that is very similar to the GE Benchmark [22,23]. In this design, an FSM module is added to the laser beam delivery system and is used to alter the laser beam path in the X-Y plane, thus removing the need for vibration and vibration transmission. It was created based on the morphological chart subfunctions of vibration direction, transmission method, and mounting. This concept was chosen because similar technology has been used before as seen in the GE Benchmark [22,23,31] so it is known that it is possible to achieve and will meet the requirement of inducing oscillations in the X-Y plane. A disadvantage of this technology, however, is that it is not very versatile and does not meet portability or manufacturability requirements due to its complex nature. Moving down the morphological chart of the attachment subfunction, a second design was selected and is shown in Fig. 11.

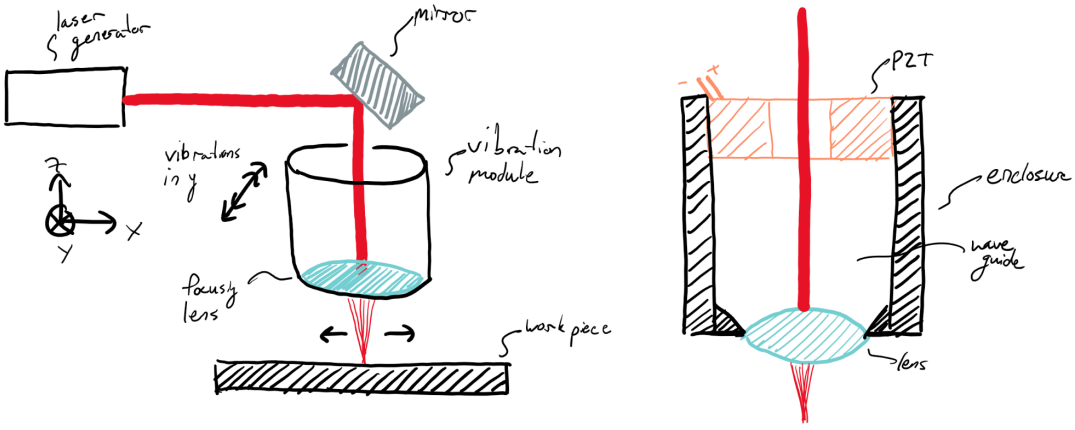


Figure 11: Concept Selection Design 2

This design uses piezoelectric transducers and a waveguide that attach to the laser delivery system and reflect the laser through a hollow device similar to the stainless steel drilling benchmark design [29],

however without the masses and booster. The basis of this design arises from the morphological chart using the vibration method, transmission, direction, and mounting subfunctions. This design showed clear advantages in several categories, most notably in the portability and being able to produce transverse vibrations. A disadvantage of this design, however, is that although it is feasible, it is not the easiest of the designs in terms of manufacturing. Using the same subfunctions of the piezoelectric transducers and the attachment method of attaching to the laser delivery system, the team was able to move down the morphological analysis chart to create the third design that is shown in Fig. 12 on p. 16.

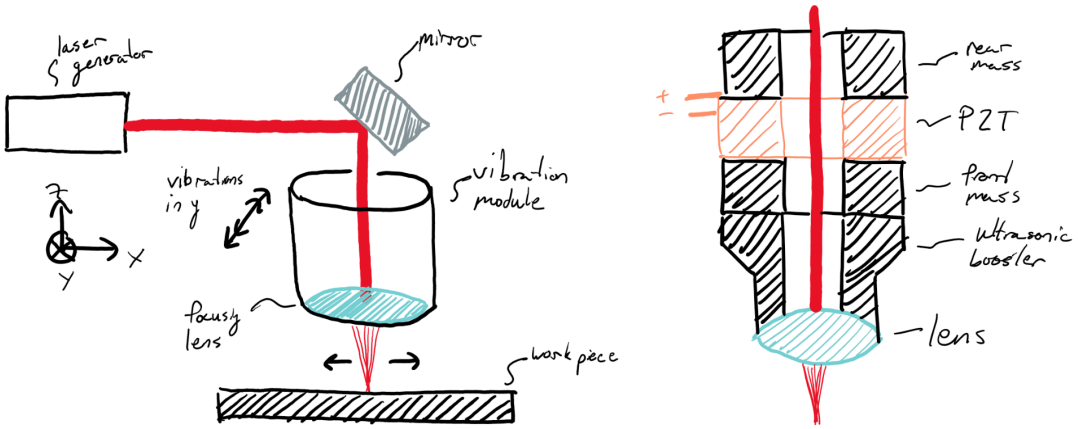


Figure 12: Concept Selection Design 3

The third design is similar to the second design shown in Fig. 11 on p. 14, and also uses the stainless steel drilling benchmark [29] as inspiration. The main difference between this design and the second design, however, is that this design uses a booster and countermass (acting as a solid waveguide) to vibrate the laser delivery system rather than a hollow waveguide. In the morphological chart, this design was created by keeping the piezoelectric vibration method and mounting subfunction the same, while moving down the chart to the booster vibration transmission method. The design has similar advantages to the previous design, notably portability and the ease of creating transverse vibrations. It poses similar challenges as well as being more complicated to manufacture than more simple designs, which in return causes the maintenance to be more difficult as well. With the advantages and disadvantages of the previous two piezoelectric designs in mind, the team decided to move down the morphological chart to a different vibration method resulting in a design that is shown below in Fig. 13.

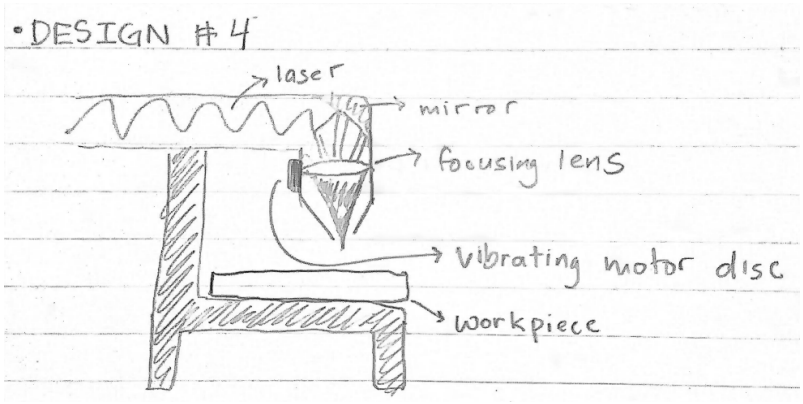


Figure 13: Concept Selection Design 4

The fourth design differs in using direct contact to induce the vibrations. This design still attaches to the laser beam delivery system, however, it uses a motor attached to a disk to directly contact the lens and induce vibrations. The advantages of this method is that it is small and therefore very portable and it does not require the manufacturing of many parts. The disadvantages, however, come from the direct contact applied to the lens, which is not the safest or most feasible method. A big worry with a design such as this is that the lens could be more susceptible to cracking, reducing the durability of the product and possibly even irreparably damaging expensive components. Therefore, the group moved down the morphological chart examining direct contact with other sub functions similar to previous designs. The fifth and final design created using morphological charts is shown in Fig. 14 below.

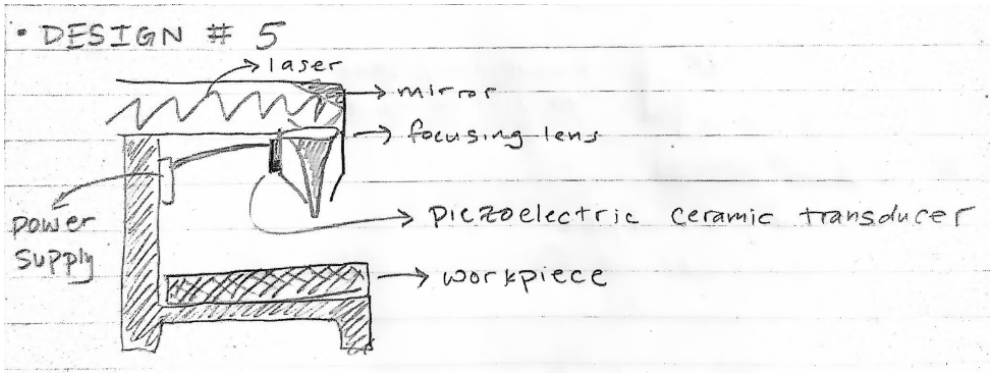


Figure 14: Concept Selection Design 5

The fifth design is almost identical to the fourth design previously shown in Fig. 13, with the only difference being that it uses a piezoelectric transducer rather than a vibration motor to induce vibrations directly onto the lens. This design has the same advantages as the previous design in that it is portable and requires very few parts to manufacture and assemble. It also poses similar disadvantages of the direct contact to the lens being detrimental to the durability of the project, however, the group believes that a piezoelectric transducer has a far lower chance of damaging components. Although there are 81 possible concepts to be explored from the morphological chart, the group decided that five quality concepts should be taken from the chart due to their consistency and feasibility in meeting all of the sub-functional requirements of the project. After selecting five designs from morphological analysis, two more concepts were selected that were generated using design heuristics, the first of which is shown in Fig. 15 below.

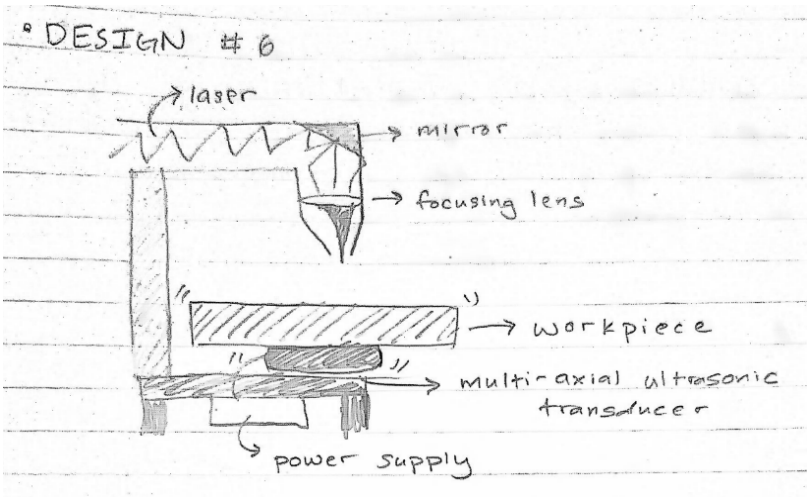


Figure 15: Concept Selection Design 6

The idea behind this design was to improve upon existing benchmarks of technology that is already being used in the manufacturing field, the technology of vibrating the workpiece. Using the “add to existing product” design heuristic card, a concept that uses a multiaxial transducer to vibrate the workpiece was created, differing from current benchmarks in that it vibrates on multiple axes and not a singular one. The advantages of this design are that it is known to work. The disadvantage, however, is that it falls into the same pitfall of the original methods in that it will not be able to provide universal vibration to any workpiece. With this disadvantage in mind, the group decided to explore a final design from design heuristic, shown below in Fig. 16.

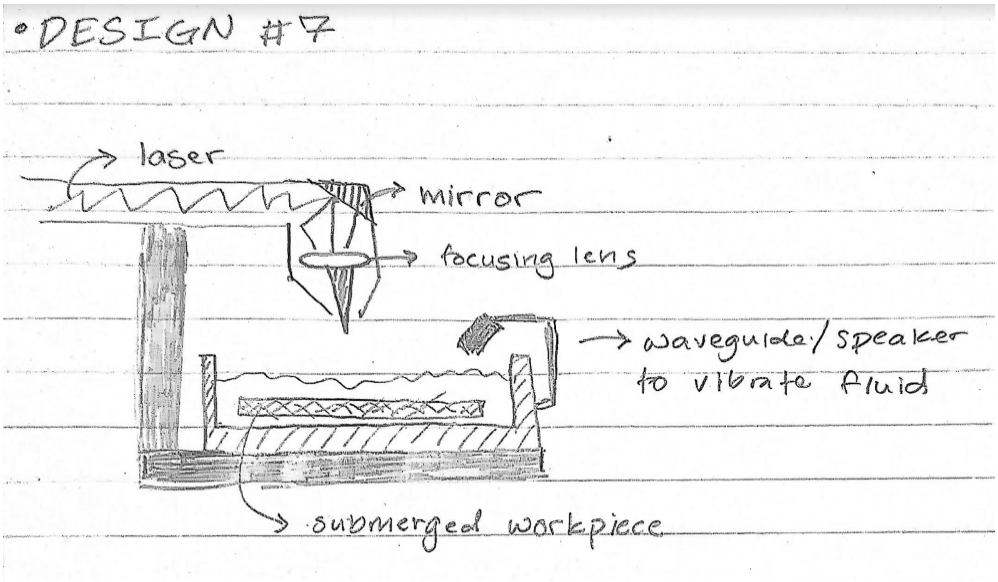


Figure 16: Concept Selection Design 7

This final design was one of the more “out there” ideas that the team came up with, and was created using the “cover or wrap” design heuristics card. The idea behind this design was to submerge the workpiece in some sort of fluid and then vibrate the fluid using a waveguide or speaker. The only advantage to this design is that it is effective in inducing vibrations to the workpiece and it is known that with a high viscosity fluid, the workpiece will not translate. The main disadvantage, however, is that it is completely novel technology and has therefore not been researched heavily by other groups. In addition, it is not portable and not as feasible as other designs, as not every workpiece will be able to be submerged in fluid. Still, it was a creative idea with potential, and was therefore chosen as one of the seven final designs.

Furthermore, these seven ideas were selected due to the designs being consistent with the nine engineering and design requirements set forth. This ensured that all seven remaining ideas were viable in case one was chosen. This prevented an idea from being chosen by the Pugh Chart and being pursued throughout the semester and eventually discovering that it did not meet one of the key engineering requirements and specifications set forth at the beginning of the project. With this in mind, we found that Design 1 (Fig. 10 on p. 14) might pose an issue in regards to the manufacturability requirement as it is a complex design and may cause us to go over the 3 week limit. Additionally, we found that Design 7 (Fig. 16) did not meet the portability requirement as well since the volume of water might pose an issue to the dimensions specified. However, in general all 7 concepts meet the subfunction requirements, but some do it better than others. Since these remaining seven ideas were determined to be the most practical, a Pugh Chart was created to compare the ideas amongst each other while giving a quantitative score based on four predetermined metrics in order to ensure one design would come out on top. These four metrics were ability to vibrate transverse to the laser axis, safety, portability, and feasibility for manufacturing. The first

metric was chosen as it was a direct requirement of the sponsor, and thus was imperative that the design be able to meet it. The safety and portability requirements were chosen such that the design would be usable by a larger population of people - those with and without formal laser training as well as researchers without constant access to their own laser such that they could attach and remove the device as needed. The last metric - feasibility or manufacturability - was chosen to ensure a high-quality, working prototype could be delivered by the end of the semester.

These criterias were assigned weights based on priority to the team and to the sponsor. As a result, the vibrate transverse criteria was given the highest weight of three, since a failure in this category meant it would fail to be useful to the sponsor in any way. Secondly, the safety requirement was given a one. This is because, although safety is important, the sponsor notified us that the solution would only be utilized by trained students in his lab. Thus, safety was not as important, since the device would be assumed to be used by students who would already be trained and experienced in using new laser technology, and thus would know the dangers of laser operation. Lastly, the portability and manufacturability criteria were given weights of two, as they were both equally important. Portability is important so that the end design could be moved from the University of Michigan, Ann Arbor campus to the General Motors facility which houses the laser used for research by the sponsor. Furthermore, manufacturability was important so that the team could deliver a high quality prototype within the time constraints of ME450, as, if the team was unable to manufacture the solution, the sponsor's needs would remain unmet.

Next, a benchmark design was chosen to compare the designs against in order to 'standardize' the ratings - the benchmark chosen being traditional workpiece vibration methods. These ratings were given on a scale of -2 to +2. A -2 or +2 score was assigned if the design lacked the ability to meet the criteria or meet the criteria in an exceeding manner, respectively. A -1 or +1 score was given if the design failed to meet the criteria but could be adapted to, or if it just barely met the criteria, respectively. A score of 0 was given if the design met the metric to the same degree as the benchmark. Furthermore, each criteria was given equal weight due to equal importance in selecting a design. This resulted in the Pugh Chart shown below in Table 2.

Table 2: Pugh Chart

Criteria	Weight	Benchmark	#1	#2	#3	#4	#5	#6	#7
Vibrate Transverse	3	0	+1	+1	+1	+1	+1	+1	+1
Safety	1	0	0	+1	+1	-2	-2	0	-2
Portability	2	0	-2	+2	+1	+2	+2	0	-2
Manufacturability	2	0	-2	+1	+2	+1	+1	-1	-2
Total		0	-5	+10	+10	+7	+7	+1	-7

Both Designs 2 and 3 were given a +1 for the vibration metric because they met the criteria and were able to create vibrations in the x and y plane. Both were given a +1 as the vibration device would be fixed to the outside of the laser delivery system and thus reduced the risk of reaching into the laser delivery system and accidentally cutting or burning something. Design 2 was awarded +2 for portability due to being lightweight as a result of the hollowed out geometry of the waveguide. Design 3 in comparison was given a +1 due to the solid booster essentially being a solid block of mass and thus more heavy. For the feasibility category Design 2 was assigned a +1 in comparison to the +2 of Design 3. This was a result of the hollowed out geometry of the waveguide in Design 2 being more complex and thus harder to

manufacture in comparison to a solid booster machined into a horn geometry as shown in Fig. 12 on p. 15.

From the Pugh Chart, Design 2 and Design 3, were tied for the best design. In order to converge on just one design, some rough, preliminary analysis relating to acoustic power transfer was completed. Modeling Designs 2 and 3 (Figs. 11 and 12 on p. 14-15) as infinite, three material layers with ultrasonic vibrations represented as normally incident plane waves allows for the derivation of a transmission intensity coefficient. This transmission intensity coefficient represents the ratio of the transmitted intensity into material three and the incident intensity from material one. Note that intensity is power per unit area, so this intensity transmission coefficient physically represents how much acoustic power is flowing through the layer interface into the glass lens (material three) from the PZT (material one), where a higher value means a larger amount of acoustic power is transferred. By changing the material properties of material two (the layer separating the glass and PZT), intensity transmission of Designs 2 and 3 can be represented as cases A and B respectively and compared. Since Design 2 utilizes an acoustic waveguide to transmit ultrasonic vibrations, material two can be approximated as air in case A, while since Design 3 utilizes an aluminum booster, acting as a solid waveguide, material two can be approximated as bulk aluminum in case B [14]. A diagram of the three material layer along with the calculation process to find the transmission intensity coefficient for cases A and B is provided in Appendix 2. From these calculations, the transmission intensity coefficient is much higher for case B, corresponding to Design 3, by a factor of 10^8, meaning that vibrations from the PZT will more efficiently and effectively transfer to the glass lens using the booster design. Therefore, Design 3 was selected to move forward with.

Problem Analysis

A variety of scientific fields within the engineering disciplines will need to be considered in order to determine if the final manifestation of Design 3 meets the requirements and specifications outlined in Table 1 on p. 9. A deep knowledge of dynamics, specifically acoustics, will be most applicable, as this field studies mechanical waves, including vibrations and ultrasound - topics which are a core part of this project and correspond to the first three most important engineering requirements. In addition, in order to address the requirement limiting power use of the design, skills studied in electrical engineering, specifically power systems, will be needed. The only other major scientific field relevant to the design is solid mechanics, as the working principles of piezoelectric materials, those that experience stresses in response to induced voltage, are heavily influenced by the topics studied in this discipline. Solid mechanical principles will also govern failure modes of the final product, relating to the durability and safety requirements.

Using the fundamental techniques and simplified models studied in these fields, the performance of the final design will be able to be predicted and then validated in testing. The most important requirements of the end product, other than the vibration direction, which is determined by piezoelectric ceramic material choice, are vibration frequency, vibration amplitude, and power use. In literature, methods have been created to design ultrasonic Langevin transducers, similar to the proposed solution in Design 3, through optimization of a matrix model of the booster, PZT, and rear mass geometry and material properties. These methods will allow for the design of the vibration amplitude and power use at a set frequency - thus allowing these requirements to be met [6]. The success of the dimensions and geometry of the design in regards to meeting these requirements can then be evaluated by driving a prototype at the optimal current and voltage determined and comparing the observed vibration frequency and amplitude to the predicted values. Alternatively, simulation can be used to validate the predicted results by importing the 3D geometry into a finite-element analysis (FEA) multiphysics software and examining the frequency response [12]. FEA simulation techniques can also be utilized to perform static structural analysis to compute the stresses and strains across the geometry [29]. Examination of these distributions will allow

for failure analysis to ensure that the requirements of durability, as well as safety, albeit indirectly, are met. Physical experiment in the form of cyclic loading fatigue testing can also be used to validate these requirements.

Engineering Analysis

After Design 3 was selected to move forward with, it was designated as the “Alpha Design” and was further elaborated on. This was objectively the “best” choice, as most benchmarks found in literature achieved success with similar designs. Because of this, the team firmly believes it was not chosen due to sponsor influence since he was not the originator of the idea. He did point us in the direction of some benchmarks, but none of them are like the team’s alpha design. Although sponsor input and feedback was taken into account, it was not a major factor - instead the criteria put forth in the Pugh Chart was a larger influence. Although it is a valid concern, this team can confidently state that no numbers were fudged or edited to yield a certain outcome for the sponsor and objective selection was used. Furthermore, since manufacturability was taken into account, the team is confident that this project will be able to come to fruition within the constraints of the ME450 class and semester. To begin the design, key dimensions of the cylindrical sections, such as diameter, were obtained through material selection.

PZT-8 was first chosen as the preferred piezoelectric material used in the transducer due to its frequent application in ultrasonic transducers. The direct reasoning behind this choice is contained in the **Final Design Description**. A 30mm OD x 10mm ID x 6mm PZT-8 annulus was chosen, as the only other suitable option was a 50mm OD x 20 mm ID x 5 mm PZT-8 annulus, whose size could cause issues with the portability requirement later down the line. Thus, the initial outer diameter of the design was now set, and the lengths and other key dimensions of each individual section could be calculated through analytical and computational means.

In order to determine and calculate the dimensions of the booster, calculations were done utilizing the equations and processes laid out in the Steel Drilling and Polishing benchmark [12].This benchmark was chosen mainly due to its thoroughness in laying out the steps for all the needed calculations to derive the dimensions of each section of the booster. Furthermore, the application of the booster was similar to that of the group’s planned application and thus many of the methods could be adapted for the group’s needs. First, the device was split into four subsections - the rear mass, the piezoelectric ceramic stack, the front mass, and the booster horn. Firstly, an electrically coupled mechanical equivalent circuit representation of the transducer (the section corresponding to the PZT stack sandwiched between the front and rear mass) was created, shown in Fig. 17 [12].

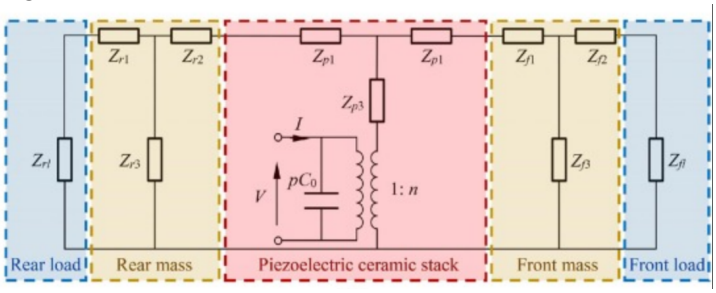


Figure 17: Equivalent circuit representation of the transducer section of the design [12].

To determine the impedances of the rear mass and front mass, it was simply a matter of choosing a material and calculating the mechanical impedance. Thus, as outlined in the benchmark, a high mechanical impedance material needed to be chosen for the rear mass and a low mechanical impedance material for the front mass. This was done to ensure that the vibrations would follow the path of least resistance and be “funneled” towards the horn - resulting in maximum tip displacement. After assessing a

wide array of materials, 4140 steel and 7075 aluminum were chosen for the rear mass and front mass, respectively. The mechanical impedances are calculated with Eqs. 1 and 2 below.

$$Z_{f2} + \frac{Z_{f1} \times Z_{f3}}{Z_{f1} + Z_{f3}} = \frac{j\rho_2 c_2 \pi (D_2 - d_2)^2 \tan(k_2 l_2)}{4} \tag{1}$$

$$Z_{r2} + \frac{Z_{r1} \times Z_{r3}}{Z_{r1} + Z_{r3}} = \frac{j\rho_1 c_1 \pi (D_1 - d_1)^2 \tan(k_1 l_1)}{4} \tag{2}$$

To compare the two materials, the same length and diameter values were used. Since they have similar acoustic wavenumbers (k), the material with the higher mechanical impedances will be that with the higher acoustic impedance (the product of density and speed of sound). The acoustic impedance of 4140 steel is $4*10^7$ kg/m^{2}s while the acoustic impedance for 7075 aluminum is $1.4*10^7$ kg/m^{2}s - almost a quarter of that of steel. Thus, the material choices were valid and supported by this analysis. With the materials chosen, focus could be set to determine the lengths of the booster sections. Initially, it was decided that the booster design could be simplified for manufacturing purposes by removing the conical section of the booster. This viewpoint was validated by Professor Grosh, who is a researcher within the ultrasonic transducer field and supports advancement within the field, thus giving the team confidence to proceed forward with the simplification. Thus, only the dimensions of the rear mass, front mass, and smaller cylindrical section needed to be calculated. Utilizing the impedance values and setting the reactance to zero - the condition for resonance, which is the desired operating condition - the lengths of the rear mass and front mass could easily be calculated via the two equations below [12].

$$\tan\left(\frac{pk_e l_e}{2}\right) \times \tan(k_1 l_1) = \frac{\rho c_e (D-d)^2}{\rho_1 c_1 (D_1 - d_1)^2} \tag{3}$$

$$\tan\left(\frac{pk_e l_e}{2}\right) \times \tan(k_2 l_2) = \frac{\rho c_e (D-d)^2}{\rho_2 c_2 (D_2 - d_2)^2} \tag{4}$$

Calculating the lengths through these equations allows for the transducer section to be fully defined, allowing for the design of the booster to be completed. The important geometrical parameters of the booster are shown in Fig. 18 [12].

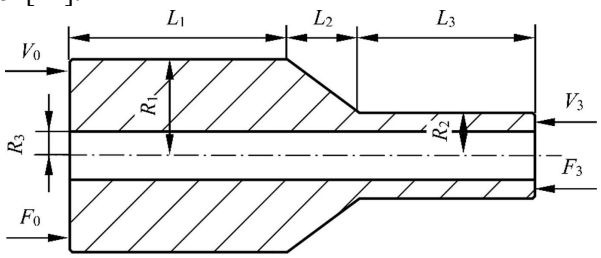


Figure 18: Diagram of key geometrical parameters of the booster with a conical transition [12].

The length of the first section, L_1 should be equal to a quarter wavelength of an acoustic wave in aluminum at the chosen operating frequency to ensure a nodal point at the tapered transition for maximal acoustic power transfer. The radii values (R_1, R_2, R_3) can all be chosen by the designer so long as they are less than L_1. A radius value the same as L_1 would cause instability in the device due to high vibration in the radial direction. By representing this geometry as a series of three 4-port networks and solving for the

amplification factor, the ratio of tip velocity to input velocity, from the resultant matrix equation, the following equation is derived [12].

$$M_{\mathrm{p}} = \left| \frac{V_3}{V_0} \right| = \left| \frac{(R_1 - R_3)\cos(kL_1 + kL_2) - (R_1 - R_2)\cos(kL_1)\sin(kL_2)/kL_2}{(R_2 - R_3)\cos(kL_3)} \right| \quad (5)$$

Since the velocity of a vibrating body is related linearly to the displacement of the body, this amplification factor is equal to the ratio of tip displacement to input displacement as well. Thus, the designer has the freedom to choose an amplification factor that will result in the desired tip velocity. The remaining lengths, L_2 and Lr_3, of the booster can then be determined by creating a 3D mesh plot in Matlab with the two lengths varied on the x and y-axes with M_p on the z-axis and choosing a point with the desired amplification value.

The team is quite confident in the analysis conducted here. Modeling piezoelectric ultrasound transducers with equivalent electromechanical circuits, especially those of the Langevin type, is a method commonly used in research and industry and provides a basis for many of the concepts studied in the field of engineering acoustics. The conducted analysis is highly detailed and is derived from fundamental governing laws in the field of acoustics in order to fully describe the behavior of the transducer and booster device [6,8,9,12,14,17]. Thus, the team believes that the current level of detail used is highly appropriate and more analysis will not be needed.

Final Design Description

The first major selection that needed to be made was regarding the PZT ring to be used. Thus, in-depth engineering analysis needed to be conducted in order to sort through the multitude of PZT materials. To accomplish this, an initial literature review was conducted of the benchmark articles, their cited sources, and interview with Professor Karl Grosh [9]. This revealed three potential PZT materials - PZT-4, PZT-5A, and PZT-8. More in-depth literature review was done on these three materials and Table 3 was constructed as a pugh chart to compare the three options and settle on the best one.

Table 3: Pugh Chart for selection of PZT material

Criteria	Weight	PZT-4	PZT-5A	PZT-8
Strength	1	0	-1	+1
Ultrasonic Applications	3	0	+1	+1
Output (Frequency)	2	0	0	-1
Mechanical Quality Factor (Q_m)	1	0	0	+1
Total		0	2	3

Here the criteria for ultrasonic applications was weighted the highest as the team believed that frequent use in ultrasonic transducer applications was a good sign that the PZT material could be utilized in an ultrasonic booster. Thus, it was weighed at 3. The output frequency was the next most important criteria as the design needed to have a vibration frequency over 25 kHz thus PZT materials needed to meet this

such that the driving voltage could also be kept below 500 V. Thus, it was weighed at 2. The strength and mechanical quality factor criterias were both weighed at 1 as they were less important than the two mentioned above, but still contributed to meeting the life cycle fatigue requirement and specification laid out earlier. With this PZT-8 was chosen due to its frequent use in ultrasonic transducers. After sourcing, a 30mm OD x 10mm ID x 6mm PZT-8 annulus was chosen, as mentioned earlier, as the only other suitable option was a 50mm OD x 20 mm ID x 5 mm PZT-8 annulus which could cause issues with the portability requirement later down the line. With the rings selected, the next major hurdle was selecting the materials to be used. As mentioned previously, the material of the rear mass needed to have a high acoustic impedance and the front mass needed to have a low impedance such that vibrations would be 'funneled' towards the front tip of the booster. Thus, the acoustic impedance, the product of density and speed of sound, of various materials was calculated. With this, common metals and other materials were considered and their acoustic impedances were calculated as shown below in Table 4.

Table 4: Table comparing acoustic impedances of various materials.

Material	**Density (g/cm^3)**	**Speed of Sound (m/s)**	**Impedance (kg/m^2s)**
7075 Aluminum	2.81	3100 - 6350	$1.8 * 10^7$
4041 Steel	7.85	5100	$4.0 * 10^7$
PLA	1.25	2246	$2.8 * 10^6$
Titanium	4.506	3125 - 6070	$2.7 * 10^7$
Wood	0.3 - 0.9	3300 - 5000	$4.5 * 10^6$

From the calculations, it was apparent that 4041-steel had the highest impedance while PLA provided the lowest impedance. PLA however was quickly eliminated due to its lack of durability and strength. The next lowest impedance material was wood. This, however, was also eliminated due to its difficulty in manufacturing. Due to wood's variable density and speed of sound along with issues in splintering while manufacturing, it was deemed not suitable for the purposes of the project. Thus, the group pivoted towards the next lowest impedance material - 7075 aluminum, which offered ease of manufacturability and durability. With the materials now selected, focus could be shifted towards assembly of the booster. Originally, it was planned that the rear mass, PZT stack, front mass, and horn be bolted together. But, after an interview with Professor Karl Grosh, a second solution emerged - epoxy. Due to Professor Grosh's in-depth knowledge and background in ultrasonic boosters, he recommended epoxy as by bolting together the booster, an additional impedance would need to be accounted for - thus changing the dimensions of the booster completely. Thus the group began to look into epoxy that would be suitable for use in ultrasonic vibration frequencies. From this the group settled on three main epoxies, from which a pugh chart was made and utilized to settle on one epoxy. This pugh chart is shown below in Table 5 on pg. 24.

Table 5: Pugh Chart for Selection of Epoxy

Criteria	**Weight**	**353 NDPK**	**T10 Vacuum**	**Hysol 9340**
Price (Under $50)	3	0	-1	+1
Curing Temperature (Under 40^{o}C)	1	0	+1	+1
Material Compatibility	2	0	0	+1
Total		0	-2	6

Here, the price was given the highest weight as it was quickly realized by the team that a large portion of the budget would be going to purchasing the PZT rings as they were being shipped from overseas. Thus, an affordable price was important to stay under budget, hence the weight of 3. The material compatibility was given a 2 as it was the next most important criteria. With an epoxy that was compatible with numerous materials - such as Loctite Hysol 9340 which is compatible with metal, ceramic, wood, and more - there would be no need to purchase multiple epoxies, thus further saving on cost. Lastly, the curing temperature was given a weight of 1. This is because the team preferred epoxies that offered curing at room temperature, but if the need arose, one of the members had access to 80^{o}C and 40^{o}C ovens for use in curing. Thus, Loctite Hysol 9340 epoxy was selected due to its ability to cure at room temperature as well as compatibility with ceramics and metal - the two materials used in the fabrication of the booster.

With the parts selected, focus could be shifted towards constructing the final design. The final design went through a few iterations before a final design was determined. For the first iteration of the design, the booster section was decided to be a series of concentric cylinders for ease of manufacturing and 25 kHz was chosen as the operating frequency in order to ensure that the most important requirement of ultrasonic vibration was met. Eq. 3 yielded a length of 8.87 mm for the rear mass while Eq. 4 was neglected in this scenario, as the front mass was decided to be combined with the first section of the booster and was set to be the quarter wavelength at 25 kHz in aluminum - 50.71 mm. For the remaining portions of the booster, the conical transition length was set to 0 mm and the smaller cylindrical section's length was determined to be 48.70 mm, with a diameter of 25 mm, after an amplification factor of 200 was chosen. This value for M_p was chosen so that a one micron input displacement would result in a 200 micron tip displacement, which would meet the requirement for vibration amplitude. The full geometry of this first iteration is shown in Fig. 19 on pg. 26.

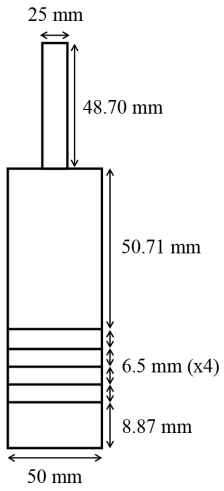


Figure 19: Geometric diagram of the first iteration of the design.

To examine the suitability of this design, the geometry was modeled as a 2D axisymmetric geometry in COMSOL Multiphysics using the Acoustic-Piezoelectric physics simulation engine. Stakeholder feedback for the design solution was crucial in the selection of this method. The primary stakeholder is an expert in modeling and his research frequently uses modeling software to solve design problems. He was on board with the idea to utilize COMSOL to verify important design parameters. Fig. 20 contains the results of the COMSOL simulation for the internal stresses of the design operating at the highest voltage allowed by the power use requirement, 500 V [20].

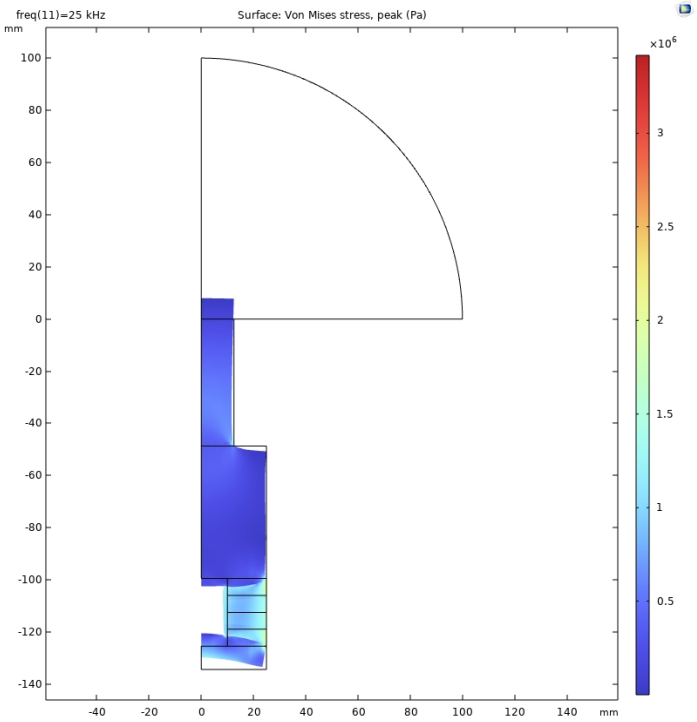


Figure 20: Stress map of the first iteration of the design, simulated in COMSOL using an input of 500 V.

Looking at the stress map, there is a small spike in stress right at the corner transition between the two concentric cylindrical sections. This makes sense, as sharp corners will result in a stress concentration. However, the presence of this stress concentration raised the concern that the device would be unable to

meet durability requirements due to fatigue failure. The group also felt that a higher amplification factor would be needed to more comfortably meet the amplitude requirement rather than aiming for the minimum displacement. Thus, the group decided to reiterate on the design.

For the second and final iteration of the final design, the group decided to pivot to including the booster's conical section to mitigate the stress concentration in the previous design as well as separating the front mass and first section of the booster. Still using an operating frequency of 25 kHz, the lengths of the rear and front mass were again calculated via Eqs. 3 and 4. These dimensions were calculated to be 11.92 mm and 26.91 mm, respectively, with diameters of 30 mm. The booster with the conical transition was then designed. As before, the first length of the horn was pre-defined as the quarter wavelength of the acoustic wave transmitted in the material being used. Thus, since aluminum 7075 was selected, the length was defined to be 50.71 mm. The diameter of this section was chosen as 40 mm. The length of the conical transition section of the horn was then chosen to be 20 mm, as this would ensure the portability requirement was met and the booster size remained within the predefined 50 x 50 x 200 mm volume. The final length of the smaller cylindrical section, set to a diameter of 20 mm, was then varied to determine the effect on the amplification factor, the relationship of which was plotted in Fig. 21 on pg. 27. The y-axis was plotted as the natural log of the amplification factor for visibility.

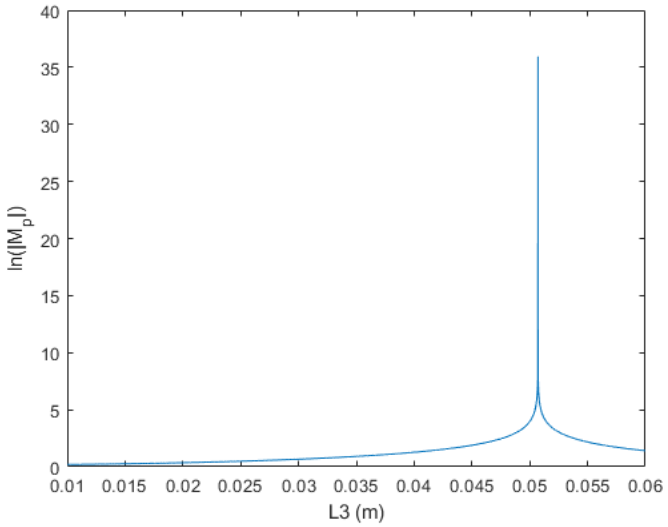


Figure 21: Plot of the natural log of amplification factor with varying lengths of L3.

This iteration, an amplification factor of 535.57 (~$e^{6.28}$ in Fig. 21) was chosen to increase the degree to which the device's tip displacement would fall within the range specified in the amplitude requirement. From Fig. 21, this amplification factor corresponded to a length of 50.69 mm. With this design now fully defined, the design of the second iteration of the device was complete. A not to scale diagram of the full device summarizing the geometry is shown in Fig. 22 on pg. 28 below.

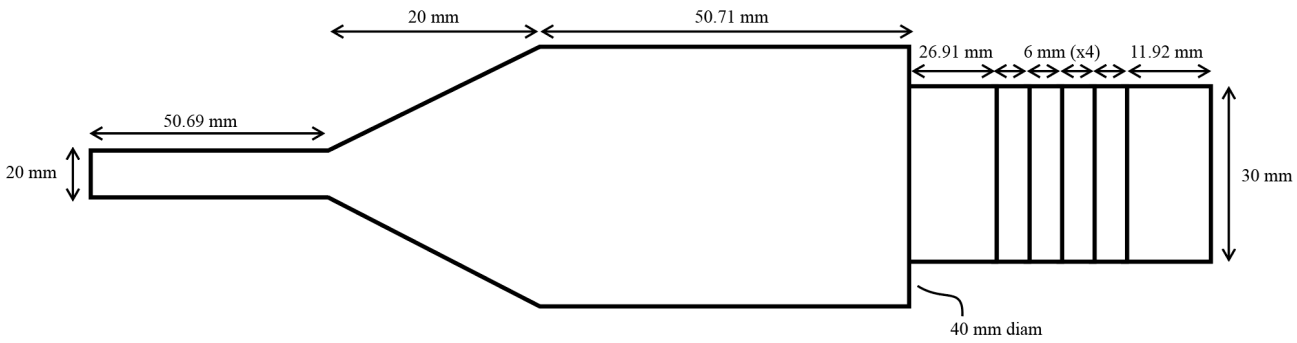


Figure 22: Geometric diagram of the second and final iteration of the design.

The final design was then modeled in COMSOL multiphysics as a 2D axisymmetric geometry, again using the Acoustic-Piezoelectric Interaction physics engine to create a displacement map of the device. The team was unable to extract accurate displacement values from the simulation within the time frame of the class, but the qualitative results are still useful. As seen in Fig. 23, the maximum displacement occurs at the tip of the booster, which is exactly what is desired. In addition, there is no vibration at the center of the piezoelectric stack, meaning that it will be a suitable location to attach the device to a laser manufacturing machine or any other surface for prototyping.

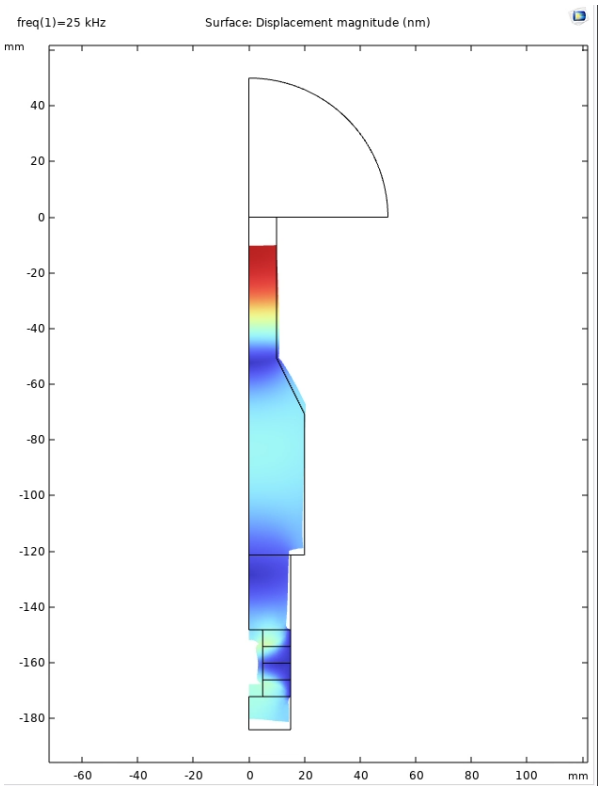


Figure 23: Displacement map of the second iteration of the device. Exact displacement values extracted from COMSOL were inaccurate, but the qualitative results still hold.

The current final design was chosen due to the engineering analysis conducted confirming that the geometry and build of the design could meet the requirements for vibration and amplitude. A prototype of

the final design will be manufactured and assembled and eventually placed on an optic table for demonstration to the sponsor. A final CAD model for the design can be seen in Fig. 24 below.

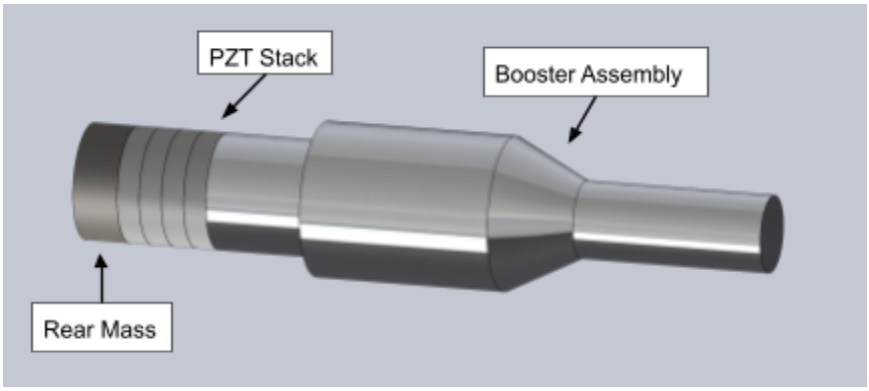


Figure 24: CAD model of the final iteration of the design.

The CAD model of the final design consists of three main components: The rear mass, the PZT stack, and the booster assembly. The piezoelectric rings that make up the PZT stack are sourced and purchased from an online vendor whereas the rear mass and booster assembly are manufactured in the machine shop using purchased stock. All parts were adhered together using a Loctite epoxy to reduce the loss of vibrations transferred towards the tip as much as possible. The engineering drawing for the rear mass part is shown below in Fig. 25.

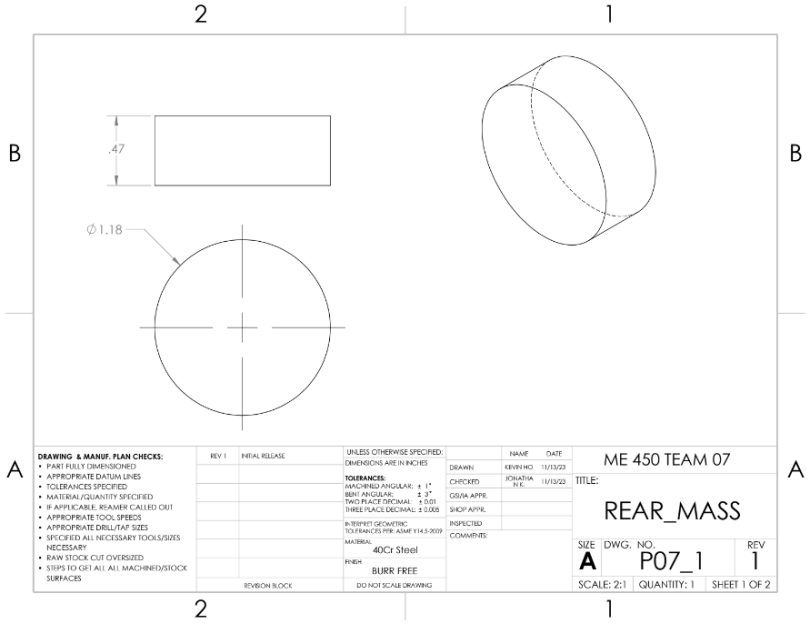


Figure 25: Engineering drawing for the rear mass.

The engineering drawing shows that the rear mass is a simple part that will be created from 4140 alloy steel. This 4140 steel was chosen due to its high mechanical impedance which is needed for the rear of the design. The part was easily manufactured in the machine shop with a lathe from a round 1.25” rod of stock steel along with deburring tools to ensure a smooth finish. The manufacturing of the part took less than an hour, although small passes were necessary due to the hardness of the steel. Since the PZT rings were purchased from an online source, they do not require manufacturing or engineering drawings and the team was able to move to the booster assembly which contains a cylindrical front mass, a conical section,

and the tip which induces vibrations onto the mirror. The engineering drawing for the booster assembly is shown in Fig. 26.

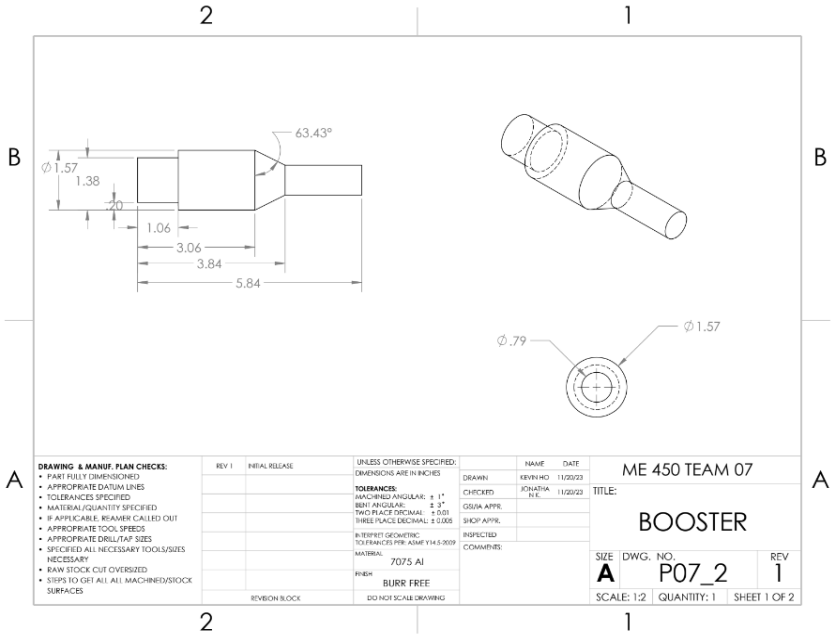


Figure 26: Engineering drawing for the booster

The booster is a part consisting of a smaller cylinder behind a larger cylinder with a conical section to attach to the tip. The entire part will be made from a 7075 Aluminum round stock which was chosen due to the low mechanical impedance and the ease of aluminum in machining. The part was also manufactured using a lathe in the ME450 machine shop, using a turning tool for the cylindrical parts and a compound at an angle to lathe the conical section. The manufacturing of the part took several hours, however that was due to the large initial size of the stock and the amount of material that needed to be removed to bring the part to size. The turning of the conical section was simple once the compound was set up and involved a simple back and forth motion at the set angle. All parts of the design were then manufactured and assembled together using epoxy. Lead wires to drive the transducer were soldered onto the top and bottom surfaces of each PZT-8 annulus before being insulated with electrical tape to prevent shorts in the PZT stack section as well. Fig. 27 contains an image of the assembled prototype.

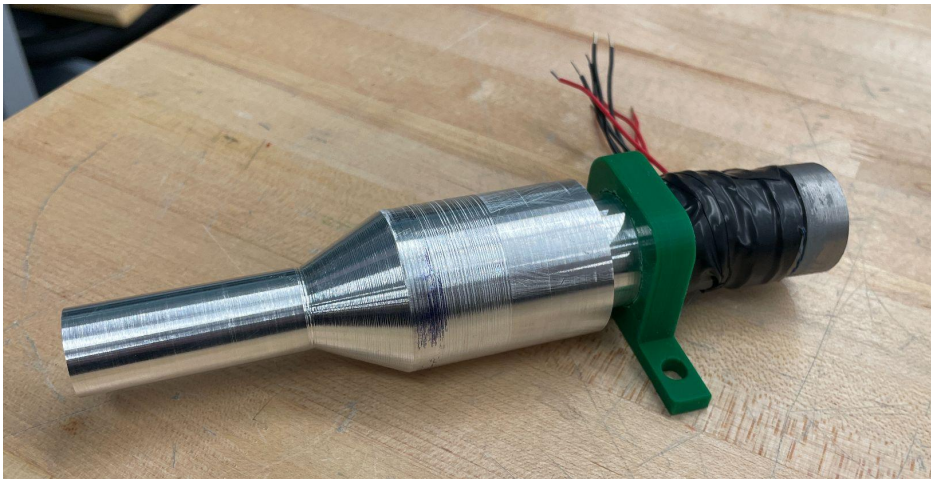


Figure 27: Manufactured and assembled prototype device.

The first step in manufacturing was the manufacturing of the rear mass. This involved simply using a bandsaw to cut the stock to length and then utilizing the lathe to bring the piece to the correct diameter. From here the booster section could be manufactured. This was done through utilizing a lathe to bring the stock down to length and to the largest outer diameter. From here the rear section was first brought to length and diameter and this section was used to hold the piece in the collet while bringing the front section to diameter and length. With this done, the compound tool was used to machine the conical transition.

With the manufacturing complete, focus could move towards assembling the device. To do this, a wire was soldered to each of the positive and negative sides of the PZT as indicated on the annuli themselves (the top and bottom faces). After soldering, each annulus surface was covered with electrical tape to electrically isolate each ring and prevent shorts. Then, the two part 9340 Hysol Epoxy was mixed and applied to both sides of the PZT rings, stacking them together with the rear mass and booster sections. Following this, a clamp was used and the PZT stack was wrapped in electrical tape to hold the device together and in shape while the epoxy cured over the course of 24 hours. The assembly and manufacturing plans are included in Appendices A4 and A5.

Once assembled, the device was planned to be attached to an optical table setup, shown in Fig. 28 to induce vibrations onto the mirror portion of the laser delivery system.

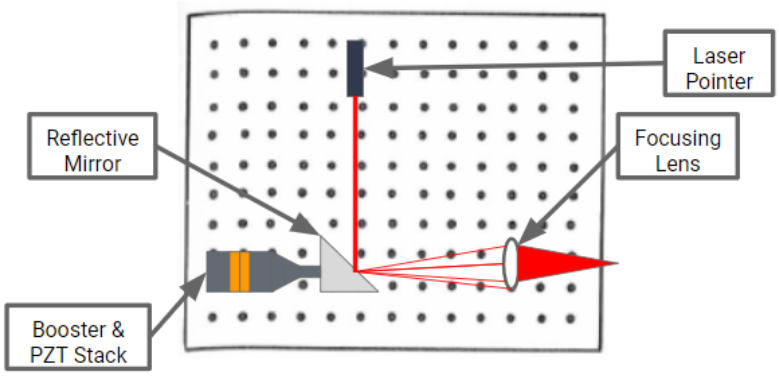


Figure 28: Prototypical set up on an optical table to demonstrate the design.

This optical setup will prove to be an efficient and effective prototype for the team to showcase the results of the design. The booster and PZT stack induce vibrations directly onto the reflective mirror which in return causes the laser to move in a transversal direction into the focal lens and onto the workpiece. A small and cheap laser pointer will be used in the prototype to visually show the effects of the vibrations. Both the reflective mirror and booster assembly will be held to the optical table using 3D printed holders that attach to the reflective mirror and in the middle of the PZT stack where vibrations will not be affected, as well as the lens and the laser pointer to ensure that they do not move while the device is on. Unfortunately, due to time constraints and the team not being able to source a waveform generator to induce the needed driving voltage across the PZT rings, the optical table set-up was not formally tested. A bill of a materials for all purchased parts and stock to create the proof of concept design is included in Appendix A3. Drawings of the designed holders for the parts on the optical table are shown below in Figs. 29-31.

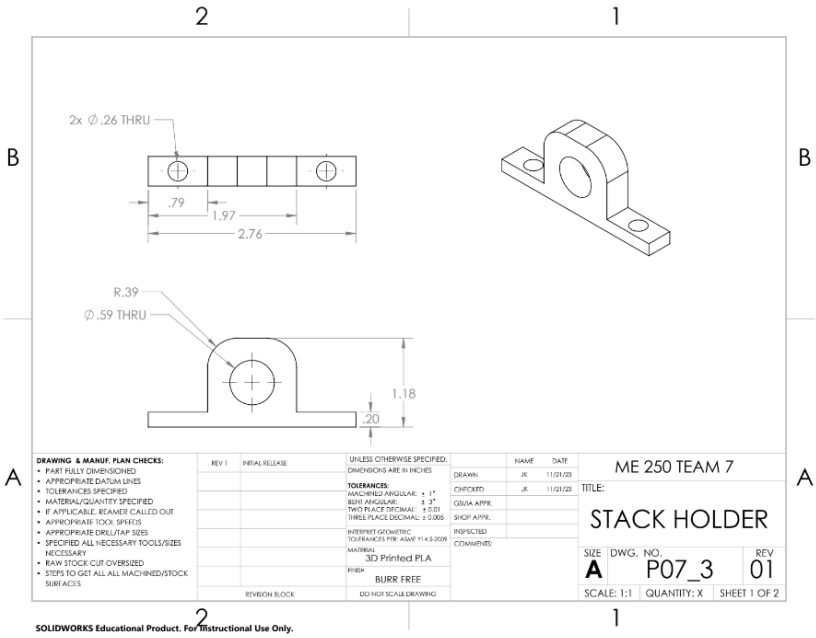


Figure 29: Engineering drawing for the 3D printed PZT stack holder.

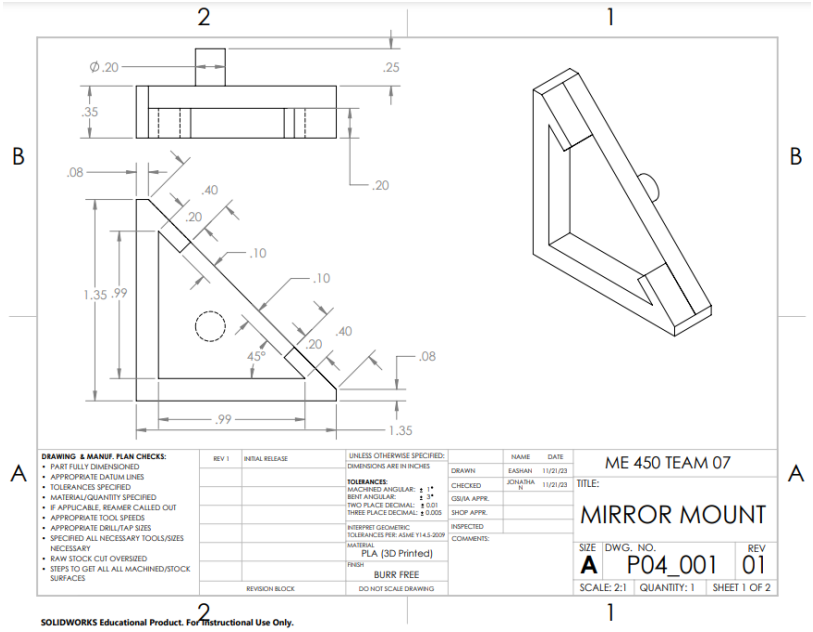


Figure 30: Engineering drawing for the 3D printed mirror mount.

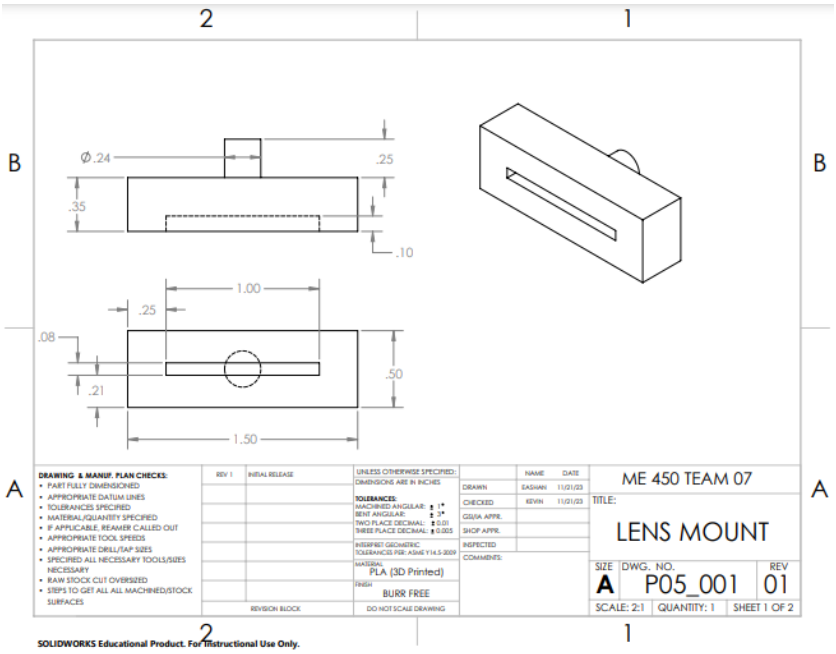


Figure 31: Engineering Drawing for the 3D printed lens mount

All holders to mount the laser pointer, PZT stack, reflective mirror, and lens were created to easily mount to the optical table with M6 screws. The parts will be 3D printed using PLA in the fabrication studio due to the easy access to PLA material and the cheap cost of the filament. Manufacturing of the parts is simple and only requires a .STL file of the CAD parts to use as an input for the 3D printers. Because the parts will not be under very much strain, the fill of the parts will not be greater than 25%. The holes used to mount the holders were designed to be clearance fit so that no tapping is required.

As the final design is manufactured, assembled, and demonstrated through the use of the prototype setup, it is important to mention that it is a final design in the scope of ME 450 that may need additional considerations for a later industry application. In the real world, the design of this project will be attached to welding and heavy duty laser manufacturing machinery, none of which is available to the team during the semester. The final design being created proves the most important aspect of the project in that it is being proven that the geometry of the booster can provide the necessary amplitude at the tip to induce ultrasonic vibrations in a laser delivery system. This final design will help the team evaluate the feasibility and performance because the vibrations and how they can be measured will remain the same regardless of whether it is attached to a prototype optical table or real manufacturing machinery. The final design demonstrates the engineering values of design iteration, analysis, and manufacturing that the team has put into the project over the course of the semester.

The team realized many lessons learned from unsuccessful outcomes and recommendations. This includes lessons from the engineering processes required to reach a final design and the many unsuccessful outcomes and roadblocks encountered along the way. The team learned the importance of iteration based on stakeholder feedback. Since the COMSOL model was complicated, iteration was necessary to fine-tune the exact dimensions of the design. Within this, the team also learned how to simplify COMSOL models down to more easily simulatable tests. For instance, since creating a full COMSOL simulation of the entire system would have been outside the scope of the semester, Professor Grosh suggested the team model the vibration amplitude of a single PZT ring and extrapolate the findings to the full booster model [9]. The team also learned the importance of checking the legitimacy of vendors since the group identified many materials that would work, but many had sketchy processes for ordering. Finally, the team had

issues figuring out how to manufacture various components of the design so the team reached out to the machine shop for guidance.

Verification and Validation Plans

Within the scope of ME 450, the team plans to test as many critical specifications as possible. The group has identified the frequency and amplitude of vibration as the most critical specifications to verify. Thus, the critical specifications that will be prioritized for verification are that the design can vibrate ultrasonically with a stable vibration mode occuring at a frequency ≥ 20kHz, that this vibration has an appropriate amplitude of a displacement of 200-500 microns. These two specifications were initially verified with a COMSOL simulation. The team considered numerous possible verification plans but decided that a computer simulation would be the most practical method within the time constraints of ME450. Using analytical equations, the key dimensions of the rear mass, front mass, and booster were determined, as described above in **Engineering Analysis**. This design was then modeled in COMSOL Multiphysics with the same methods as the first iteration of design, using the Acoustic-Piezoelectric physics simulation engine and 2D axisymmetric geometry, in order to determine if the vibration amplitude could be met [20]. Through discussion with an expert in acoustics and piezoelectric transducers, Professor Karl Grosh, it was determined that only one piece of the piezoelectric section would need to be simulated [9]. Due to there being a stack of four PZT annuli, the displacement of the one annulus could then be multiplied by a factor of 4 before being multiplied by the amplification factor to determine the tip displacement of the device. Fig. 32 contains the simulation of one PZT annulus operating at 350 V and 25 kHz, which enforces that the requirements of frequency and power use are met.

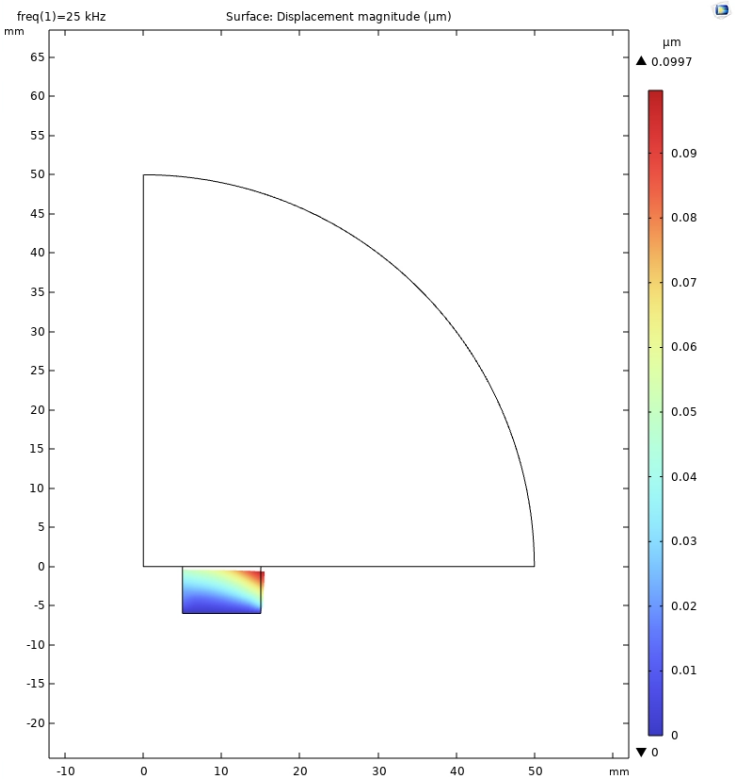


Figure 32: Displacement map of one piezoelectric annulus excited with a 25 kHz AC voltage of 350 V in COMSOL.

From this simulation, the displacement of one PZT annulus was found to be 0.0997 micron. When extrapolated to the device tip, it was found that the tip displacement would be 213.59 micron. Thus, the

requirements of frequency, vibration amplitude, and power use would be met according to this initial theoretical COMSOL verification.

There are a number of key assumptions that are made in the COMSOL simulation. As discussed, the geometry is assumed to be 2D axisymmetric, meaning that the model represents a revolution of the built geometry around x = 0, assuming that x is the horizontal axis. In addition to this, the piezoelectric annulus is modeled as being contained in a vacuum with air contacting only the top surface. Thus, atmospheric viscous damping of the system only occurs along the top face of the PZT. Another major assumption is that the displacement of four PZT annuli will be related to the response of one PZT annulus linearly. However, through discussion with an expert in acoustics, it was determined that this methodology would be valid [9]. There are also a number of limitations in using COMSOL. Like any other finite element analysis (FEA) multiphysics simulation software, the results derived from simulation are only as good as the input parameters and boundary conditions. As the adage says, with FEA, a "garbage in, garbage out" scenario must be avoided. A good way to determine if the simulation is producing "garbage" is by creating a trial problem to be solved by hand and comparing it with the simulation results. Due to time constraints and gaps in knowledge, performing this secondary analysis is not feasible within the current scope of ME450 - a large limitation. Along with this, all FEA software results are heavily impacted by the meshing and discretization of the model used. If a bad mesh is used, it can severely alter the final results. The group did take steps to mitigate this limitation by creating custom meshes for key components of the geometry, but this still limits the capabilities of COMSOL.

To further verify the amplitude and frequency of vibration, experimental testing on the machined prototype using laser doppler-vibrometry was performed. Laser-doppler vibrometry works by shining a laser on a vibrating object and measuring the characteristics of the optical wave that reflects back; this concept is shown below in Figure 33.

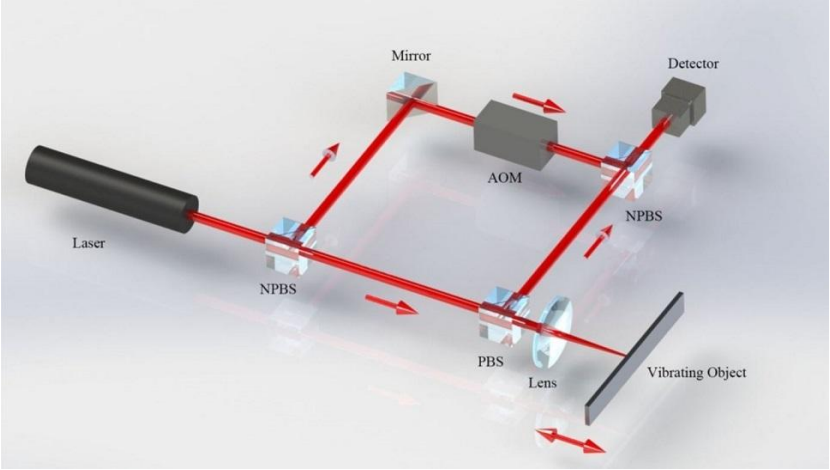


Figure 33: Sample Setup of Laser-Doppler Vibrometry Equipment [16]

The detector can measure the velocity, displacement, and frequency of a vibrating object using the principle of the doppler effect. The doppler effect is the shift in wave frequency due to relative motion between a wave source, reflecting object, or receiving system. An example of this phenomenon is the notable changing pitch of a police or ambulance siren as it approaches and passes an observer. This same principle can be applied to this project since the vibration caused by the device can be measured in relation to the laser source. Essentially, the laser is an optical wave directed at a moving object, which then reflects back passing through a series of mirrors and a detector. Depending on the movement of the object, the received wave that was reflected will have a different frequency than was originally transmitted. By measuring this "doppler frequency shift", amplitude and frequency can be determined to

confirm the critical specifications [27]. This method was selected because it was recommended by an expert in this field, Professor Grosh, and he possesses the necessary equipment for these tests in his lab. It is accurate, fast to conduct, and a common method for testing characterics of vibration used in industry. It also does not make any large assumptions by allowing for the key measurements of vibration frequency and amplitude to be directly measured. Thus, the team is confident that this method will effectively verify the amplitude and frequency of the vibration.

A session was set up with Professor Grosh to perform the verification. Fig. 34 below contains a labeled photo of the experimental setup.

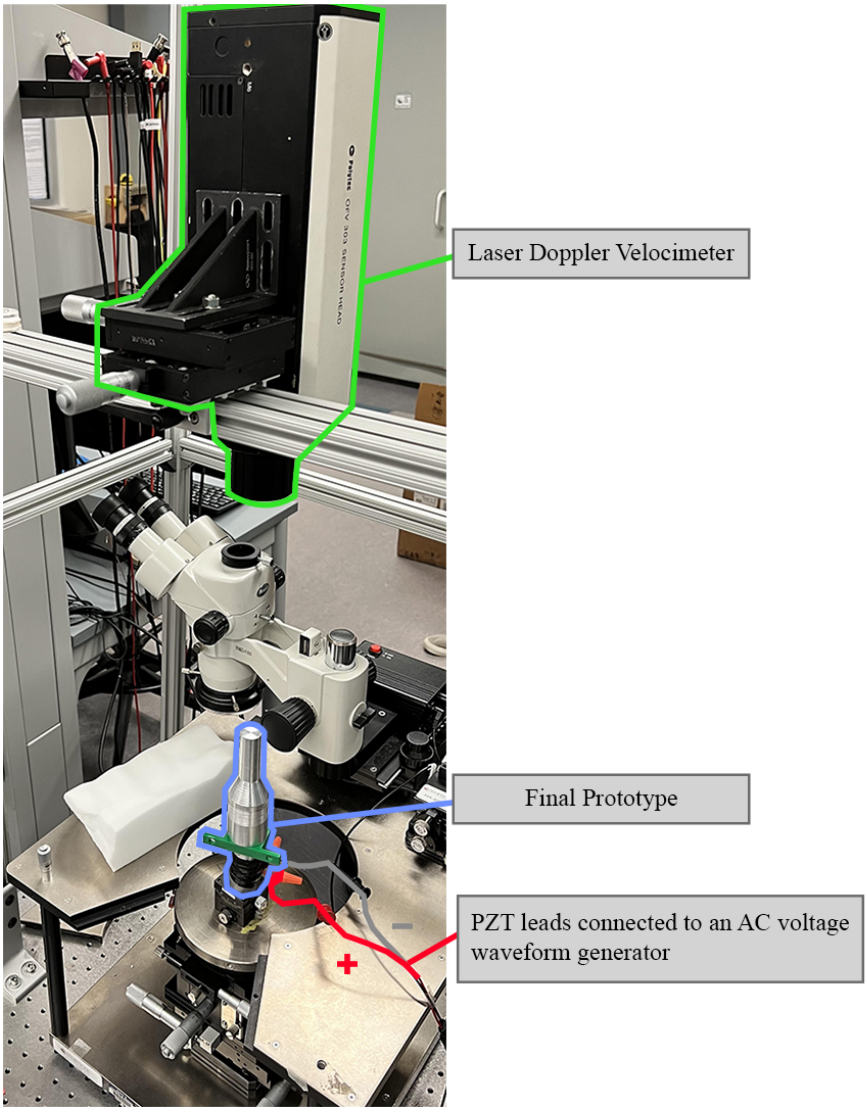


Figure 34: Laser-doppler vibrometry experimental setup. The manufactured device is placed upright with a laser from a laser-doppler velocimeter (LDV) pointed straight down onto the tip. The device is then driven with an AC voltage waveform generator operating at 25 kHz and 1 V while the doppler shift of the reflected laser is measured.

As shown, the transducer was placed upright with a laser from a laser-doppler velocimeter (LDV) incident upon the tip and connected to a waveform generator to drive the system. The device was confirmed to have moved as, when operated at sonic frequencies, a pure tone matching the driving frequency could be observed. Thus, the requirement for ultrasonic frequency was qualitatively verified to

be met, as the device's frequency of vibration will match the driving frequency - 25 kHz by design. Verification of the amplitude was, however, unable to be completed. Technical issues with the LDV resulted in the laser being unable to take measurements of the device's movement, and these issues were unable to be resolved within the available time in the lab. Despite this, since motion was qualitatively observed, the essential functions of the device were confirmed. Given more time, the team could verify the vibration amplitude requirement as well as fatigue life. But, even with this - the key requirements and specifications laid out by the sponsor, Professor Wenda Tan, in the beginning stages of the project were met.

Other requirements and specifications were verified as well. The specification that the device vibrates horizontally with vibrations produced in the x-y plane was verified qualitatively by observing the axis of the reflected laser beam in the optical table set up. This method was chosen because it is practical for accurately determining the vibration direction. It also is a simple, cheap, and easy verification plan to conduct once the prototype was manufactured. It is assumed that the vibration plane for the final design will match the vibration plane of a later application for industry. To verify the power use requirement, virtual tests on COMSOL relating to amplitude were conducted to determine if a vibration amplitude within the desired range is produced at an operating voltage below the specified upper limit. This would have been able to be confirmed experimentally with laser-doppler vibrometry given more time to fix the LDV output. This method was chosen because determining the voltage is part of measuring the amplitude and no additional work will be required. If the proper amplitude is measured as a critical specification, then the voltage will also be known since they are linked to each other. It is assumed that the power use for the final design will match the power use of a later application for industry.

Finally, the team verified that the design is portable and easily maintainable. The dimensions of the final design were determined with engineering analysis presented above and it falls within the specification limit of 50x50x200 mm. The dimensions of the prototype will match the dimensions of the CAD assuming proper machining processes. The team verified that the design is within the dimension limit using a ruler and calipers after completing machining. This method was chosen because it was already part of the design and manufacturing process. A ruler/calipers will be accurate in verifying the portability. It is assumed that the dimensions for the final design will match the dimensions of a later application for industry. The final design has also already been verified as easily maintainable since parts are sourced from 5 vendors as demonstrated in the discussion of materials in engineering analysis. This amount meets the specification of 2+ separate vendors and the specification was verified by totaling the number of vendors on the team's bill of materials. Ultimately, this method was selected because it was already part of the materials ordering process and it is a clear method for determining that the specification was met. It is assumed that the number of vendors for the final design will match the number of vendors of a later application for industry. The team notes that an application for industry use may have additional parts and vendors, but that the specification has already been proven with the final design.

For verification of the requirement that the device is safe to use, the team, given more time, would conduct compliance testing to ensure that the design complies with ISO 11553 and IEC 60825 standards. Since a final working prototype for industry will not be possible in the scope of ME 450, the full verification of this specification will not be possible. This method of verifying through standards was chosen because standards are mandated by respected organizations that are knowledgeable about the safety requirements and protections that are necessary. The team designed the build prototype to meet as many of the safety standards as possible, but some factors will not be accurately represented without a final design in an industrial environment. It is assumed that the two standards chosen will encompass all of the possible safety issues for the design, but one possible limitation is that requirements vary with each standard and between manufacturing environments based on the application. However, the experiences of past approaches following these recognized standards should remove any possible doubt from stakeholders that the device will be safe.

Finally, the group plans to verify the durability of the device by conducting cyclic loading testing to measure fatigue. This test involves applying a sinusoidal force to one end of the device while the other is kept fixed. This results in compression and tension of the device to simulate many vibrations. This method can verify that the lifetime of the design is greater than 1.5*10^11 cycles without failing. However, due to time and resource constraints, this verification plan is outside the scope of ME 450. The team does not have the time to manufacture multiple prototypes since they would be damaged in this test. If testing were to occur, it would follow methods similar to those taught in ME 382 and the dogbone lab in ME 395. This method was selected because it is the most accurate method of measuring lifetime. However, the actual preparation for the process is too rigorous in the time constraints of the project. Through the COMSOL simulations, however, only one area was identified as an area of concern. This area was the transition on the initial iteration between the large cylindrical section to the small cylindrical section in the front mass. However, after iterating on the design and settling on a conical transition between the two, the stress concentration disappeared. Furthermore, the magnitudes of all other stresses on the booster are minimal, indicating that the probability of the booster being able to withstand the required cycles without failure is very high. Given this, there still is no concrete way to eliminate any hunches or reservations that stakeholders will have about the booster not being able to meet the fatigue life requirement without conducting a cyclic loading test.

Some validation plans are out of the scope of the project due to the tight time frame of the semester, however the team has still thought of questions that would require validation plans if they were to be carried out. The first validation plan question relates to durability: Is the final project durable enough for industry use? Since it is impossible for the team to simulate 1.5*10^11 cycles in the semester, the verification plan to test this was developed by the team in order to verify that the materials being used were able to withstand this durability specification. To further validate this more, however, it is possible for the team to use these results and compare them to similar products. The amount of cycles needed to validate this question is time consuming and not realistic, however it would be possible to match the findings of the verification plan for durability with current projects being used in the industry and get an idea on the lifetime of the design from that research. Performing this validation would ensure the stakeholders know the lifetime of the design and can add feedback as necessary.

A second question the team decided would require a validation plan is: Are customers satisfied by the improvements to laser machining and welding? This is outside the scope of the course as the prototype being built is using only an optic table, whereas in the real world the design would be attached to laser manufacturing or welding equipment. This validation question is important to answer because the team wants to ensure that the improvements created by the design on finished products of laser machining and welding are as significant as the stakeholders were inspecting. A possible plan for this validation is performing a demonstration or trial on laser machining equipment and showing stakeholders first hand what the improvements looks like. This allows stakeholders to see the improvements happen and make a decision as to whether the design is suitable for their needs and is satisfactory or not. Another possible validation plan would be to perform regulatory compliance testing ensuring that critical functions meet safety and performance standards. This would aid the stakeholders into ensuring that the design is safe and performs well. A final plan would be to user test the product and then gain feedback from users after the testing. A validation plan involving the users would ensure that stakeholders are able to use the products for themselves and can give the team feedback on the design for possible future iterations.

The final validation plans relate to the questions of accessibility and marketability of the team's design. The first of these questions is: Is the design accessible for a wide range of users? This can be validated by once again performing user testing and gathering feedback from users on well designed components or possible issues to fix in future iterations. The second of these questions is: Will customers be willing to pay for this product? This is one of the most important components to validate and shows that the design

has reached its final stage of validation and is a fully functional product that customers are willing to buy. A plan for this validation if the project were to get to this stage would be to perform market testing and determine if and at what cost customers would be willing to pay for the product.

Discussion

Given the theoretical aspect and heavy analysis required, the team is happy with the results that were shown this semester in the outcome of this project, however, there are some things that could be different if given more time. The team feels that the problem definition defined at the beginning of the semester is detailed and fits the problem, though if more time was given there would have been more exploration regarding the actual attachments of the design to real life laser machinery. Doing this would allow the group to test and see the device being used in real world scenarios rather than attaching it to an optical table as a proof of concept. The most ideal method of exploring this would be to gain access to a lab with actual laser machinery and verifying the device in that scenario. If that is not possible, however, other methods could include performing analysis as if the device were attached to industrial machinery and creating models reflecting the changes in verification and validation plans. This, however, could not be realized during the semester due to not only time constraints but lack of access to a laser manufacturing machine - thereby making it difficult to design an attachment as the team could not visualize or work with a laser manufacturing machine.

The major strengths of the final build design that was assembled and tested are that it meets the majority of the requirements set forth by the sponsor and the team. Verification testing has confirmed that the device successfully vibrates ultrasonically and while there have not been experimental results yet for the amplitude, COMSOL analysis has shown that the desired amplitude is possible with the design that was created. On top of that, other strengths in the design include the device fitting into the portability requirements as well as being able to easily be manufactured. Once all parts were ordered, the team spent only two days in the machine shop manufacturing the booster and the rear mass, and an additional day after that to assemble the prototype. The parts that were manufactured were straightforward and did not require the use of any machinery outside of the bandsaw and lathe meaning that the parts could easily be remachined if needed since the drawings and manufacturing plans are already complete. Although the device did perform well given the requirements and specifications, it still did have weaknesses that should be addressed. One of the largest weaknesses in the design was the soldering that attached wires to the electrodes of the piezoelectric rings, as the soldering caused an uneven surface on all of the rings. This meant that when the team applied the epoxy, the rings were not stacked properly and the stack had a tilt causing the entire device to be slightly misaligned. The slight angle of the device was not ideal, however, it still yielded results that were favorable to the required specifications of vibration frequency. One way this could be improved in the future is to attach the parts using bolts instead of epoxy, hoping that results in a more aligned stack. This would require further engineering analysis that was out of the scope of this semester as the addition of bolts changes the mechanical properties of the parts, however, it is something that could have been done differently. Another improvement could be made in the way the wires were attached to the electrodes. Perhaps using other methods instead of soldering could limit the bumps that were on the surface of the PZT rings which ultimately caused the uneven alignment of the stack. It could be possible to find a conductive electrical tape that solves this problem in future designs. As mentioned before, another weakness in the design is that there was little to no consideration in how the device would actually be attached to real life industrial machinery. Since the team did not have access to this machinery, the main focus was on ensuring that the vibration and amplitude requirements were met and being able to show that on an optical table. If given more time, modifications could be made that take into account how the device will be attached to the machinery in real world situations. This would include the designing and manufacturing of parts that attach the device to heavy laser machinery instead of the 3D printed parts that attached it to an optical table in the prototype created.

The team did perform a risk assessment to assess the potential risks of the final design. There were several risks associated with the design process and prototyping of this project, however the main risk is simply that it was unproven technology. There have been several benchmarks doing similar projects as this which were useful in the design process and analysis stage of the design, but none of these benchmarks did so on the scale such as this. The largest challenge faced by the team during the analysis section of the process was creating a design that could meet the amplitude specification of 200-500 microns, as this was a displacement significantly larger than the benchmarks. The engineering analysis through analyzing the impedance circuits allowed for the team to obtain the dimensions and geometry required for an appropriate amplification factor that would achieve this amplitude given an input voltage of 350 V and the use of four PZT rings. This driving voltage of the final design is another associated risk that the team wants to make sure to highlight. A voltage shock over 50V is enough in some cases to be potentially lethal, and thus the team wants to reiterate that this device should only be operated by trained professionals. Verification done on COMSOL shows that the desired amplitude can be met using the geometry of the design that was built. Another challenge that was encountered during the process was the sourcing and ordering of some of the materials, specifically the PZT rings. Finding trustworthy vendors that sold PZT rings at a price that fit into the team's budget proved to be a greater challenge than expected and the team ended up ordering from an overseas supplier. The timeframe of the shipping was tight given the deadline of the design expo, though all parts arrived on time for the prototype to be assembled. It can also be mentioned that there were challenges associated with the soldering and assembling of the prototype as brought up before, but these problems were quickly fixed and still resulted in a prototype that vibrates at ultrasonic frequencies. Risks were addressed during the design process as well as they occurred in order to minimize their impact on the final design. This was done by formulating contingency plans and reaching out for the help of knowledgeable mentors and professors to work around these risks and challenges. Possible risks were also analyzed during the design process in order to create backup plans if they were to become a problem.

Reflection

This project makes the world better through its applications to manufacturing in society through the sponsor Professor Wenda Tan and his research lab. The project is a breakthrough in laser manufacturing research that has numerous social, economic, and environmental benefits to the industry. Dr. Tan's research group will build off the initial findings from this semester and the prototype the team produced to develop a refined solution. The prototype the team produced proves that the concept of vibrating the laser delivery system is possible and that it has a viable application to the laser manufacturing process. In reflection, there are many social, societal, cultural, political, global, and environmental considerations from the result of this project.

This project has some application to public health, safety, and welfare since it benefits laser manufacturing which is a greener, safer, more efficient process than many conventional methods. Additionally, these factors are relevant since the process can be automated which limits potential injuries to line workers and improves public health. In general, laser manufacturing is safer for workers since they have to touch less heavy machinery. The design also is a benefit in the global marketplace because it brings improvements to common global industry processes. Laser manufacturing has application to manufacturing all across the world and is growing rapidly as new technologies such as our project become available. If a final solution can be marketed to have quality or economic benefits to the manufacturing process, then it will have relevance in a global marketplace. The main social impacts associated with the design are the improvements to the manufacturing process and quality of the end product. This design more efficiently produces vibrations that improve the quality of products machined with laser manufacturing which is good for customers in society. In addition, the process is greener and more energy efficient, so widespread usage will reduce CO_2 emissions in the long run compared to conventional processes which is an environmental benefit. Air quality should improve for residents and workers near and around manufacturing plants that use more laser manufacturing. This additionally ties in

with disposal as disposal of the device is expected to be green. Each individual component - steel, aluminum, and piezoelectric ceramic - are all biodegradable or recyclable and thus no special arrangements or costs need to be incurred in order to dispose of the device without causing harm to the environment. Furthermore, as a result of the disposal of the device being eco-friendly and green, it will have a low social impact. This eco-friendliness is further confirmed and seen through performing an Eco-Audit, conducted using the CES/GRANTA Edupack tool. Costs were converted to perceived values of costs (P) using the equations given from the Social Context Assessment Learning Block below:

$$P\ (Recurring\ Costs)\ =\ A\frac{(1+r)^n-1}{r(1+r)^n} \tag{6}$$

$$P\ (One\ Time\ Costs)\ =\frac{F}{(1+r)^n} \tag{7}$$

where A is the cost accrued each year, r is the discount rate (used as 4% in this scenario), n is the number of years (10 years used in the team's calculations) and F is the absolute value of cost. In Table 6 below, the results of the eco-audit are shown.

Table 6: Eco-Audit Readout

Cost	Value	Source	Type of Cost	Conversion to P
Material	$31	CES	Present	$31
Manufacturing	$6.9	CES	Present	$6.9
Transport	$0.42	CES	Present	$0.42
Acquisition	$50000	Sponsor	Present	$50000
Energy Use	$20000	CES	Annual (10 years)	$162217.92
Environmental	$20000	CES	Annual (10 years)	$162217.92
Disposal	$0.01	CES	Future	$0.01
			Total Cost:	$374474.17

The low disposal cost highlights that the parts are eco-friendly, as non-eco-friendly parts often need expensive and convoluted disposal methods in order to dispose of properly without harming the environment. The largest cost is the environmental cost - largely due to the amount of energy being used to power laser manufacturing machines. But, by putting this in context, it is apparent that the costs incurred here are significantly lower than that of traditional laser manufacturing.

The increased automation of widespread rollout of this design, however, may have social and political impacts in reducing the number of positions available for assembly line workers since some of their jobs may be replaced by robots. Similarly, these tie into the many economic impacts associated with our device mainly related to the manufacturing process. Automated processes are cheaper because less workers need to be paid, and the improved efficiency of the process in regards to energy can save utility costs. Additionally, automation is a major political and ethical issue currently and thus by contributing to automation by releasing this device to market may potentially lead to more debates and backlash from automation rejectors. This backlash is the result of the belief that companies will become slaves to

automation thereby removing the need for real workers completely - disturbing and potentially destroying communities. The government and other political entities may not support the rollout of this product since it may increase unemployment, but supporters will justify it as part of the progress of technology in the modern age. Finally, customers will be more willing to pay for higher quality end products from laser manufacturing, which the vibration from our design will contribute to. To characterize the potential societal impacts of the design, the team mainly analyzed the in-depth stakeholder map and looked for connections between the design and society. It also used an eco-audit to consider life cycle costing as discussed above. From this, it was determined that the groups most affected will be Dr. Tan's research group and those close to the manufacturing industry. Afterwards, it was determined how those groups related to manufacturing would be impacted by the success of this design and a possible rollout of a finished product down the line to industry. The team related most of the societal impacts to the manufacturers, the people who work in the factories, and the customers who buy the products from laser manufacturing.

The cultural, privilege, identity, and stylistic similarities and differences between team members did not have a significant impact on the approaches the team took throughout the project because the team choose to be in a group together and everyone was motivated to produce quality work.The team itself was a diverse group of individuals with many different backgrounds and skill sets. Thus, each team member brought their own ideas to the engineering challenge, but there was never really any confrontation between members of the team because everyone respected the opinions of each other. There were some stylistic similarities in how the members of the team wanted to operate and work together which turned out to be beneficial because it reduced conflict. Almost all of the time, the team was on the same page with each other in regards to approaches for the project. For a decision to be made, all team members had to agree to it. During the concept generation process, the team's unique backgrounds resulted in numerous ideas. The team was able to consolidate these ideas into a specific design easily due to some of the stylistic similarities in thinking. The culture, privilege, and identity of each team member did not directly influence the approaches of the team since the group was united in the goal of developing a successful product and a person's background was not going to change that. However, each team member's background did influence the work that they specifically worked on for the project since it made sense for each member to contribute to their strengths - whether that be coding, modeling, CAD, machining, etc. For example, since one member had a background in vibrations from taking a vibrations class, often he took the lead in regards to some of the design approaches that he was an "expert" on compared to the rest of the group while others worked on content they were familiar with.

The cultural, privilege, identity, and stylistic similarities and power differences with the sponsor of the project influenced the design processes and final design subtly but Dr. Tan was not overly controlling. The sponsor Dr. Tan has expertise in laser manufacturing, so the team deferred to his opinion on certain topics that he was knowledgeable about. Since Dr. Tan had the privilege of being the sponsor and section leader for the group, the team was able to interact with him more often so he was able to be updated on the status of the project more easily than other groups. This was beneficial for the design process and final design because the team was able to consider his input for every step of the process and a satisfactory design could be produced. With English as a second language for the sponsor, sometimes the team would have to reiterate some concepts or re-word them in a more simple way to be more easily understood, but this cultural difference was never a burden. In fact, his unique experiences gave positive feedback and advice to many portions of the design process, since he had some experience with a similar project before and knew exactly what he wanted to be produced for this project. Often, there were stylistic similarities that made it simple to work through the design process together. The final design was heavily influenced by the requirements set forth by the sponsor. Overall, the dynamics between the sponsor and the team were positive and the working relationship allowed for the creation of a successful project.

The power dynamics between the team and the main stakeholders were rigid around requirements but lax around other design choices. Dr. Tan, the primary stakeholder and end user, required certain requirements to be met that guided the design direction, but how these requirements were met was up to the team. There was a power dynamic of mutual respect between the team and the stakeholders/end users since everyone wanted the project to be successful. There was not really a power dynamic between group members since everyone was treated equally and there was not one single leader making decisions. All decisions were made together as a team. The identity and experience of the team shaped the perspective compared to the end users for the project because it was assumed that the end user had more background on what was required. While the team did research to become experts on this specific project, the end user is still generally more knowledgeable about laser manufacturing so his perspective was valued heavily. The identity and experience between the team members did not affect the design choices, but it did cause the project work to be divided up into areas of strength for each member. Approaches were taken throughout the project to include diverse viewpoints of both the stakeholders and team members. All opinions were considered from every team member and the primary stakeholder. Then analysis was performed to determine what ideas were worth pursuing. The ideas of stakeholders and team members were balanced following this method of considering all input and then analyzing to choose the best path forward as well. Generally, engineering analysis was the tool for selecting between multiple viewpoints. However, when ideas were required by the stakeholder, the team deferred to his input. If the team knew more about a specific topic, the team usually stuck with its viewpoint since it had performed the research to back up the decision-making. The cultural similarities between team members affected some of the decision making throughout the design process. Most of the team members have a similar background in mechanical engineering education, so some decisions were made because the team took the same classes at U of M. However, there were some differences in culture since everyone had different internship and research experience. This may have resulted in some unique thinking in some cases to influence the design process and final product. For example, Nick is minoring in electrical engineering, so he brought forward specific ideas he was knowledgeable about such as using PZT materials and how to wire the device. Other cultural similarities/differences such as race or gender did not influence the project (other than possibly idea generation) since the team members treated each other equally as engineers. As touched upon earlier, cultural similarities in thinking with the sponsor made it easier to work together. The team believes that the sponsor had a similar methodology of working on the project and he supported making decisions based on through research and engineering analysis. However, it was the differences in culture that really influenced the final product. The sponsor has a long background in laser manufacturing, so he brought forward many ideas from his past research and projects that influenced the design process and final product. With English as a second language, he also brought many unique perspectives from his culture that may have subtly affected the design processes indirectly.

The main ethical dilemmas faced in the design of the project result from the manufacturing jobs that may be replaced with the automation from the enhanced laser manufacturing of this project. If this product were to enter the marketplace, assembly line workers in manufacturing plants would get replaced and lose their jobs to automated laser manufacturing machines - a major ethical problem. This ethical dilemma was managed by taking a utilitarian perspective and justifying the project to be beneficial for the overall good of the world due to its improvements to end projects. In addition, the energy and environmental benefits helped to justify overall societal benefits for this project. In addition, the product needed to be accessible to all users, so it was made sure that the device was designed to be something that everyone can use. During the design process, the team made sure the product was fit for users of all demographics. The team's personal ethics were the same as the professional ethics expected to be upheld by the University of Michigan. The team was instructed and abided by the ethical standards introduced by the University during the ethics portion of this class. However, these ethics may differ from those of a future employer who is motivated solely by profits. For this project, the focus was on making the world work better overall and the decisions of the project reflected that, while future employers may only be focused on decisions to improve on economic gain.

Overall, the team's perspectives have changed from the initial thinking at the beginning of the project. Coming into the project, each group member came with a varied background and various different perspectives. These perspectives underwent profound transitions over the course of the semester. As the team began to delve deeper into the complexities of laser manufacturing and ultrasonic technologies, the group realized that many of the principles learnt in earlier classes were applicable. These skills from classes such as ME240, a dynamics class, or ME 424, an acoustics class, came into play when helped the team design and prototype the booster horn. Furthermore, the hands-on experience of machining the booster horn itself while simultaneously working with electric components such as the PZT rings deepened the team's manufacturing skillset and technical knowledge. The team learned many new techniques such as lathing a conical transition as well as utilizing COMSOL and MATLAB to model and optimize parts. Given this, the project went mostly as planned, and the societal impacts are still believed to be the same as at the start of the project. However, the team now has an enhanced understanding of the complete engineering design process and respect for what all engineers do. The team has learned more about laser manufacturing and has an enhanced appreciation for manufacturing processes as well as an appreciation for engineers working to improve the quality of manufacturing processes in general.

Recommendations

The group first recommends a more comprehensive COMSOL model. Due to time constraints, a comprehensive COMSOL model could not be developed by the team as it required knowledge and expertise outside the scope of the class which the team would need additional help to flush out. Thus, the team modeled the vibrations from a single PZT ring and utilized the force transfer and amplification factor from modeling the booster as a four-port network to extrapolate the tip displacement. Thus, a more comprehensive COMSOL model would allow for a better estimate of the tip displacement. This model proved to be too complicated for the time constraints of the project, but with additional time, a refined model could make the design even better.

Furthermore, upon completion of the initial prototype of the ultrasonic booster horn, it was apparent some slight modifications could be made to vastly improve the quality of the device. The first issue was a slight tilt in the PZT stack. This was the result of soldering the wires to the same side of all four PZT rings within the stack thus causing a slight tilt. The group recommends that a future design should consider how the wires will be soldered to it. In addition, a process for soldering the wires while maintaining alignment of the PZT rings should be determined. A re-design must take into account the soldered wires and how they may affect the vibration potential. This slight tilt had further implications than expected as it is anticipated that it will result in worse force transfer. Furthermore, it was apparent that during testing with the laser-doppler vibrometer that the tilt created an issue in regards to properly reading the vibration amplitude. This was solved by placing the device on an angled platform such that the laser beam would reflect directly into the sensor. Given this, however, the laser-doppler vibrometer was still unable to read the vibration amplitude - likely due to a rough surface finish on the aluminum booster tip. Thus, the group recommends that in future a less coarse aluminum stock is used or a final pass utilizing the lathe is completed to insure a burr free surface. Overall, the team recommends continuing research into this project to refine the design and fix the weaknesses of the initial prototype.

Conclusions

The use of lasers in manufacturing is growing at an exponential rate due to their superiority over other manufacturing methods in regards to speed, versatility, and energy efficiency. It is a very attractive alternative as laser manufacturing can not only cut and weld, but also join, clad, clean, cast, and deposit. With this increasing interest in laser manufacturing, many research groups have been looking into vibration assisted manufacturing and have shown that vibrations greatly aid in increasing the quality of the end product. This improvement in quality is the result of the randomness from vibrations causing defects to be mitigated. But, currently in order to reap these benefits, the workpiece must be vibrated. The

issue, however, arises in that each workpiece differs in size, shape, and material, thus resulting in different resonant frequencies. Consequently, a universal frequency cannot be applied. As a result, current research groups and literature have revealed a promising future direction - vibration of the laser beam optics using an acoustic waveguide to transfer the vibrations over a distance. Thus, the team aims to create a device vibrating laser beam optics, eliminating the need for vibrating the workpiece and increasing end product quality.

With preliminary research and literature review completed, the team assembled a list of requirements and specifications to match as shown in Table 1 on p. 9**.** These requirements and engineering specifications aided and guided individual and group brainstorming. With this, the group was able to accumulate a grand total of 254 concepts. Not all of these concepts were unique or worth pursuing and, through deliberation, this number was reduced to seven. These seven concepts were analyzed with the help of a Pugh Chart, shown in Table. 2 on p. 18, and compared to the current industry standard of vibrating the workpiece on the basis of four metrics: vibration transverse to laser axis, safety, portability, and feasibility/manufacturability. With this analysis, both Design 2 (Fig. 11 on p. 14) and Design 3 (Fig. 12 on p. 15) scored evenly, and thus further engineering analysis needed to be done to select one final concept. This engineering analysis (Appendix 2) involved examining the power transfer from the vibrations, and revealed that Design 3 would be more effective, and it was thus chosen as the “Alpha Design”.

With the “Alpha Design” now selected, the team moved forward with further design and analysis, detailed in the **Engineering Analysis** section to iterate on this concept and create a more complete and detailed CAD model. Analysis was mostly completed by representing the sections of the “Alpha Design” as equivalent electrically coupled mechanical circuits, following a process used by Kang, Di, et al. [12]. Solving these circuits allowed for the determination of key dimensions, and the group was then able to create an initial design. The first design was created without a conical transition in the booster section. This decision was made after discussion with Professor Grosh [9] in the interest of making the manufacturing process easier. However, after simulating the design in COMSOL, results indicated the design would fall short of meeting the vibration amplitude requirement as well as potentially run into issues with fatigue failure due to stress concentrations. Thus, the conical transition was re-incorporated to mitigate these problems. From this iteration, the COMSOL simulation results indicated that a tip vibration amplitude of 213.59 um could be achieved at 350 V, thus meeting the 200 micron minimum vibration amplitude and staying under the 500 V maximum. A full CAD model and engineering drawings of the parts were then created. When this was complete, parts were then ordered, as outlined in the bill of materials in Appendix A3. The purchased stock was then machined into the correct geometries and the full device was assembled following the plans outlined in Appendices A4 and A5. This yielded an initial prototype which could be validated as a high-quality product meeting the needs of the sponsor, keeping in mind the impact on secondary and tertiary stakeholders.

With the final prototype fabricated, focus was shifted towards designing verification and validation plans. The primary verification plan involved utilizing laser doppler-vibrometry. Through the use of a laser-doppler velocimeter (LDV), the amplitude and frequency of vibration of the tip can be effectively measured in response to a determined AC voltage input. However, technical issues compounded with time limits resulted in incomplete verification. Only the movement of the device at an ultrasonic frequency could be qualitatively confirmed. In addition to this, the team qualitatively verified that vibrations would occur in the x-y plane from observation of the proof of design setup. Further verification and validation plans have also been laid out given more time. These range from formal compliance testing to ISO-15533 and IEC-60825 standards to cyclic loading fatigue testing, and stakeholder/market testing. With the completed verification testing, the team delivers a functional prototype to aid the sponsor, Professor Wenda Tan, in furthering the field of laser manufacturing.

Acknowledgements

The team would like to acknowledge and thank Professor Wenda Tan, Professor Karl Grosh, Panagiota Kitsopoulos, and the entirety of the MECHENG 450 FA ‘23 staff for their continued support throughout the duration of the project.

References

[1] Alavi, S. Habib, and Sandip P. Harimkar. "Ultrasonic Vibration-Assisted Laser Atomization of Stainless Steel." Powder Technology, vol. 321, Nov. 2017, pp. 89–93. DOI.org (Crossref), https://doi.org/10.1016/j.powtec.2017.08.007.

[2] Chen, Y. J., et al. "Laser Joining of Metals to Plastics with Ultrasonic Vibration." Journal of Materials Processing Technology, vol. 249, Nov. 2017, pp. 441–51. DOI.org (Crossref), https://doi.org/10.1016/j.jmatprotec.2017.06.036.

[3] Deswal, Neeraj, and Ravi Kant. "Radial Direction Ultrasonic-Vibration and Laser Assisted Turning of Al3003 Alloy." Materials Research Express, vol. 10, no. 4, Apr. 2023, p. 044004. DOI.org (Crossref), https://doi.org/10.1088/2053-1591/acce24.

[4] Displacement Modes of Piezoelectric Actuators. https://www.piceramic.com/en/expertise/piezo-technology/properties-piezo-actuators/displacement-modes. Accessed 13 Nov. 2023.

[5] Dym, Clive L. Engineering Design: A Project-Based Introduction. Wiley, 2013.

[6] Fu, B., et al. "Piezoelectric Transducer Design via Multiobjective Optimization." Ultrasonics, vol. 44, Dec. 2006, pp. e747–52. DOI.org (Crossref), https://doi.org/10.1016/j.ultras.2006.05.087.

[7] Gallego-Juarez, J. A. "Piezoelectric Ceramics and Ultrasonic Transducers." Journal of Physics E: Scientific Instruments, vol. 22, no. 10, Oct. 1989, pp. 804–16. DOI.org (Crossref), https://doi.org/10.1088/0022-3735/22/10/001.

[8] Grosh, Karl. An Experimental System for Measuring the Wavenumber Frequency Response of Timoshenko Beams. 1988. The Pennsylvania State University, Engineering Science.

[9] Grosh, Karl. In-Person, Oct. 2023.

[10] Gupta, Vinay, et al. "Piezoelectric, inductive and capacitive transducers." Pathshala Electronics, no. 9, https://epgp.inflibnet.ac.in/epgpdata/uploads/epgp_content/S000028PS/P000786/M029859/ET/1525244033Quad1.pdf.

[11] Gusev, Vitalyi E., et al. "Special Issue on Laser Ultrasonics." Applied Sciences, vol. 9, no. 24, Dec. 2019, p. 5561. DOI.org (Crossref), https://doi.org/10.3390/app9245561.

[12] Kang, Di, et al. "A Lens Ultrasonic Vibration-Assisted Laser Machining System for Laser Polishing and Laser Drilling of 304 Stainless Steel." Optics & Laser Technology, vol. 144, Dec. 2021, p. 107419. DOI.org (Crossref), https://doi.org/10.1016/j.optlastec.2021.107419.

[13] Kim, Woo-Jin, et al. "Design and Optimization of Ultrasonic Vibration Mechanism Using PZT for Precision Laser Machining." Physics Procedia, vol. 19, 2011, pp. 258–64. DOI.org (Crossref), https://doi.org/10.1016/j.phpro.2011.06.158.

[14] Kinsler, Lawrence E., editor. Fundamentals of Acoustics. 4th ed, Wiley, 2000.

[15] Kumar, Sudhir, et al. "An Insight into Ultrasonic Vibration Assisted Conventional Manufacturing Processes: A Comprehensive Review." Advances in Mechanical Engineering, vol. 14, no. 6, June 2022, p. 168781322211078. DOI.org (Crossref), https://doi.org/10.1177/16878132221107812.

[16] *Laser Doppler Vibrometer 0.1Hz to 5Mhz | SIMTRUM Photonics*. https://www.simtrum.com/WebShop/ProductList5.aspx?pid=1778. Accessed 21 Nov. 2023.

[17] Mason, Warren Perry. Physical Acoustics: Principles and Methods Vol.1 - Part A. Academic Press, 1964.

[18] Ning, Fuda, and Weilong Cong. "Ultrasonic Vibration-Assisted (UV-A) Manufacturing Processes: State of the Art and Future Perspectives." Journal of Manufacturing Processes, vol. 51, Mar. 2020, pp. 174–90. DOI.org (Crossref), https://doi.org/10.1016/j.jmapro.2020.01.028.

[19] Ogawa, Toshio. "Acoustic Wave Velocity Measurement on Piezoelectric Ceramics." Piezoelectric Materials and Devices - Practice and Applications, edited by Farzad Ebrahimi, InTech, 2013. DOI.org (Crossref), https://doi.org/10.5772/53117.

[20] Ohrdes, H., et al. "Influence of the Ultrasonic Vibration Amplitude on the Melt Pool Dynamics and the Weld Shape of Laser Beam Welded EN AW-6082 Utilizing a New Excitation System for Laser

Beam Welding." Production Engineering, vol. 15, no. 2, Apr. 2021, pp. 151–60. DOI.org (Crossref), https://doi.org/10.1007/s11740-020-01008-0.
[21] Piezoacoustic Transducer. COMSOL, https://www.comsol.com/model/piezoacoustic-transducer-1477.
[22] Roychowdhury, Subhrajit, et al. Systems and Methods for Dynamic Shaping of Laser Beam Profiles for Control of Micro-Structures in Additively Manufactured Metals. US10814429B2, 27 Oct. 2020, https://patents.google.com/patent/US10814429B2/en.
[23] Roychowdhury, Subhrajit, et al. Systems and Methods for Dynamic Shaping of Laser Beam Profiles in Additive Manufacturing. US20190232427A1, 1 Aug. 2019, https://patents.google.com/patent/US20190232427A1/en.
[24] Safety of Laser Products - Part 4: Laser Guards. IEC 60825-4:2006, BSI, 8 Aug. 2016.
[25] Safety of Machinery. Laser Processing Machines. Laser Safety Requirements. ISO 11553-1:2020, BSI, 30 July 2020.
[26] "Steminc Piezoelectric Ceramic Supplier." STEMINC, https://www.steminc.com/PZT/ring-50x20x65mm-25-khz-pzt-8. Accessed 13 Nov. 2023.
[27] Ulaby, Fawwaz T., and Umberto Ravaioli. *Fundamentals of Applied Electromagnetics*. Seventh edition, Pearson, 2015.
[28] Wang, Yan, et al. "Mechanism Modelling and Validation of Ultrasonic Vibration-Assisted Laser Processing on Metal Surfaces." Ultrasonics, vol. 128, Feb. 2023, p. 106886. DOI.org (Crossref), https://doi.org/10.1016/j.ultras.2022.106886.
[29] Wang, Zhaozhao, et al. "Design and Verification of a Novel Hollow Vibrating Module for Laser Machining." Review of Scientific Instruments, vol. 86, no. 4, Apr. 2015, p. 045104. DOI.org (Crossref), https://doi.org/10.1063/1.4918618.
[30] Wenda, Tan. In-Person, Sept. 2023.
[31] Wu, Ziheng, et al. "High Frequency Beam Oscillation Keyhole Dynamics in Laser Melting Revealed by In-Situ x-Ray Imaging." Communications Materials, vol. 4, no. 1, Feb. 2023, p. 5. DOI.org (Crossref), https://doi.org/10.1038/s43246-023-00332-z.
[32] Wynn, David, and John Clarkson. "Models of Designing." Design Process Improvement: A Review of Current Practice, edited by John Clarkson and Claudia Eckert, Springer, 2005, pp. 34–59. Springer Link, https://doi.org/10.1007/978-1-84628-061-0_2.
[33] Yazdian, Amir, and Mohammad Reza Karafi. "An Analytical Approach to Design Horns and Boosters of Ultrasonic Welding Machines." SN Applied Sciences, vol. 4, no. 6, June 2022, p. 166. DOI.org (Crossref), https://doi.org/10.1007/s42452-022-05044-6.
[34] Zhang, Guangzhou, et al. "A Biodegradable and Recyclable Piezoelectric Sensor Based on a Molecular Ferroelectric Embedded in a Bacterial Cellulose Hydrogel." ACS Nano, March. 2022. DOI.org (Crossref), https://doi.org/10.1021/acsnano.1c07614

Author Biographies

Kevin Ho is a senior currently pursuing a B.S. in Mechanical Engineering with a minor in Climate and Space Sciences and Engineering at the University of Michigan. Growing up in Houston, TX, he has always had an interest in STEM and figuring out how things work. Surrounded by the energy and aerospace industries in his hometown, he was inspired to pursue a degree in engineering. He is on track to graduate in May 2024 and either begin working full-time or return for graduate school through the University of Michigan's Sequential Undergraduate Studies program. Over the past two summers he gained valuable engineering experience interning in the HVAC & semiconductor industries. Outside of his studies, Kevin enjoys playing tennis and he is a 4-year member of the Michigan Club Tennis team. He also loves to watch professional sporting events, discover good restaurants, travel, and play team-based strategy games.

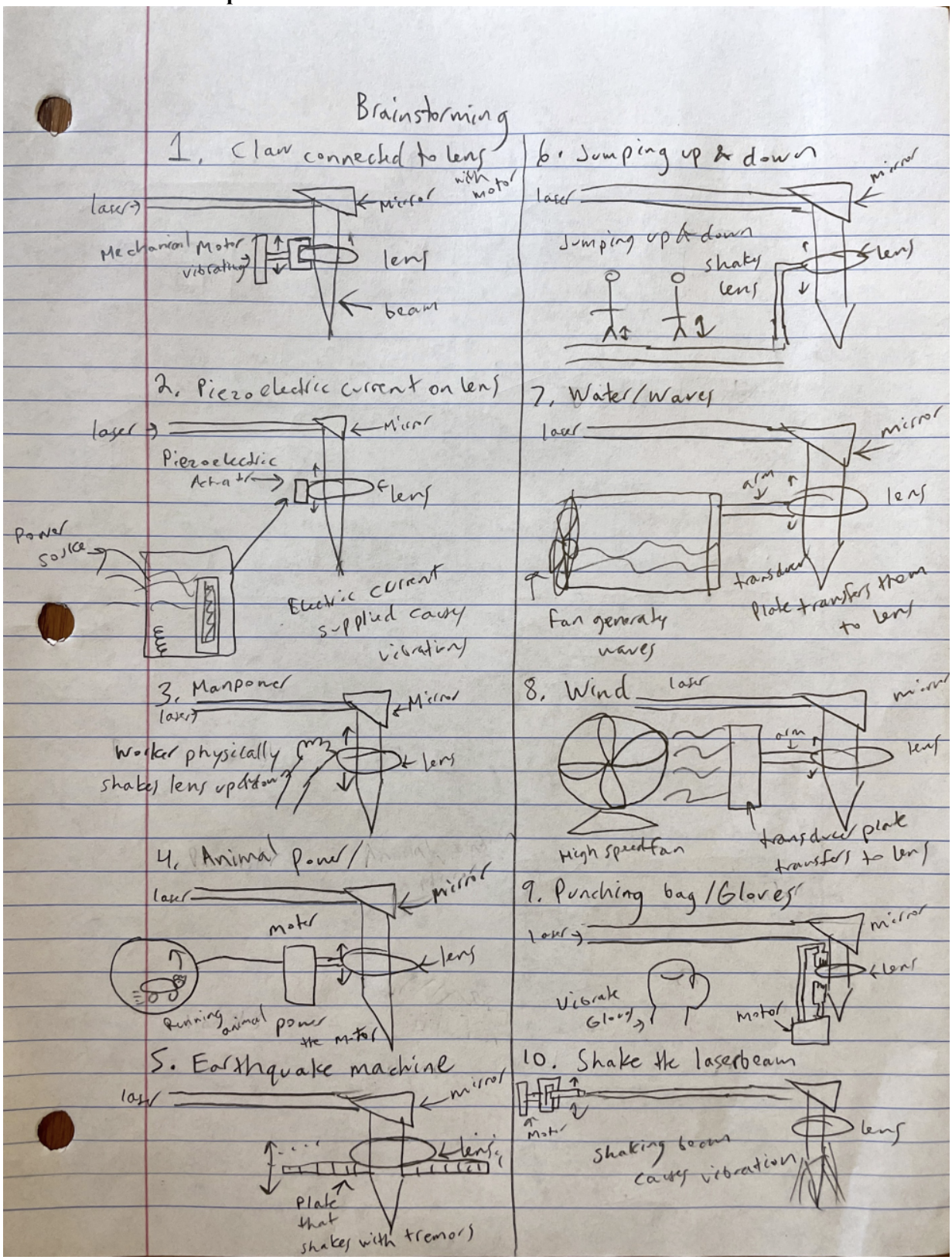
Jonathan Kazleskis is a B.S student in Mechanical Engineering at the University of Michigan. He was born and raised outside Las Vegas, NV and always had an interest in math as well as simulators and design. His desire to become an engineer started after visiting theme parks at a young age and wanting to pursue the job of being a roller coaster designer. He is planning on graduating with a Bachelor's degree in May 2024 and either entering the workforce or enrolling in a Master's program in mechanical engineering. While he previously has and would love to continue working in the theme park industry, he is also interested in pursuing a career in green and renewable energy generation. Outside of class, Jonathan loves to travel, visit new cities, and hike various national parks. In his free time, he loves to watch NHL, NFL, or Youtube. If you're ever at a hockey game at Yost Ice Arena, you will most likely see him there.

Eashan Prabhu is a B.S student in Mechanical Engineering at the University of Michigan. Growing up in Shrewsbury, MA he would frequently visit the Boston Science Museum on the weekends. Even from a young age, he always loved math and science and knew early on he wanted to pursue engineering. Upon completing his undergraduate degree, anticipated May 2024, he plans on enrolling in graduate school. He plans on pursuing a PhD in Biomedical Engineering focusing on tissue engineering, angiogenesis, and cancer metastasis. Outside of class and research, in the little free time he has, Eashan loves to explore his hobbies. He likes to stay active by working out and can be found scarfing down food at Mojo Dining Hall after. He can also frequently be found playing pool with his friends or lazing on the couch watching the NFL, NBA, and WNBA while placing bets on them.

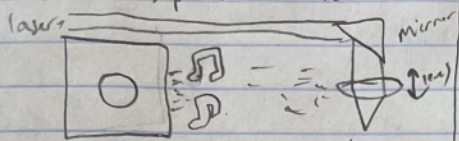
Nick Ventresca is a senior currently pursuing a B.S. in Mechanical Engineering at the University of Michigan. He was raised in New England, attending high school in Brookline, MA. However, as a dual Italian-American citizen, Nick now lives in Italy with his family and four pet donkeys named Gino, Gisele, Margherita, and Peppino. He decided to study Mechanical Engineering due to his strong interest in math and physics and his long-time childhood obsession with science-fiction. After completing his undergraduate degree, Nick plans to remain in Ann Arbor another year to pursue a Master's degree in Electrical Engineering, specializing in electromagnetics and antenna engineering, through the University of Michigan Sequential Undergraduate Studies program. Outside of academics, some of his hobbies include playing piano, working out, and cooking. He also loves to watch the NBA, NFL, and Serie A soccer.

Appendices

1.A - Kevin Ho's Concepts

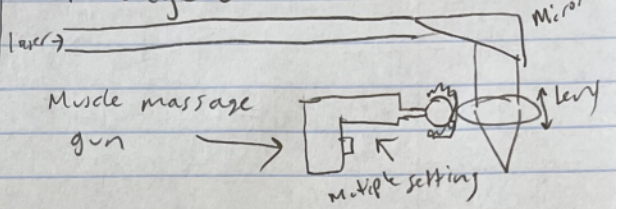


11. Music / Speaker Vibration

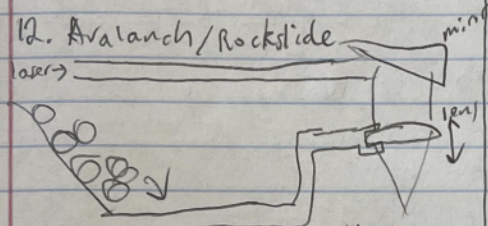


Loud Music causes lens to shake

16. Massage Gun Vibration

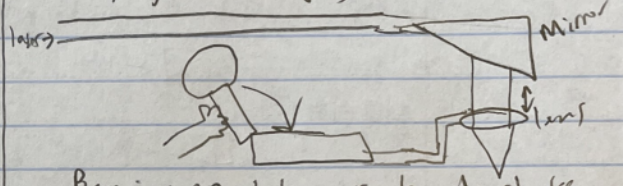


12. Avalanch / Rockslide



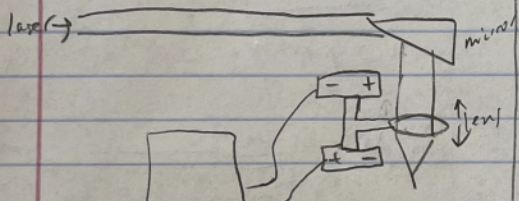
Rocks cause vibrations and shakes lens

17. Frying Pan Banging / Wack a mole



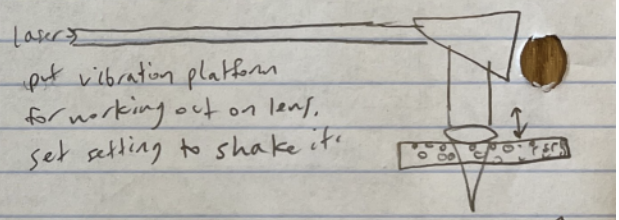
Banging on plate causes lens to shake

13. Magnets / Electromagnet

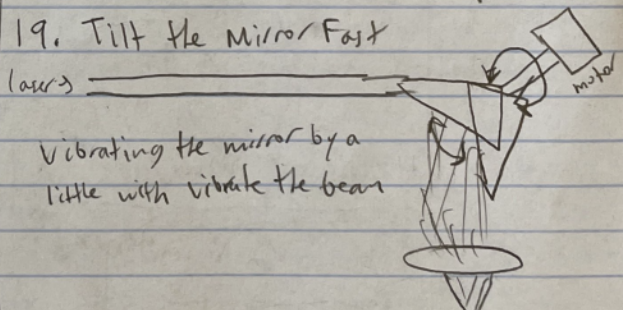


Turning magnet on and off quickly shakes lens

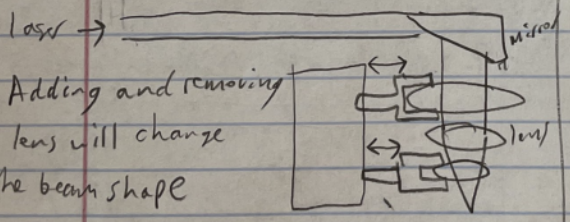
18. Exercise Vibration Platform / Plate



19. Tilt the Mirror Fast

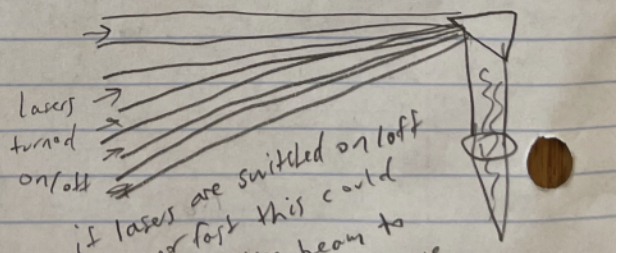


14. Add more lens

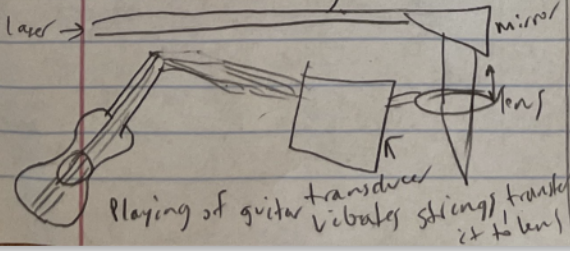


If done fast, like vibration

20. Multiple Lasers & Turning them on / off



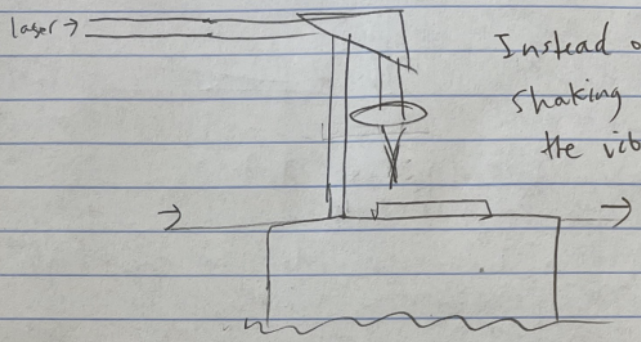
15. Guitar / String Vibration



Iteration

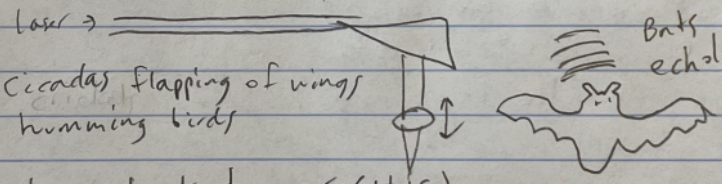
Design Heuristics

1. Use multiple components for one motion (#72)
   combine Part 1 #18 with vibration of manufacturing machine



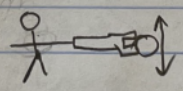
Instead of a separate shaking plate, just use the vibrations from the machinery

2. Mimic natural mechanisms (#46)
   Build off Part 1 #4, instead of having animals power it, we should use their ways of making vibration to shake the lens

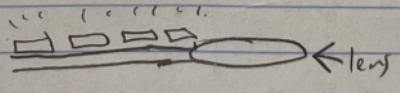


- cicadas flapping of wings
- humming birds

3. Attach product to user (#15)
   Builds off Part 1 #3 and #1, attach lens to the person with claw arm to make it less tiring when they shake it

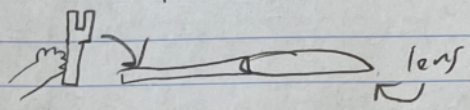


4. Use different Energy source (#70)
   Builds off Part 1 #2 Instead of electric current, lets use a bunch of vibrating cell phones

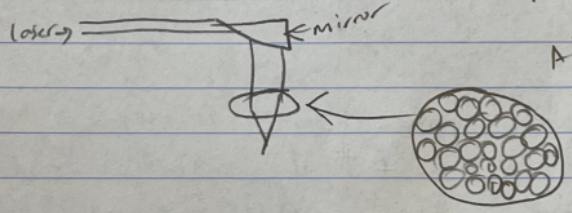


Vibrating phones shake the lens

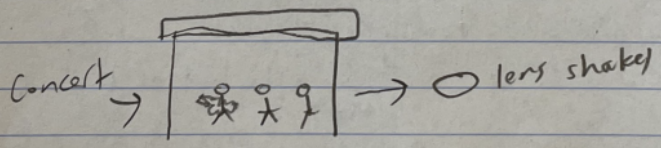
5. Change Geometry (#20)
Builds of Part 1 #17
use a tuning fork with better vibration geometry rather than the pan



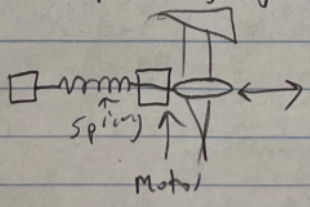
6. Scale Up or down (#58)
Builds of Part 1 #14
Add a lot of small lens on one plate



7. Incorporate Environment (#39)
Builds off Part 1 #11
Put the laser in a loud environment where there will be a lot of sound waves



8. Redefine joints (#52)
Builds off Part 1 # 9
Instead of punching gloves, use a mass-spring damper system



Morphological chart () is part 1 idea being built off

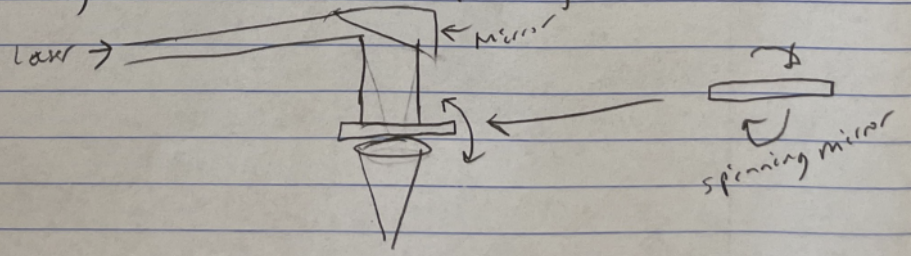
Power Source / Transducer	What is being vibrated?	# lasers & lens
Piezoelectric materials (2)	vibrate laser (10)	1 laser, 1 lens (11)
Motor (1)	vibrate mirror (19)	many lasers, 1 lens (20)
Nature (7, 8, 12)	vibrate lens (1)	1 laser, many lens (14)

Concepts 9-20+: 3x3 Morph chart → 27 new concepts

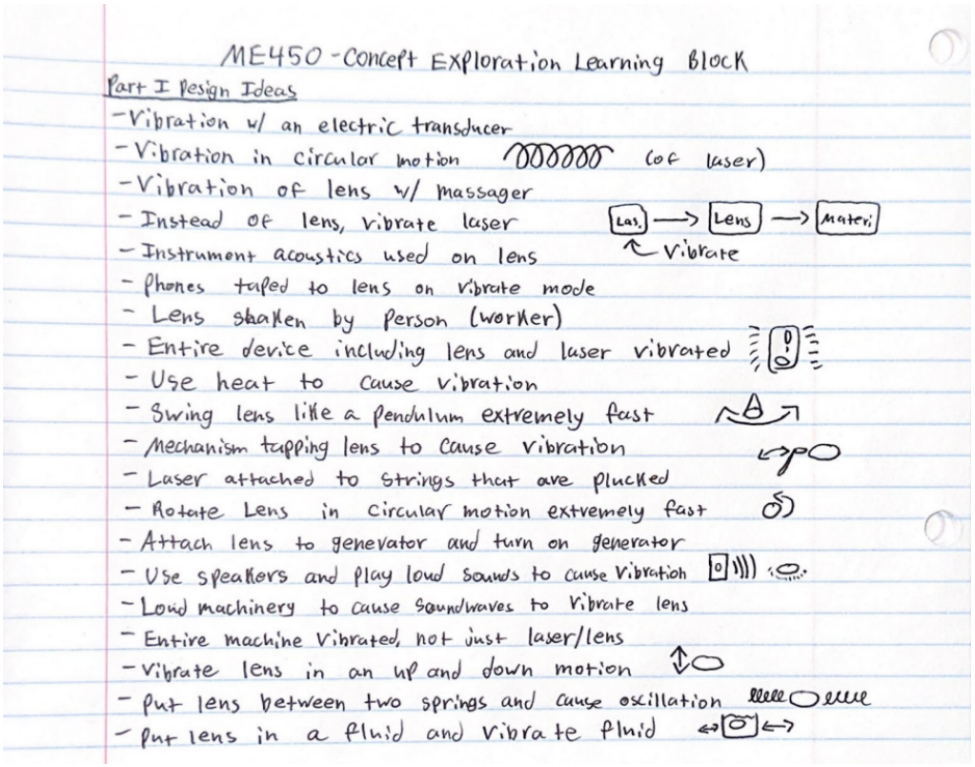
9. Piezoelectric materials, vibrate laser, 1 laser + 1 lens
10. Piezoelectric materials, vibrate mirror, 1 laser + 1 lens
11. Piezoelectric materials, vibrate laser, many lasers + 1 lens
12. Piezoelectric materials, vibrate mirror, many lasers + 1 lens
13. Nature, vibrate laser, 1 laser + 1 lens
14. Nature, vibrate laser, many lasers + 1 lens
15. Nature, vibrate mirror, 1 laser + 1 lens
16. Nature, vibrate mirror, many lasers + 1 lens
17. Motor, vibrate laser, 1 laser + 1 lens
18. Motor, vibrate laser, many lasers + 1 lens
19. Motor, vibrate mirror, 1 laser + 1 lens
20. Motor, vibrate mirror, many lasers + 1 lens

↓ and more

21. Fast steering mirror module (Fast spinning Mirror)



1.B - Jonathan Kazelskis's Concepts

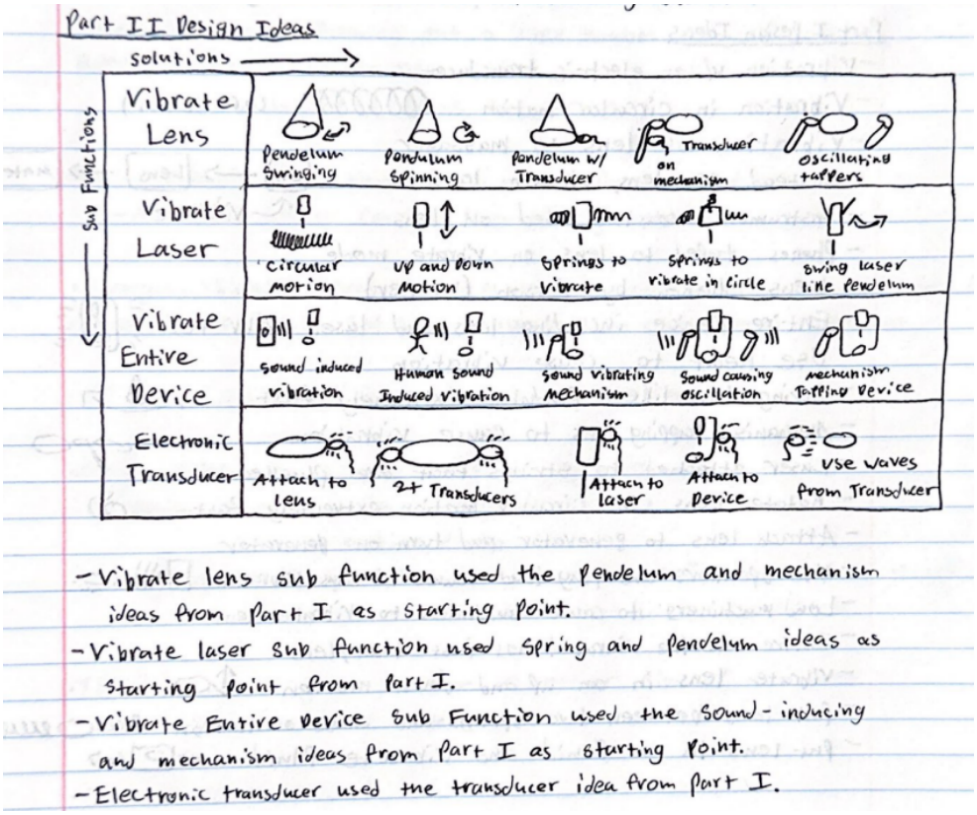


ME450 - Concept Exploration Learning Block

Part I Design Ideas

- Vibration w/ an electric transducer
- Vibration in circular motion (of laser)
- Vibration of lens w/ massager
- Instead of lens, vibrate laser
- Instrument acoustics used on lens
- Phones taped to lens on vibrate mode
- Lens shaken by person (worker)
- Entire device including lens and laser vibrated
- Use heat to cause vibration
- Swing lens like a pendulum extremely fast
- Mechanism tapping lens to cause vibration
- Laser attached to strings that are plucked
- Rotate Lens in circular motion extremely fast
- Attach lens to generator and turn on generator
- Use speakers and play loud sounds to cause vibration
- Loud machinery to cause soundwaves to vibrate lens
- Entire machine vibrated, not just laser/lens
- Vibrate lens in an up and down motion
- Put lens between two springs and cause oscillation
- Put lens in a fluid and vibrate fluid

Jonathan's designs created using design heuristics



Part II Design Ideas

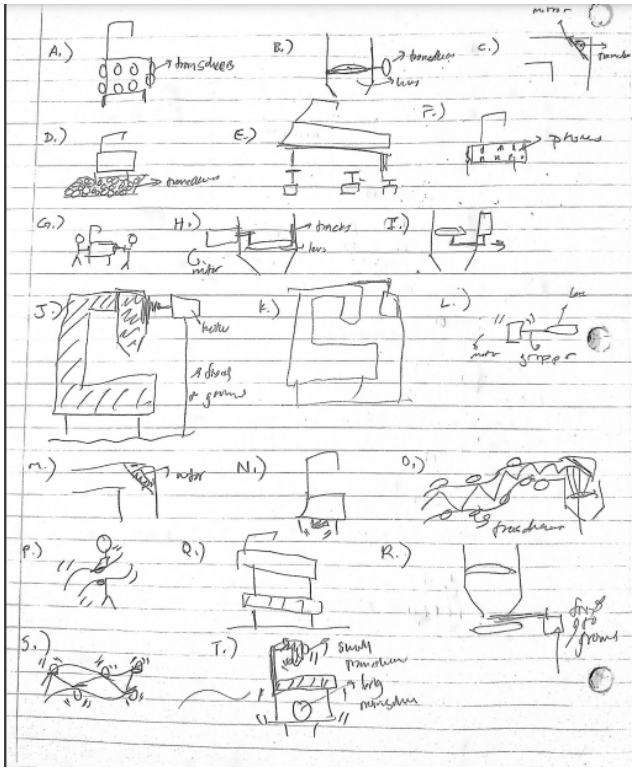
Sub Functions \ Solutions →					
Vibrate Lens	Pendelum Swinging	Pendulum Spinning	Pendelum w/ Transducer	Transducer on mechanism	Oscillating tappers
Vibrate Laser	Circular motion	Up and down motion	Springs to Vibrate	Springs to vibrate in circle	Swing laser like pendelum
Vibrate Entire Device	Sound induced vibration	Human sound induced vibration	Sound vibrating mechanism	Sound causing oscillation	Mechanism Tapping Device
Electronic Transducer	Attach to lens	2+ Transducers	Attach to laser	Attach to device	Use waves from Transducer

- Vibrate lens sub function used the pendelum and mechanism ideas from Part I as starting point.
- Vibrate laser sub function used spring and pendelum ideas as starting point from Part I.
- Vibrate Entire Device sub Function used the sound-inducing and mechanism ideas from Part I as starting point.
- Electronic transducer used the transducer idea from Part I.

Jonathan's designs creating using a morphological chart

1.C - Eashan Prabhu's Concepts

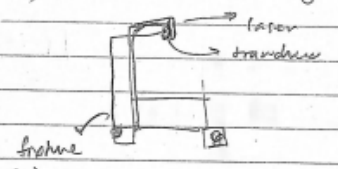
A. Vibrate the laser manufacturing machine itself through attaching many piezo-electric ceramics transducers
B. Vibrate the focal lens within the machine via attaching just one piezp-electric ceramic transducers
C. Vibrate the mirror within the laser manufacturing machines via attaching just one or two piezo-electric ceramics transducers
D. Vibrate the ground beneath the machine through thousands of piezo-electric ceramic transducers
E. Attach pistons to the underside to vibrate the machine up and down
F. Attach cell phones to the sides of the laser machine and have them receive phone calls to vibrate the machine
G. Have manufacturing workers shake the machine
H. Use a motor to move the focal lens up and down
I. Use a motor to move the focal lens left and right
J. Use a motor to vary the height of the nozzle from which the laser comes out of
K. Use a motor to vary the x and y of the nozzle from which the laser comes out of
L. Attach a vibrating motor to the focusing lens
M. Attach a vibrating motor to the mirror within the laser manufacturing device
N. Attach a vibrating motor to the underside of the machine
O. Vibrate the tube through which the laser is transmitted via attach piezo-electric ceramics to it
P. Have a worker hold onto and shake the tube through which the laser is transmitted continuously
Q. Have a platform beneath the machine that tilts it on an angle continuously
R. Have a second focusing lens beneath the first one that moves in and out of the laser beam
S. Create a tunnel of mirrors, which are all shifting, within the tube through which the laser is transmitted and vibrate all of them via piezo-electric ceramics transducers
T. Vibrate both the workpiece and the laser at half of ultrasonic frequency each via piezo-electric ceramic transducers



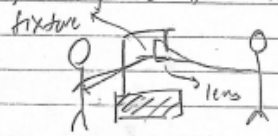
Morph Chart

Ultrasonic Vibrations	transducer	man power	cell phones
X-y plane	laser head	focusing lens	machine
Stable/ Durable	bolted to ground	fixed to machine	within machine

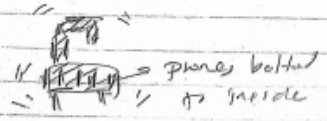
1.) transducer bolted to ground to vibrate laser head



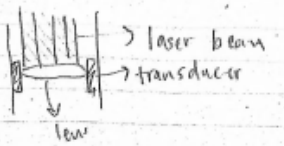
2.) man power to shake lens fixed to machine



3.) cell phones to vibrate machine fixed within machine

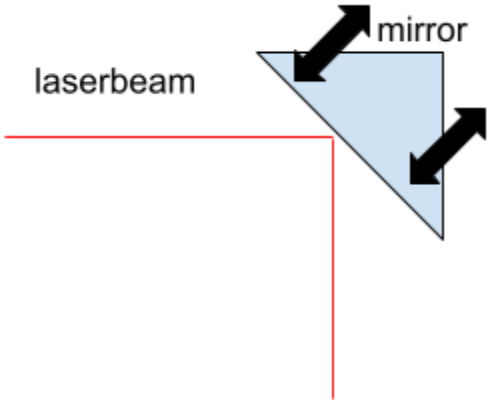


4.) transducer fixed inside machine to vibrate fixed lens

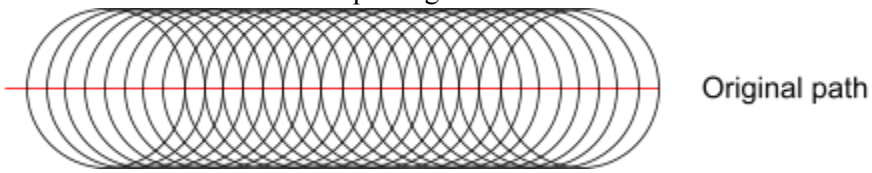


1.D - Nick Ventresca's Concepts

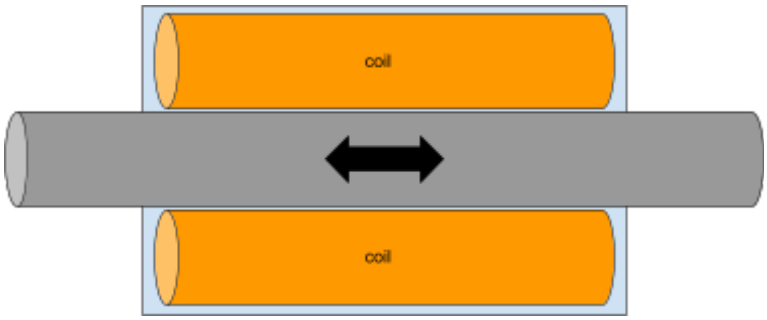
1. Move mirror ultrasonically with motors



2. Use cam and follower to create vibrations/chaotic motion
3. Use mirror to move laser in repeating circles



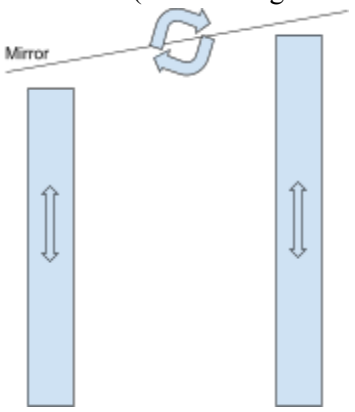
4. Use piezoelectric materials to vibrate the machine
5. Transmit ultrasonic acoustic vibrations using a waveguide
6. Vibrate lens left and right to vibrate laser position
7. Grab laser and shake it as you manufacture
8. Similar concept to tuning fork - find resonant frequency of machine and use that to strengthen vibrations
9. Use an unbalanced motor to create vibrations
10. Use an unbalanced fan to create vibrations
11. Use a solenoid to create vibrations



12. Use a spring mass damper system that is undamped to create vibrations
13. Get a gun massager for cheap and modify it to be more powerful/vibrate faster and attach to laser
14. Check out animals that create noise/vibrations and use their mechanics
15. Put the manufacturing machine in a room with speakers all creating tones at the resonant frequency of the laser/optics
16. Attach phones to the laser and have them all get a notification at once
17. Put the manufacturing machine on top of a vibrating platform
18. Use a magnetostrictive material to create vibrations
19. Use an electrostatic transducer to create vibrations
20. Morphological Chart (3x3) - 27 concepts

Vibration	Quartz crystal	Vibration motor	Electrostrictive materials
Vibration transmission	Waveguide	Direct contact	Solid nanowire
Mounting	Clips onto laser lens	Clips onto laser mirror	Attaches to machine workpiece

21. Use an acoustic metamaterial to transform sound waves into ultrasonic waves
22. Use a FSM (fast steering mirror module) to control laser position



23. Using design heuristics:
    - Mimic Natural Mechanisms - Look into how crickets create noise/generate vibrations
    - Use multiple components for one function - vibrate the laser using vibrations from the manufacturing machine itself
    - Use human power - Shake the whole machine with your body

1.E - Other Concepts

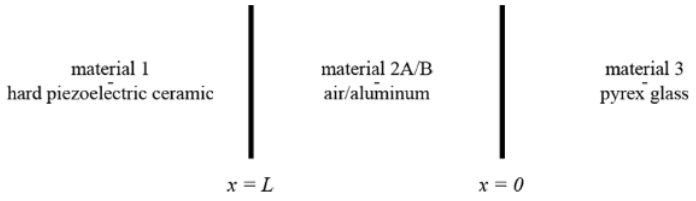
1. Morphological Chart (4x3) - 81 concepts

Vibration	Piezoelectric Materials	Vibration motor	FSM Module
Vibration transmission	Waveguide	Solid Booster	Direct Contact (no transmission)
Vibration Direction	X-Y Plane	Z-Axis	Y-Axis
Mounting	Attached to laser	Attached to workpiece	Attached to beam delivery system

2. Using design heuristics:
    - Add to Existing Product - Modify existing benchmark to vibrate in different directions
    - Cover or Wrap - Submerge the workpiece in a fluid and vibrate the fluid

2 - Transmission Intensity Coefficient Calculations

assuming plane waves normally incident on a layer



$T_I \equiv$ transmission intensity coefficient $= \frac{|\tilde{I}_t|_3}{|\tilde{I}_i|_1}$

$$T_I = \frac{4}{2 + (\frac{r_3}{r_1} + \frac{r_1}{r_3})\cos(k_2 L)^2 + (\frac{r_2^2}{r_1 r_3} + \frac{r_1 r_3}{r_2^2})\sin(k_2 L)^2} \tag{1}$$

where, using ρ_n as the density and c_n as the speed of sound in material n

$$r_n = \rho_n c_n \tag{2}$$

$$k_n = \frac{\omega}{c_n} \tag{3}$$

let $f = 20$ kHz so $\omega = 4\pi * 10^4$ rad/sec (bulk properties from [6,11,14])

n	material	$\rho_n[\frac{kg}{m^3}]$	$c_n[\frac{m}{s}]$	$r_n[\frac{Pa*s}{m}]$	$k_n[\frac{1}{m}]$
1	hard piezoelectric ceramic	7600	~ 4700	$35.72 * 10^6$	26.74
2A	air	1.21	323	415.03	366.37
2B	aluminum	2700	6300	$17.01 * 10^6$	19.95
3	pyrex glass	2300	5200	$11.96 * 10^6$	24.17

assuming $L = 100m = 0.1m$

for Design 2 (case A):

$$T_{IA} = 2.11 * 10^{-9}$$

for Design 3 (case B):

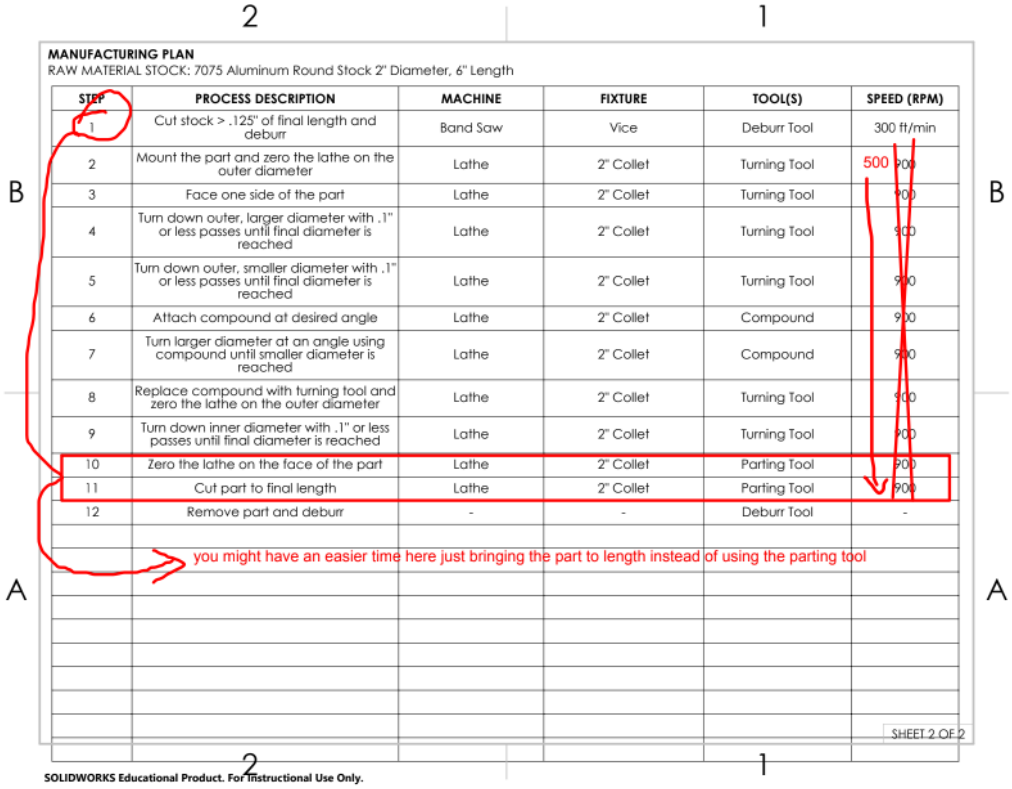
$$T_{IB} = 0.92$$

3 - Bill of Materials

Part	Quantity	Source	Catalog No.	Cost	Contact	Notes
4140 Steel Rod	1	McMaster-Carr	8927K15	$16.81	mcmaster.com	
7075 Aluminum Rod	1	McMaster-Carr	90465K19	$46.93	mcmaster.com	
PZT-8 Rings	12	K&M Technologies	KM-RSP30	$267.00	sales001@plasticjoining.net	
Laser Pointer	1	Amazon	B09Y1V54ZM	$5.97	amazon.com	
Mirror	1	Amazon	B08HR5P9V2	$16.95	amazon.com	
9340 Hysol Epoxy	1	Amazon	B00VFP1LAM	$35.24	amazon.com	
Meniscus Lens	1	Thorlabs	LE1234	$23.65	thorlabs.com	

4 - Manufacturing Plans

Booster Manufacturing Plan:



MANUFACTURING PLAN

RAW MATERIAL STOCK: 7075 Aluminum Round Stock 2" Diameter, 6" Length

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut stock > .125" of final length and deburr	Band Saw	Vice	Deburr Tool	300 ft/min
2	Mount the part and zero the lathe on the outer diameter	Lathe	2" Collet	Turning Tool	500 900
3	Face one side of the part	Lathe	2" Collet	Turning Tool	900
4	Turn down outer, larger diameter with .1" or less passes until final diameter is reached	Lathe	2" Collet	Turning Tool	900
5	Turn down outer, smaller diameter with .1" or less passes until final diameter is reached	Lathe	2" Collet	Turning Tool	900
6	Attach compound at desired angle	Lathe	2" Collet	Compound	900
7	Turn larger diameter at an angle using compound until smaller diameter is reached	Lathe	2" Collet	Compound	900
8	Replace compound with turning tool and zero the lathe on the outer diameter	Lathe	2" Collet	Turning Tool	900
9	Turn down inner diameter with .1" or less passes until final diameter is reached	Lathe	2" Collet	Turning Tool	900
10	Zero the lathe on the face of the part	Lathe	2" Collet	Parting Tool	900
11	Cut part to final length	Lathe	2" Collet	Parting Tool	900
12	Remove part and deburr	-	-	Deburr Tool	-

you might have an easier time here just bringing the part to length instead of using the parting tool

SHEET 2 OF 2

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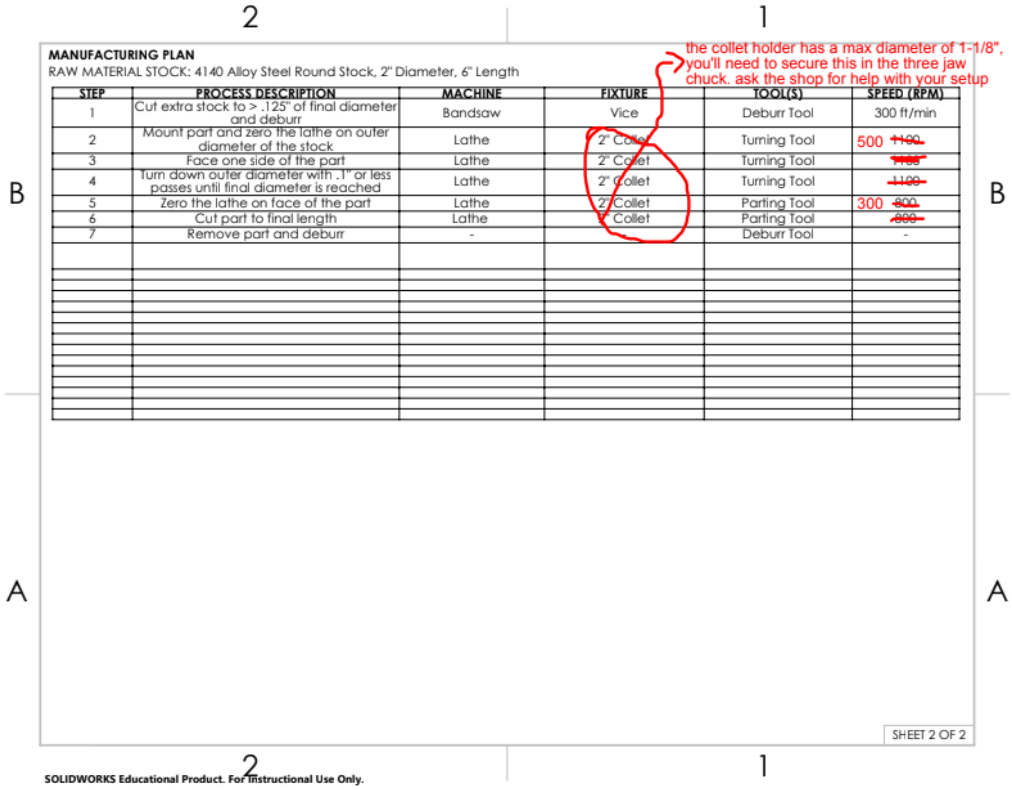
Rear Mass Manufacturing Plan:



MANUFACTURING PLAN

RAW MATERIAL STOCK: 4140 Alloy Steel Round Stock, 2" Diameter, 6" Length

the collet holder has a max diameter of 1-1/8", you'll need to secure this in the three jaw chuck. ask the shop for help with your setup

STEP	PROCESS DESCRIPTION	MACHINE	FIXTURE	TOOL(S)	SPEED (RPM)
1	Cut extra stock to > .125" of final diameter and deburr	Bandsaw	Vice	Deburr Tool	300 ft/min
2	Mount part and zero the lathe on outer diameter of the stock	Lathe	2" Collet	Turning Tool	500 ~~1100~~
3	Face one side of the part	Lathe	2" Collet	Turning Tool	~~1100~~
4	Turn down outer diameter with .1" or less passes until final diameter is reached	Lathe	2" Collet	Turning Tool	~~1100~~
5	Zero the lathe on face of the part	Lathe	2" Collet	Parting Tool	300 ~~800~~
6	Cut part to final length	Lathe	2" Collet	Parting Tool	~~800~~
7	Remove part and deburr	-		Deburr Tool	-

SHEET 2 OF 2

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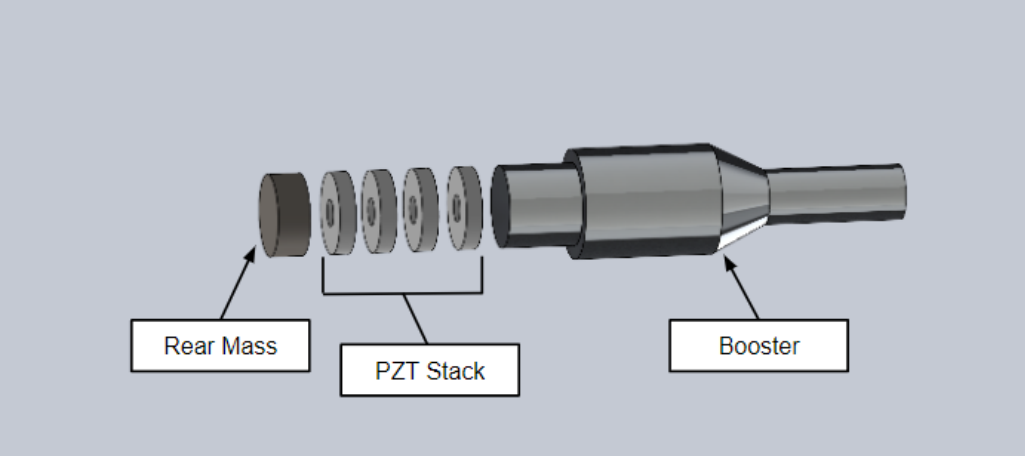
5 - Assembly and Fabrication Plan



1. Manufacture the rear mass on lathe following the provided manufacturing plans (A5).
2. Manufacture the booster on lathe following the provided manufacturing plans (A5).
3. Solder one wire to the positive electrode of the piezoelectric ring (top surface marked with a "+") and solder another wire to the negative electrode on the opposite side. Repeat for all four piezoelectric rings.
4. Cover both upper and lower surfaces of piezoelectric rings with electrical tape to prevent shorts from one ring to another. Repeat for all four piezoelectric rings.
5. Layer both manufactured parts and four piezoelectric rings in a stack, applying the mixed two-part 9340 Hysol Epoxy on each of the interior surfaces. Assemble parts with epoxy in the configuration shown above and apply pressure using clamp or other device to prohibit slippage. Allow 24 hours for the epoxy to cure.
6. Optionally, if there is difficulty keeping the PZT stack straight, the stack can be wrapped in electrical tape while the epoxy cures.