

Dampening vibration by use of lattice structures made by AM

Bachelor's thesis
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Author:
Vili Hartonen

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Turku

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Author: Vili Hartonen

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Supervisor: Mohsen Amraei and Francesco Trevisan

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Abstract: Vibration damping is a crucial part of design in mechanical systems. Unwanted vibrations can damage mechanical systems and compromise safety as well as causing user discomfort. Traditional methods for damping vibrations - ranging from passive materials to active systems - can have limitations in terms of efficiency and usage in harsh conditions. Lattice structures present a promising alternative due to their highly tunable geometry and frequency ranges, light weight and structural integrity. Through a comprehensive literature review, this work examines different lattice configurations, such as truss-based, surface-based and auxetic designs along with their respective mechanisms for vibration attenuation. The study also evaluates manufacturing methods and applications for lattice structures. Findings highlight the growing potential of use of lattice structures in tailored vibration damping applications and the importance of lattice structure metamaterials as structural elements.

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1 Introduction

Unwanted vibrations are a problem in numerous different industries and everyday life. These vibrations are caused by unbalanced motion or reciprocating force and can travel through air, liquids and solids. In different industries, vibrations are often caused by machinery. These vibrations can be caused by the design of a system or damage to the system. Examples for unwanted vibrations by machinery include pumps, engines, ship propulsion devices and high-speed cutting tools. Some vibrations can be caused by large electrical currents in transformers in high voltage lines.[1]

The downsides of these unwanted vibrations range from loud noises and uncomfortable conditions for humans to failing equipment and shorter service life for machinery. Unwanted vibrations have been suppressed and isolated for a long time by using materials and mechanisms to mitigate the production of vibration and the travel of vibration. The simplest ways of vibration control have been cushions and malleable materials that isolate the source of vibration from a system. These have allowed for sources of vibration to be isolated while being structurally sound with the system. An example of this system is an engine mount. It consists of a series of rubber blocks between the engine and the frame of a car. The vibrations are less likely to travel from the engine to the frame.[2]

A new mechanic for vibration damping and isolation is the use of a material with vibration damping properties built into itself. These are lattice structures that can be used in either vibration isolation between the source of vibration and the system and damping within the source of vibration itself. Many of these lattice structures are visualized to be produced using additive manufacturing (AM) because of the complex geometries some structures might possess.

This thesis is about conducting a literature review on lattice structures and vibration damping. This includes a brief introduction to vibration damping mechanics and methods other than lattice structures. The materials for this thesis have been searched for on the internet using search engines such as google and DuckDuckGo. In addition, language models Keenious and OpenAI's ChatGPT have been used to help in search for articles and sources. ChatGPT was also used to generate a rough structure for the thesis using a prompt: "give me a structure for bachelor's thesis about a literature review on vibration damping by lattice structures". These language models have not been used to generate text or pictures.

2 Literature review

2.1 Vibration damping techniques

Vibration damping systems can be passive, active or hybrid systems. Passive vibration damping systems do not require external power sources to function. Passive vibration damping systems can be divided into three different categories as stated by Kandasamy et. al. [3]. These are called Free-layer damping treatment, Passive constrained layer damping and tuned mass and viscoelastic dampers. The first two methods work by incorporating flexible materials between structures that dampen vibrations by deforming. Tuned mass dampers work by using a large mass connected to a structure by springs. They can dampen resonations by interfering with the natural frequency of the system.

Active systems require external energy or power to function. These are more prone to malfunctions as they are more complex but can easily adapt to different situations by use of sensors and smart usage. Active methods include piezoelectric damping, active constrained layer damping and active mass dampers. Piezoelectric dampers produce electric current with piezoelectric materials which in turn provide counteracting movement with similar materials. Active constrained layer damping works in a similar manner but reduces shear forces. An active mass damper is similar to a passive mass tuned mass damper but is moved with external power to mitigate vibrations. Hybrid methods combine both active and passive methods.[3]

Traditionally vibration damping has been solved by use of springs and viscoelastic materials or devices that mimic this function, i.e. shock absorbers. One widely used material for this application is bitumen based viscoelastic damping material (B-VDM)[2]. These include rubber blocks and tyres that are used between vibration sources and control systems. Other method to combat unwanted vibration is to design systems with large differences in natural frequency and the frequency of vibration. This minimises the resonance between source and the system.[4], [5]

New types of damping techniques have been researched. One technique consists of trapped particles inside a hollow structure, a steel beam, for example. It has been shown to be effective in vibration damping and a lightweight solution. It could be incorporated into additive manufacturing methods using powder as the base material. Combining lattice structures with voids and captured powder could increase the effectiveness of the vibration damping structure.[6], [7]

2.2 Lattice structures

Lattice structures are hollow, porous, periodic structures. They fall under the category of metamaterials. This is because of the properties that are not found in materials usually used in

vibration damping or other cases.[8] Truss-based lattice structures have been used in military applications in 1980s. These were used in French navy's submarines for floating raft-type vibration isolation purposes.[6] They are formed from multiple unit cells. A unit cell is the basis for the structure as the cell is iterated through the structure and dictates the geometry of the structure. [9] Lattice structures are not only good for vibration damping but also vibration isolation, thermal management and weight reduction. A lattice structure can be easily designed to have a preferred property for its designed use (For example a directionally rigid structure).[4] As porous structures, lattice structures are ideal for application where large surface areas are needed, for example heat exchangers. Other uses include cooling and filtering liquids as well as medical applications.

Lattice structures are highly customizable and allow for various geometries to be used. This ability combined with suitability for making them with additive manufacturing makes lattice structures great materials for industrial applications. These structures have already been used for their light weight and high strength in automotive and aviation applications. Lattice structures can be also found in more common applications as in cardboard. A repeating lattice is easier to configure, construct and manage than a foam structure. [5]

Lattice structures can be divided into multiple different groups. This division depends on the physical quantities of the lattice structure, its design parameters and the design of its cell or uniformity. This division can be for example a divide in 3D or 2D lattices[9], or division between number of nodes used in the structure[4].

2.2.1 Truss-based lattices

A truss-based lattice structure (*Figure 1*) can be simplified as being made out of nodes (corners or connecting points) and struts (connecting structures, "pipes or scaffolding"). Truss-based lattices can be configured extensively by connecting struts and nodes in different ways. Many truss-based lattices are modelled based on existing mathematical functions or geometries. These lattices are the most used for their relative simplicity and ease of manufacture. The geometries include, but are not limited to, body-centred-cube (BCC), simple cube (SC), Face-centred Cubic (FCC) and diamond. These base geometries have various variations with different truss configurations.[4], [9]

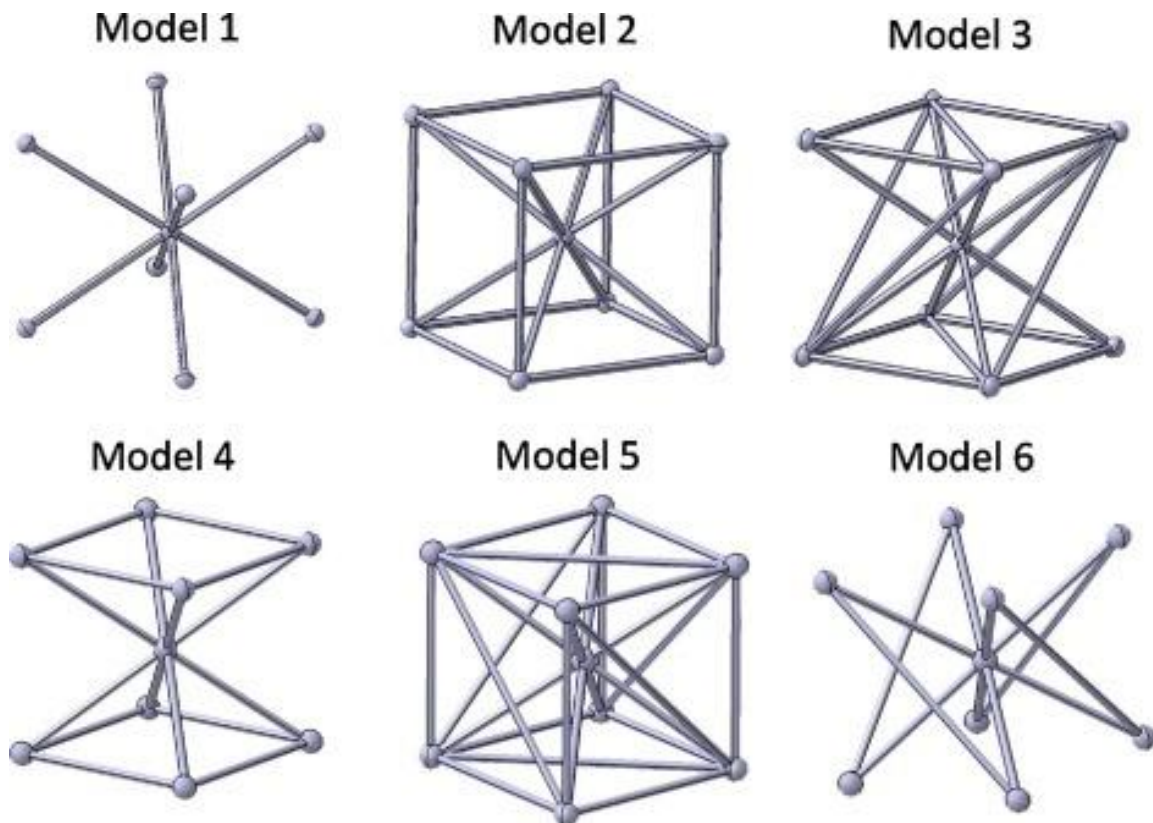


Figure 1. Models of six strut-based BCC lattice structure variations. Nodes in the corners of the struts are enlarged for visual representation. The nodes stay unaffected between variations. Modified from Syam et al.[3] Copyright 2017 Syam, published by Elsevier Inc

2.2.2 Two dimensional lattices

Two dimensional lattices include all lattice structures that can be extended as a two-dimensional plane. A honeycomb structure is a great example of a 2D lattice. It is repeatable in only one plane. Multiple honeycomb planes can be stacked on top of each other, but it does not generate a continuous, uniform lattice. Two dimensional lattices such as honeycomb structures can be found in light weight walls and structural elements. The light weight and ease of manufacture makes them feasible for mass production for construction and aviation. 2D-lattices often have a honeycomb-type structure. This is because of the nature of stacking round objects or circles along a plane. Honeycomb-structures are easily produced and do not need complicated manufacturing systems. Auxetic materials are easier to manufacture and design in two dimensions. The usage of auxetic materials in two dimensional applications is easier for the simplicity of mounting or installation.[9], [10]

2.2.3 Surface-based lattices

Surface based lattices (*figure 2*) can be constructed and modelled by using mathematical functions. These lattices are three dimensional and are generated whole surfaces instead of struts and nodes. The modelling and parametrization can be complicated due to the complex nature of the lattice. Research done on vibration characteristics of surface based lattices is lacking as the computations required for modelling are far more complex compared to truss-based lattices or two-dimensional lattices. Some minimal surface based lattices have been found to have vibration damping properties in terms of bandgaps.[11]

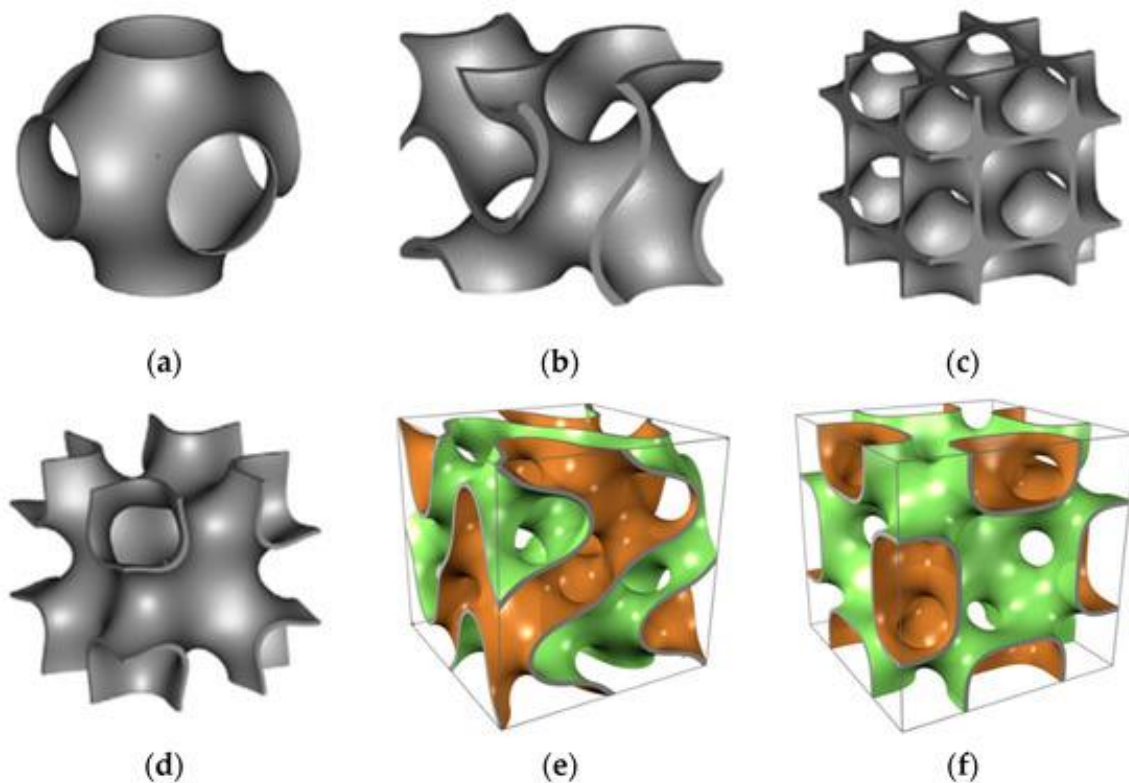


Figure 2. Models of six different minimal surface surface-based lattice structures. Modified from Pan et al. [5]. Copyright 2025 Pan, published by MDPI

The lattices can be expressed as mathematical formulas as they are surfaces with a volume:

- a) $\cos(x) + \cos(y) + \cos(z) = c$
- b) $\sin(x) * \cos(y) + \sin(y) * \cos(z) + \sin(z) * \cos(x) = c$
- c) $\cos(x) * \cos(y) * \cos(z) - \sin(x) * \sin(y) * \sin(z) = c$
- d) $2(\cos(x) * \cos(y) + \cos(y) * \cos(z) + \cos(z) * \cos(x)) - (\cos(2x) + \cos(2y) + \cos(2z)) = c$
- e) $\cos(2x) * \sin(y) * \cos(z) + \cos(x) * \cos(2y) * \sin(z) + \sin(x) * \cos(y) * \cos(2z) = c$
- f) $4(\cos(x) * \cos(y) * \cos(z)) - (\cos(2x) * \cos(2y) + \cos(2y) * \cos(2z) + \cos(2z) * \cos(2x)) = c$

where $x = 2\pi X/L_x$, $y = 2\pi X/L_y$ and $z = 2\pi X/L_z$

L_x , L_y and L_z are the unit cell sizes in the X, Y, and Z directions[5].

2.2.4 Mesh structures

Foams made by additive manufacturing can be useful in medical industries as they replicate bone tissue and can accelerate tissue growth and healing. Materials and structures similar to structures found inside human bodies should be used in artificial replacements for parts of the body. The human body is less likely to reject familiar structures and can more easily adapt to replacement joints, for example. An artificial foot made out of mesh structures can mimic bone mass and lessen the strain on joints compared to solid structures.[9]

2.2.5 Uniform and non-uniform lattices

Lattice structures can be uniform or non-uniform. This this property can be observed in both two dimensional and three-dimensional lattices. A uniform lattice has similar unit cells throughout the whole structure. This means that the size, strength and shape of the lattice stays the same. A uniform lattice will behave similarly throughout the whole structure. This makes a uniform lattice predictable and simple to both simulate and manufacture.

Non-uniform lattice changes throughout the structure (*figure 3*). The lattice might change shape or size along one or multiple axis. This property allows the lattice to experience different mechanical properties compared to a uniform lattice. Non-uniform lattice can be beneficial in applications where a vibration damping, or energy absorption gradient is needed throughout the structure. Non-uniform lattices can also be used in part optimization. [5], [12], [13] The non-uniformity is achieved by changing one or more of the design parameters. This smooth change of parameters and the following change of the lattice is called a gradient. A gradient can be used in a real-world application in two different ways: A gradient can be specifically optimised for a specific structure. Known parameters for the structure, such as yield strength or stresses in specific locations, are calculated and given to a topology calculator. It calculates a lattice model for the specific need. The other type of usage is making the lattice before the structure. A lattice structure is not modelled to any specification. The structure that the lattice is used in is optimized for the lattice.

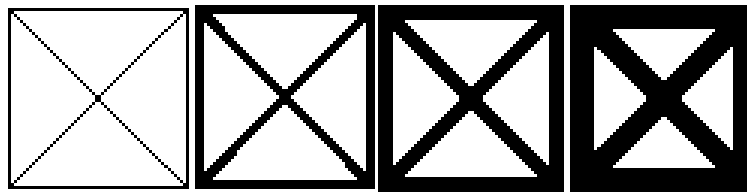


Figure 3, A graded lattice with increasing truss width from left to right

2.3 Applications of lattice structures in vibration damping

Lattice structures can be widely used in industrial applications and various special cases. One example is CNC (Computer Numerical Control) lathe spindle vibration mitigation. Lathes have large rotational speeds that amplify small imperfections in balance. The cutting tools demand high precision between the spindle and the tool holder. This makes lattice structures ideal for dampening unwanted vibrations as they are light and can withstand comparable forces to traditional tools. This makes these machines ideal for vibration dampening applications.[10]

2.3.1 Challenges and disadvantages in using lattices

There can be problems with implementing vibration damping materials in already existing machines as the auxetic or lattice structures might not be as strong as a traditional alternative. In some cases it has been noticed that tools and structures can deflect and bend in unwanted ways due to them being made out of auxetic and porous material. While this can be neglected in some cases, it might be a problem in applications which demand high force and high tolerance. Parts including lattice structures manufactured by AM can behave differently to parts manufactured by subtractive manufacturing. Other methods, such as molding, can be impossible due to the complex shapes used in lattice structures. Some properties of AM material can make them more prone to cracking and distortion.[10], [12]

2.3.2 Advantages

Making structures with additive manufacturing is very efficient with materials. Compared to traditional manufacturing methods, lattices made by AM need much less post production. Lattice structures are highly modifiable and tunable which makes it suitable to manufacture them for specific needs. Different lattice structures have different characteristics. A lattice structure can be chosen for a

specific need based on parameters. These include volume fraction, unit cell size, density, yield strength and stiffness.[5], [14]

2.4 Gaps in research

Many sources of research used in this thesis mentioned the need for more research [4], [12]. Real world examples and research of lattice structures for vibration damping are limited. This is because experimental lattices, such as many surface-based lattices, have not been incorporated into these applications. Most vibration damping methods used today in real world applications do not use lattice structures in vibration damping. They use different methods as in materials and systems. Many of these systems and materials have similar properties and behaviour as some lattice structures and similar structures. The structures have only been modelled and simulated using FEA software.

3 Theoretical background of vibration damping

Lattice structures can dissipate energy and dampen vibrations in different frequency ranges. Some lattices, such as matrix phase gyroid lattices, create bandgaps at high frequencies around 10kHz. At lower frequencies different lattices need to be used to mitigate vibrations.[10], [15]

Without any damping, a system would be turned into a mass-spring model. This means that the system would act as a mass fixed to a spring and is let to oscillate freely. An ideal system with no losses to heat due to bending of materials would have a natural frequency of:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad [16]$$

Where f_n is the natural frequency of the system, k is the spring constant of the system and m is the mass of the system. [16]

3.1 Fundamentals of damped vibration

Vibration damping includes a damper to the previous mass-spring model. To calculate the damping done in a system, a formula can be used:

$$\zeta = \frac{c}{2\sqrt{km}} \quad [16]$$

where ζ is the damping ratio, k is the spring ratio, m is mass of the system and c is the damping coefficient. ζ can also be defined as the “decay rate relative to the frequency”[17]. A damped system can be represented as a graph as shown in *Figure 4*.

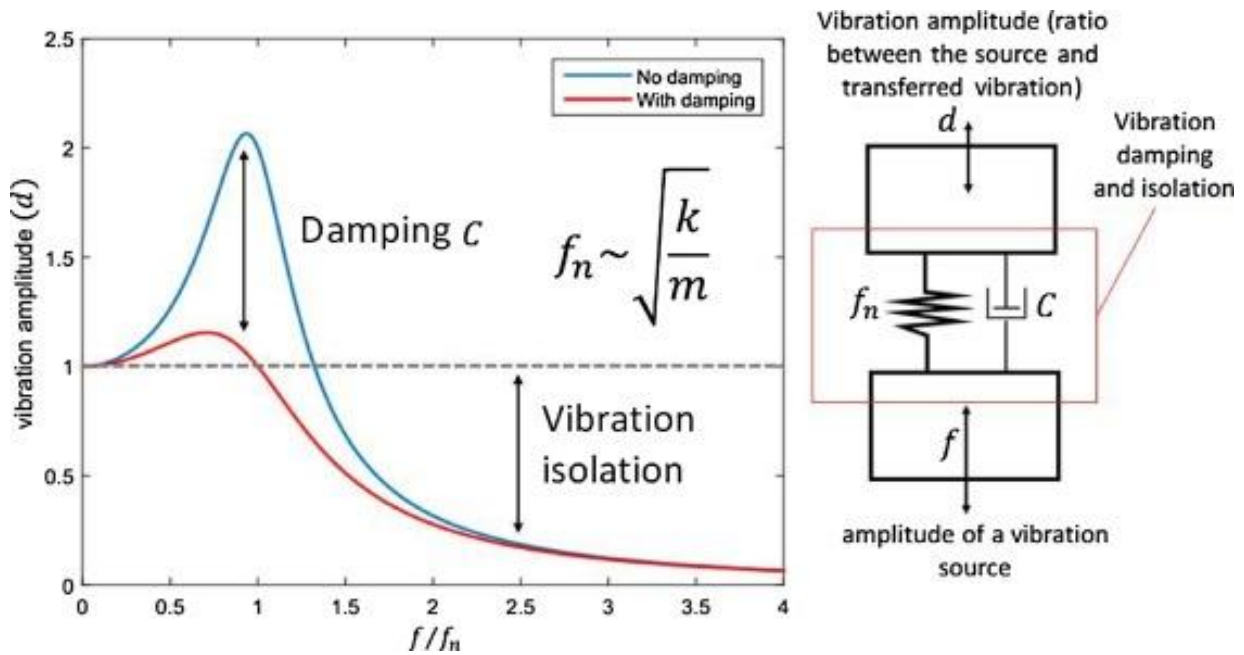


Figure 4. Representation for vibration in a system with an external vibration source. Modified from Syam et al.[3] Copyright 2017 Syam, published by Elsevier Inc.

3.1.1 Vibration measurement

There are multiple different ways to determine the effectiveness of the structure. These include crush tests, approximations by density, volume and cell size and special testing equipment for measuring vibration dampening. In the end, all of these tests measure the absorbed energy.[9], [18]

3.2 Mechanisms of vibration damping in lattice structures

3.2.1 Bragg scattering

Bragg scattering is one of the ways in which lattice structures make bandgaps. Bragg scattering revolves around the destructive interference of waves propagating through the lattice. A wave is reflected inside a unit cell and the reflections of the wave interfere with each other, cancelling out. This phenomenon is caused by the shape or geometry of the unit cell. Bragg scattering is highly dependent on the unit cell size.[11], [15]

3.2.2 Local resonance

Another way to produce bandgaps is by local resonance. Locally resonant structures create bandgaps by absorbing energy while resonating with a propagating wave. This phenomenon is caused by the internal mass of the unit cell.

3.3 Bandgaps

A bandgap is a range of frequencies that is blocked from going through the material. These can be caused by Bragg scattering or local resonance. Bandgaps allow for highly effective vibration isolation and damping to be achieved on a certain range of wavelengths.

Bandgaps appear as 1-dimensional, 2-dimensional and 3-dimensional. This means that the bandgap is dependent on the lattice structure and its dimensionality. A 1-dimensional band gap is effective in only one axis. A wave can propagate through a lattice structure in x- and y- directions but not in z- direction, for example. The same goes for the 2-dimensional band gap. This bandgap is effective as a plate or a plane. 3-dimensional bandgaps stop the propagation of waves in all directions.

A bandgap more effective for a large lattice with a number of unit cells.

On frequency – wave vector- plot bandgaps can be observed as region in which no dispersion curves overlap. This region is left empty on the frequency axis. Computing these bandgaps is most effective using FEM-software.[15]

3.4 Poisson's ration and auxetic materials

Some materials and lattices can exhibit a negative Poisson's ratio. These materials are called auxetic materials. This property means that the structure contracts as it is put under load or shear and expands as the load is lifted. A lattice structure can be constructed out of auxetic unit cells to form an auxetic lattice. These can also be constructed in two dimensions is a honeycomb-pattern. Multiple different geometries have been found and simulated using finite element simulation. The negative Poisson's ratio can be figured by calculating through simulations. Auxetic structures have been studied for energy absorption purposes and for vibration damping and isolation. The research suggests that auxetic structures as a lathe spindle vibration mitigator succeeded at damping vibrations at high speeds. These structures were noticed to deform when using high forces on the cutting head. More research needs to be done on auxetic materials for their usability in industrial applications to be fully utilized.[9], [10], [19]

3.5 Volume fraction

Volume fraction is one of the parameters that affects the properties of a lattice. Volume fraction is the amount of volume that the structure takes compared to a control volume. Volume fractions usually are between 10% and 20% in surface-based lattices. Tests and modelling has been done with lattices with volume fraction of up to 40% [11]. A volume fraction can be calculated with the following equation:

$$\rho^* = \frac{V_s}{(V_s+V_0)} \quad [15]$$

Where ρ^* is the volume fraction, V_s is a volume of a solid region in a unit cell and V_0 is an empty void region inside a unit cell. The volume fraction simply tells the amount of material in a unit cell compared to void, or empty space. The most noticeable effect of increasing volume fraction is the higher stiffness and strength of the lattice. This makes the lattice heavier and effects the natural frequency of the lattice.[15], [20]

4 Methodology

4.1 Manufacture of lattice structures

There are multiple different methods to manufacture lattice structures. These include traditional “subtractive” methods in which material is removed and additive manufacturing methods where material is added layer by layer.

4.1.1 Subtractive manufacturing

Subtractive manufacturing includes milling, drilling and honing along with all manufacturing methods whose operating principle is based on removal of material. These methods are well researched and have been in use in industries for a long time. Machining solid parts out of raw rolling stock can be made in relatively short time and with low cost. The downside of subtractive manufacturing is the large amount of unused material that needs to be removed. Lattice structures are hollow and porous structures. A solid steel cube might lose 80% of its material and mass .[5], [11] Traditional methods can be more time consuming and less efficient in terms of energy and material usage compared to other methods.

4.1.2 Casting

Certain types and shapes of lattice structures can be cast using molten metal alloys and cast made out of clay or sand. This process of manufacturing lattice structures is similar to manufacturing other products such as engine blocks or plastic containers. While producing less wasted material, the casting method requires post-processing as the lattice still has left over material attached to it from the mold. The lattice can also be partially complete and can need machining. It is also mentioned that due to the fine geometry of the lattice, the alloy needs to be low in viscosity and must be able to flow easily inside the mold.[5], [11]

4.1.3 Additive manufacturing.

Additive manufacturing (AM) is a relevant topic in today’s research. Additive manufacturing methods allow the manufacture of complex geometries with high precision. Many different additive manufacturing methods are used to manufacture lattice structures. These include laser powder bed fusion (LPBF), selective laser melting (SLM), fused deposition modeling (FDM), selective laser sintering (SLS) and electron beam melting (EBM). [5], [21]

Additive manufacturing methods can incorporate defects in the material. Common defects include unmelted powder and bubbling inside the molten metal. These defects may lead to delamination.

Unmelted metal powder or plastic does not fuse correctly with the following layers. This is caused by wrong parameters in the printing process, mainly too low temperature or (volumetric) energy density. Even though AM allows complex geometries to be manufactured, it still has limitations. Both extrusion and powder-based AM methods rely on stacking layers on top of a base plate. This means that the lattice structure in manufacturing needs to be attached to the printing apparatus with some type of geometry. Extrusion based printers need this attachment for stability and powder-based printers, especially LPBF, needs the attachment for temperature control. The printers also cannot accommodate large empty spaces between layers. The partially manufactured structure can't support the printed material which causes drooping (*figure 5*). This causes some geometries to be harder to manufacture.

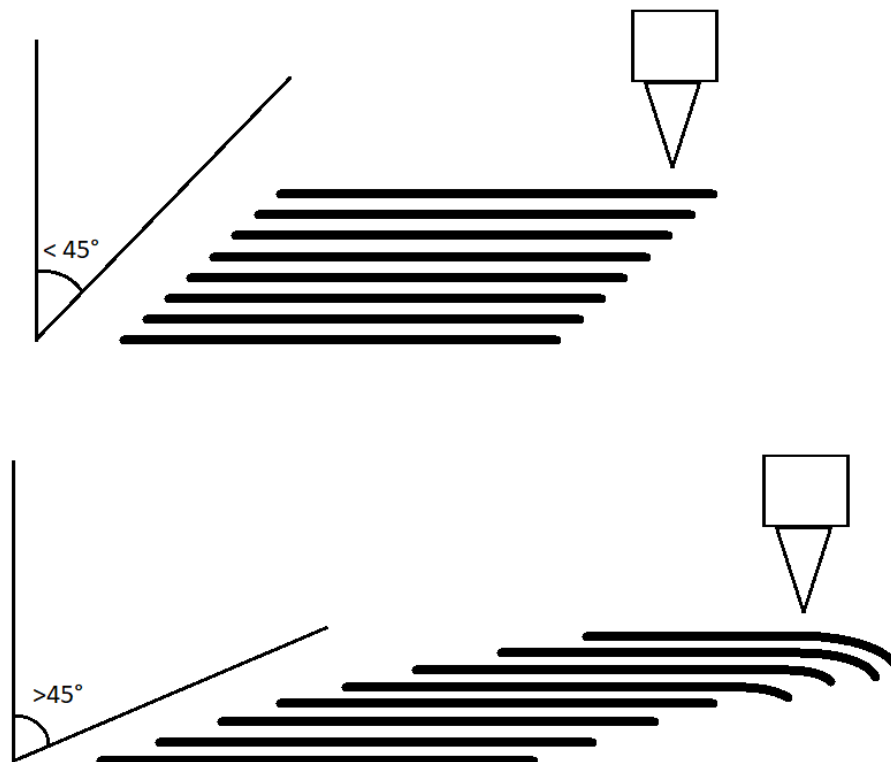


Figure 5, illustration of low amount of empty space (above) and high amount of empty space (below)

4.2 Material used in lattice structures

Different materials can be used in the production of lattice structures. Naturally appearing lattice structures are made from tissue (in bone) or other naturally occurring materials (beeswax in beehives). Artificially made structures are often made from metal, plastic or composite materials. This selection of materials often used because of its high strength compared to weight. Metals are often made into alloys. These can include steel, titanium or aluminum as a base metal and can have nickel, cobalt and nonmetals mixed into the alloy. Plastics are often used especially in research for their low price and

high manufacturability using AM. Composites can include both alloys and plastics and are used in existing, already researched applications.[4], [14]

Compared to traditional materials used for vibration damping and isolation, metals and plastics suffer less from changes in the environment. Rubber is often used in engine mounts and suspension systems. It can become stiff or brittle in cold temperatures. This may lead to failure in critical systems. L316 Stainless Steel has been found to possess promising characteristics in deformation tests.[21]

4.3 Research methods for lattice structures

Multiple different methods are used to find out the properties of different lattice structures. These tests are performed to confirm hypotheses regarding the strength, energy absorption rate or the overall structural integrity of the structure. Many structures have been simulated by using finite element analysis (FEA) software to speed up the research. Multiple different software are used. Using software removes the need for a physical object and saves in manufacturing time and costs. After simulating, physical equivalents for the simulated lattices can be constructed. A lattice is usually made out of multiple unit cells to simulate an uniform lattice. It is connected to a base plate to help with mounting. Tests done on the structure include vibration tests, shear tests, impact tests and crush tests. These are all done to define the properties of the structure. FEA is also used to wave propagation in the structure.[13]

5 Other uses for lattice structures

5.1 Industrial applications

5.1.1 Marine industry

A great problem in the marine industry, mainly in container and passenger ships, is the transmittance of vibrations from the main powerplant to the hull or a superstructure of the ship. As a power plant a ship usually has a conventional diesel engine that runs on diesel or heavy fuel oil. A conventional diesel engine experiences a large amount of reciprocating motion that is transferred to the surrounding systems via the engine mount. These engines are large and can weight over 250 metric tons[22]. The power of these engines can reach tens of thousands of kilowatts. These powerful vibrations transmitting through the hull will damage equipment and cause discomfort for the crew, passengers and cargo. Multiple methods to combat vibrations have been used and more have been researched.

A “raft- system” (*figure 6*) consists of a floating plane that the vibration source (power plant, turbine, generator) is mounted. This platform is isolated from the superstructure and is weighed down by large mass. This large mass lowers the frequency of vibration and suppresses them. This method combines vibration damping with vibration isolation. Lattice structures are a valid choice for “locally resonant systems” similar to raft-system (*figure 7*). This system is based on bandgaps made by local resonance. This has been studied with highly optimized combinations of materials and composites. A lattice structure has similar properties and could be tuned for usage in powerplant vibration mitigation. [6]

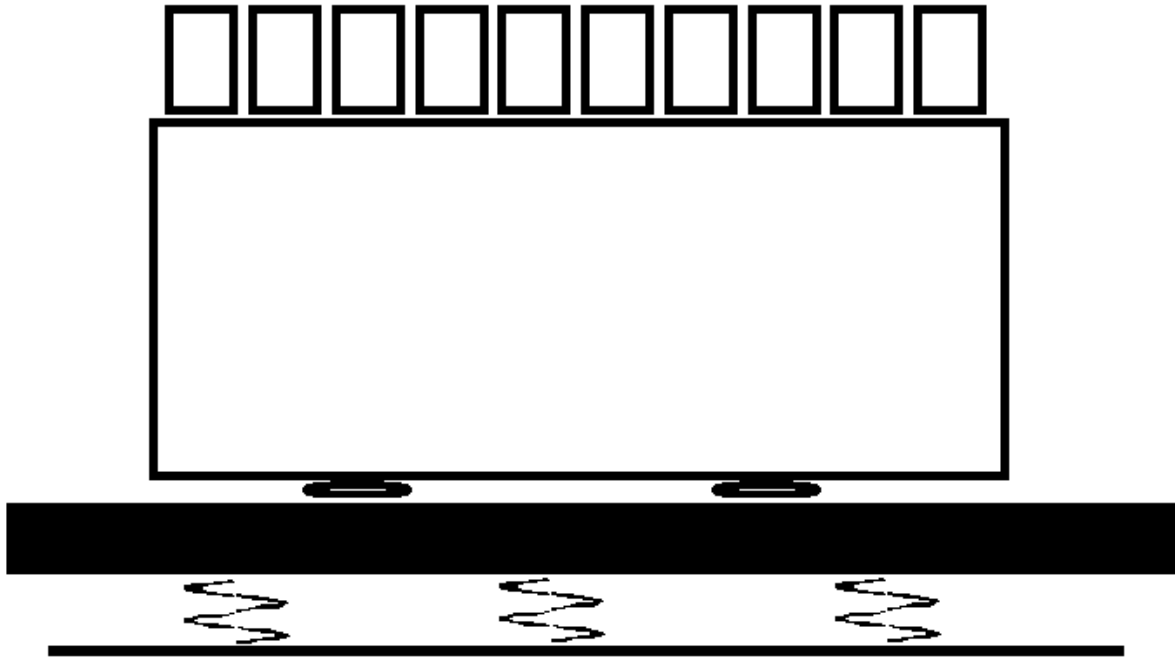


Figure 6, Drawing of a ship main powerplant mounted on a raft-system. The white box represents the power plant and the black rectangle a large mass or a raft which is isolated by springs

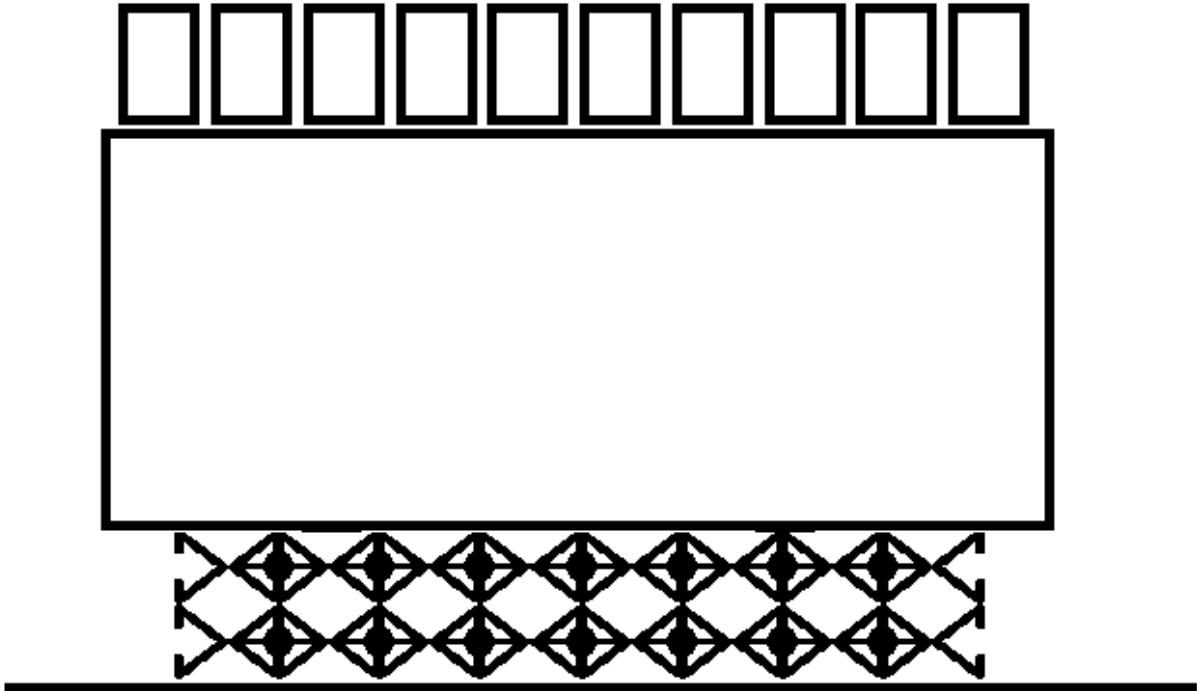


Figure 7, Drawing of a ship main powerplant mounted on top of locally resonant lattice structures. The lattice structures are represented as diamond shapes with circles inside of them.

Multiple navies around the world have used lattice structures and similar systems to combat unwanted vibrations. The main uses have been in submarines to mitigate noise to help camouflage the submarine under water.

5.1.2 Medical applications

Lattice structures can be used as shock absorbing materials. As stated previously, this property paired with light weight and high strength can allow lattices to be used in medical applications. Especially mesh structures are suitable because of their resemblance to soft tissue found in bones. A material mimicking the existing structure can make healing faster and allow for lower risk of rejection.[9]

5.1.3 Automotive and aviation industry

On both automotive and aviation industry, weight reduction is a crucial matter. A more lightweight car or aircraft uses less fuel than its heavier counterpart. This allows for more efficient manufacturing with less materials and cost savings in terms of fuel usage. This in turn can increase profits. Depending on the structure or a part of an aircraft or a vehicle, different lattice structures can be chosen to be incorporated into the design. Topology optimization and specialized computer software can be used to optimize the lattice structure and grade it if needed. Some aircraft manufacturers, such as Airbus, have used topology optimized parts for their aircraft.[20], [23]

6 Summary and conclusions

6.1 About research and writing process

This literature review was concluded to search for lattice structures that have been or could be used for vibration damping purposes. During the writing process many ways of analyzing research material were learned. The further into the literature review the writing process proceeded, the easier the writing process was. At the beginning of the literature review the writing of text based on the articles and research was difficult. The number of articles discussing vibration damping and lattice structures was overwhelming. This led to a need for redoing the thesis, as it lacked any correct structure. A language model was used to make research questions and to generate a rough template for a thesis with headings for chapters. This helped in forming this thesis. Writing on top of an existing structure helped a lot in the writing process as it narrowed down the subject area for each chapter. This in turn made it easier to search for information from each source.

The way of gathering information from different sources changed dramatically during the time of writing the thesis. In the first steps of gathering information and writing down important notes I made the mistake of focusing too much on one source material at a time. From each material or article, interesting paragraphs and sections were written down and marked using Zotero. This tool allowed me to gather research papers, articles and websites in one folder where they could be cited from. Citations for this thesis were also made using Zotero. The paragraphs and sections were then read through and based on the information contained in them, text was written. This method allowed for great understanding of the topic though it lacked efficiency in terms of progressing forward. The slow progress led to almost complete stalling of the thesis writing process.

After the slow progression the decision was made to start a new thesis with a different strategy. A rough sketch of the structure for the thesis was made and modified with the help of a language model. This helped to rearrange the already written text. The review of the literature was made easier as the focus shifted to finding answers to research questions and for chapter titles. This strategy dramatically sped up the review and writing process and allowed me to stay close to schedule. These strategies and tools used during the writing of this thesis will help in research and literature reviews during the remainder of the time in university and during work life.

6.2 About the literature review

Conducting the literature review started from articles found using Keenious. Using the references of these articles as help, new articles and research were found. The number of references found was immense and many of them were discarded as they were not close enough to the subject of the thesis.

Many of the articles used in the thesis are review articles that gather the main findings in the field of vibration damping, lattice structures or additive manufacturing.

The literature review taught me a lot of new facts about the importance of vibration damping and the versatility of lattice structures. Vibration damping is a crucial part of design in different systems ranging from electrical grids to ship hull designs. Another interesting topic found during the writing process is vibration isolation. This phenomenon prioritizes the isolating effects of damping systems over energy absorption. Both vibration isolation and damping are present in most usages of damping systems as they try to mitigate the same problem.

The use of lattice structures to mitigate vibrations and isolate them was a completely new concept for me. Repeated lattice structures have already been used as structural components for some time in various components and structures for their high strength and low usage of materials. The damping aspect of these structures and the mechanisms of damping have been intriguing to read about. Even though it is quite simple to understand in principle, the physical phenomena occurring inside the structure can be very complex. This can be observed in the modeling and calculation of stresses inside different lattice structures during testing[13].

According to the literature reviewed during the thesis, lattice structures can and have been used to mitigate and isolate vibrations. This has been achieved with multiple different lattice unit cell designs[4], [11], [13]. This does not mean that all unit cell designs are optimal for damping. The literature shows that the damping characteristics of each lattice profile can be tuned for a certain frequency or a frequency range. The ability to modify the lattice design to suit a special usage makes it very difficult to choose the most optimal or appropriate lattice design. The design of the unit cell can also change within the structure making the lattice non-uniform. Lattices are rarely used only for vibration damping characteristics but also for their light weight and strength and for some purposes their high surface area. This complexity necessitates the use of computer software to simulate and calculate the optimal lattice.

A main problem for usage in vibration damping and isolation is dependence on size. A high frequency vibration is easier to control than a low frequency vibration found in marine propulsion, for example. The lattice unit cell needs to be bigger if the frequency is lower. This makes the lattice unit cell count smaller and the lattice less effective in vibration control. Using lattice structures that rely on the mechanism of local resonance can be effective in mitigating low frequency vibrations compared to structures that rely on Bragg scattering. By choosing a correctly tuned and optimized lattice, it can be used to effectively dampen vibration and reduce weight, size and material.

6.3 Future remarks

More research needs to be done on lattice structures, especially in the field of vibration characteristics and vibration damping. This research should be not focused only on traditional lattice structures such as strut based and honeycomb-based lattices but also on auxetic lattices and minimal surface lattices. These structures have some research done on them and they seem to have promising characteristics in vibration mitigation. The real-world implementation however has been lacking. As more research is done, different industries are more likely to incorporate designs for systems which incorporate lattice structures. Additive manufacturing techniques are constantly going forward and getting more efficient and faster. The cost of producing lattice structures and optimized parts for mechanical systems will lower as the production and design costs lower. This will make using designs incorporating lattice structures more attractive for larger scale industrial applications and manufacturing.

7 References

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