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Design and analysis of strut-based lattice structures for vibration isolation

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ABSTRACT

This paper presents the design, analysis and experimental verification of strut-based lattice structures to enhance the mechanical vibration isolation properties of a machine frame, whilst also conserving its structural integrity. In addition, design parameters that correlate lattices, with fixed volume and similar material, to natural frequency and structural integrity are also presented. To achieve high efficiency of vibration isolation and to conserve the structural integrity, a trade-off needs to be made between the frame's natural frequency and its compressive strength. The total area moment of inertia and the mass (at fixed volume and with similar material) are proposed design parameters to compare and select the lattice structures; these parameters are computationally efficient and straight-forward to compute, as opposed to the use of finite element modelling to estimate both natural frequency and compressive strength. However, to validate the design parameters, finite element modelling has been used to determine the theoretical static and dynamic mechanical properties of the lattice structures. The lattices have been fabricated by laser powder bed fusion and experimentally tested to compare their static and dynamic properties to the theoretical model. Correlations between the proposed design parameters, and the natural frequency and strength of the lattices are presented.

1. Introduction

Additive manufacturing (AM) allows almost infinite geometrical design freedom [1], and the range and mix of potential materials is increasing [2,3]. However, despite the benefits afforded with having such freedom in design, there is a correspondingly larger design space that can be difficult to navigate. In this paper, we demonstrate how relatively simple design parameters can be used to reduce the design space and pinpoint a near-optimum design.

AM lattices are popular because they exhibit various advantages over solid stuctures and non-additively manufactured cellular solids. AM lattices have all the advantages of cellular solids, for example, low-mass and high impact energy absorbtion, and have an additional advantage: a high degree of design freedom. The freedom to exploit lattice designs is a big advantage that enables, for example, the design of lattices with material grading to provide variations in their structural properties and a controllable deformation property to avoid undesirable failure modes [4]. Another advantage of the freedom of lattice design is that topologically optimised solutions to various problems, for example mechanical, thermal, vibration and energy absorption, can be implemented. In addition, AM lattices can provide better solutions to problems where the loading condition is unpredictable during operation [4].

1.1. Design for AM to isolate vibration: motivation

This study presents design, experimental methodology and design parameters focusing on how to select a lattice design from many feasible strut-based lattice designs, within the same volume and from one material, to be used for a high-efficiency vibration isolation structure and to have sufficient structural integrity to sustain a mass load. Potential applications include metrology frames, machine frames and mounting brackets to support rotary components. Conventionally, to reduce the effect of vibration, both from the system itself and from the environment, high-stiffness structures are used, for example, a high-mass solid structure. However, the use of a solid structure does not isolate vibration transferred to the system, rather, the structure attenuates the vibration amplitude [5].

Vibration isolation is compared to vibration damping in Fig. 1, which considers a simple case where vibration is transferred from an external vibration source to a machine. In Fig. 1, the abscissa is the ratio r between the frequency of an external vibration f and the natural frequency of the machine f_n. The ordinate is the displacement amplitude d of the machine with respect to the displacement amplitude of the

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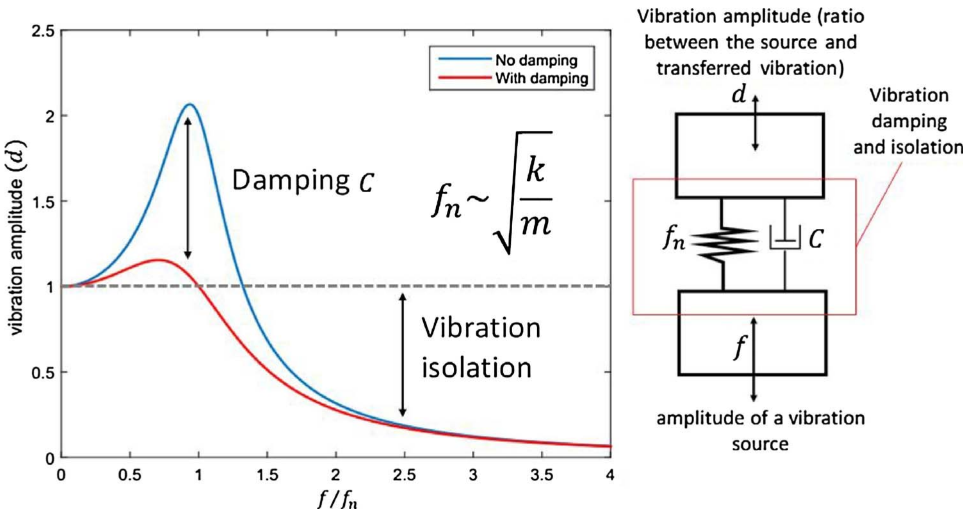

Fig. 1. Graph illustrating vibration damping and isolation.

external vibration source. C is damping coefficient that can be in the form of a different component or can be from the structure itself [5].

In Fig. 1, vibration damping reduces the amplitude of the transferred displacement due to the vibration. The machine is considered to become one structure with the external vibration source when the fraction of the transferred displacement to the part is equal to unity (see Fig. 1). When the ratio between the frequency of the vibration source and the natural frequency of the part is equal to unity, the amplitude of the part displacement will be amplified, having a significantly higher value than the original source displacement; this phenomenon is called resonance [5].

As an alternative to vibration damping, vibration isolation can be used to reduce the vibration amplitude transferred to the machine, with respect to the external vibration, by separating (isolating) the part from the external vibration source (see Fig. 1). Vibration isolation is more effective at reducing the effect of vibration compared to damping because it does not require high mass (weight) to suppress the machine's displacement due to the vibration and it can reduce the displacement of the machine to less than that of the external vibration. The higher the ratio r, the more the part is isolated from the external vibration. To have a high value of r, f_n should be smaller than f. A high r value can be achieved by lowering the stiffness of a structure, but, there is a practical limit: if the stiffness is too low, the structure will be unable to sustain mass loads. In Fig. 1, f_n is directly proportional to square root of stiffness over mass ($\sqrt{k/m}$) [5].

1.2. Research aim

In this paper, design and analysis of several lattices and experimental methodology to verify the lattices' natural frequency and stiffness (mainly due to bending) are presented. In addition, design parameters are proposed to allow comparison and selection of the optimum design for a strut-based lattice structure, from the potentially large number of feasible designs. All considered designs have the same volume and are fabricated from the same material. The selection focuses on two properties: high-efficiency vibration isolation and sufficient structural integrity to be able to sustain specific mass loads. The design parameters should be able to capture the information about different lattice topologies (configurations) and can be correlated to the natural frequency of different lattices. To capture topology information, the total area moment of inertia of a strut-based lattice and its mass (at fixed volume) are proposed as design parameters.

In this study, because the strut material is identical for all the examined lattice types, two hypotheses are proposed: (1) the stiffness of a lattice is proportional to its total area moment $\sqrt{I/m}$ of inertia I, and (2) the natural frequency f_n of a lattice is proportional to $\sqrt{\mathrm{I/m}}$. By using $\sqrt{\mathrm{I/m}}$ and I to represent f_n and the stiffness of a lattice, respectively, at the design stage, a significant reduction in computational effort to compare f_n and stiffness can be obtained, compared to multiple experimental tests or finite element analysis (FEA) procedures. FEA methods, commonly used to predict the natural frequency and compressive strength of a lattice structure, are computationally intensive and require specific procedures to be followed, such as convergence tests [4]. Moreover, the two hypotheses allow the selection of an optimum lattice design from many feasible designs. For each of the lattice structures considered in this work, the stiffness is dominated by bending stress. This was determined by considering Maxwell's criterion [7], which relates the deformation mechanism of a structure to its nodal connectivity

2. Lattice structure designs, analyses and simulations

There are a large number of feasible options for designing strut-based lattice structures within a defined volume. A lattice structure consists of nodes (n) and struts (p), as illustrated in Fig. 2. A node is a joint where two or more struts meet, and a strut is a link or member that connects two nodes. If the number of nodes and struts are not constrained, then there will be a potentially large number of feasible strut-based lattice configurations that can be designed within a fixed volume. The large number of options results from the variation of the number of

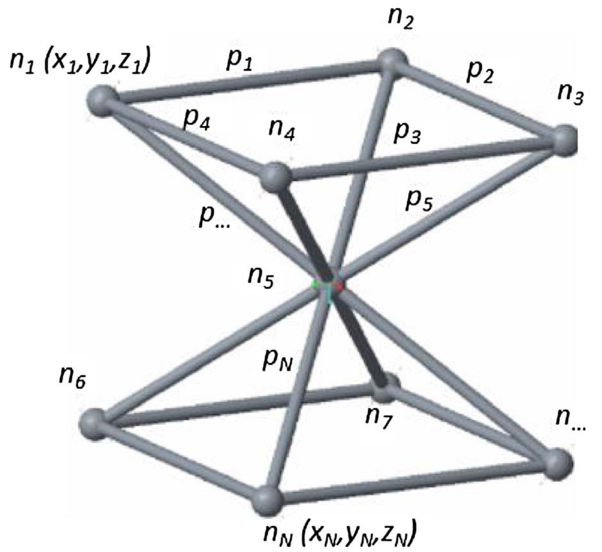

Fig. 2. Illustration of a lattice configuration with nodes n = 9 and struts p = 16.