Bio-Inspired Methods to Avoid Vibration Problems in Lightweight Structures

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Summary

Lightweight design technology aims to reduce the weight of a component without restricting its functionality or service life. The implementation of lightweight design structures inspired by aquatic plankton organisms (diatoms, radiolaria) has allowed the development of optimized lightweight components across different industry sectors. But structural design principles found in these plankton organisms are also used beyond lightweight design: they are highly multifunctional characterized by a high permeability, mechanical robustness, and high energy absorption. However, a major problem with lightweight structures is that they are very susceptible to external vibrations. In contrast to massive constructions, lightweight structures can easily be excited to vibrate, which greatly limits the use of these structures. Thus, different biologically inspired methods have been investigated to avoid vibration problems in lightweight structures. The methods included (1) pre-deformations of structures according to their vibration mode shapes, (2) the application of irregular honeycomb structures, (3) using irregular lattice structures, and (4) conducting evolutionary strategic optimizations. What all methods had in common is that they efficiently increase structural eigenfrequencies so that resonance phenomena, i.e., high vibration amplitudes, could be prevented. At the same time, the structural mass remained constant. The methods examined were then applied to a technical problem: the development of a biologically inspired magnet carrier structure for a particle accelerator. This case study showed that using the biologically inspired methods efficiently improves the vibration characteristics and thus prevents unwanted vibration amplitudes.

Zusammenfassung

Ziel der Leichtbautechnologie ist es, das Gewicht eines Bauteils zu reduzieren, ohne dessen Funktionalität oder Lebensdauer einzuschränken. Die Implementierung von Leichtbaukonstruktionen, die von aquatischen Planktonorganismen (Kieselalgen, Radiolarien) inspiriert sind, hat die Entwicklung optimierter Leichtbaukomponenten in verschiedenen Industriesektoren ermöglicht. Die strukturelle Designprinzipien dieser Planktonorganismen werden aber auch über den Leichtbau hinaus genutzt: Sie sind hochgradig multifunktional und zeichnen sich durch eine hohe Durchlässigkeit, mechanische Robustheit und eine hohe Energieaufnahme aus. Ein großes Problem von Leichtbaukonstruktionen besteht jedoch darin, dass sie sehr anfällig gegenüber äußeren Vibrationen sind. Im Gegensatz zu massiven Konstruktionen können Leichtbaukonstruktionen leicht zu Schwingungen angeregt werden, was den Einsatz dieser Konstruktionen stark einschränkt. Daher wurden verschiedene biologisch inspirierte Methoden untersucht, um Vibrationsprobleme in Leichtbaustrukturen zu vermeiden. Zu den Methoden gehören (1) die Vorverformungen von Strukturen nach ihren Schwingungsmodenformen, (2) die Nutzung unregelmäßiger Wabenstrukturen, (3) der Einsatz unregelmäßiger Gitterstrukturen und (4) die Durchführung von Optimierungsrechnungen inspiriert von der natürlichen Evolution. Allen Methoden war gemein, dass sie strukturelle Eigenfrequenzen effizient erhöhen, sodass Resonanzerscheinungen, also hohe Schwingungsamplituden, verhindert werden konnten. Gleichzeitig blieb die Strukturmasse konstant. Anschließend wurden die untersuchten Methoden auf ein technisches Problem angewendet: Die Entwicklung einer biologisch inspirierten Magnetträgerstruktur für einen Teilchenbeschleuniger. Dieses Fallbeispiel zeigte, dass der Einsatz der biologisch inspirierten Methoden die Schwingungseigenschaften effizient verbessert, wodurch unerwünschte Schwingungsamplituden vermieden werden.

Introduction

Lightweight design structures are often susceptible to external vibrations because of the reduced weight. However, traditional methods to avoid unwanted vibration amplitudes including mass increase or implementing damping devices contradict the aim of using lightweight structures. Thus, there is a high demand of other methods to efficiently prevent high vibration amplitudes.

The here studied methods include the adaptation of the geometry without increasing the mass to shift the eigenfrequencies above external, exciting frequencies. In doing so, the system's eigenfrequencies do no longer match critical frequency values and high vibration amplitudes (and resonance phenomena) can be avoided. As an increase in eigenfrequency can considerably reduce the dynamic response of a structure, an eigenfrequency maximization is of great interest for numerous technical applications.

Aside from the technical world, also in nature, organisms are excited by external vibrations and have to deal with unwanted vibration amplitudes. Diatoms, for example, are shaked by their predators as they try to crack the algae's shells. Diatom shells are very complex structures that often show irregular honeycomb and lattice structures. First numerical studies presented that many diatom shells show deformations according to the shells' vibrational mode shapes, which indicates that vibrational load cases somehow impact the development of these shells [1].

With the objective to significantly shift eigenfrequencies without increasing the mass, different methods primarily inspired by diatoms have been studied. These methods that are presented below include the pre-deformation of structures according to eigenmodes and the application of irregular honeycomb and lattice structures.

In a then following case study, biologically inspired structures and optimization techniques primarily inspired by diatoms were applied to a magnet carrier structure ('girder') planned to be implemented in the synchrotron radiation facility PETRA IV ('Positron-Elektron-Tandem-Ring-Anlage') at the Helmholtz research center DESY (Deutsches Elektronen-Synchrotron) in Hamburg.

Synchrotron radiation sources permit the study of structures, materials, and processes in different time and length scales in situ/in vivo to get a deeper understanding of complex biological, physical, and chemical processes in nature and technical research [2]. The heart of a synchrotron radiation facility is a storage ring, in which electrons circle at a constant energy. Deflecting their trajectory using magnetic fields generates electromagnetic waves, i.e., synchrotron radiation [3]. The magnets are usually positioned on carrying structures called 'girders'.

The PETRA IV project at DESY aims at upgrading the currently running synchrotron radiation facility PETRA III. For more information about this project it is referred to [4; 5]. Generally, a high particle beam stability is essential for an optimum operation of particle accelerators. Here, magnet-girder assemblies play an important role, because they have to prevent amplified ground vibrations to reach the particle beam.

The objective of the case study was to design an innovative, bio-inspired PETRA IV girder.

It shall be mentioned, that in all studies presented in the following, the parametric and algorithm-based constructions were performed using the software Rhinoceros (version 6 SR10, Robert McNeel & Associates) and its plug-In Grasshopper® (version 1.0.0007, Robert McNeel & Associates). The additional Grasshopper®-based module ELISE (version 1.0.36, Synera GmbH, www.synera.io) allowed the construction of the workflows and the entire study procedure including the connection to the solver OptiStruct (Altair® HyperWorks® Version 2017) used to obtain the numerical results.

Pre-Deforming Structures According to Eigenmodes

Inspired by the pre-deformation according to mode shapes observed in diatoms, the pre-deformation of a beam and a plate was studied [6]. The investigated beam (l x b x h_b = 600 x 30 x 3 mm) and the squared plate (a = 100 mm, h_p = 2 mm) are shown in fig. 1 and fig. 2, respectively.

Both structures were axially constrained and then pre-deformed according to the i-th mode shape (beam: i = 1 - 5, plate: i = 1 - 4), while varying the height of the structural pre-deformation according to the mode shapes. A maximum relative pre-deformation delta was defined as $\delta = \delta_{max}/h_b$ for the beam and $\delta = \delta_{max}/h_p$ for the plate (maximum pre-deformation δ_{max} = 0 mm - 60 mm).

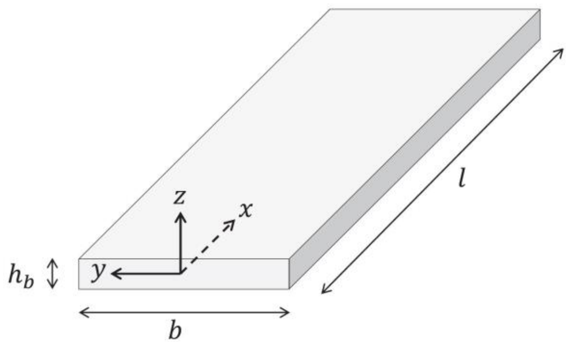

Figure 1: 3D view of the studied beam (according to [6])

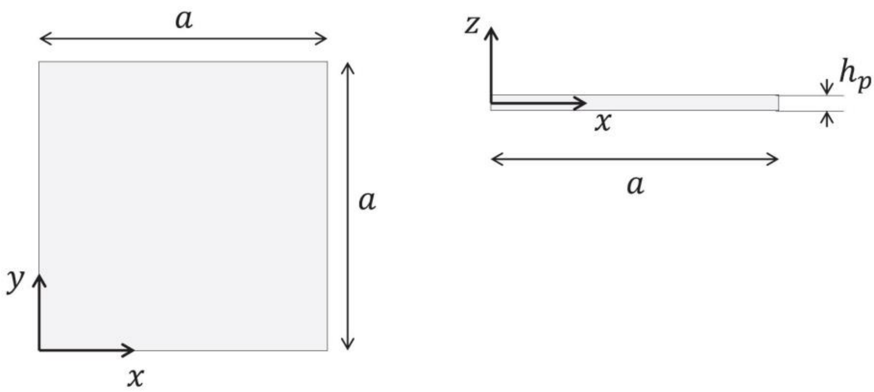

Figure 2: Top view (left) and side view (right) of the studied plate (according to [6])

The results showed that it is possible to almost exclusively raise the frequency of the targeted i-th mode shape of a beam. As exemplarily displayed in fig. 3, the pre-deformation of the beam according to the 1st mode shape increased the 1st eigenfrequency by 641% for δ = 3.0 and by more than 4,000% for δ = 20.0.The other studied eigenfrequencies stayed almost constant. Similar results are shown for the beam adaptation according to the 2nd mode shape.

Regarding the plate, the increase of the i-th plate mode shape frequency strongly raises the corresponding eigenfrequency, but simultaneously alters other eigenfrequencies.

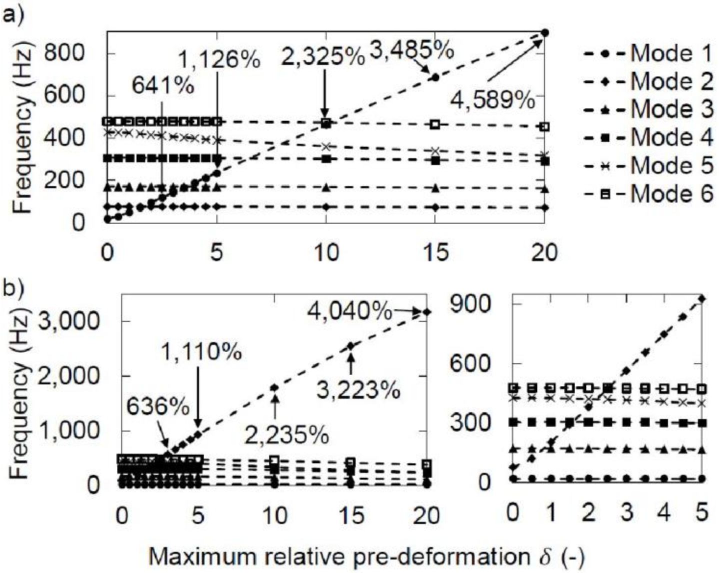

Figure 3: Mode shape frequencies of the slender beam pre-deformed according to the 1st (a) and the 2nd (b) mode shape. In (b), a detailed view is given on the right-hand side (according to [6])

In conclusion, the studied mode shape adaptation method inspired by diatoms allowed a strong eigenfrequency raise of axially constrained 1D and 2D structures by performing only small structural deformations without adding additional weight.

3. Application of Irregular Honeycomb and Lattice Structures

In two different studies, the impact of structural irregularities in cellular plates and 3D lattice structures on the 1st eigenfrequency was investigated.

Regarding the study on the 2D plates [7], the overall geometrical and material properties were constant. A squared plate with an edge length of 100 mm and a thickness of 2 mm was investigated. The mass had a constant value of 20 g. Aluminium (Young's modulus: 69,000 MPa, density: 2,688 kg/m^3, Poisson's ratio: 0.34) was specified as material.

A solid plate was compared to cellular plates characterized by a regular rectangle structure, a regular honeycomb structure, a Voronoi structure with constant cell size, and an optimized Voronoi structure obtained by evolutionary strategic optimizations. The 1st eigenfrequency was calculated in modal analyses as well as the maximum displacement due to a static load of 1,000 N applied to the plate's surface.

The results showed that all cellular plates had a higher 1st eigenfrequency and a lower maximum displacement compare to the solid plate (fig. 4), e.g., the 1st eigenfrequency was increased by a factor of 2.6 comparing the irregular Voronoi plate to the solid plate.

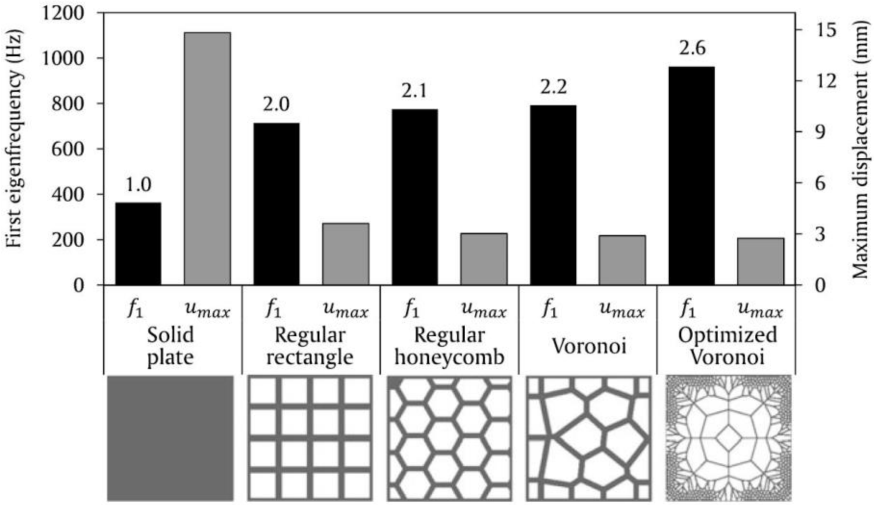

Figure 4: 1st eigenfrequency (black) and maximum static displacement (grey) of the different plate structures. Above the black bars, the eigenfrequency increase compared to the solid plate is shown (according to [7])

The study on lattice structures also followed the overall goal to create lightweight structures with high 1st eigenfrequencies [8]. Different lattice structures have been designed and optimized, before for each optimization loop, the lattice structure with the highest 1st eigenfrequency was chosen as the best. The chosen lattices (fig. 5) differed in the following characteristics:

a) Lattice with regularly distributed struts showing a constant circular cross section (L1)
b) Lattices with regularly distributed struts showing irregular circular cross section (L2, L2*)

c) Lattices with irregularly distributed struts showing irregular circular cross section (L3, L3*, L4, L4*)

The 1st eigenfrequency of the lattices increased with rising degree of structural irregularities (fig. 6), i.e., the use of complex bio-inspired structures enables the possibility to increase the eigenfrequencies of lightweight design structures.

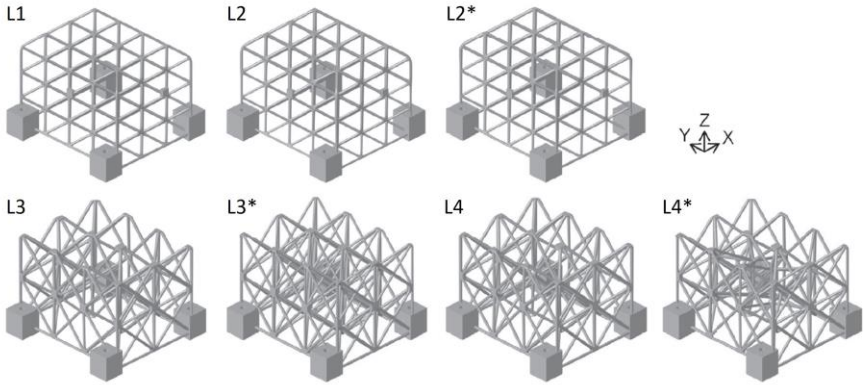

Figure 5: 3D view of the seven chosen lattice structures (adapted from [8])

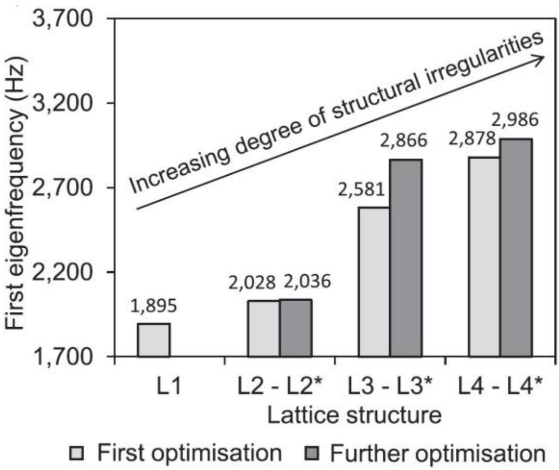

Figure 6: 1st eigenfrequency of the lattice structures (according to [8])

To sum up, the conducted investigations show the high potential of bio-inspired, irregular Voronoi plates and 3D lattices not only for lightweight design structures, but also for structures with improved vibration properties. By increasing the degree of structural irregularities, eigenfrequencies can be raised and thus removed from the range of external, exciting frequencies.

Case Study

In the here presented case study, an innovative PETRA IV girder was designed. The design objectives were a structural eigenfrequencies above 50 Hz, a maximum static deformation due to dead load of 0.5 mm, and a structural mass as low as possible. In the design process, bio-inspired structures and optimization methods studied beforehand were implemented [9].

Fig. 7 shows the general model assembly for the design process. The design space shown in light grey was 2.9 m long, loaded with eight magnets, and connected to pedestals at three positions.

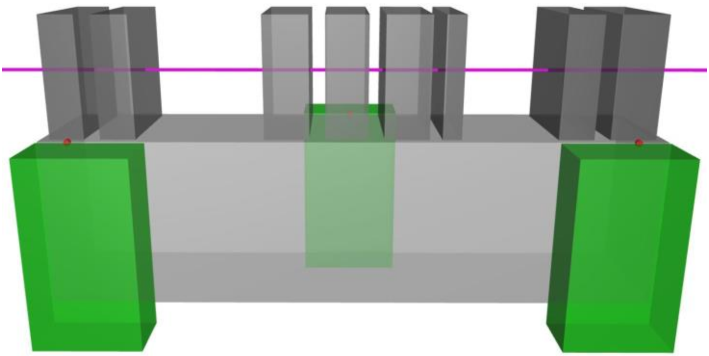

Figure 7: Model assembly including the girder design space (light grey), the magnets (dark grey), the pedestals (green), and the connection of the design space to the pedestals using beams (red). The position of the vacuum chamber is demonstrated in magenta (according to [10])

Based on a topology optimization result, a parametric beam-shell model including biologically inspired structures was generated. The subsequent cross section optimization using evolutionary strategic optimization revealed an optimum girder structure that fulfilled the design objectives. This biologically inspired girder design included irregular Voronoi combs, hierarchical branching structures, smooth connections, round holes, and 45° oriented ribs.

The designed girder structure was the successfully manufactured using the casting technology. Fig. 8 shows the manufactured girder positioned on springs during the then conducted vibration experiments (impact testing). The results indicated a very good coincidence of the numerically obtained and measured eigenfrequencies.

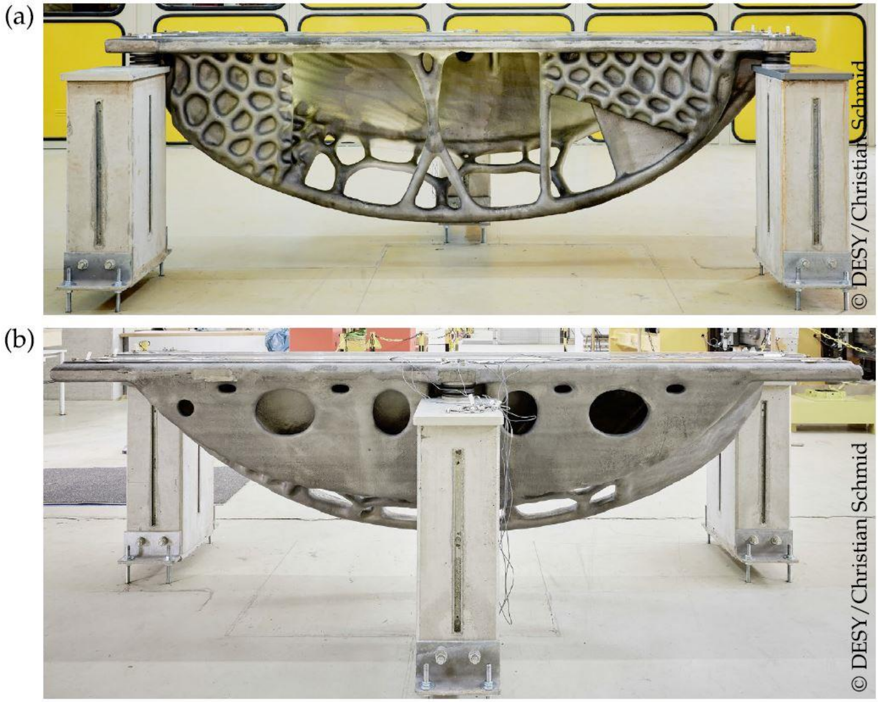

Figure 8: Photos of the manufactured bio-inspired girder in a front view (a) and back view (b) (according to [9])

Conclusion

The presented studies indicate the high potential of bio-inspired, complex structures to efficiently increase eigenfrequencies of especially lightweight structures in order to prevent unwanted vibration amplitudes. In a case study, bio-inspired structures were successfully applied to a magnet carrier structure implemented in a particle accelerator and showed a very good performance.

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