ISBN: 978-3-95450-229-5 ISSN: 2673-5520 doi:10.18429/JACoW-MEDSI2020-THOB03

INNOVATIVE AND BIOLOGICALLY INSPIRED PETRA IV GIRDER DESIGN*

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Abstract

DESY (Deutsches Elektronen Synchrotron) is currently expanding the PETRA III storage ring X-ray radiation source to a high-resolution 3D X-ray microscope providing all length scales from the atom to millimeters. This PETRA IV project involves an optimization of the girder magnet assemblies to reduce the impact of ambient vibrations on the particle beam. For this purpose, an innovative and biologically inspired girder structure has been developed. Beforehand, a large parametric study analyzed the impact of different loading and boundary conditions on the eigenfrequencies of a magnet-girder assembly. Subsequently, the girder design process was generated, which combined topology optimizations with biologically inspired structures (e.g., complex Voronoi combs, hierarchical structures, and smooth connections) and cross section optimizations using genetic algorithms to obtain a girder magnet assembly with high eigenfrequencies, a high stiffness, and reduced weight. The girder was successfully manufactured from gray cast iron and first vibration experiments have been conducted to validate the simulations.

INTRODUCTION

Biomimetics is a scientific discipline that deals systematically with the technical implementation and application of constructions, processes, and development principles of biological systems. Biological models are not copied, but investigated, understood, and applied to technical problems [1,2].

Natural structures are often complex and show good mechanical properties. They are highly optimized during the process of evolution and usually fulfil different functions.

In particular, aquatic plankton organisms with silicate cell covers (such as diatoms and radiolaria) have developed an extremely high diversity of irregular structures that show efficient lightweight design principles. Aside from the high stiffness and strength observed in these lightweight structures [3,4], diatom shells are expected to also protect the inner cell against vibrational load cases.

In different studies, irregular biologically inspired structures were analyzed regarding their natural vibrations. Irregular honeycomb and lattice structures show significantly higher eigenfrequencies compared to regular structures [5,6]. In addition, pre-deforming structures according to mode shapes, which can be observed in diatom shells [7], strongly raises the eigenfrequencies [8].

In a case study, biologically inspired structures and optimization techniques were applied to a PETRA IV girder. 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 [9,10]. Generally, a high particle beam stability is essential to obtain a low-emittance and diffraction limited storage ring [11]. Magnet-girder assemblies play an important role, because they have to prevent that amplified ground vibrations reach the particle beam.

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

MATERIAL AND METHOD

The applied girder design process was based on seven steps:

Definition of the Boundary Conditions

Figure 1 shows the considered boundary conditions. The girder was equipped with eight magnets and connected at three locations to three pedestals.

The overall design objectives were the maximization of the 1st magnet-girder eigenfrequency, the minimization of the static deformation due to gravity, and the minimization of the girder mass.

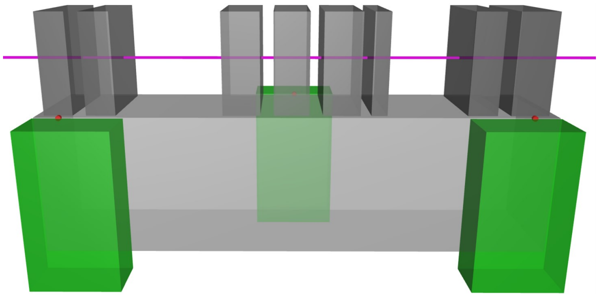

Figure 1: Model assembly including the girder design space (light gray), the magnets (dark gray), the pedestals (green), and the connection of the design space to the pedestals using beams (red). The position of the vacuum chamber is demonstrated in magenta.

Topology Optimization

A topology optimization was conducted to reveal an optimum material distribution. Thus, during the optimization process, material was removed from the design space shown in Fig. 1.

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[*] Work financed by the Alfred Wegener Institute and the Deutsches Elektronen-Synchrotron.

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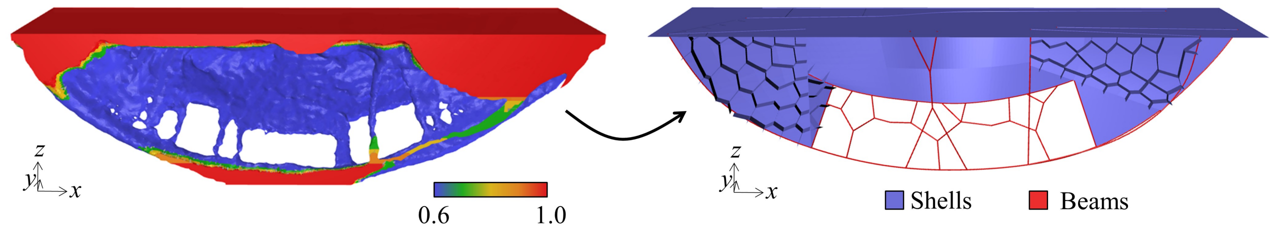

Figure 2: Topology optimization result (left), in which the coloring represents the artificial element density, and the abstracted beam-shell model (right).

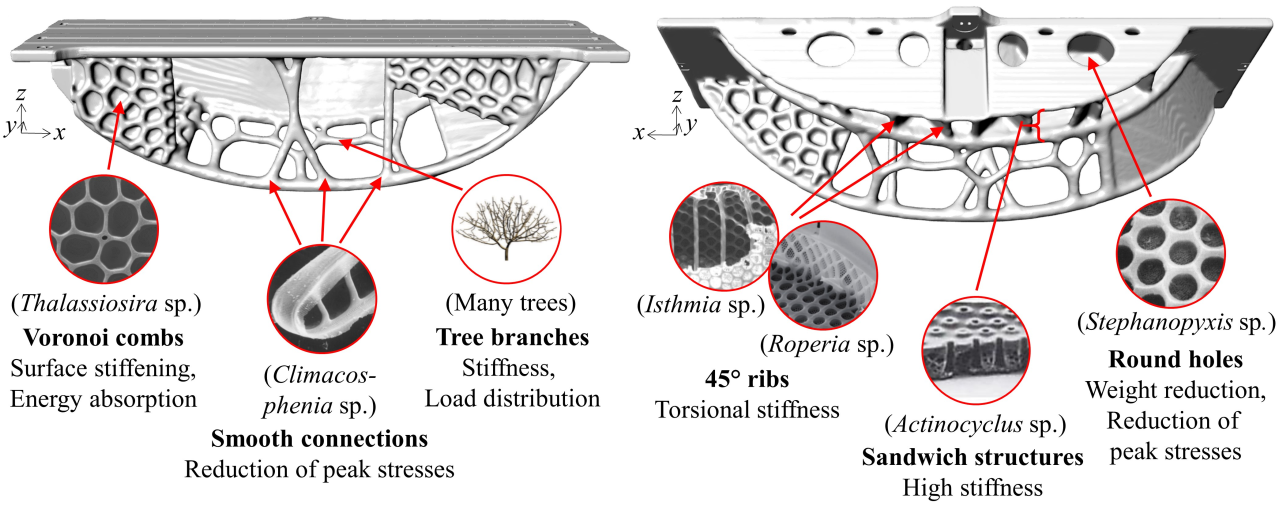

Figure 3: Front view (left) and rear view (right) of the final biologically inspired girder structure. The different structural elements inspired by nature are explained.

Parametric Beam-Shell Model

The structure resulting from the topology optimization was abstracted into a beam-shell model. This included the replacement of strut- and beam-like parts by lines (beams). Surface-like parts were abstracted as surfaces (shells) or – in the case of rather thick surfaces – as sandwich structures. The result of this step was a parametric beam-shell model.

Cross Section Optimization

In a large evolutionary strategic optimization, the thickness values and cross section diameters of all shells and beams were varied in order to obtain an optimum parameter combination. In this optimization procedure, the principles of biological evolution were applied to the present technical problem including accidents (mutation, cross over) and the proximate election strategies (selection). In several iterations, many parameter combinations were analyzed. The structure showing the highest 1st eigenfrequency and a tolerable maximum static deformation and mass was chosen as the optimum girder structure.

Final Girder Structure

The optimum beam-shell model was converted into a volume model that was meshed and numerically analyzed regarding its eigenfrequencies.

Manufacturing

The designed girder was manufactured using casting technology in connection with 3D printed sand molds. Grey cast iron (EN-GJL-250) was utilized. The interface surfaces to the magnets and pedestals were machined afterwards.

Vibration Measurement

The eigenfrequencies of the free and unloaded, manufactured girder were measured in an impact test. The girder was hit at the middle front of the upper girder surface. Eight accelerometers fixed to the upper girder surface recorded the girder movement. The power spectral density of the upper girder surface was plotted and the measured eigenfrequencies were compared to those obtained in the simulations.

RESULTS

The topology optimization result was a continuous structure that reminded of a bridge. It was composed of arch-like and surface-like structures as well as several interconnections. Figure 2 shows the topology optimization result and the abstraction into a beam-shell model, which contained multiple beams and shells.

The subsequent cross section optimization using the evolutionary strategy revealed an optimum dimension of each strut and shell leading to the final bio-inspired girder structure displayed in Fig. 3. It is based on different structural elements inspired by, in particular, aquatic plankton organisms.

In Fig. 4, the manufactured girder is positioned on three pedestals. Springs were located between the girder and the bases. This set-up was used for the impact testing.

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Figure 4: Front view of the manufactured bio-inspired girder connected via springs to the three pedestals.

Figure 5 shows the PSD (power spectral density) obtained for the eight accelerometers. The measured and numerically obtained eigenfrequencies were compared among each other (Table 1).

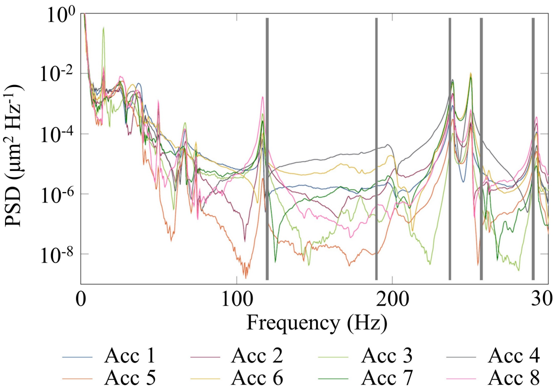

Figure 5: Power spectral density (logarithmic scale) obtained for the eight accelerometers (Acc.). The vertical gray lines illustrate the numerically obtained eigenfrequencies.

Table 1: Comparison of the Measured and the Numerically Obtained Eigenfrequencies of the Bio-inspired Girder Design

	Simulation	**Measurement**
f_1	119.6 Hz	116.6 Hz
f_2	189.8 Hz	199.7 Hz
f_3	236.8 Hz	238.7 Hz
f_4	257.1 Hz	250.2 Hz
f_5	290.4 Hz	292.5 Hz

DISCUSSION

The high potential of applying biologically inspired structures and optimization techniques to girder design processes has been demonstrated.

A development process for a girder structure of the synchrotron radiation facility PETRA IV has been generated. It resulted in an innovative girder design that combined different biologically inspired structural elements. The numerically obtained eigenfrequencies were validated by performing eigenfrequency measurements on the manufactured girder structure. In addition, the high conformity of the measured and simulated eigenfrequency values indicated a successful manufacturing process despite of the high complexity of the structure.

Future changes in the specifications can be implemented in the development process to obtain adapted girder structures.

CONCLUSION

In this case study, a girder design process was generated with the objective to design an innovative and biologically inspired girder structure. The successful manufacturing of the designed girder and the subsequent vibration measurements allowed a validation of the numerically obtained results.

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