

Innovative and Biologically Inspired PETRA IV Girders Design

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11th International Conference on Mechanical Engineering Design
of Synchrotron Radiation Equipment and Instrumentation (MEDSI)

July 26-29, 2021



Outline

- 1 Introduction
- 2 Impact on Eigenfrequencies: Parametric Study
- 3 Design Process for Bio-Inspired Girders
- 4 Conclusion

1

Introduction

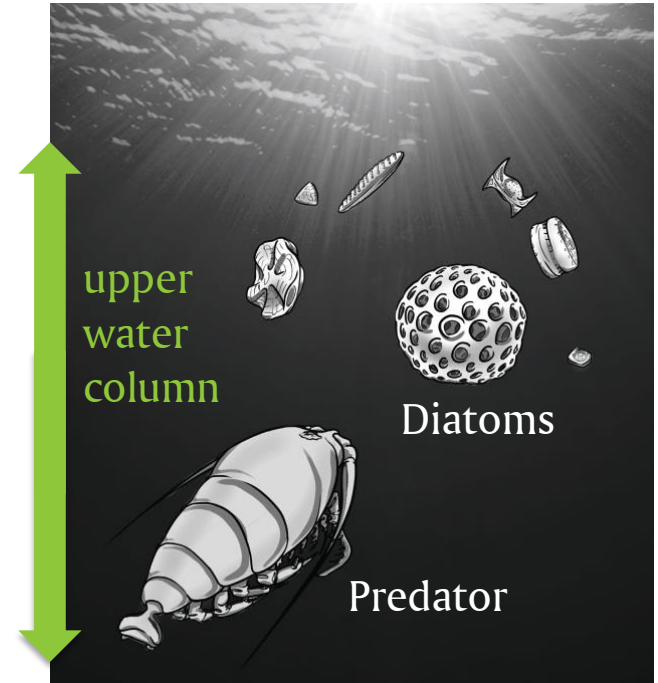
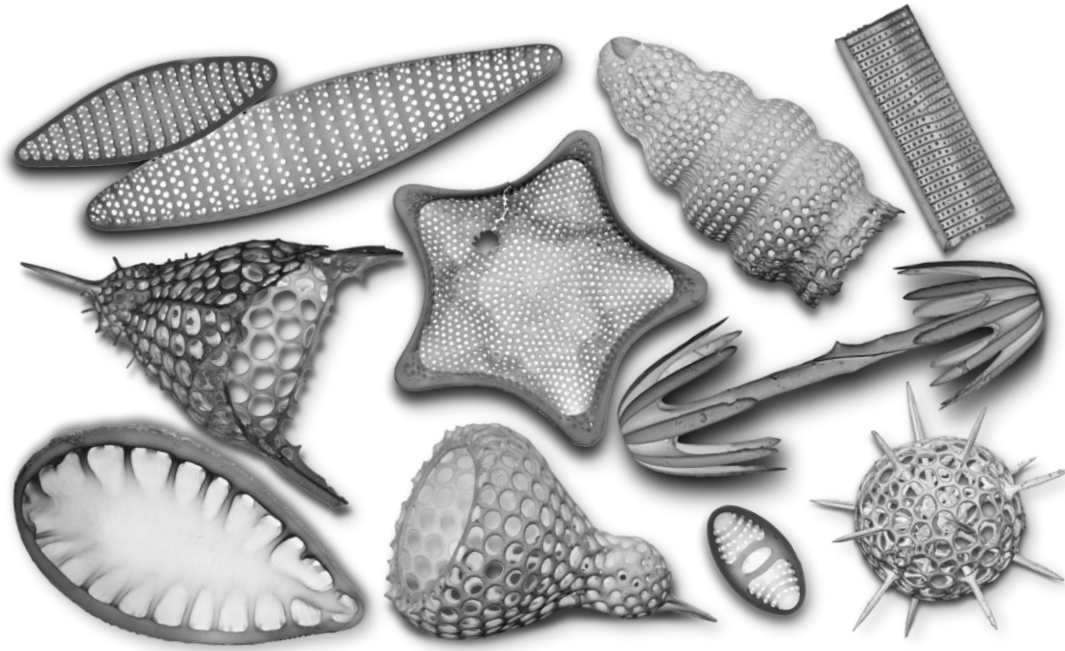


Alfred Wegener Institute

- Leading position in polar and marine research
- ~1,100 employees
- Intensifies its activities in the field of technology transfer



Structures of Aquatic Plankton Organisms

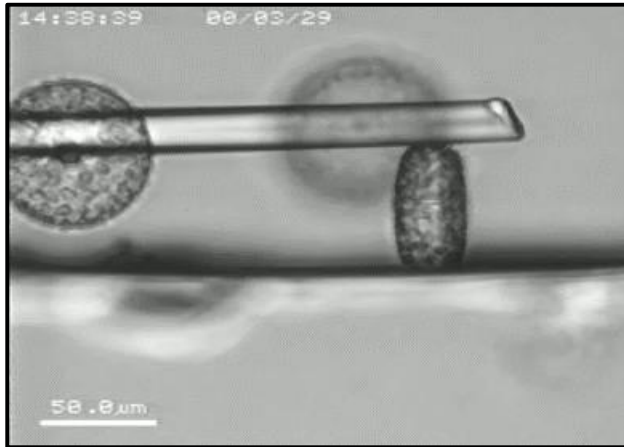


Highly Efficient Lightweight Design Principles in Aquatic Plankton Organisms

Diatom shells can resist pressures up to **700 t m⁻²**



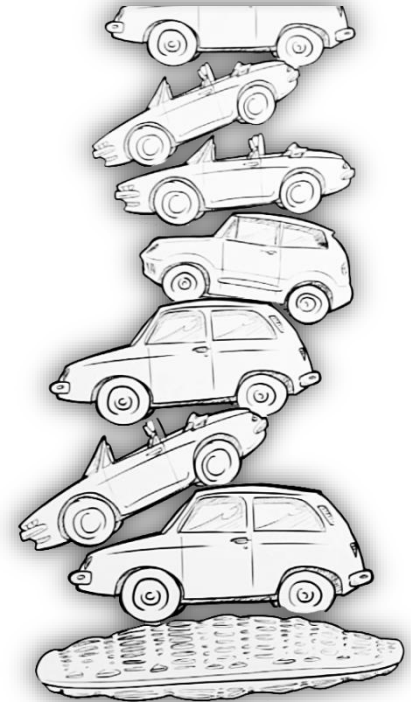
This corresponds to 150 cars on a manhole cover



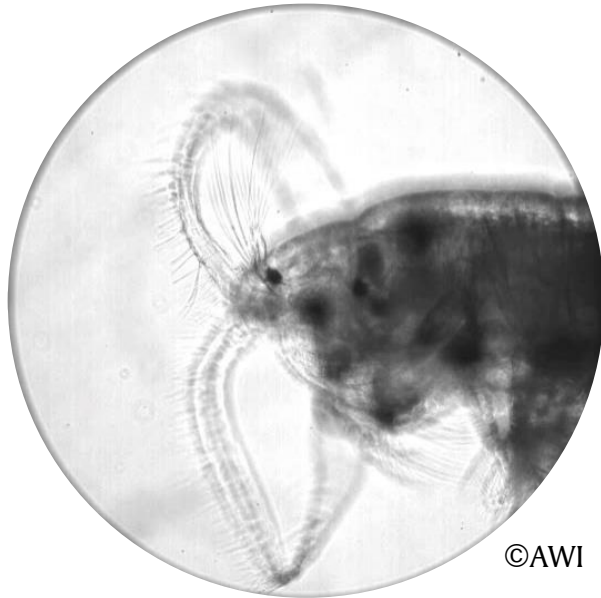
(Hamm et al. 2003)



[1]



Vibrational Load Cases Acting upon Aquatic Plankton Organisms



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Note: In this movie, the diatom is circled in red.

Predators shake the diatom shells like a jackhammer.

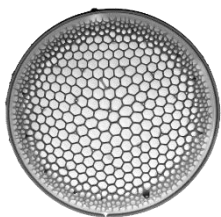


It is expected that the shell structure protects the inner cell against these vibrational load cases.

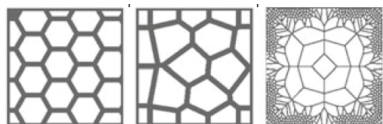
Vibration Properties of Structures Inspired by Plankton Organisms

Application of irregular bio-inspired structures to maximise eigenfrequencies

Irregular honeycombs

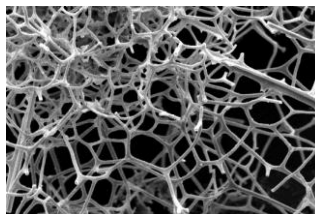


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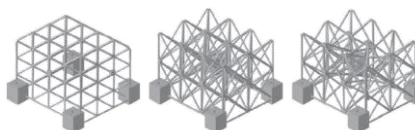


(Andresen et al. 2021a)

Irregular lattices

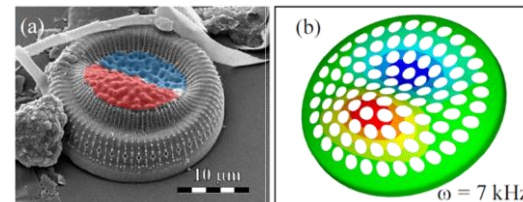


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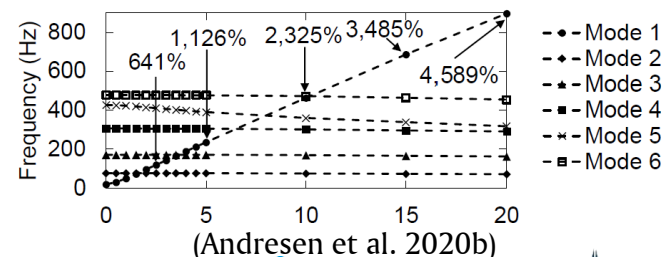


(Andresen et al. 2020a)

Structural pre-deformation according to eigenmodes

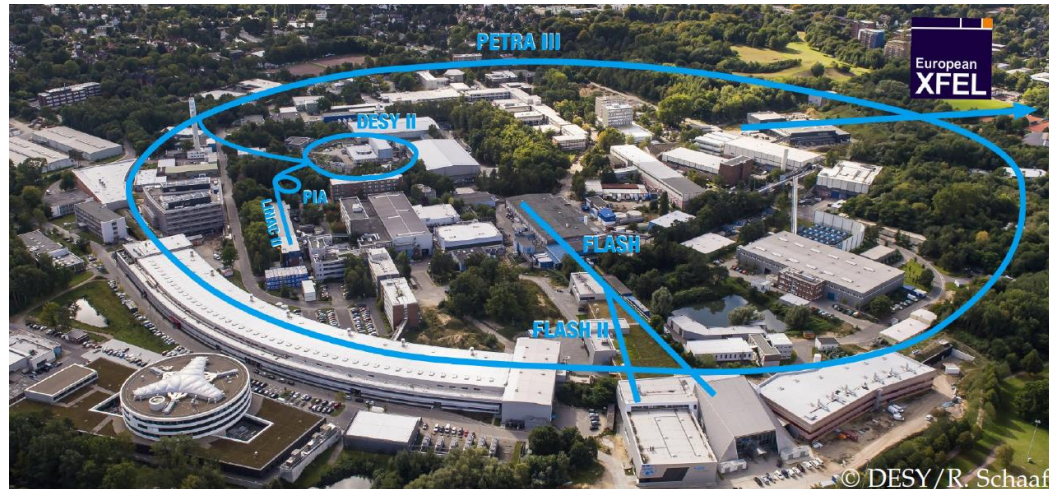


(Gutiérrez et al. 2017)



Case Study: PETRA IV Girder

- Magnet-girder assemblies are essential for a high particle beam stability.
- Case study: Development of a biologically inspired PETRA IV girder design



2

Impact on Eigenfrequencies: Parametric Study

Impact of Different Boundary Conditions and Components on the Girder Eigenfrequencies

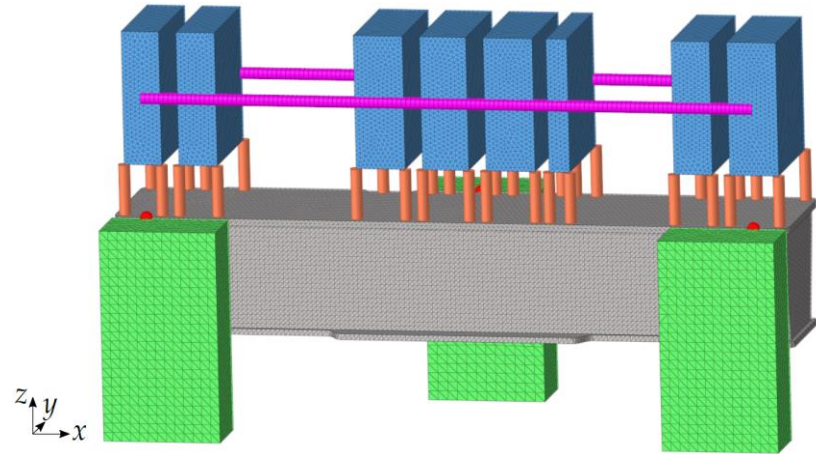
- Magnet-girder assemblies play a key role for the performance of accelerator machines
→ High structural eigenfrequencies are required
- Study objective:
Investigating the impact of different boundary conditions and components on the magnet-girder eigenfrequencies

(Andresen 2021b, *submitted*)

Analysis of Different Boundary Conditions and Components

The following boundary conditions and components of a magnet-girder assembly were varied and their impact on the eigenfrequencies was studied:

- Magnet position height and magnet connection
- Stiffness of the magnet-girder connection
- Magnet mass
- Girder support point position
- Stiffness of the girder support
- Material properties of the girder and the bases



(Andresen 2021b, *submitted*)

Analysis of Different Boundary Conditions and Components

Main findings: How to raise the eigenfrequencies of a magnet-girder assembly

- Magnets:
- low position of the magnets
 - connecting the magnets to each other
 - high stiffness of the connection between girder and magnets
 - low magnet mass
 - low frequency mode shapes that show a global rotation around an axis close to the particle beam

(Andresen 2021b, *submitted*)

Analysis of Different Boundary Conditions and Components

Main findings: How to raise the eigenfrequencies of a magnet-girder assembly

Girder support:

- high position of the support points
- horizontal support point positioning in form of a large (isosceles) triangle
- high girder support stiffness

Materials:

- $\sqrt{E/\rho}$ ratio is very useful as a first approach to compare the effectiveness of different girder/bases materials

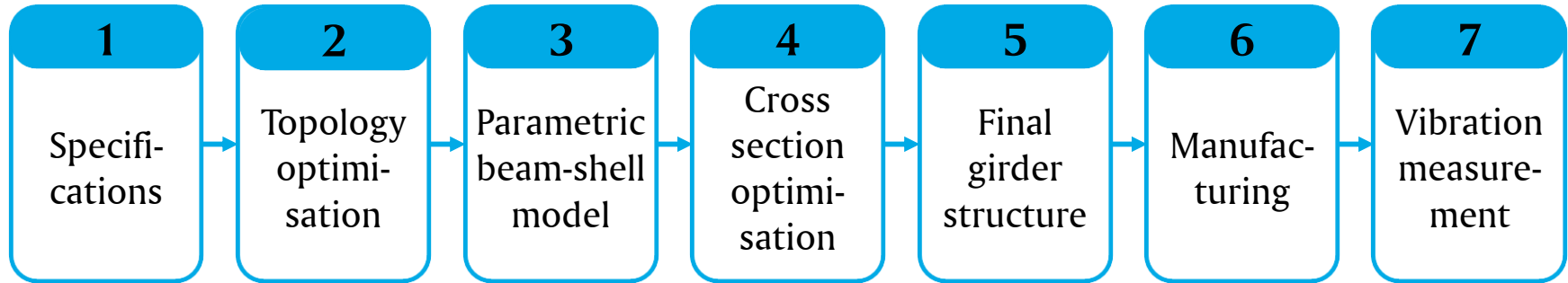
(Andresen 2021b, *submitted*)

3

Design Process for Bio-Inspired Girders

Development of a Biologically Inspired Girder Design for PETRA IV at DESY

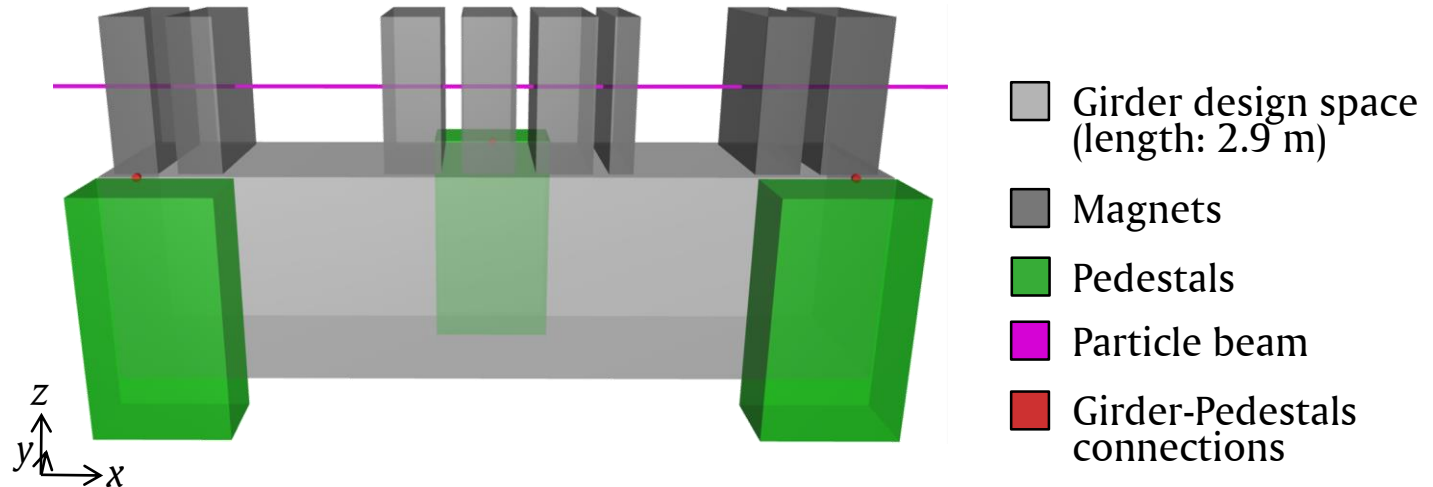
Design process:



Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

1 Specifications



Development of a Biologically Inspired Girder Design for PETRA IV at DESY

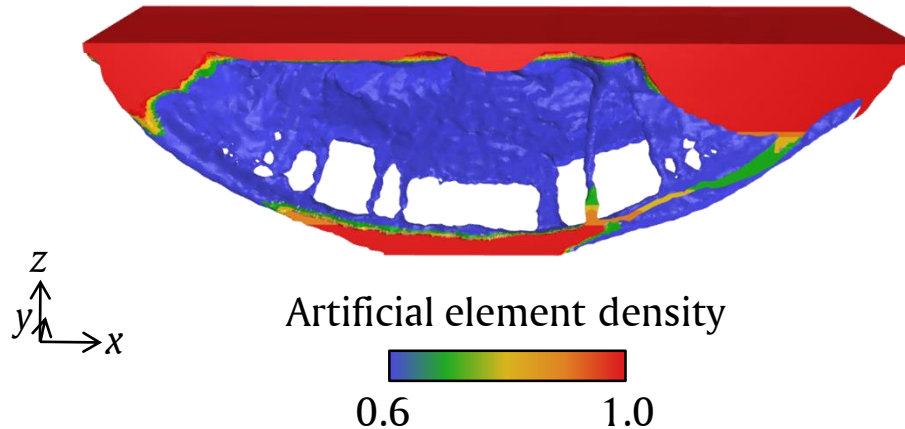
Design process:

Topology optimisation result

- indicates an optimum material distribution
- optimum dimension of each strut/surface is missing

2

Topology
opti-
misation



Optimisation objectives:

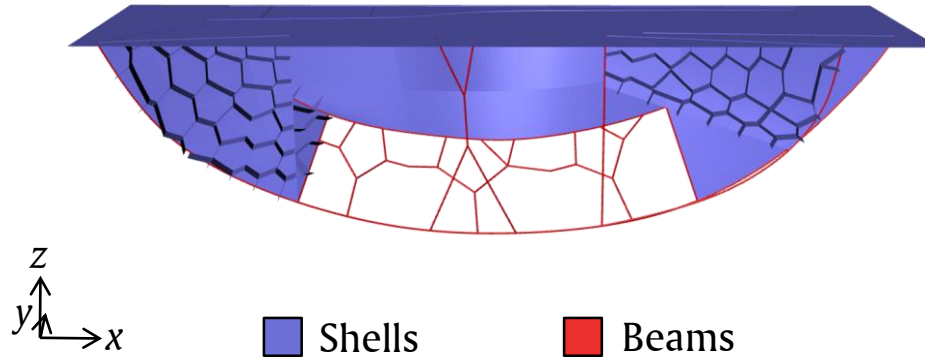
- max 1st eigenfrequency
- max stiffness
- min girder mass

Development of a Biologically Inspired Girder Design for PETRA IV at DESY

- Design process:
- Biologically inspired beam-shell model
 - based on the topology optimisation result
 - different biologically inspired structures were implemented

3

Parametric
beam-shell
model



Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

Evolutionary strategic cross section optimisation

- multi-objective optimisation
- optimisation algorithms inspired by the biological evolution

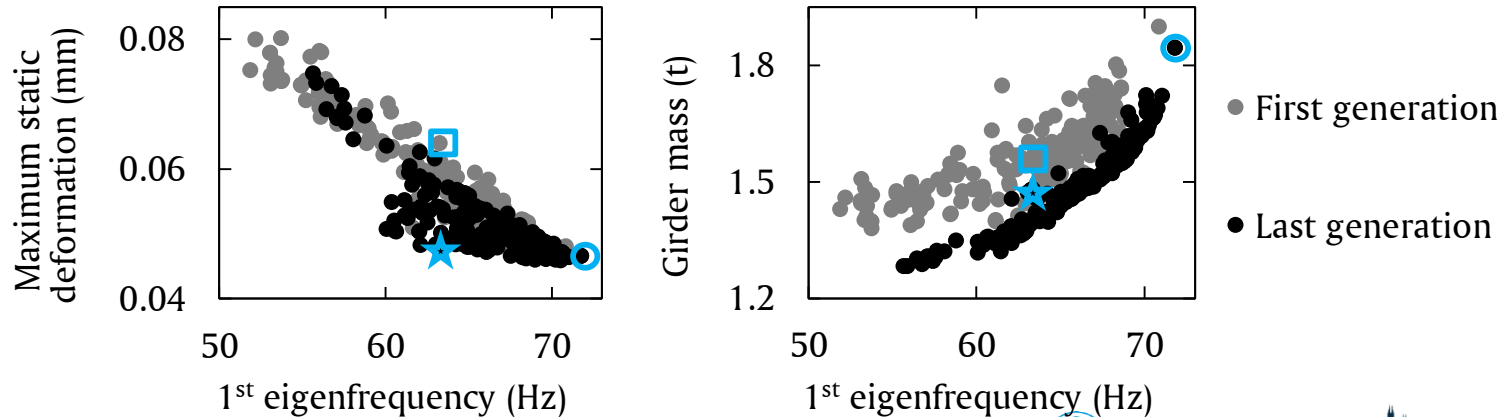
Optimisation objectives:

- max 1st eigenfrequency
- max stiffness
- min girder mass

4

Cross
section
optimi-
sation

Numerous girder structures with different properties.

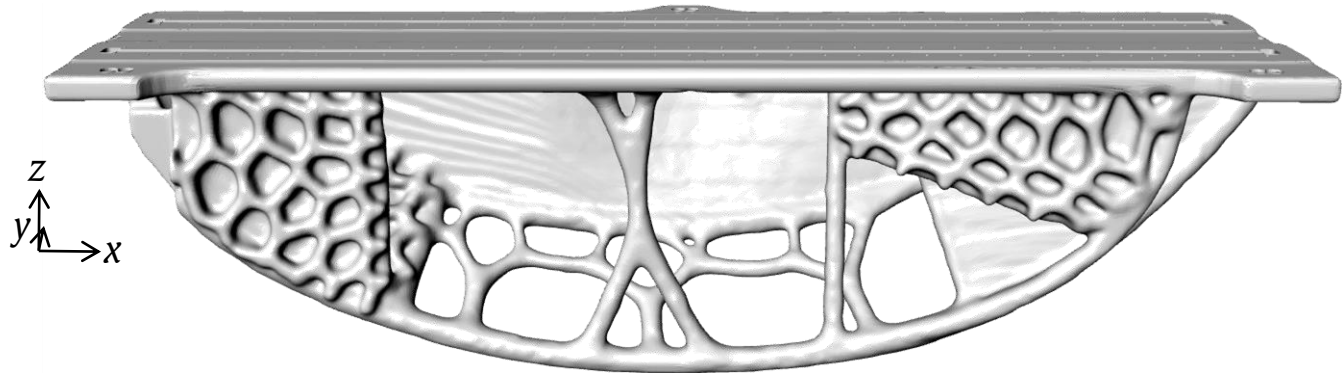


Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

5

Final
girder
structure



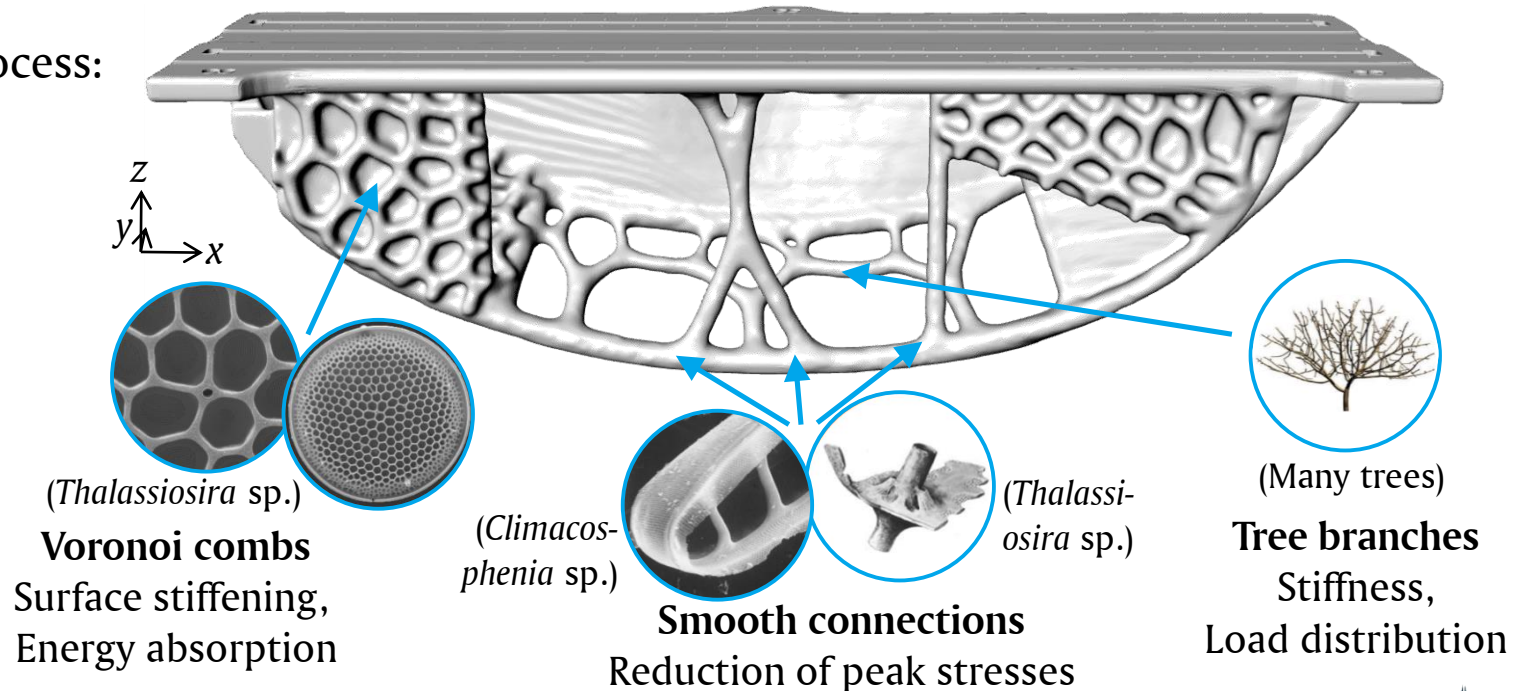
1st eigenfrequency (unloaded free girder): 120 Hz
Volume: 2.76 m³

Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

5

Final
girder
structure

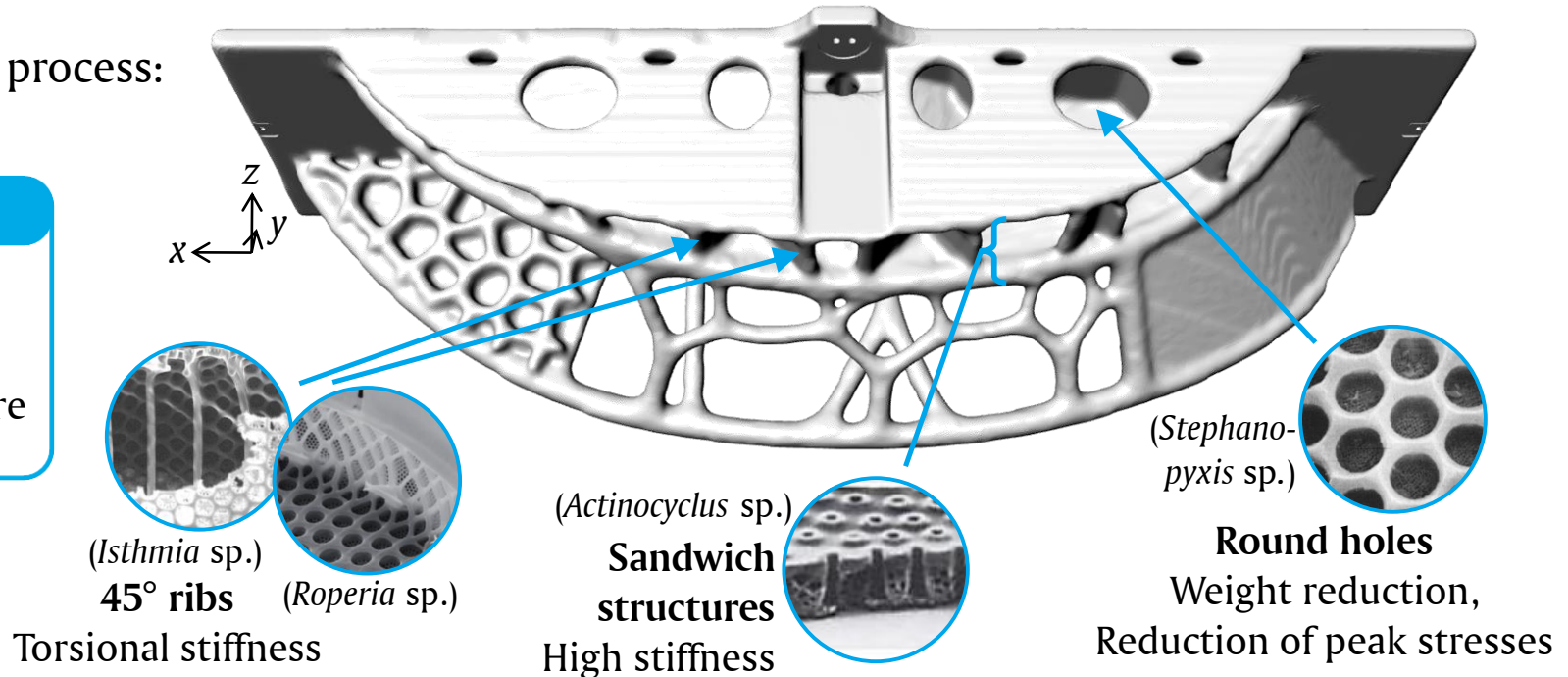


Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

5

Final
girder
structure



Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process: Casting process with 3D printed sand moulds

- Successful manufacturing out of grey cast iron (EN-GJL-250)

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Manufacturing



©DESY/Christian Schmid

Development of a Biologically Inspired Girder Design for PETRA IV at DESY

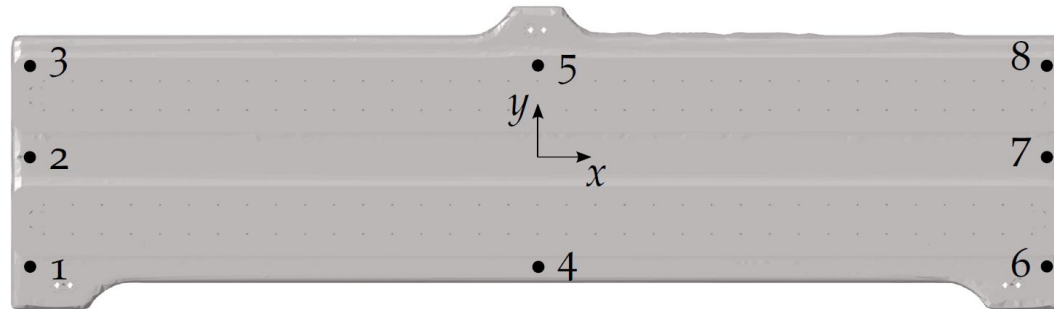
Design process:

Impact testing

- Girder positioned on 3 springs ('free' and unloaded girder)
- 8 uniaxial accelerometers
- Structure was hit with a recoilless hammer on position 4

7

Vibration
measure-
ment



Positioning of the accelerometers on the upper girder surface

Development of a Biologically Inspired Girder Design for PETRA IV at DESY

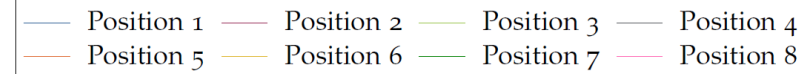
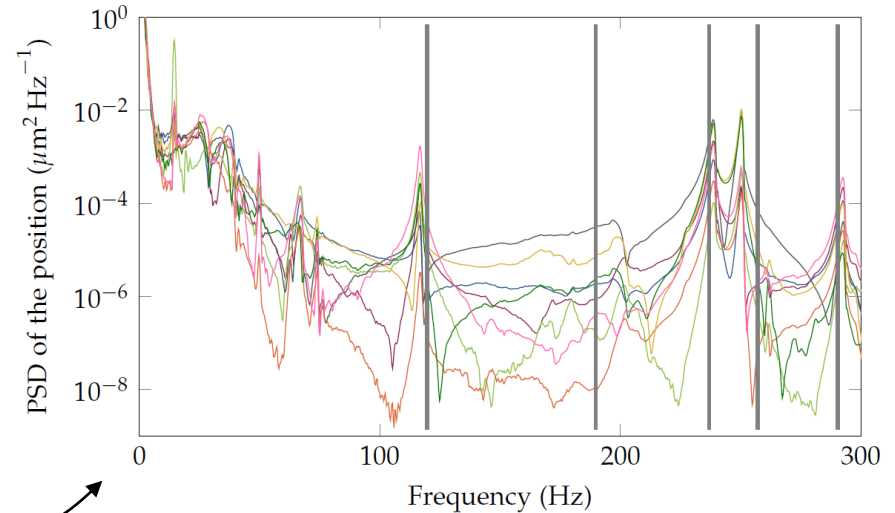
Design process: Impact testing: Results

7

Vibration measurement

	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

Grey vertical lines: numerically obtained eigenfrequencies



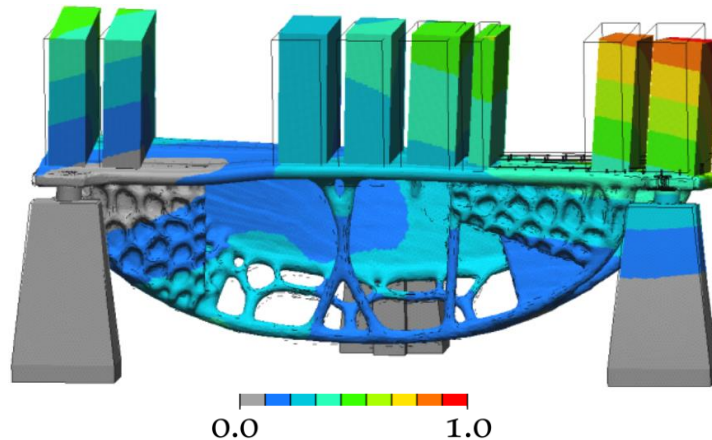
Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process: Impact testing: Results – 1st mode shape: Torsion

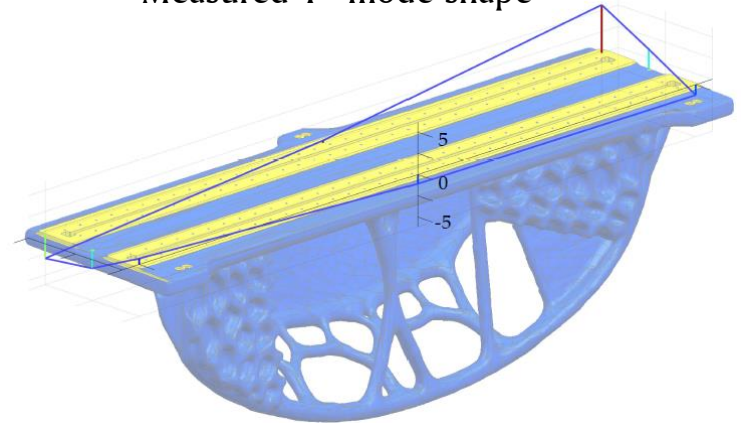
7

Vibration
measure-
ment

Numerically obtained 1st mode shape



Measured 1st mode shape



4

Conclusion

Conclusion

- The application of structures inspired by aquatic plankton organisms allows the generation of vibration-optimised lightweight design structures.
- Based on a large parametric study varying different components and boundary conditions of a magnet-girder assembly, the impact of the analysed components on the eigenfrequencies was investigated and quantified.
- A girder design process including biologically inspired optimisation techniques and structures was exemplarily applied to PETRA IV leading to an organic-looking girder structure. The experiments on the casted bio-inspired girder resulted in eigenfrequencies that match the numerically obtained values.

References

References:

1. Andresen et al. 2020a: S. Andresen, A. Bäger, and C. Hamm (2020) “Eigenfrequency maximisation by using irregular lattice structures.” In: *Journal of Sound and Vibration* 465, p. 115027
2. Andresen et al. 2020b: S. Andresen, L.M. Lottes, S.K. Linnemann, and R. Kienzler (2020) “Shape adaptation of beams (1D) and plates (2D) to maximise eigenfrequencies.” In: *Advances in Mechanical Engineering* 12 (11), pp. 1–18.
3. Andresen et al. 2021a: S. Andresen (2021) “Impact of Bio-inspired Structural Irregularities on Plate Eigenfrequencies.” In: *Proceedings of the 14th International Conference on Vibration Problems. Lecture Notes in Mechanical Engineering*. Ed. by Sapountzakis E.J., Banerjee M., Biswas P., and Inan E. Singapore: Springer, pp. 1117–1125.
4. Andresen et al. 2021b: S. Andresen (2021) “Impact of Different Components and Boundary Conditions on the Eigenfrequencies of a Magnet-Girder Assembly.” In: *Instruments* (special issue: *Recent Advance in Particle Accelerator Instrumentation*) (submitted).
5. Gutiérrez et al. 2017: A. Gutiérrez, R. Gordon, and L.P. Dávila (2017) “Deformation modes and structural response of diatom frustules.” In: *Journal of Materials Science and Engineering with Advanced Technology* 15, pp. 105–134.
6. Hamm et al. 2003: C.E. Hamm, R. Merkel, O. Springer, P. Jurkojc, C. Maier, K. Prechtel, and V. Smetacek (2003) “Architecture and material properties of diatom shells provide effective mechanical protection.” In: *Nature* 421.6925, pp. 841–843.

Figures

Figures:

- [1] <https://iotbusinessnews.com/2019/09/16/90700-new-iot-system-prevents-manhole-cover-explosions/> (July 6, 2021)
- [2] <https://www.pngwing.com/en/free-png-nhrwk> (July 6, 2021)

Thank You Very Much for Your Attention.



Please contact me for questions or discussions:

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