Innovative and Biologically Inspired PETRA IV Girder Design

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Outline

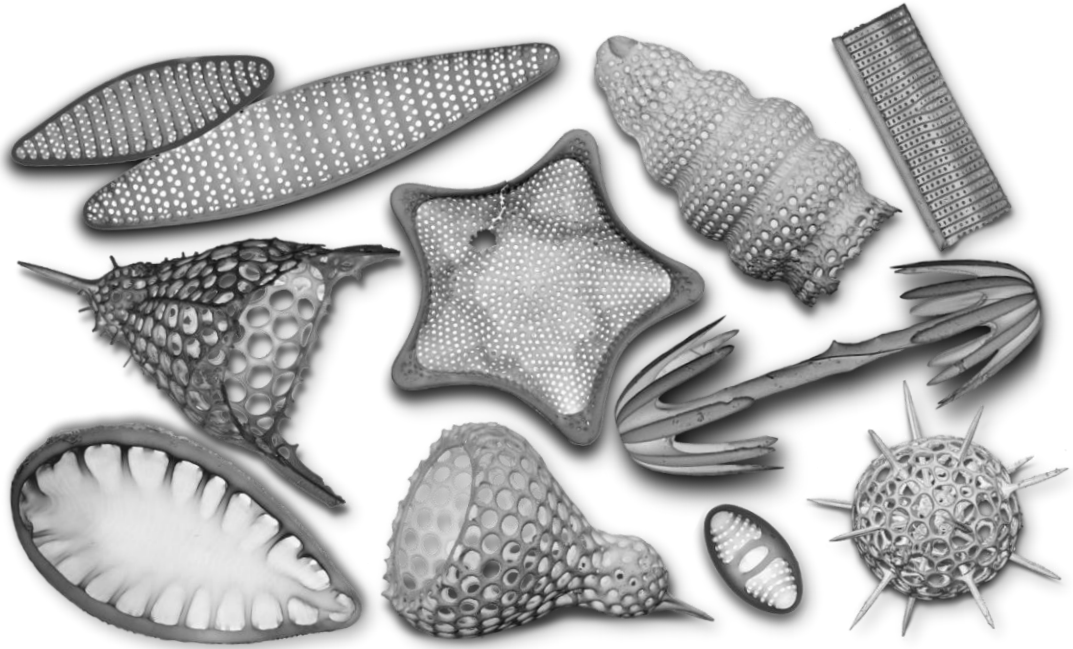
1. Introduction
2. Impact on Eigenfrequencies: Parametric Study
3. Design Process for Bio-Inspired Girders
4. Conclusion

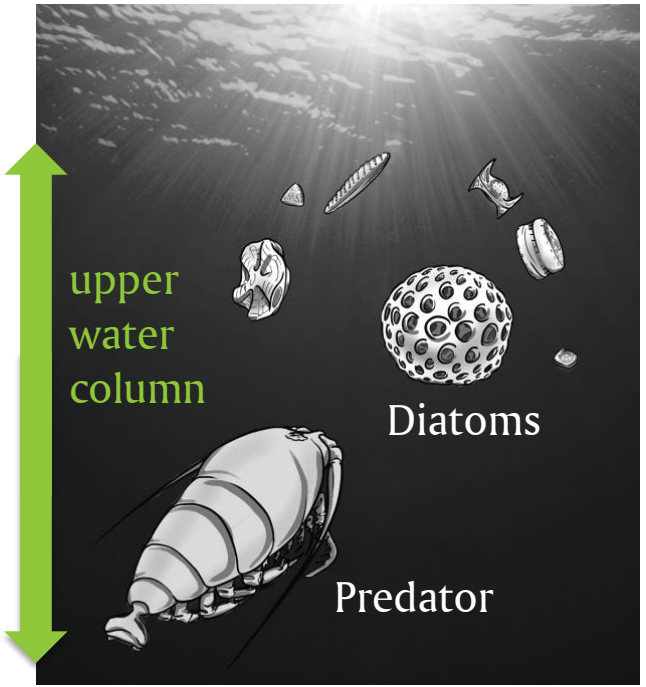
1 Introduction

Alfred Wegener Institute

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

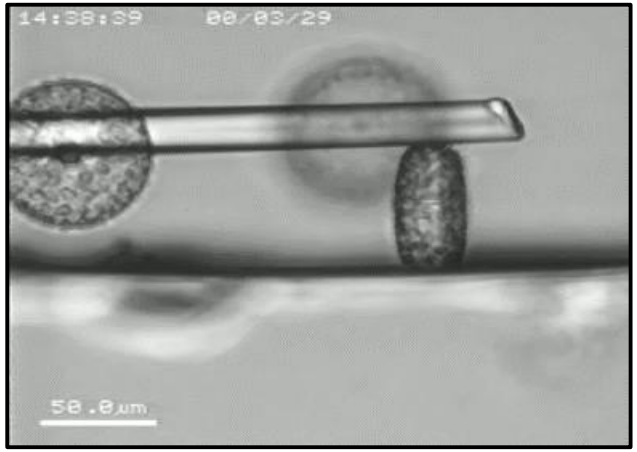
Structures of Aquatic Plankton Organisms





Highly Efficient Lightweight Design Principles in Aquatic Plankton Organisms

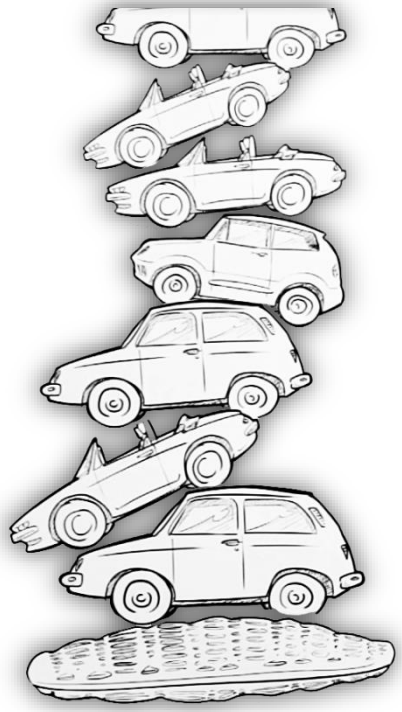
Diatom shells can resist pressures up to **700 t m^{-2}**



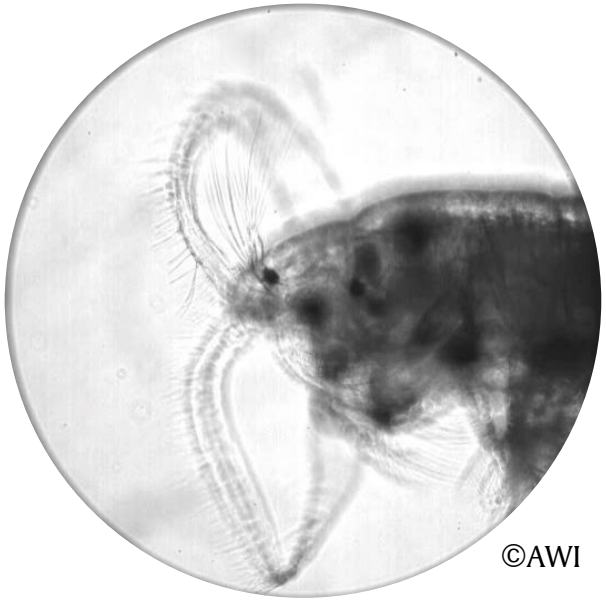
(Hamm et al. 2003)

This corresponds to 150 cars on a manhole cover

[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.

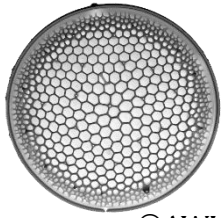
↓

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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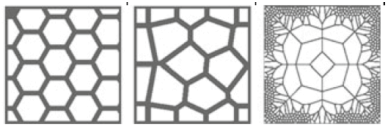
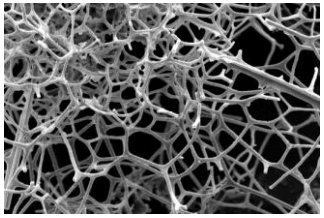


(Andresen et al. 2021a)

Irregular lattices



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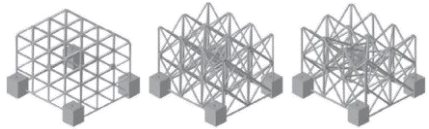
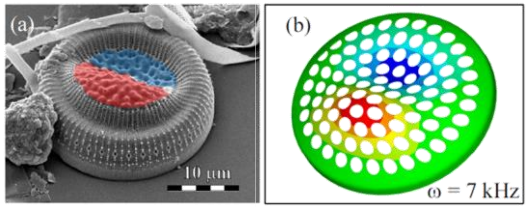
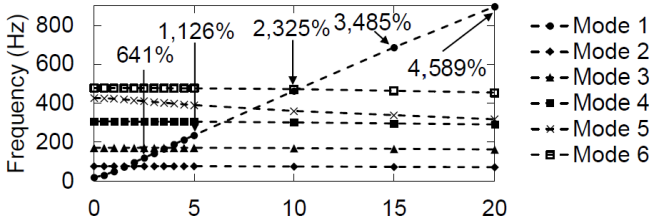


(Andresen et al. 2020a)

Structural pre-deformation according to eigenmodes



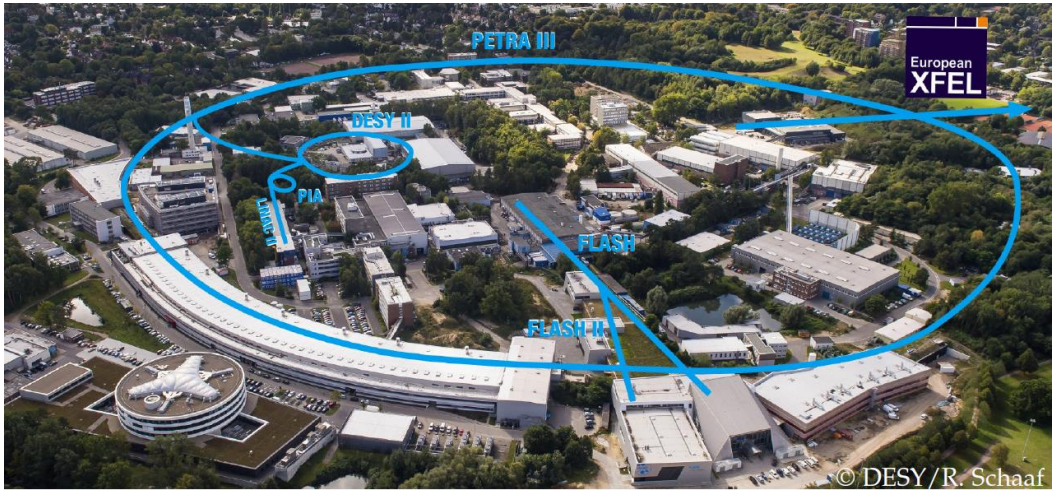
(Gutiérrez et al. 2017)



(Andresen et al. 2020b)

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

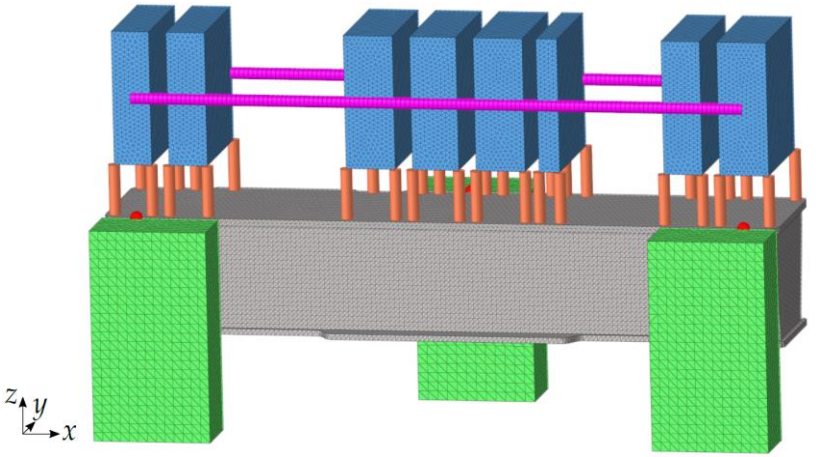
- Study objective:
  Investigating the impact of different boundary conditions and components on the magnet-girder eigenfrequencies

(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

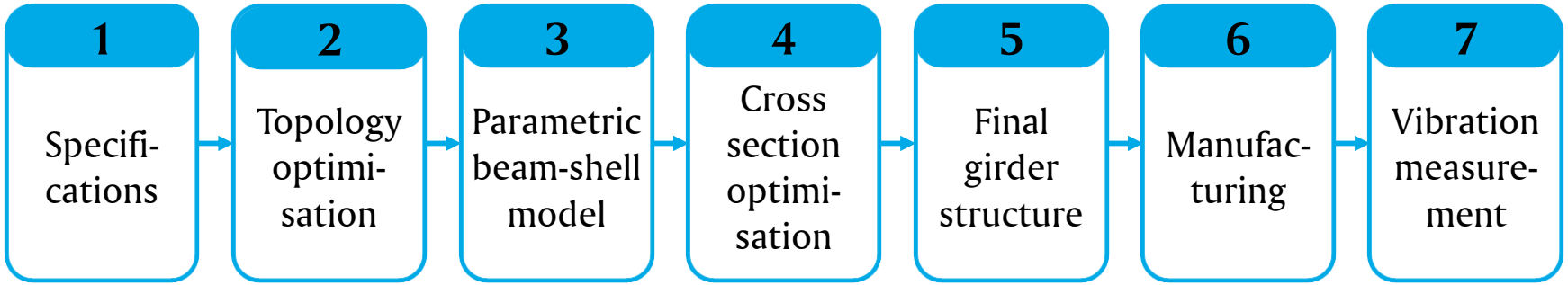
Materials:
- $\sqrt{E/\rho}$ ratio is very useful as a first approach to compare the effectiveness of different girder/bases materials

(Andresen 2021b, *submitted*)

3 Design Process for Bio-Inspired Girders

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

Design process:

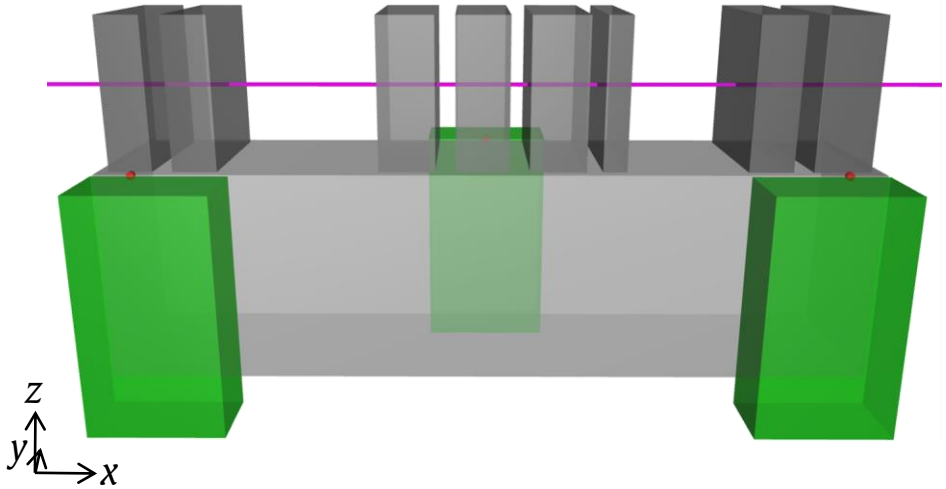


Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

1

Specifi-
cations



- Girder design space (length: 2.9 m)
- Magnets
- Pedestals
- Particle beam
- Girder-Pedestals connections

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

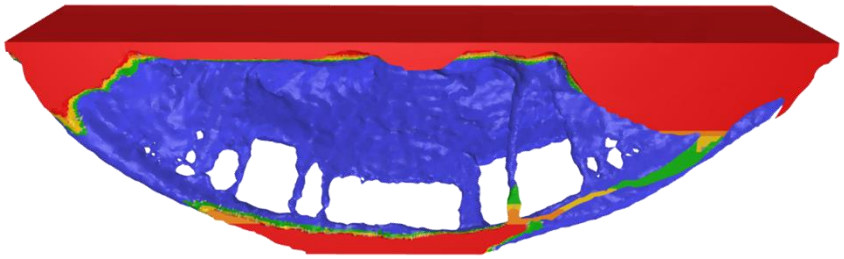
Design process:

2

Topology optimi-sation

Topology optimisation result

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



Optimisation objectives:
- max 1st eigenfrequency
- max stiffness
- min girder mass

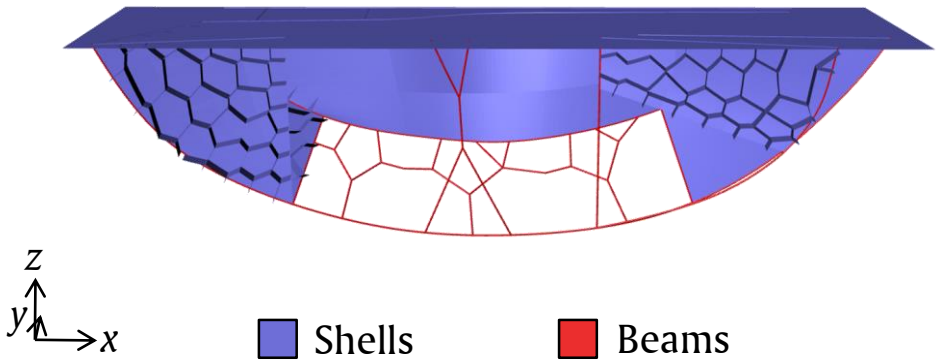
Development of a Biologically Inspired Girder Design for PETRA IV at DESY

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

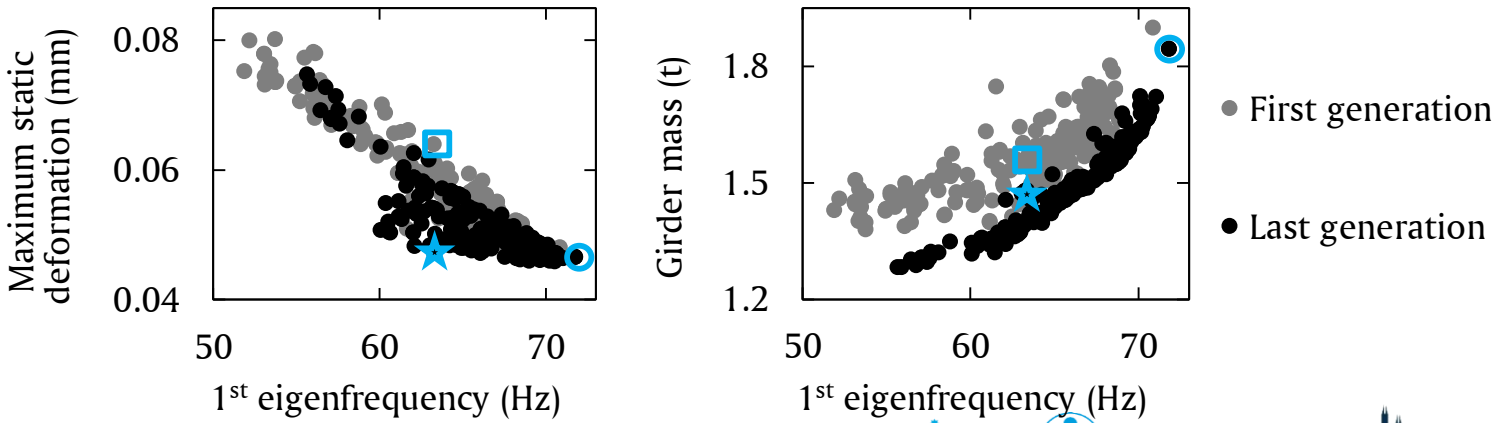
Optimisation objectives:
- max 1st eigenfrequency
- max stiffness
- min girder mass

Design process: Evolutionary strategic cross section optimisation

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

4 Cross section optimi-sation

Numerous girder structures with different properties.

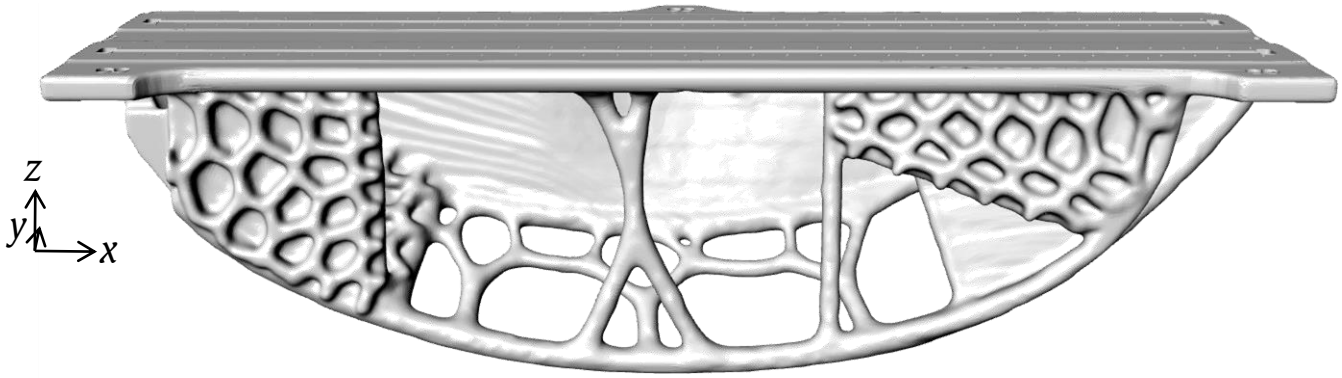


Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

5

Final girder structure



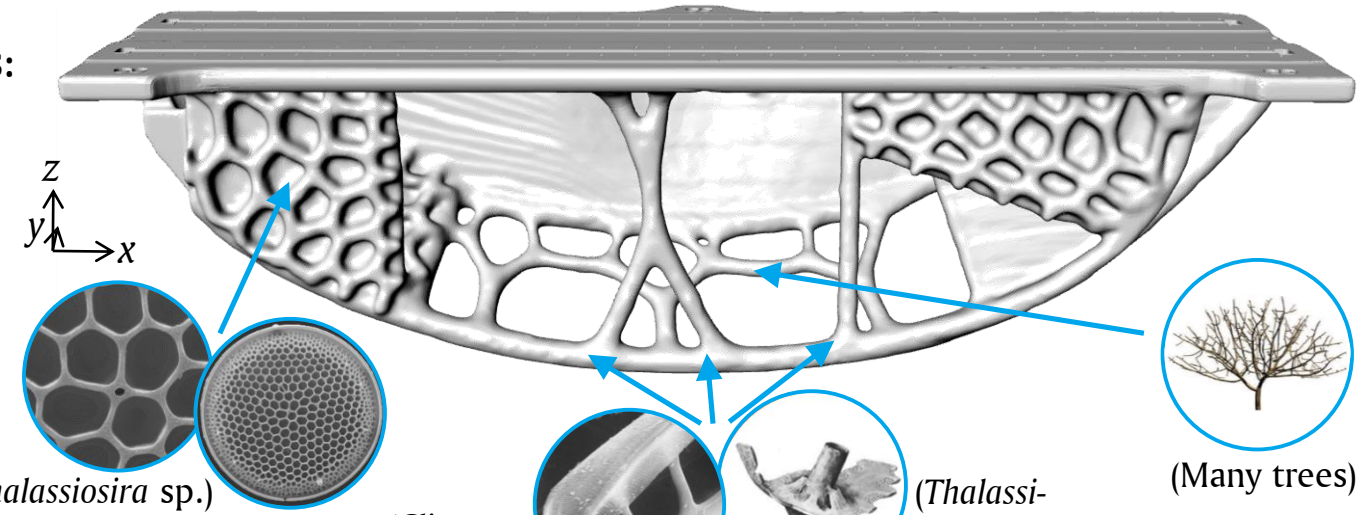
1st eigenfrequency (unloaded free girder): 120 Hz
Volume: 2.76 m^3

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

Design process:

5

Final girder structure



(*Thalassiosira* sp.)

Voronoi combs
Surface stiffening,
Energy absorption

(*Climacosphenia* sp.)

(*Thalassiosira* sp.)

Smooth connections
Reduction of peak stresses

(Many trees)

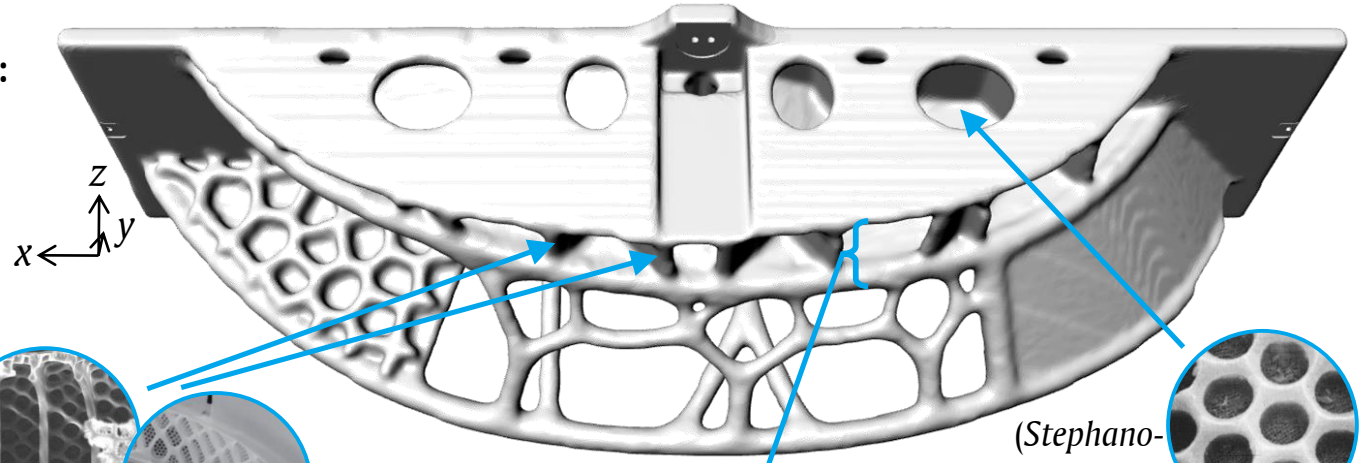
Tree branches
Stiffness,
Load distribution

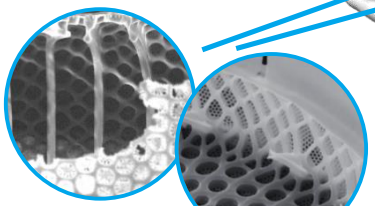
Development of a Biologically Inspired Girder Design for PETRA IV at DESY

Design process:

5

Final girder structure





(*Isthmia* sp.)

45° ribs

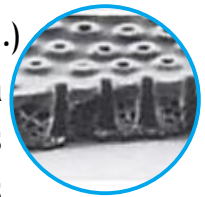
Torsional stiffness

(*Roperia* sp.)

(*Actinocyclus* sp.)

Sandwich structures

High stiffness



(*Stephano-pyxis* sp.)

Round holes

Weight reduction,
Reduction of peak stresses

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)

6

Manufac-turing

©DESY/Christian Schmid

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

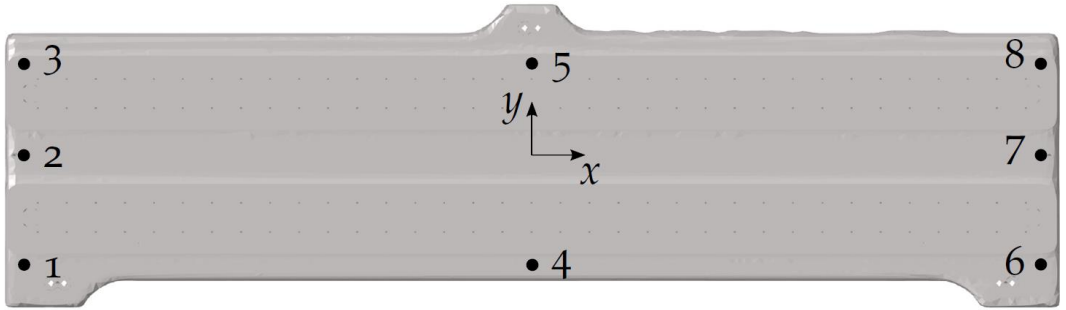
Design process:

7

Vibration measure-ment

Impact testing

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



Positioning of the accelerometers on the upper girder surface

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

Design process:

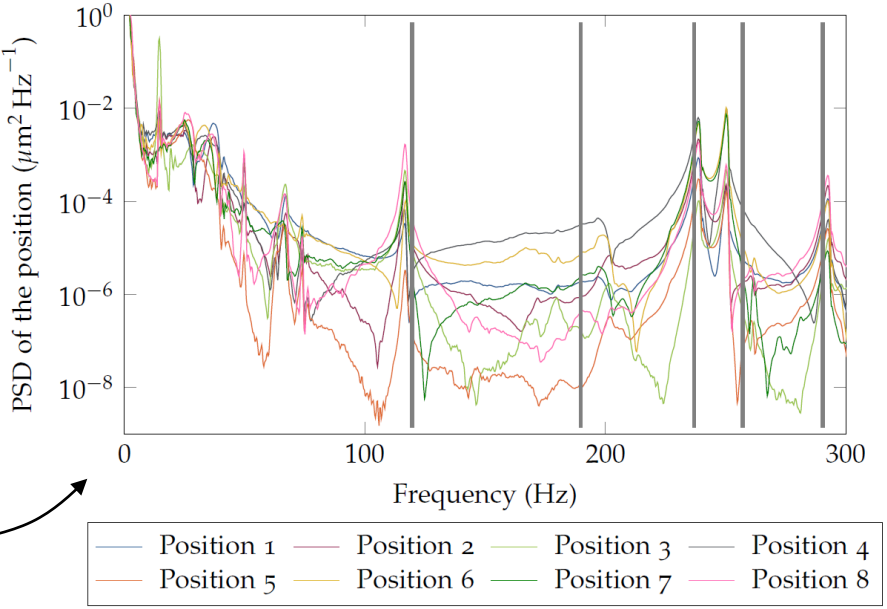
7

Vibration measure-ment

Impact testing: Results

	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

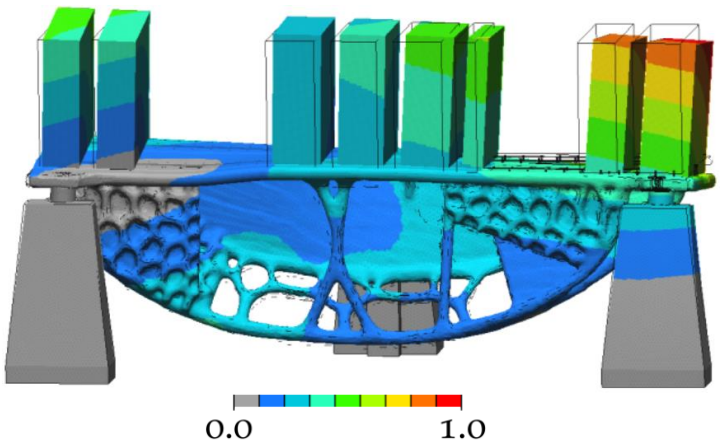
Design process:

7

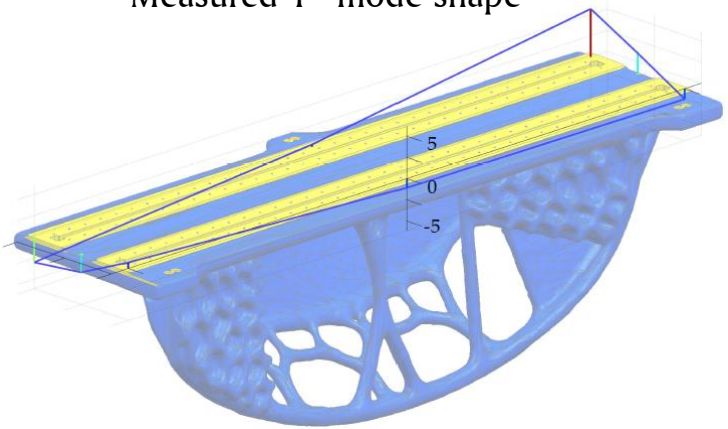
Vibration measure-ment

Impact testing: Results – 1st mode shape: Torsion

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.

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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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[2]

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