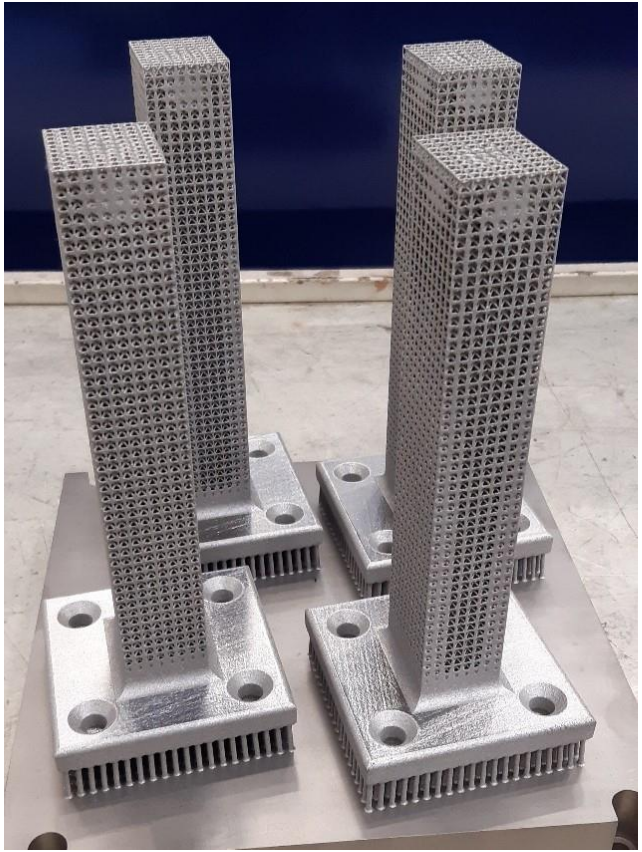
Imperial College
London

Matthew Santer

Structural Metamaterials for frequency control and vibration mitigation during launch



Structural Metamaterials Group

- Co-led by Matthew Santer and Rob Hewson in the Department of Aeronautics at Imperial College London
- https://www.imperial.ac.uk/structural-metamaterials/
- Design optimization that works in the real world. Generate ***manufacturable***, multiscale structures for a range of objectives such as, ***stiffness, weight, controlled displacement, failure, uncertainty, frequency*** and ***vibration modes, thermostructural response, [insert pde here]…***
- Take a look at our poster and models

Engineering and Physical Sciences Research Council

AIRBUS

MBDA MISSILE SYSTEMS

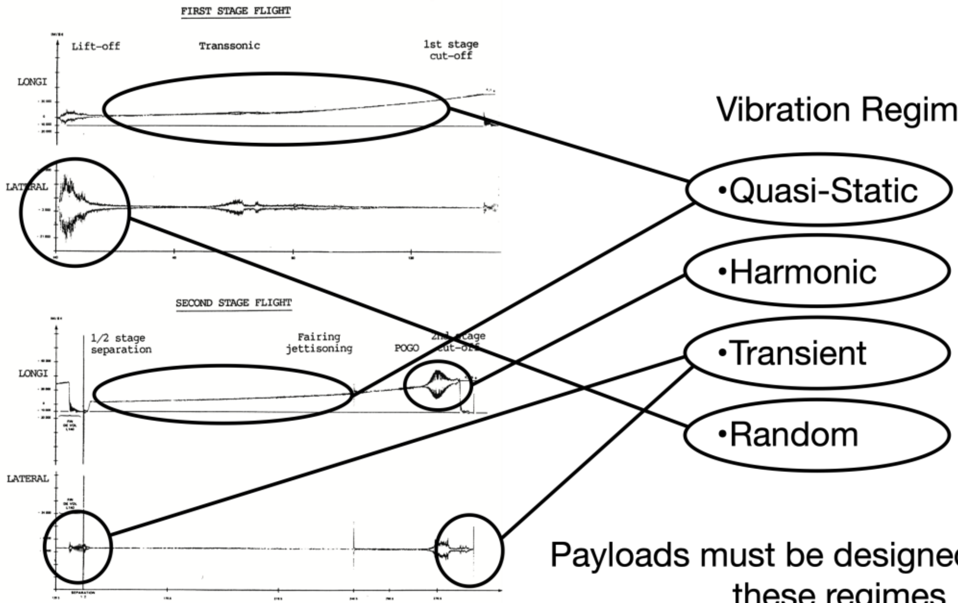
Innovate UK

Dynamic Launch Loads

Launch is usually the most challenging environment a spacecraft must endure

© SpaceX Falcon Heavy launch

Ariane 1 first flight data



Vibration Regimes:

- Quasi-Static
- Harmonic
- Transient
- Random

Payloads must be designed to endure these regimes

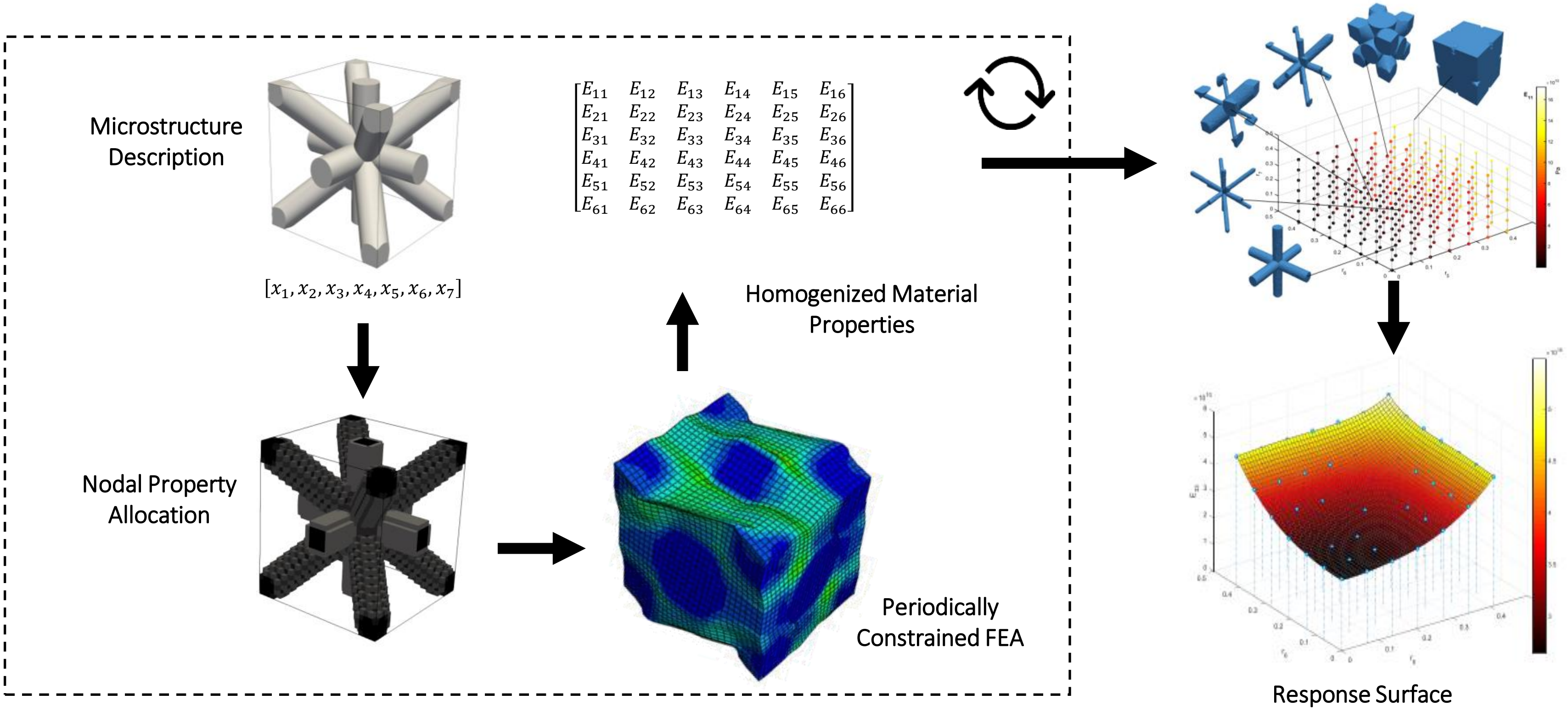
Launch Qualification

- Launcher specific sinusoidal, random and shock dynamic loading
- Industry standard qualification process
  - Linear finite element analysis in the frequency domain
  - Experimental validation on a shaker
- If the launcher changes so does the launch environment
- Often necessitates a costly and time-consuming redesign
- Use of structural metamaterials avoids this need
  - We can tailor resonant response without changing bulk structural properties

My shaker!

© ESA BepiColumbo vibe test

Microscale Material Properties



Microstructure Description

$[x_1, x_2, x_3, x_4, x_5, x_6, x_7]$

Nodal Property Allocation

Periodically Constrained FEA

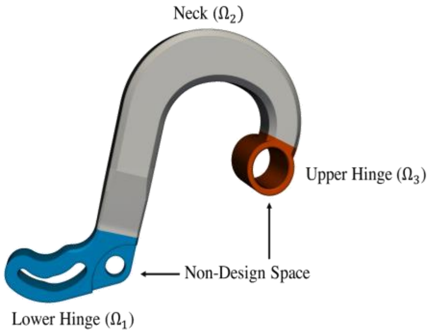
Homogenized Material Properties

$$\begin{bmatrix} E_{11} & E_{12} & E_{13} & E_{14} & E_{15} & E_{16} \\ E_{21} & E_{22} & E_{23} & E_{24} & E_{25} & E_{26} \\ E_{31} & E_{32} & E_{33} & E_{34} & E_{35} & E_{36} \\ E_{41} & E_{42} & E_{43} & E_{44} & E_{45} & E_{46} \\ E_{51} & E_{52} & E_{53} & E_{54} & E_{55} & E_{56} \\ E_{61} & E_{62} & E_{63} & E_{64} & E_{65} & E_{66} \end{bmatrix}$$

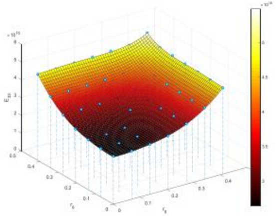
Populate Database

Response Surface

Macroscale Optimization

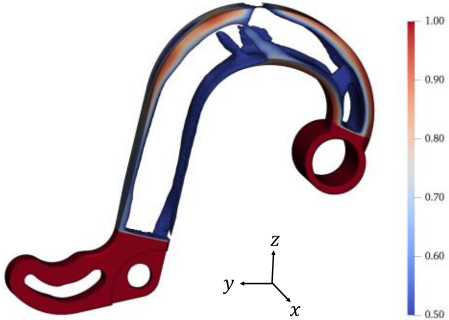


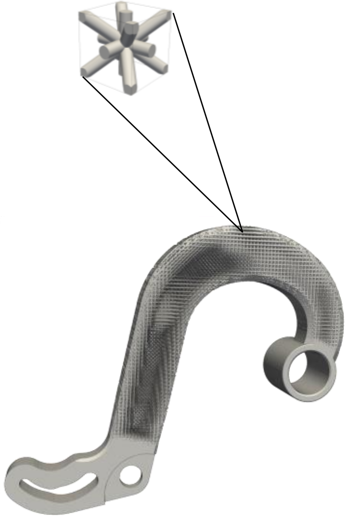
Response surfaces define material properties



$$\text{Minimize:} \quad J = u^T \boldsymbol{K} u$$

$$\text{Subject to:} \quad \begin{gathered} F(u, x) = 0 \\ V \leq V_d \\ x_{min} \leq x \leq x_{max} \end{gathered}$$





Problem Definition → Optimization loop → Optimization Output → Lattice Reconstruction

Frequency Tailoring

Frequency Optimization

$[\boldsymbol{K} - \lambda_i\ \boldsymbol{M}]\boldsymbol{\phi_i} = \boldsymbol{0}$ → Resonance eigenvalue equation

$\omega_i = \frac{\sqrt{\lambda_i}}{2\pi}$ → Eigenvalue to resonant frequency

$\boldsymbol{\phi}_i^T \boldsymbol{M} \boldsymbol{\phi_i} = 1$ → Mass normalised mode shapes

$\omega_{lb} \leq \omega_n \leq \omega_{ub}$ or $Max\colon\ \omega_n$ → Frequency constraint or objective

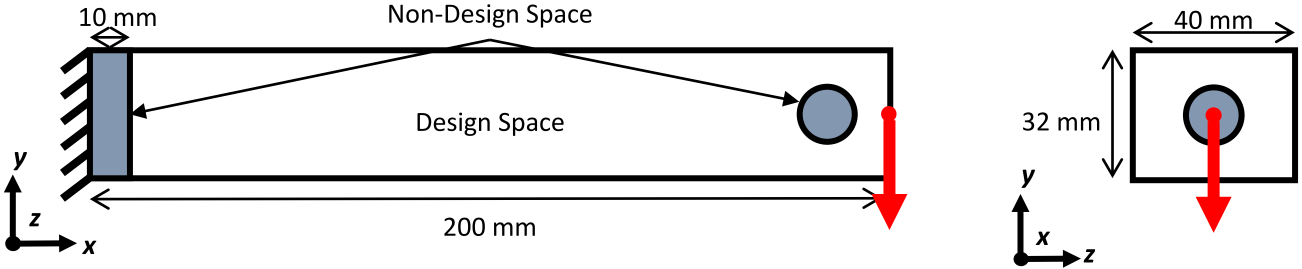
Mode Shape Optimization

$MAC_i \geq 0.9$ → MAC constraint

$$\boldsymbol{MAC} = \frac{(\boldsymbol{\varphi}^T\boldsymbol{\phi})^2}{(\boldsymbol{\varphi}^T\boldsymbol{\varphi})(\boldsymbol{\phi}^T\boldsymbol{\phi})}$$

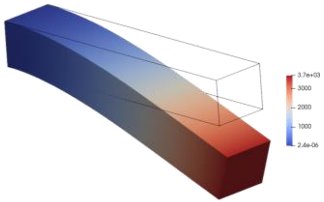
$\boldsymbol{\varphi}$ is the desired mode shape

$\boldsymbol{\phi}$ is the current mode shape

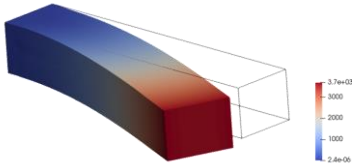


Metamaterial Results

1. Uniform Lattice
2. (Static) Compliance Optimized – No frequency constraints
3. Compliance Optimized – Increase 1st bending mode $\omega_1 \geq 800$
4. Compliance Optimized – Swap the order of frequencies $\omega_2 \leq 650$



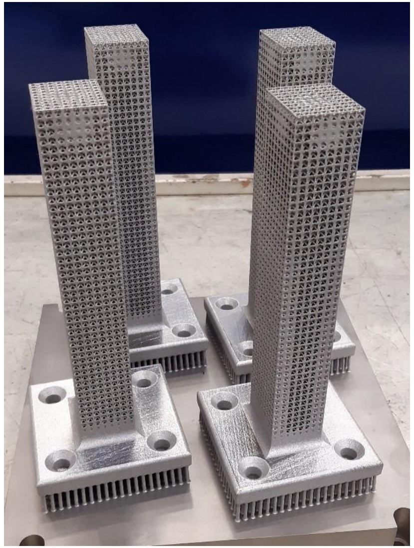
First Bending Mode



Second Bending Mode

Specimen	Compliance	Volume Fraction, V_D	ω_1	ω_2
1	17.74	0.4	345	426
2	5.10	0.4	757	792
3	5.29	0.4	**800**	878
4	5.17	0.4	708	**650**

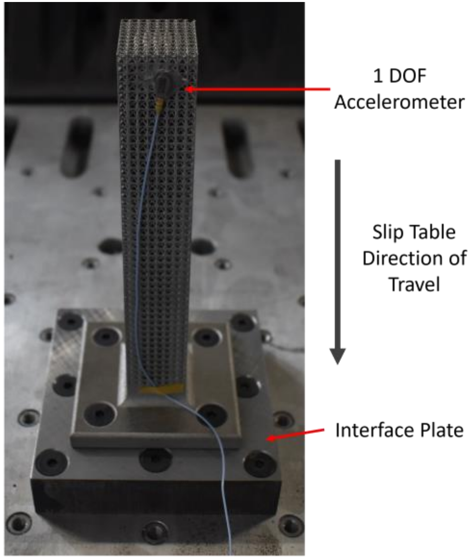
Experimental Verification



AIRBUS

- EOS M290 Machine
- Titanium Alloy Ti64

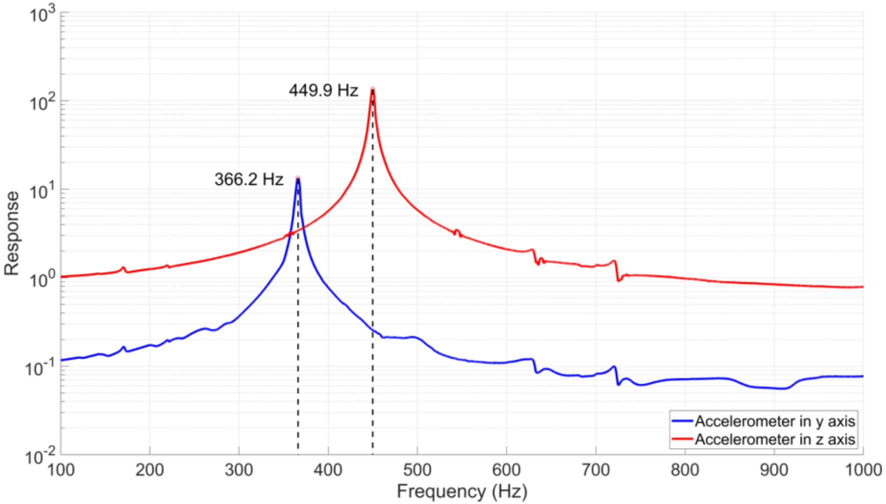
- Heat Treatment
  - 720°C
  - 2 hours
- Ultrasound Bath



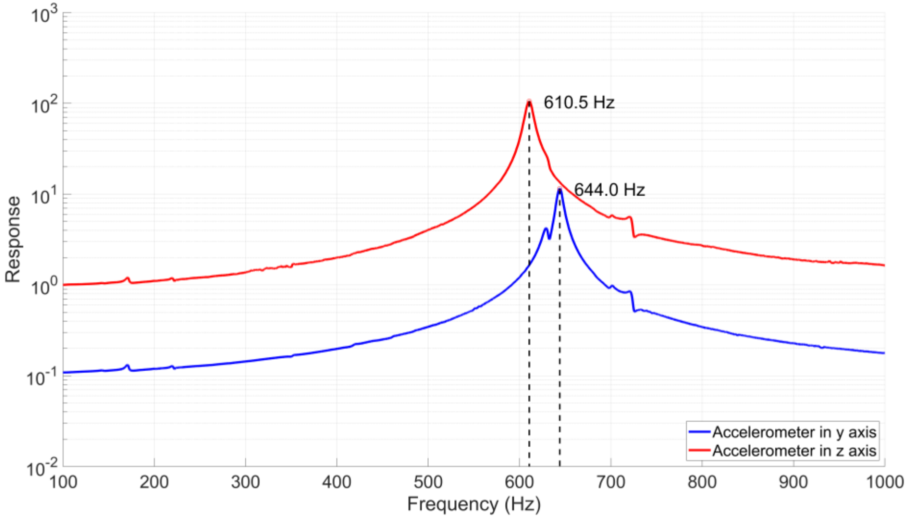
- Brüel & Kjær 440 mm shaker
- LDS hydrostatic-bearing slip table
- 0.5 g Sinusoidal sweep 10-1000 Hz

Validation Example

Case 1



Case 4

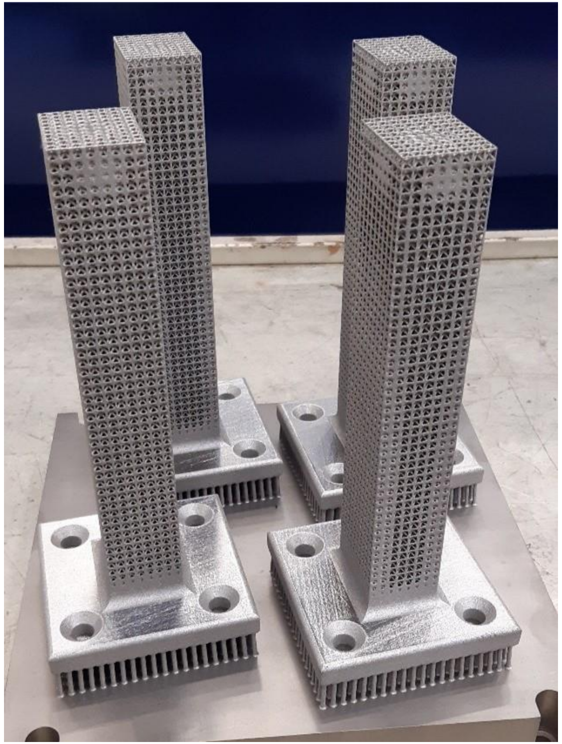


Same mass; same static compliance

Conclusion

- Metamaterials enable frequency tailoring
    - Avoid undesired resonance
    - Enforce band gaps
    - Define mode shapes
- Performance has been validated
- Enables rapid optimal redesign of components whilst maintaining bulk structural properties

- The biggest roadblock is the manufacturing and qualification not the science



Contact me at:
m.santer@imperial.ac.uk