Interaction of shock-waves with a compliant wall

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Doctorante 2 ème année

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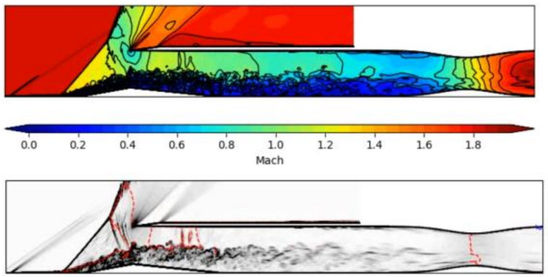
Introduction

Military & Civil Aircraft → Transonic & Supersonic Regimes → Shock Wave Oscillation

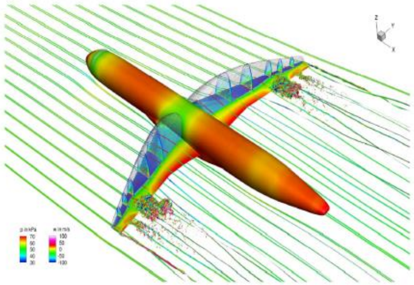
Limitations to the flight envelope

Buzz Engine Air Intake



P. Grenson and S. Beneddine AIAA 2018

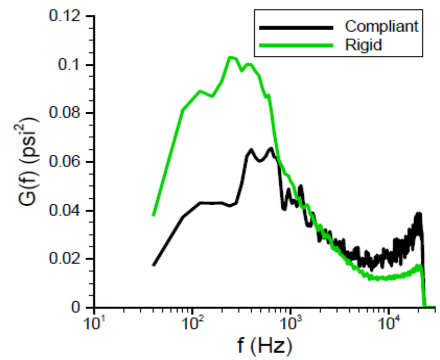
Transonic Buffet on Wings



Sartor et al. AIAA 2015

Passive Control Compliant Wall

- Soft material or thin plate → Deforms passively
- Incompressible flow → Favorable results[1,2]
- Compressible flow: Few studies but successful[3]



PSD rigid/rubber wall[3]

M. O. Krame Naval Engineering Journal 1960[1] M. Gad-el-Hak Progress in Aerospace Sciences 38 2002[2]
H. T. Pham et al. AIAA 2018[3]

Introduction

Possible Mechanisms FSI Shock Wave - Soft Material:

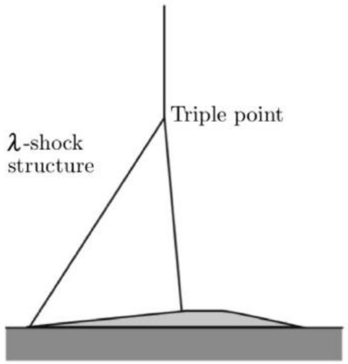
Static Deformation[4,5]

- Pressure difference across the shock
- Lambda shape → Drag saving
- Shock stabilizing effect → anchoring front leg

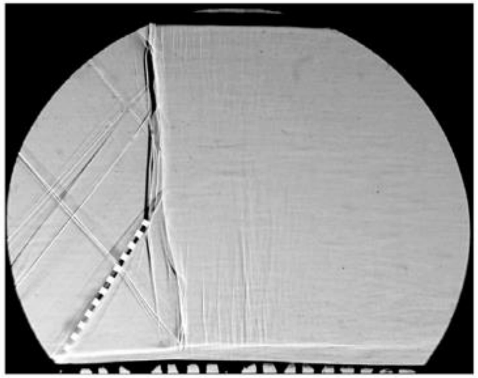
Coupled Dynamics[1,2]

- Vibration modes
- Damping: out of phase response
- Energy absorption

Lambda shock due to bump[6]



Lambda shock due to deformed thin plate[4]



M. O. Krame Naval Engineering Journal 1960[1] M. Gad-el-Hak Progress in Aerospace Sciences 38 2002[2] Michela Gramola Journal of Fluids and Structures 2018[4] Michela Gramola AIAA 2020[5] Ogawa AIAA 2006[6]

Objective and Steps

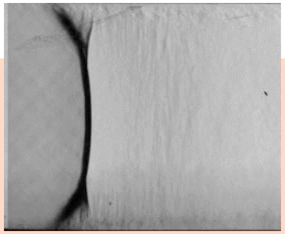
"Studying shock wave interaction with a compliant wall to develop a passive control device"

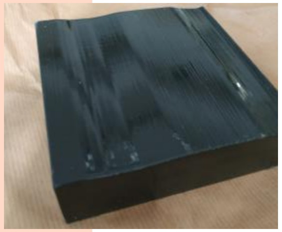
Experimental: S8Ch

I. Shock + Rigid Wall → Shock dynamics

II. Compliant wall design

III. Shock + Compliant wall → Compliant wall and flow dynamics





Numerical

I. Shock + Rigid Wall

II. Shock + Static deformation

→ Flow Stability Analysis: Singular-value decomposition of the resolvent operator[7]

Sartor F. et al. 2015[7]

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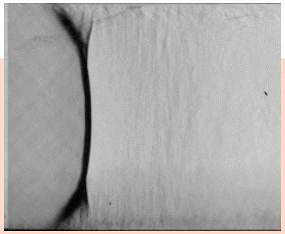

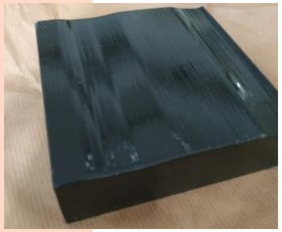

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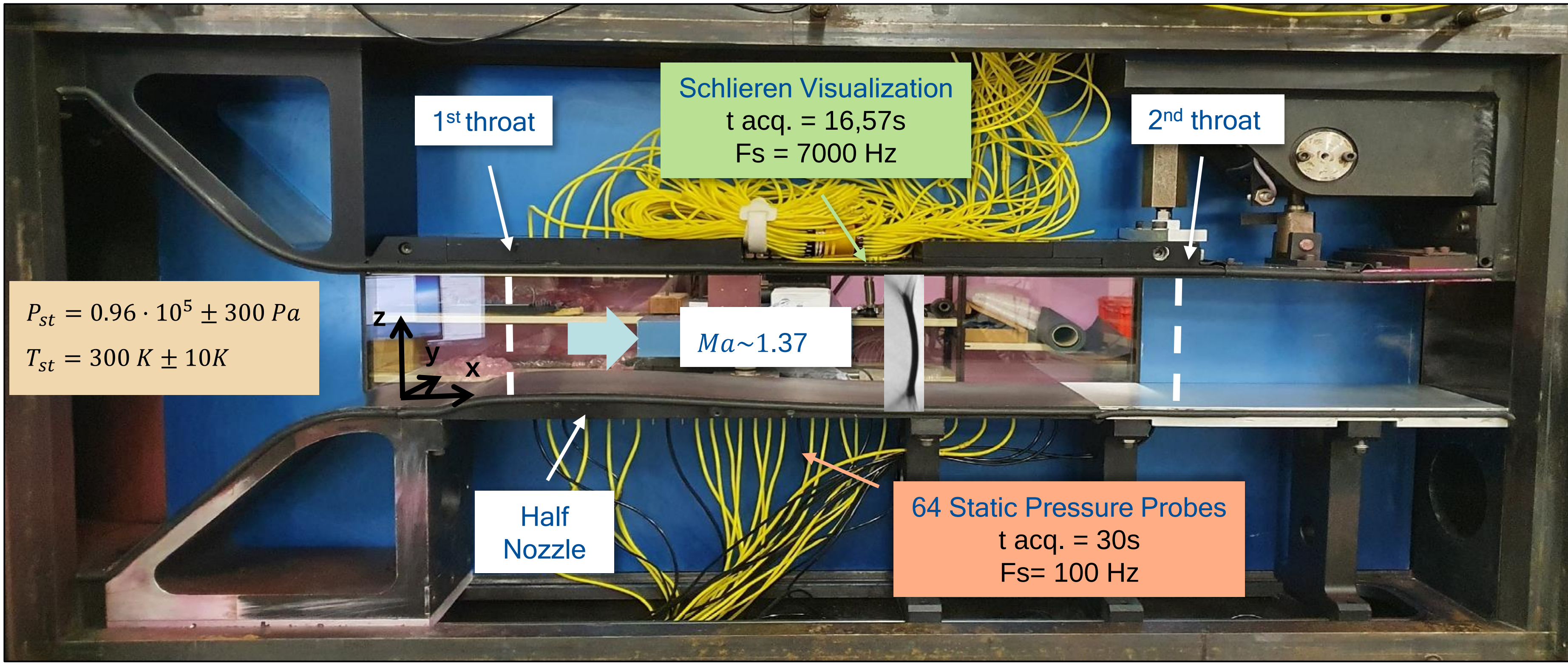
I. Shock + Rigid Wall: Setup

S8Ch Meudon

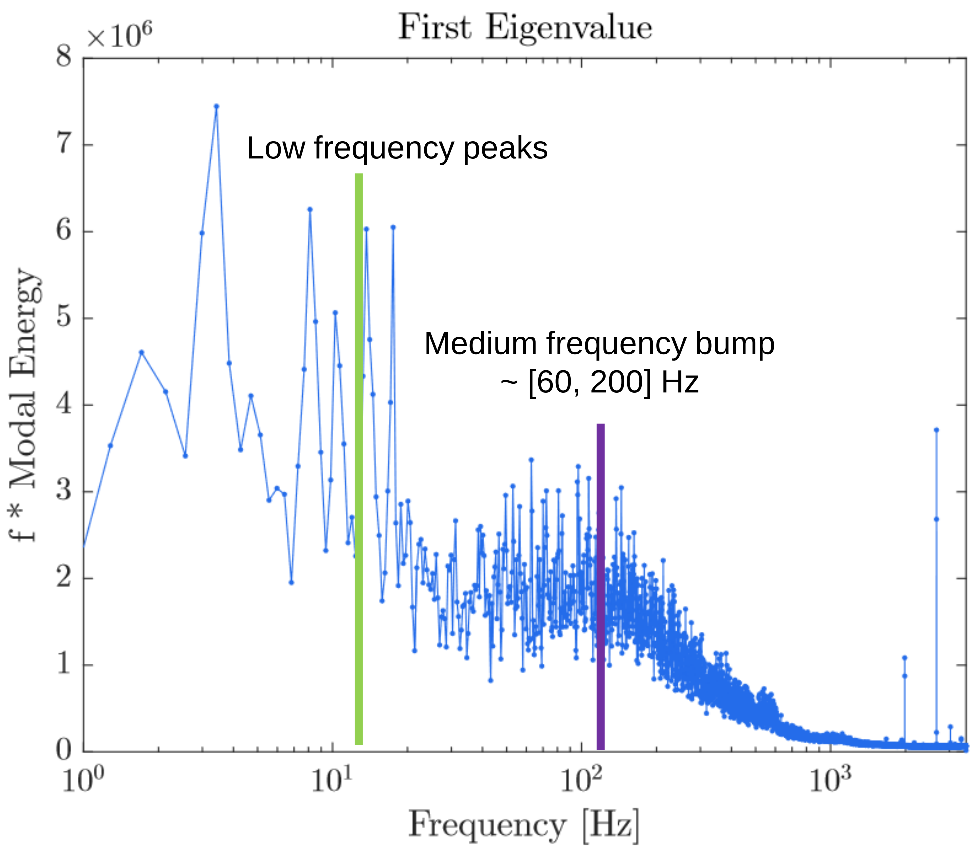


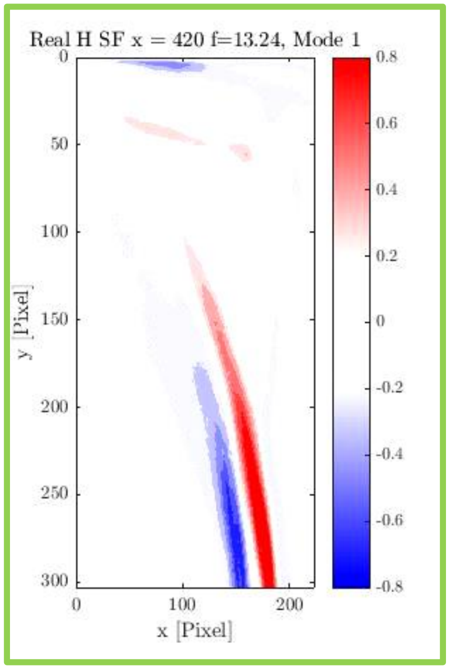
I. Shock + Rigid Wall: Results SPOD

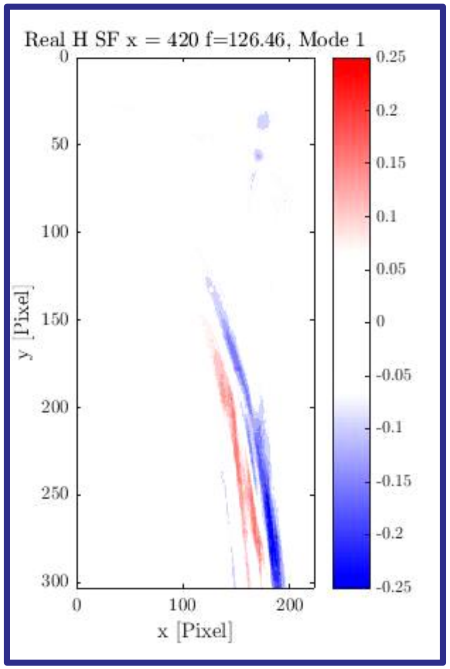
Spectral Proper Orthogonal Decomposition

Parameters: 13 Blocks 16384 Samples 50% overlap

- Pure oscillation BL and shock → Independent shock positions
- More energetic oscillations downstream



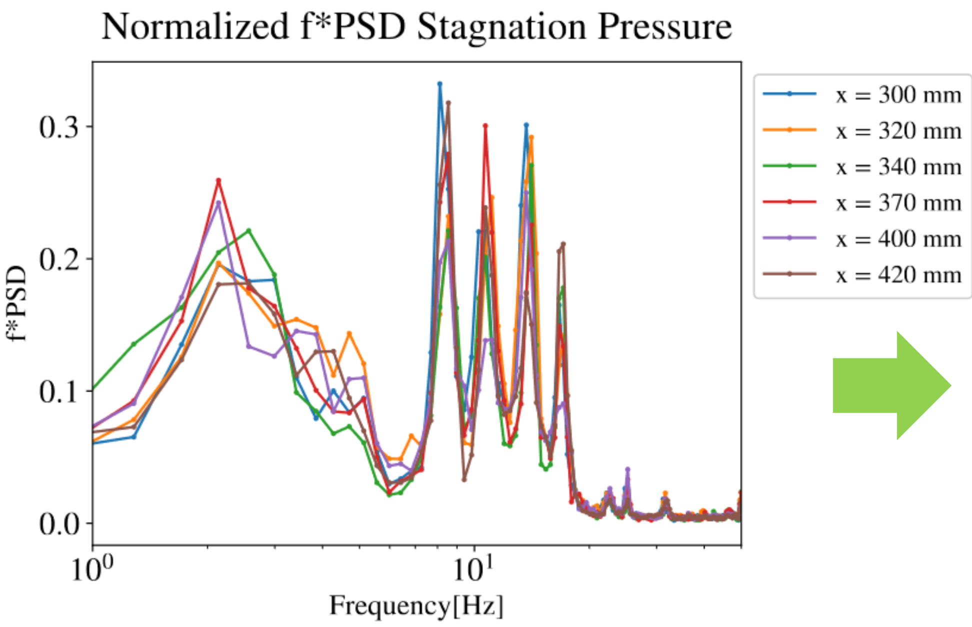




I. Shock + Rigid Wall: Results Pressure

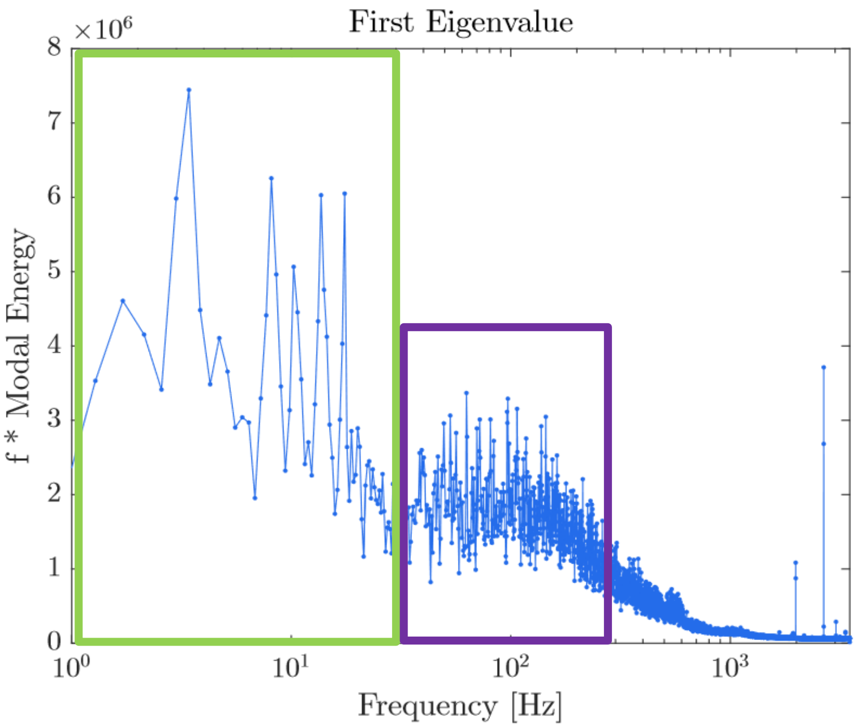
Stangation Pressure PSD Welch

- Settling Chamber
- Samples per block = 234
- Overlap = 50%
- FR = 0.42 Hz → Same as SPOD results

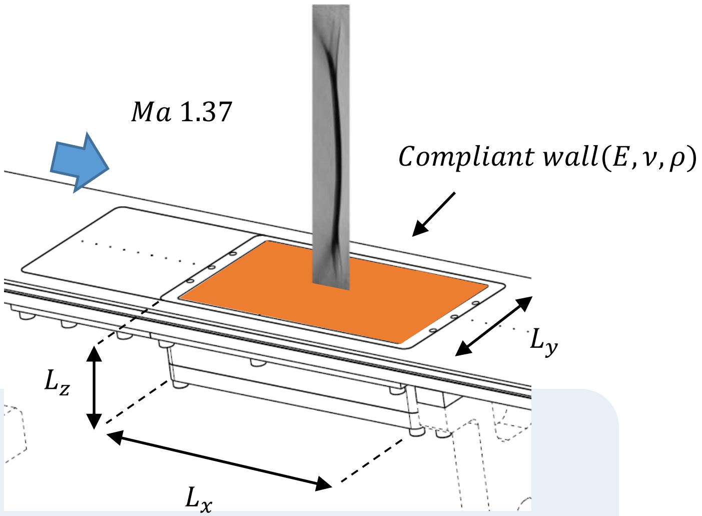


Stagnation Pressure Forcing

Shock Turbulent Boundary Layer Interaction



II. Compliant Wall Design



Material & Dimensions

Requirements & Constrains

- Test section dimensions
- Natural frequency > Shock oscillation ➔ > 200 Hz

Model Compliant Wall → Predict behaviour

- Different types of models: Linear elasticity, Hyperelasticity, Linear viscoelasticity, Plasticity…

First approach → Simplest model ➔ Linear elasticity

II. Compliant Wall Design

Linear Elasticity

I. Balance of linear momentum

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} = \rho \frac{\partial^2 \xi}{\partial t^2}$$

$\nabla \cdot \boldsymbol{\sigma}$: Cauchy Stress Tensor; $\boldsymbol{F}$: Body Forces

Constitutive equation
Hook's Law

$$\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon}$$

$\boldsymbol{C}$: Relationship Internal Stress - Strain

→ Isotropic

$$\boldsymbol{\sigma} = 2\mu\boldsymbol{\varepsilon} + \lambda tr(\boldsymbol{\varepsilon})\boldsymbol{I}$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}((\nabla\xi)^T + \nabla\xi))$$

1st Lame coefficient (Shear Modulus)

$$\mu = G = \frac{E}{2(1+\nu)}$$

2nd Lame coefficient

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$$

Young Modulus

E

Poisson Coefficient

ν

II. Adimensionalized → Function of Geometry(Lx,Ly,Lz) and Poisson Coefficient ν

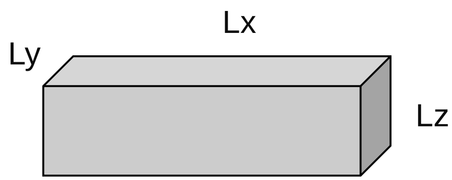
III. FEM formulation
- Modal Analysis → Adimensional frequency $\tilde{\Omega}$(Geom., ν)
- Static Deformation → Adimensional displacement $\tilde{\xi}$(Load, Geom. ν)

IV. Parametric study → Satisfy requirements → Range of thickness Lz; Elastomer → Viscoelastic Model Ongoing work

II. Compliant Wall Design

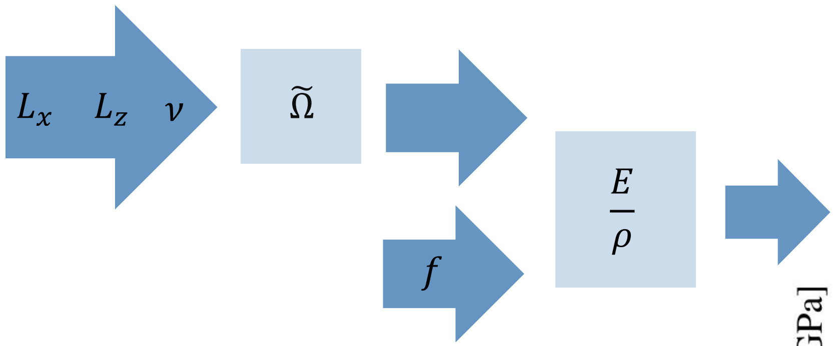
Parametric Study: Modal Analysis → $\tilde{\Omega}$

- Poisson Coefficient ν → Same range of $\tilde{\Omega}$ values
- Geometry → Region of interest Lz/Ly = 0,2 - 0,4
- Material → Elastomer



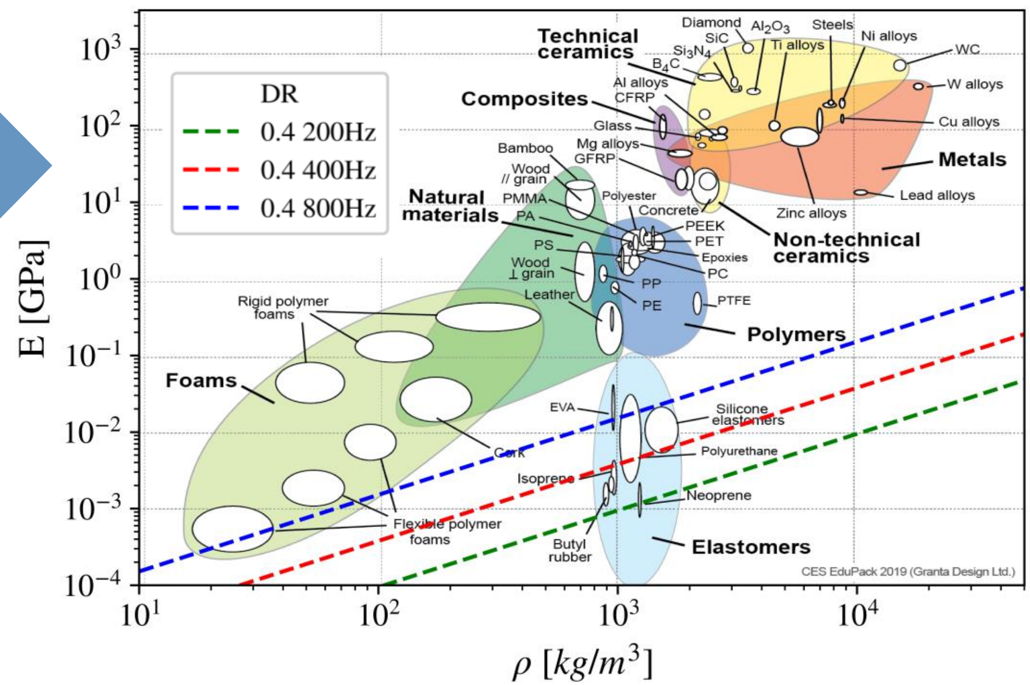
Aspect ratio = Lx/Ly

Depth ratio = Lx/Ly



$$\frac{E}{\rho} = \left(\frac{f 2\pi L_y}{\tilde{\Omega}}\right)^2$$

AR Lx/Ly 1.9, Poisson 0.49

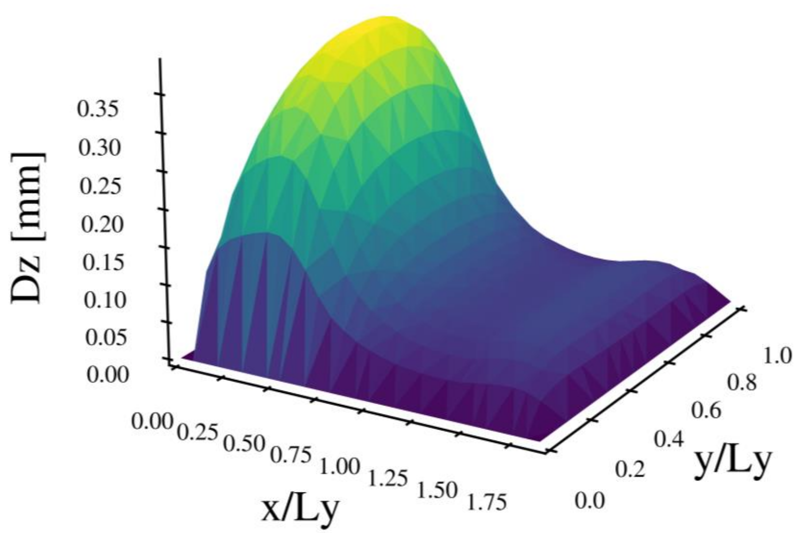


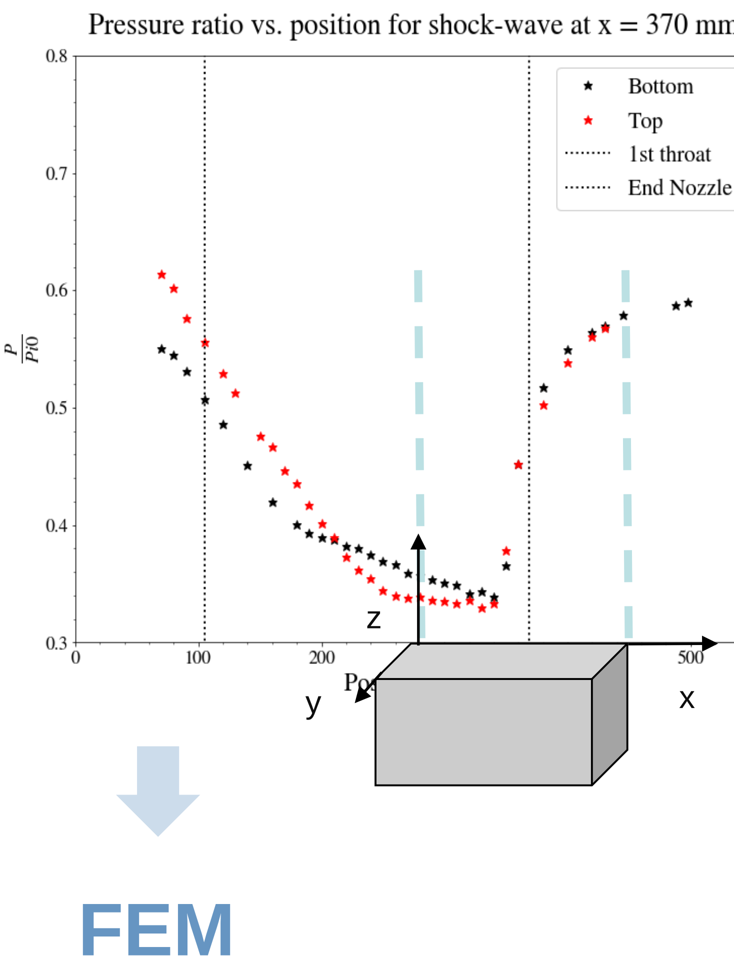
II. Compliant Wall Design

Parametric Study: Static Deformation → ξ

- ↓ Displacement with ↑ Young Modulus E ↑ Poisson Coefficient ν or ↓ Lz/Ly
- Main displacement → Dz
- Dependency of shock position on the compliant wall
- Small deformations < 1 mm

x = 370 Location 50% ν 0.49 Lz/Ly 0.4 E 0.9 MPa





Conclusion

Shock + Rigid

I. Low frequencies → Forcing Stagnation Pressure
II. Medium bump frequencies → STBLI
III. Oscillation shock and BL → Do not depend on shock position
IV. More energetic oscillations downstream

Compliant Wall

I. Linear elasticity → First approximation
II. Elastomer
III. Viscoelastic model

Future Work

I. Dynamic Mechanical Analysis → Characterization Material (DMAS)
II. Viscoelastic model
III. Experimental campaign with compliant wall
  - Digital Image Correlation (DIC) → Dynamic Wall
  - Schlieren → Dynamic shock
IV. Stability analysis

Thank you