Classification of Engineering Problems

- Crandall (1956)

- Equilibrium Problems
  - Time-independent problem
  - equilibrium stress, steady state temperature, pressure
- Eigenvalue Problems
  - natural frequency (vibration)
  - buckling load (stability)
- Propagation Problems
  - Time-dependent problem
  - propagation of displacements, heat, wave
  - IVP, transient and unsteady-state phenomena

Eigenvalue Problems

Linear $\left(\text{elastic}\right)$ dynamic problems

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{f}\left(t\right)$$

Zero damping and external loads

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = 0$$

Solution form: $\boldsymbol{u}\left(t\right) = \Phi e^{i\omega t}$

Generalized eigenvalue problem

$$\left(\boldsymbol{K} - \omega^2 \boldsymbol{M}\right)\Phi = 0$$

$$\text{Non-trivial (eigen-)solutions}: \left(\underbrace{\omega_i}_{\text{eigenfrequency}} \quad , \quad \underbrace{\Phi_i}_{\text{modeshape}} \right)$$

Optimization Problem

$$\max_{\boldsymbol{\rho}} \quad \omega_i^2$$

$$\text{subject to} \quad \sum_{e=1}^{N} v_e \rho_e \le V^*$$

$$0 < \rho_{\min} \le \boldsymbol{\rho} \le 1$$

$$\left(\boldsymbol{K} - \omega^2 \boldsymbol{M}\right)\Phi = 0$$

design sensitivity of single eigenvalue

$$\frac{d\omega_i^2}{d\rho_e} = \phi_i^T \left(\frac{\partial \boldsymbol{K}}{\partial \rho_e} - \omega_i^2 \frac{\partial \boldsymbol{M}}{\partial \rho_e} \right) \phi_i$$

$$\phi_i^T \boldsymbol{M} \phi_i = 1$$

Fundamental problems

- Optimization problem is not well posed (less structure → higher eigenfrequency)
  - Solutions: impose mass equality constraint, solve problem as a reinforcement problem or include non-structural masses
- Spurious modes in low density regions
  - Solution: tailored interpolation functions
- Mode switching (non-smooth)
  - Solutions: include more modes or use bound formulation
- Multiple eigenvalues → incorrect sensitivities
  - Solution: compute correct sensitivities !

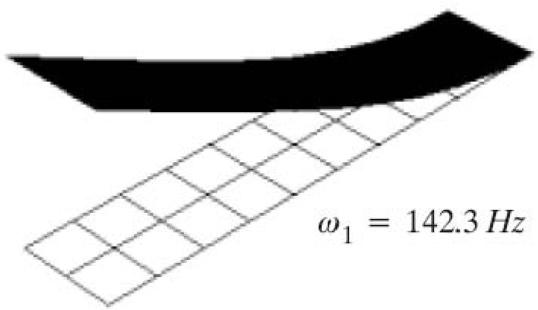
Spurious Modes

Research papers

Struct Multidisc Optim 20, 2–11 © Springer-Verlag 2000

Maximization of eigenvalues using topology optimization

N.L. Pedersen



Analytical first eigenfrequency
(using beam theory)

$\omega_1 = 142.9\ Hz$

$$\left.\begin{aligned} E_e &= {\rho_e}^{p_1} E_0 \\ m_e &= {\rho_e}^{p_2} m_0 \\ v_e &= {\rho_e}^{p_3} v_0 \end{aligned}\right\}$$

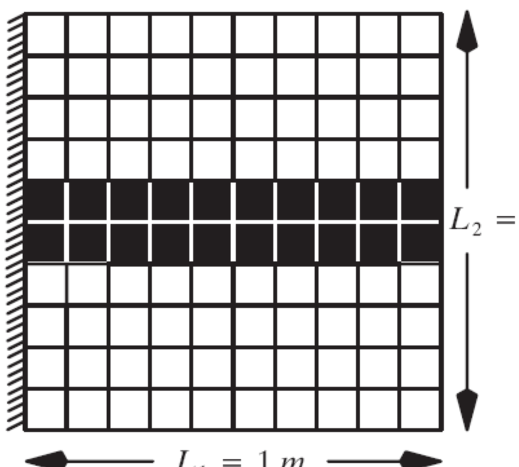
SIMP: $p_1 = 3, p_2 = p_3 = 1$

$\rho_e \to \rho_{\min}$: ${\rho_e}^{p} \ll \rho_e$

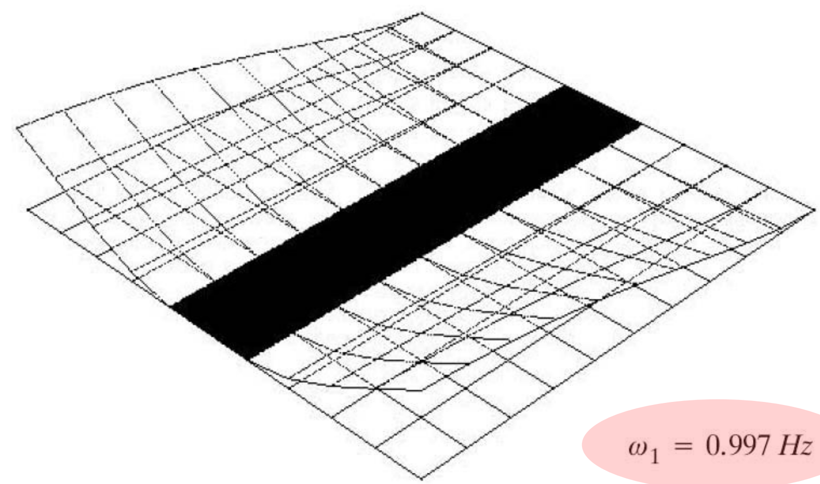
Modulus of elasticity
$E = 1.8 \cdot 10^{11}\ N/m^2$

Poisson's ratio
$\nu = 0.06$

Mass density
$\hat{\rho} = 2300\ kg/m^3$

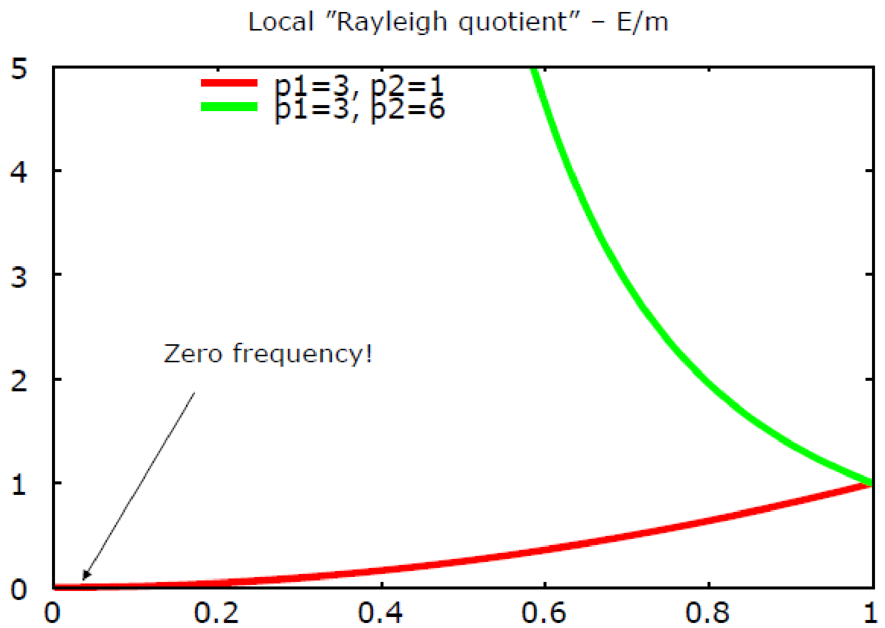


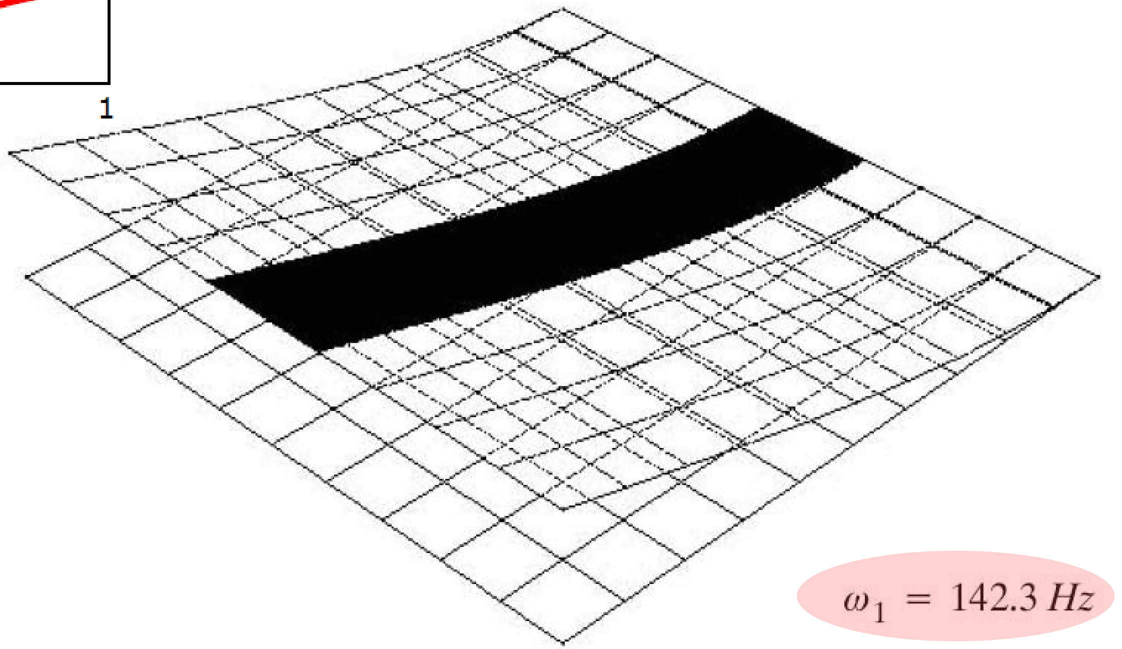
Thickness $T = 0.01\ m$



$\omega_1 = 0.997\ Hz$

Modified SIMP

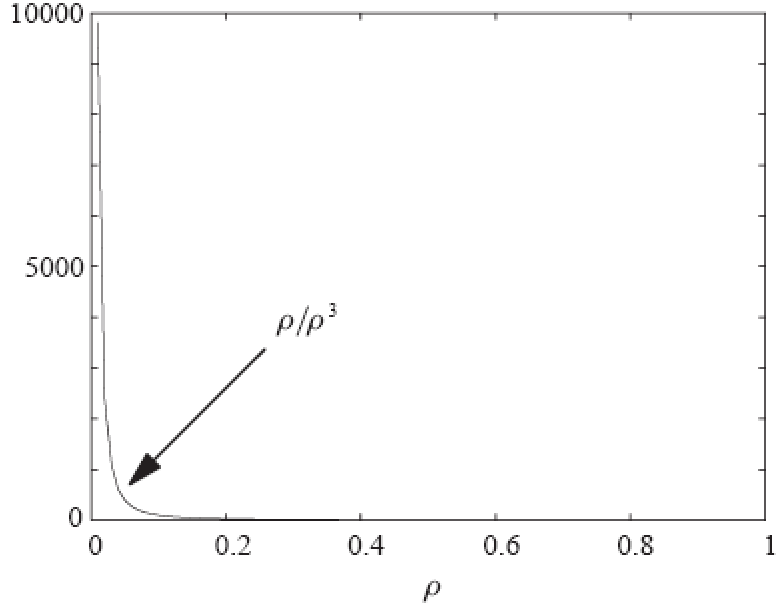


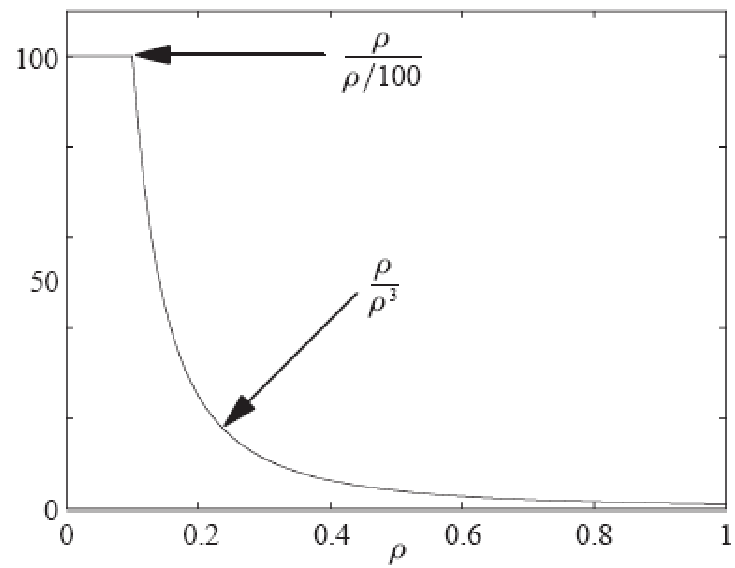


Discontinuous Stiffness

$$m_e = m_0 \rho_e, \;\; 0 < \rho_{\min} \le \rho_e \le 1$$

$$E_e = \begin{cases} E_0 \rho_e^{\;3}, \;\; 0.1 \le \rho_e \le 1 \\ \dfrac{1}{100} E_0 \rho_e, \;\; \rho_{\min} \le \rho_e \le 0.1 \end{cases}$$



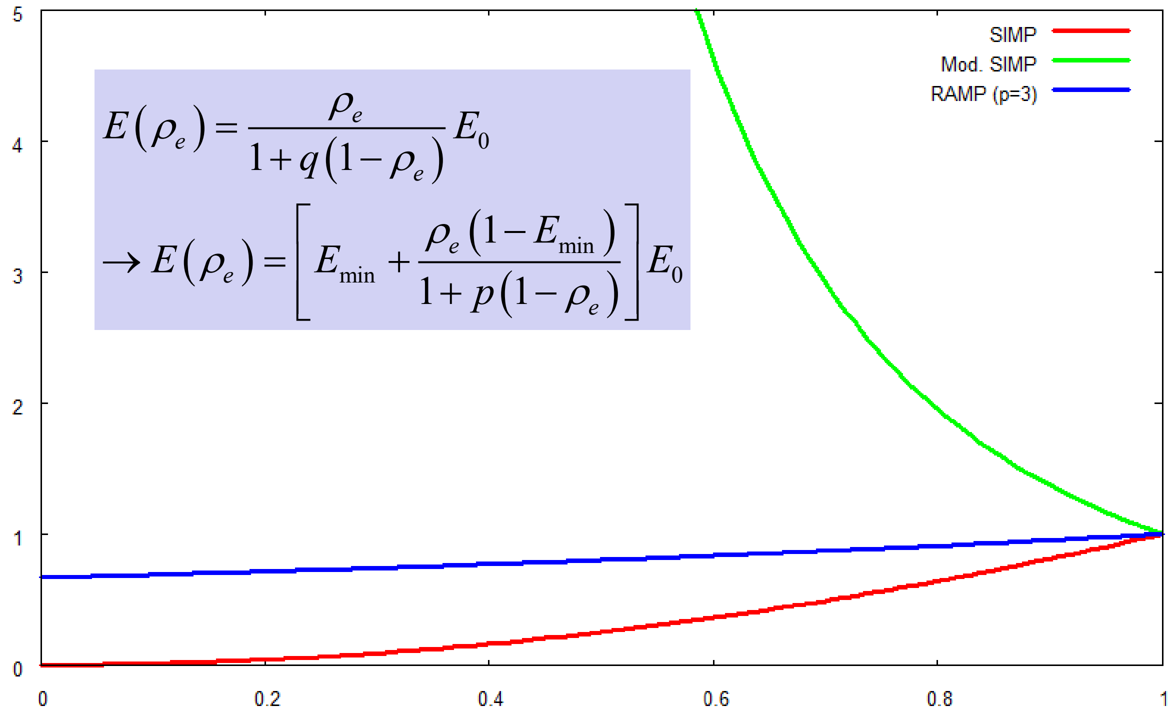


RAMP Interpolation

Struct Multidisc Optim 22, 116–124 © Springer-Verlag 2001

An alternative interpolation scheme for minimum compliance topology optimization

M. Stolpe and K. Svanberg



$$E(\rho_e) = \frac{\rho_e}{1+q(1-\rho_e)} E_0$$

$$\rightarrow E(\rho_e) = \left[E_{\min} + \frac{\rho_e (1-E_{\min})}{1+p(1-\rho_e)} \right] E_0$$

Mode Switching (1)

- Weighted average

$$\max_{\boldsymbol{\rho}} \quad \frac{1}{\sum_{i=1}^{i_{\max}} \frac{1}{\omega_i^2}}$$

$$\text{subject to} \quad \sum_{e=1}^{N} v_e \rho_e \leq V^*$$

$$0 < \rho_{\min} \leq \boldsymbol{\rho} \leq 1$$

$$\left(\boldsymbol{K} - \omega^2 \boldsymbol{M}\right)\Phi = 0$$

- Bound formulation

$$\max_{\boldsymbol{\rho}} \quad \beta$$

$$\text{subject to} \quad \beta - \omega_i^2 \leq 0, \quad i \in \{1, i_{\max}\}$$

$$\sum_{e=1}^{N} v_e \rho_e \leq V^*$$

$$0 < \rho_{\min} \leq \boldsymbol{\rho} \leq 1$$

$$\left(\boldsymbol{K} - \omega^2 \boldsymbol{M}\right)\Phi = 0$$

Choose $i_{\max}$ large enough to ensure smoothness !

Mode Switching (2)

- Mean eigenvalue

$$\boxed{\Lambda = \lambda_0 + \left(\sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^n \Big/ \sum_{i=1}^{m} w_i \right)^{\frac{1}{n}}} \quad \left(\text{for } n = \pm 1, \pm 2, \ldots ; n \neq 0 \right)$$

λ_{n_i}: chosen eigenvalues

w_i: given weighting coefficients

λ_0, λ_{0_i}: given shift parameters

m: number of eigenvalues of interest

n: given power

$$\begin{cases} \text{case 1: } n = -1,\ m = 1,\ \lambda_0 = 0,\ \sum_{i=1}^{m} w_i = 1 \Rightarrow \Lambda = \lambda_{n_1} \quad \left(\text{lowest eigenvalue}\right) \\ \text{case 2: } n = -1,\ \sum_{i=1}^{m} w_i = 1 \Rightarrow \Lambda = \lambda_0 + \dfrac{1}{\sum_{i=1}^{m} \dfrac{w_i}{\lambda_{n_i} - \lambda_{0_i}}} \rightarrow \tilde{\Lambda} = \dfrac{1}{\Lambda - \lambda_0} = \sum_{i=1}^{m} \dfrac{w_i}{\lambda_{n_i} - \lambda_{0_i}} \end{cases}$$

$$\begin{cases} \text{Maximize } \Lambda \text{ (maximize the mean eigenvalue)} \\ \text{Maximize } \Lambda \text{ with } \lambda_{0_i} = \left(2\pi\omega_{0_i}\right)^2 \text{ (away from the specified eigenvalue)} \\ \text{Minimize } \Lambda \text{ with } \lambda_{0_i} = \left(2\pi\omega_{0_i}\right)^2 \text{ (approach to the specified eigenvalue)} \end{cases}$$

Sensitivity Analysis (1)

$$\underset{x}{\text{Maximize}}\ \Lambda \rightarrow \underset{x}{\text{Minimize}}\ \ f(x) = -\Lambda$$

$$\Lambda = \lambda_0 + \left(\sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^n \Big/ \sum_{i=1}^{m} w_i \right)^{\frac{1}{n}} \rightarrow \left(\Lambda - \lambda_0 \right)^n = \frac{\sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^n}{\sum_{i=1}^{m} w_i}$$

$$\rightarrow \bar{f} = \left(\Lambda - \lambda_0 \right)^n \sum_{i=1}^{m} w_i - \sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^n = 0$$

$$\rightarrow \frac{\partial \bar{f}}{\partial \rho} = n \left(\Lambda - \lambda_0 \right)^{n-1} \frac{\partial \Lambda}{\partial \rho} \sum_{i=1}^{m} w_i - n \sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^{n-1} \frac{\partial \lambda_{n_i}}{\partial \rho} = 0$$

$$\rightarrow \frac{\partial \Lambda}{\partial \rho} = \frac{\left(\Lambda - \lambda_0 \right)^{1-n}}{\sum_{i=1}^{m} w_i} \sum_{i=1}^{m} w_i \left(\lambda_{n_i} - \lambda_{0_i} \right)^{n-1} \frac{\partial \lambda_{n_i}}{\partial \rho}$$

$$\xrightarrow{n=-1} \frac{\partial \Lambda}{\partial \rho} = \frac{\left(\Lambda - \lambda_0 \right)^2}{\sum_{i=1}^{m} w_i} \sum_{i=1}^{m} \frac{w_i}{\left(\lambda_{n_i} - \lambda_{0_i} \right)^2} \left(\frac{\partial \lambda_{n_i}}{\partial \rho} \right)$$

Sensitivity Analysis (2)

$$\frac{\partial\bar{\Lambda}}{\partial\rho_e}=\frac{\left(\Lambda-\lambda_0\right)^2}{\sum_{i=1}^{m}w_i}\sum_{i=1}^{m}\frac{w_i}{\left(\lambda_{n_i}-\lambda_{0_i}\right)^2}\frac{\partial\lambda_{n_i}}{\partial\rho_e}$$

$$\text{where}\quad\begin{cases}\dfrac{\partial\lambda_{n_i}}{\partial\rho_e}=\phi_{n_i}{}^T\left(\dfrac{\partial\boldsymbol{K}}{\partial\rho_e}-\lambda_{n_i}\dfrac{\partial\boldsymbol{M}}{\partial\rho_e}\right)\phi_{n_i}=\phi_{n_i}{}^T\left(\dfrac{\partial\boldsymbol{k}_e}{\partial\rho_e}-\lambda_{n_i}\dfrac{\partial\boldsymbol{m}_e}{\partial\rho_e}\right)\phi_{n_i}\\ \dfrac{\partial\boldsymbol{k}_e}{\partial\rho_e}=\displaystyle\int_{\Omega_e}\boldsymbol{B}_e{}^T\frac{\partial\boldsymbol{E}_e}{\partial\rho_e}\boldsymbol{B}_e d\Omega\\ \dfrac{\partial\boldsymbol{m}_e}{\partial\rho_e}=\displaystyle\int_{\Omega_e}m_0\boldsymbol{N}_e{}^T\boldsymbol{N}_e d\Omega\end{cases}$$

$$\xrightarrow{\text{filtering}}\frac{\partial\tilde{\Lambda}}{\partial\rho_e}=\frac{1}{\rho_e\sum_{f=1}^{N}H_f}\sum_{f=1}^{N}H_f\rho_e\frac{\partial\bar{\Lambda}}{\partial\rho_e}$$

$$\frac{\partial g}{\partial x_e}=\frac{v_e}{V_0}$$

Modified Optimality Criteria Method

$$\begin{cases} \underset{x}{\text{Minimize}} \;\; f(x) = \tilde{\Lambda} \\ \text{subject to} \;\; g(x) = \dfrac{V(x)}{V_0} - 1 = \dfrac{\sum_e v_e \rho_e}{V_0} - 1 \le 0 \\ \qquad\qquad\quad 0 < \rho_{\min} \le \rho_e \le 1 \end{cases}$$

$$\rightarrow \frac{\partial f}{\partial \rho_e} + \lambda \frac{\partial g}{\partial \rho_e} = \alpha_i^l - \alpha_i^u \rightarrow D_e = \frac{1}{\lambda}\left(-\frac{\partial f}{\partial \rho_e} \Big/ \frac{\partial g}{\partial \rho_e} \right) = 1 \quad \text{for } 0 < \rho_{\min} \le \rho_e \le 1$$

$$\rightarrow \rho_e^{k+1} = \left(D_e^k\right)^\eta \rho_e^k \quad \text{for } 0 < \rho_{\min} \le \rho_e \le 1$$

D_e^k : positive ?

$$\left(\frac{\partial f}{\partial \rho_e} - \mu \frac{\partial g}{\partial \rho_e} \right) + \lambda^* \frac{\partial g}{\partial \rho_e} = 0 \quad \text{for } \rho_e^l < \rho_e < \rho_e^u \quad \left(\lambda^* = \lambda + \mu\right)$$

$$\bar{D}_e = \frac{1}{\lambda^*}\left(\mu - \frac{\partial f}{\partial \rho_e} \Big/ \frac{\partial g}{\partial \rho_e} \right) = 1 \quad \text{for } \rho_e^l < \rho_e < \rho_e^u \quad \text{where } \mu \ge \max_e \left(\frac{\partial f}{\partial \rho_e} \Big/ \frac{\partial g}{\partial \rho_e} \right)$$

$$\rightarrow v_e^{k+1} = \left(\bar{D}_e^k\right)^\eta \rho_e^k \quad \text{for } 0 < \rho_{\min} \le v_e \le 1$$

Multiple Eigenvalues (1)

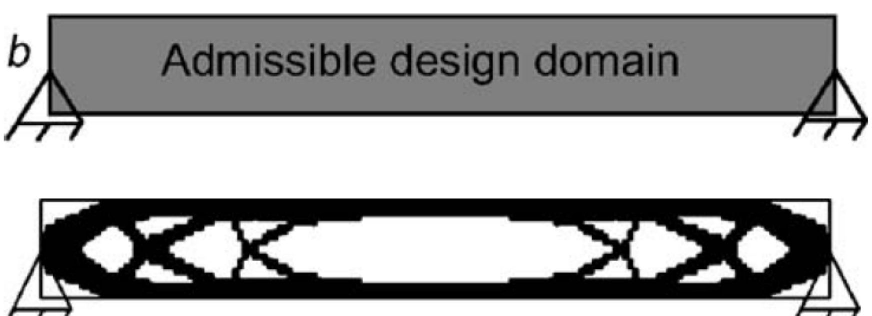
- Inherent property for 2- or 3-dimensional homogeneous and symmetric (eg square or cubic) structures
- Often an outcome of the optimization procedure

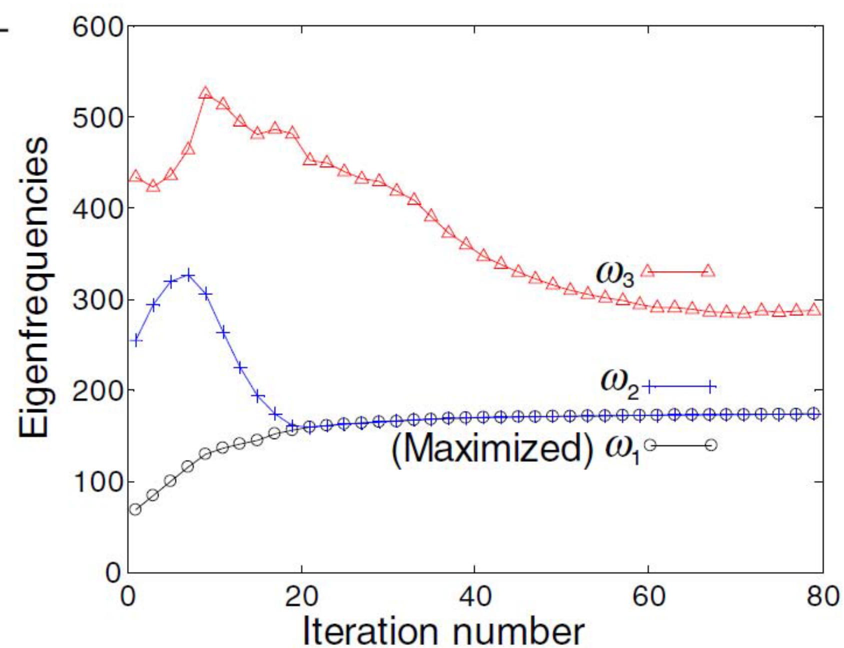
Struct Multidisc Optim (2007) 34:91–110
DOI 10.1007/s00158-007-0101-y

RESEARCH PAPER

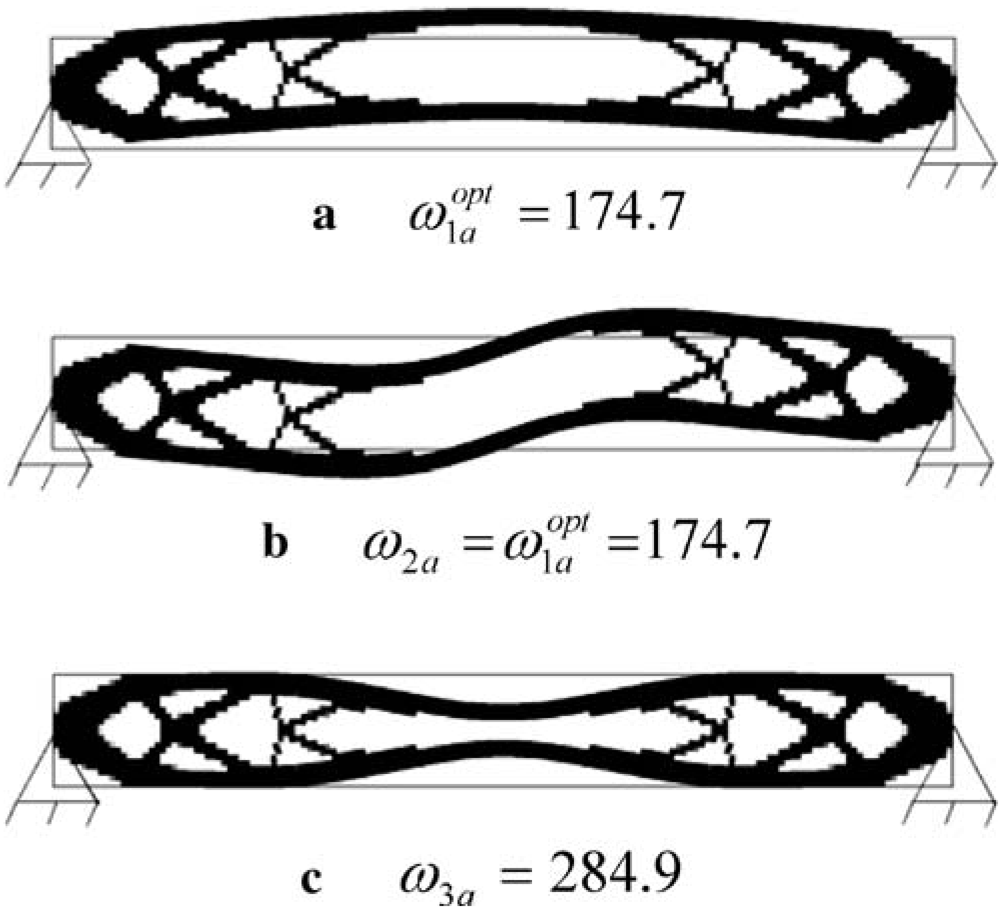
Topological design of freely vibrating continuum structures for maximum values of simple and multiple eigenfrequencies and frequency gaps

Jianbin Du · Niels Olhoff





Multiple Eigenvalues (2)



double eigenvalue: $\left(\lambda = \omega^2, \phi_1, \phi_2\right)$

normalized mode shapes

$$\begin{cases} \phi_1^T \boldsymbol{M} \phi_1 = 1 \\ \phi_2^T \boldsymbol{M} \phi_2 = 1 \end{cases}$$

mode shapes are orthogonal

$$\phi_1^T \boldsymbol{M} \phi_2 = 0$$

Sensitivity of Multiple Eigenvalue

Available online at www.sciencedirect.com
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Journal of Sound and Vibration 289 (2006) 967–986
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

On maximal eigenfrequency separation in two-material structures: the 1D and 2D scalar cases

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[b] Institute of Mechanical Engineering, Aalborg University, Pontoppidanstræde 101, DK-9220 Aalborg East, Denmark

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$$\left.\begin{matrix}(\lambda,\phi_1,\phi_2)\\ \phi_1^T\boldsymbol{M}\phi_2=0\end{matrix}\right\}\rightarrow\begin{cases}\bar{\phi}=c_1\phi_1+c_2\phi_2\rightarrow\dfrac{d\lambda}{d\rho_e}=\bar{\phi}^T\left(\dfrac{d\boldsymbol{K}}{d\rho_e}-\lambda\dfrac{d\boldsymbol{M}}{d\rho_e}\right)\bar{\phi}\\ \bar{\phi}^T\boldsymbol{M}\bar{\phi}=1\end{cases}$$

$$\frac{d\lambda}{d\rho_e}=c_1^{\ 2}g_{11}+c_2^{\ 2}g_{22}+2c_1c_2g_{12}\quad\text{where}\quad g_{\alpha\beta}=\phi_\alpha^{\ T}\left(\frac{d\boldsymbol{K}}{d\rho_e}-\lambda\frac{d\boldsymbol{M}}{d\rho_e}\right)\phi_\beta$$

$$[\text{finding values of constants}]\quad\begin{cases}\bar{\phi}_1=c_{11}\phi_1+c_{12}\phi_2\\ \bar{\phi}_2=c_{21}\phi_1+c_{22}\phi_2\end{cases}\quad\begin{cases}c_{11}^{\ 2}+c_{12}^{\ 2}=1\rightarrow\bar{\phi}_1^{\ T}\boldsymbol{M}\bar{\phi}_1=1\\ c_{21}^{\ 2}+c_{22}^{\ 2}=1\rightarrow\bar{\phi}_2^{\ T}\boldsymbol{M}\bar{\phi}_2=1\end{cases}$$

$$\left[\text{finding extreme values of }\frac{d\lambda}{d\rho_e}\text{ leads to new (small) eigenvalue problem}\right]$$

$$\left.\begin{matrix}\dfrac{d}{dc_1}\left(\dfrac{d\lambda}{d\rho_e}\right)=0\\ \dfrac{d}{dc_2}\left(\dfrac{d\lambda}{d\rho_e}\right)=0\end{matrix}\right\}\rightarrow\begin{bmatrix}g_{11}&g_{12}\\ g_{12}&g_{22}\end{bmatrix}\begin{Bmatrix}c_1\\ c_2\end{Bmatrix}=\begin{Bmatrix}0\\ 0\end{Bmatrix}\xrightarrow[\text{eigenvectors}]{\text{eigenvalues}}\left(\bar{\lambda}_1,\begin{Bmatrix}c_{11}\\ c_{12}\end{Bmatrix}\right),\left(\bar{\lambda}_2,\begin{Bmatrix}c_{21}\\ c_{22}\end{Bmatrix}\right)$$

$$\frac{d\lambda}{d\rho_e}=\begin{cases}\bar{\lambda}_1\ \text{ with eigenvector }\bar{\phi}_1=c_{11}\phi_1+c_{12}\phi_2\\ \bar{\lambda}_2\ \text{ with eigenvector }\bar{\phi}_2=c_{21}\phi_1+c_{22}\phi_2\end{cases}$$

Mode Tracking (1)

  - the order of eigenmodes may fluctuate
  - critical to keep track of the target modes accurately during the optimization process
- MAC (modal assurance criterion)
  - used mostly in checking the correlation between experimental and numerical mode shapes
  - not explicitly used in the definition of the objective or the constraint function

PERGAMON

Computers and Structures 74 (2000) 375–383

Computers & Structures

www.elsevier.com/locate/compstruc

Mac-based mode-tracking in structural topology optimization

Tae Soo Kim, Yoon Young Kim*

$$\mathrm{MAC}\left(\boldsymbol{\Phi}_a, \boldsymbol{\Phi}_b\right) = \frac{\left|\boldsymbol{\Phi}_a{}^T \boldsymbol{\Phi}_b\right|^2}{\left(\boldsymbol{\Phi}_a{}^T \boldsymbol{\Phi}_a\right)\left(\boldsymbol{\Phi}_b{}^T \boldsymbol{\Phi}_b\right)}$$

$\boldsymbol{\Phi}_a, \boldsymbol{\Phi}_b$: two mode shape vectors of interest

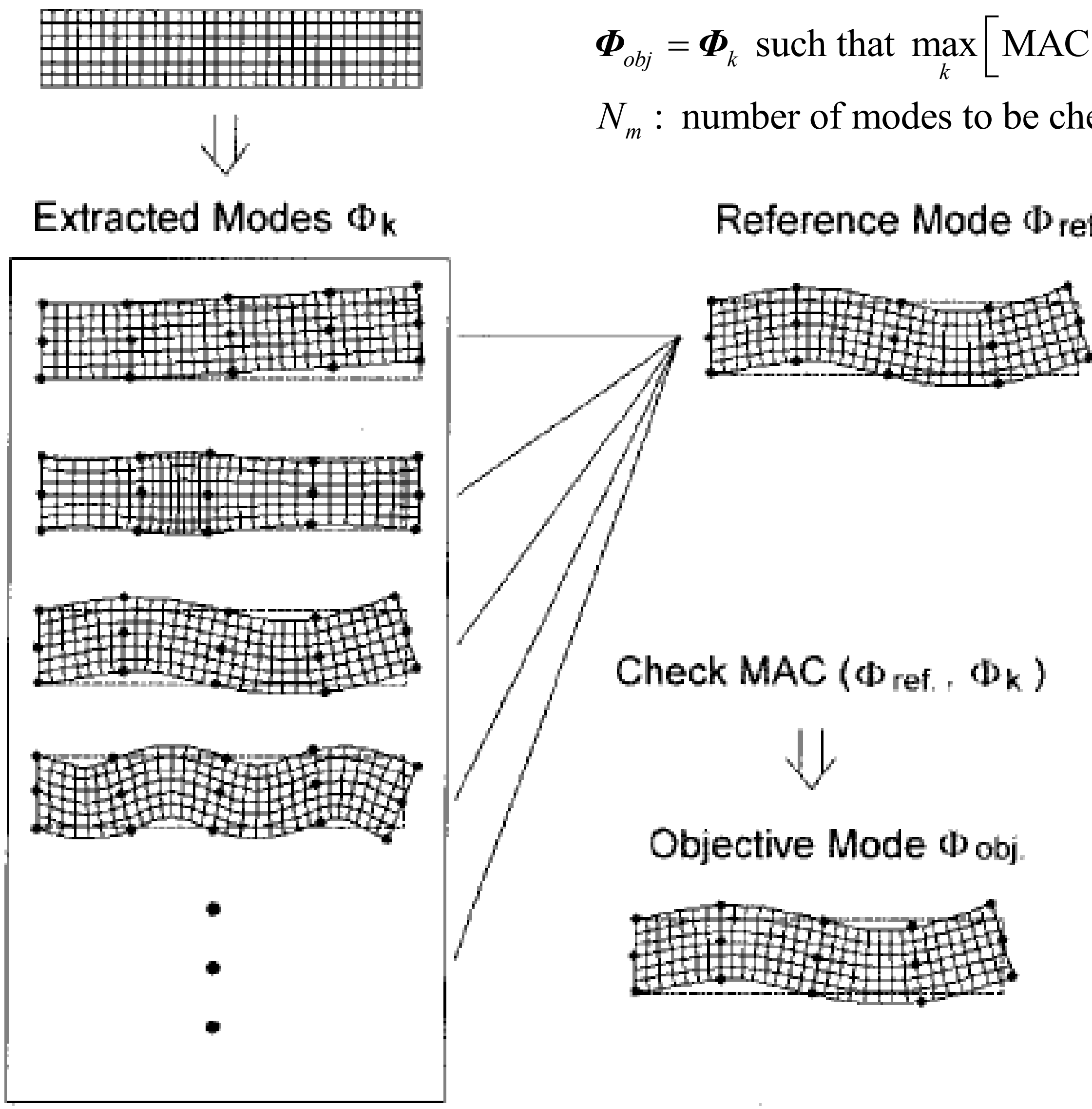
$0 \le \mathrm{MAC}\left(\boldsymbol{\Phi}_a, \boldsymbol{\Phi}_b\right) \le 1$

$\mathrm{MAC}\left(\boldsymbol{\Phi}_a, \boldsymbol{\Phi}_b\right) = 1 \Rightarrow$ exactly the same mode shape

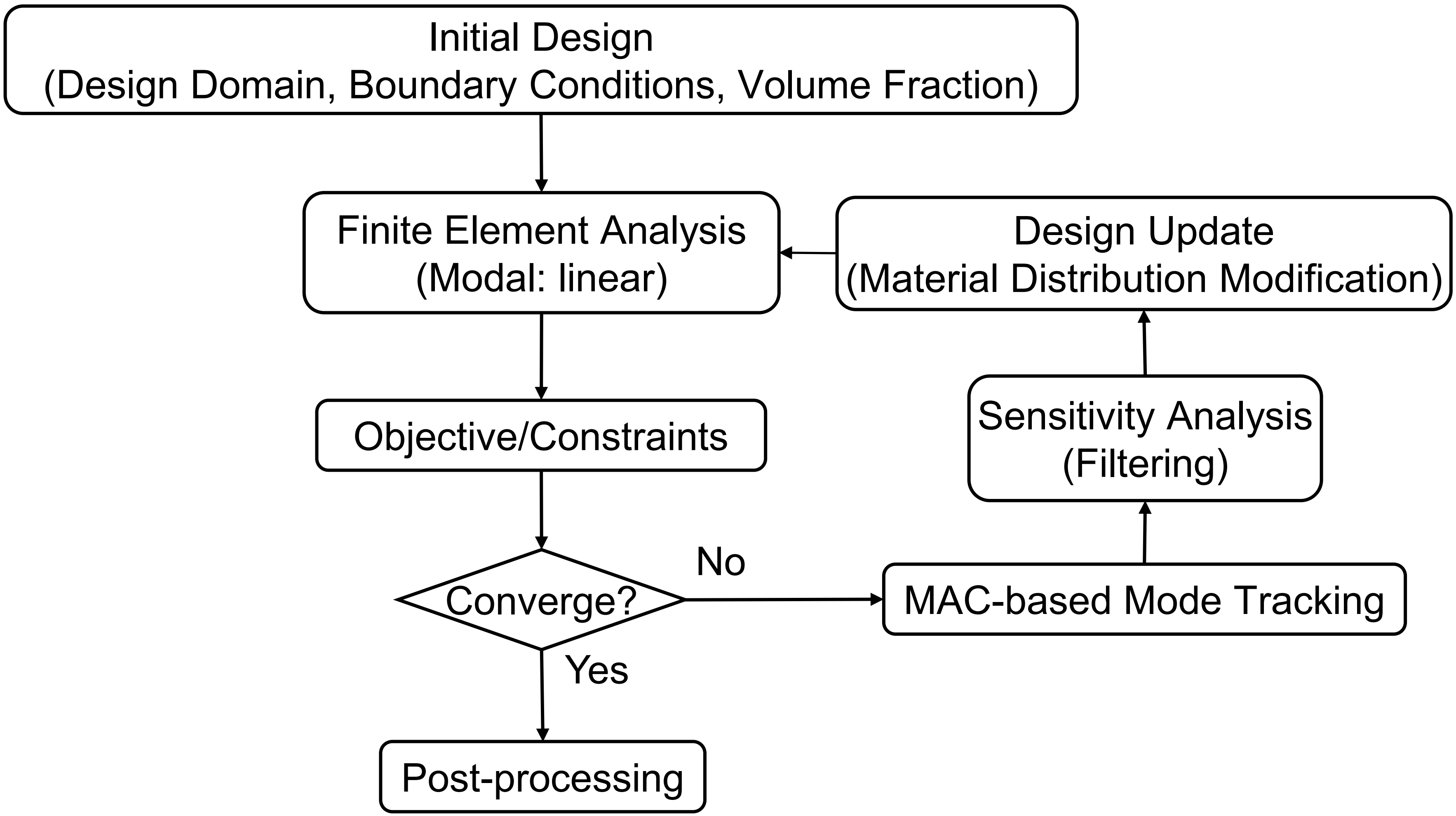
Mode Tracking (2)

$$\boldsymbol{\Phi}_{obj} = \boldsymbol{\Phi}_k \text{ such that } \max_k \left[\mathrm{MAC}\left(\boldsymbol{\Phi}_{ref}, \boldsymbol{\Phi}_k \right) \right], \quad k = 1, \ldots, N_m$$

N_m : number of modes to be checked



Flowchart


Initial Design
(Design Domain, Boundary Conditions, Volume Fraction)
Finite Element Analysis
(Modal: linear)
Design Update
(Material Distribution Modification)
Objective/Constraints
Sensitivity Analysis
(Filtering)
No
Converge?
MAC-based Mode Tracking
Yes
Post-processing

Buckling Problem

Free vibration problem: $\left(\boldsymbol{K}-\omega^2\boldsymbol{M}\right)\Phi = 0$

Linear buckling problem: $$\left[\underset{\text{geometric stiffness}}{\boldsymbol{G}(\boldsymbol{u})} - \underset{\text{critical load}}{\frac{1}{P}}\boldsymbol{K}\right]\underset{\text{buckling shape}}{\Phi} = 0$$

Structural Optimization 10, 71–78 © Springer-Verlag 1995

Technical Papers

Generalized topology design of structures with a buckling load criterion

M.M. Neves, H. Rodrigues and J.M. Guedes

IDMEC-Instituto Superior Técnico, Mechanical Engineering Department, Av. Rovisco Pais 1, P-1096 Lisboa Codex, Portugal

INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN ENGINEERING

Int. J. Numer. Meth. Engng 2002; **54**:809–834 (DOI: 10.1002/nme.449)

Topology optimization of periodic microstructures with a penalization of highly localized buckling modes

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Frequency Response Problems

- 지배방정식(유한요소)

$$\boldsymbol{M}\ddot{\boldsymbol{u}}+\boldsymbol{C}\dot{\boldsymbol{u}}+\boldsymbol{K}\boldsymbol{u}=\boldsymbol{f}\xrightarrow[\boldsymbol{u}=\boldsymbol{U}e^{j\omega t}]{\boldsymbol{f}=\boldsymbol{F}e^{j\omega t}}\left(\boldsymbol{K}+j\omega\boldsymbol{C}-\omega^2\boldsymbol{M}\right)\boldsymbol{U}=\boldsymbol{F}$$

- 직접법(Direct Frequency Response): $\boldsymbol{U}=\left(\boldsymbol{K}+j\omega\boldsymbol{C}-\omega^2\boldsymbol{M}\right)^{-1}\boldsymbol{F}$

- 모드중첩법(Modal Frequency Response):

$$\boldsymbol{u}=\sum_{i=1}^{n}\phi_i p_i\rightarrow\boldsymbol{M}\ddot{\boldsymbol{u}}+\boldsymbol{K}\boldsymbol{u}=\boldsymbol{f}\rightarrow\underbrace{\bar{\phi}_i^T\boldsymbol{M}\phi_i}_{m_i}\ddot{p}_i+\underbrace{\bar{\phi}_i^T\boldsymbol{K}\phi_i}_{k_i}p_i=\underbrace{\bar{\phi}_i^T\boldsymbol{f}}_{f_i}\quad\left(i=1,\ldots,n\right)$$

$$\xrightarrow[\boldsymbol{u}=\boldsymbol{U}e^{j\omega t},\ p_i=q_ie^{j\omega t}]{\boldsymbol{f}=\boldsymbol{F}e^{j\omega t},\ \text{orthogonality}}q_i=\frac{\bar{\phi}_i^T\boldsymbol{F}}{k_i-\omega^2m_i}=\frac{\bar{\phi}_i^T\boldsymbol{F}}{m_i\left(\omega_i^2-\omega^2\right)}$$

$$\leftrightarrow\boldsymbol{U}=\sum_{i=1}^{n}\phi_i\left(\frac{\phi_i^T\boldsymbol{F}}{\omega_i^2-\omega^2}\right)=\sum_{i=1}^{n}\phi_iq_i=\Phi Q\leftarrow\begin{cases}\omega_i^2\text{: eigenvalue}\\ \phi_i\text{: eigenvector}\end{cases}$$

Frequency Response Problems: Objective Function

$$\text{Minimize } \pi = \frac{1}{2}\left|\boldsymbol{U}^T \boldsymbol{D} \boldsymbol{U}\right|$$

- Dynamic mean compliance: $\boldsymbol{D} = 2\left(\boldsymbol{K} + j\omega \boldsymbol{C} - \omega^2 \boldsymbol{M}\right)$
- Internal energy of the structure: $\boldsymbol{D} = \boldsymbol{K}$
- Kinetic energy of the structure: $\boldsymbol{D} = \boldsymbol{M}$
- Norm of frequency responses: $\boldsymbol{D} = \boldsymbol{I}$
- Frequency response at specified DOF of the structure:

$$\boldsymbol{D} = diag\left\{w_i\right\} \text{ where } \begin{cases} w_i \neq 0 \text{ at specified DOF's} \\ w_i = 0 \text{ at the other DOF's} \end{cases}$$

- 특정 주파수 대역($\left[\omega_a, \omega_b\right]$)에서 고려

$$\text{Minimize } \Pi = \int_{\omega_a}^{\omega_b} \pi(\omega) d\omega = \underbrace{\sum_i w_i \pi(\omega_i)}_{(w_i, \omega_i)\text{: quadrature weights and points}}$$

Journal of Sound and Vibration 444 (2019) 1–20

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journal homepage: www.elsevier.com/locate/jsvi

A critical analysis of using the dynamic compliance as objective function in topology optimization of one-material structures considering steady-state forced vibration problems

Olavo M. Silva [a,*], Miguel M. Neves [b], Arcanjo Lenzi [a]

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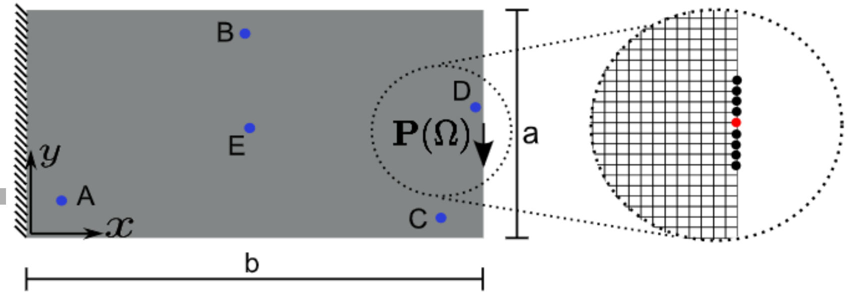
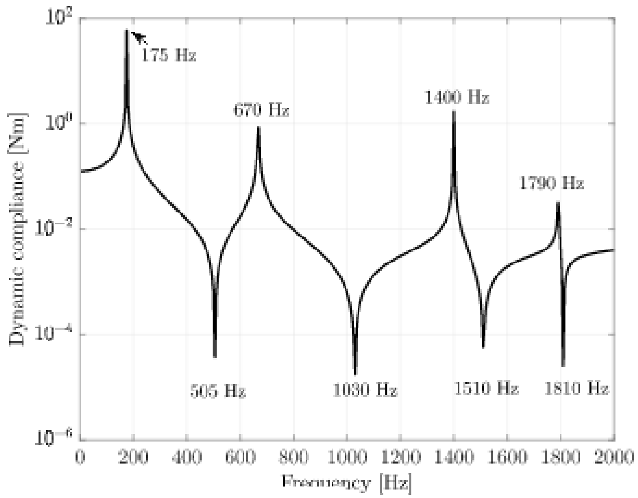
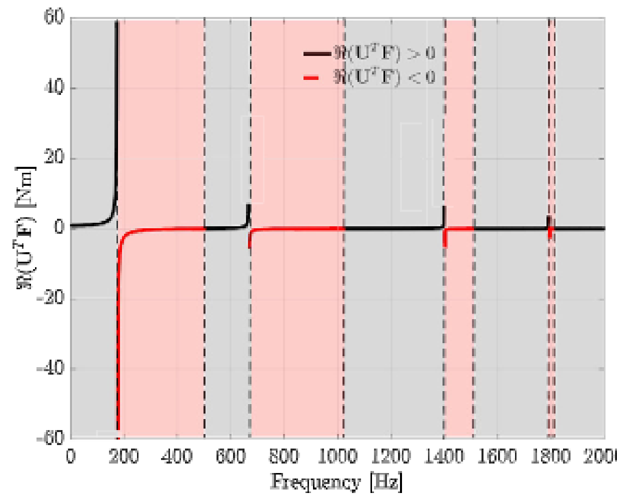
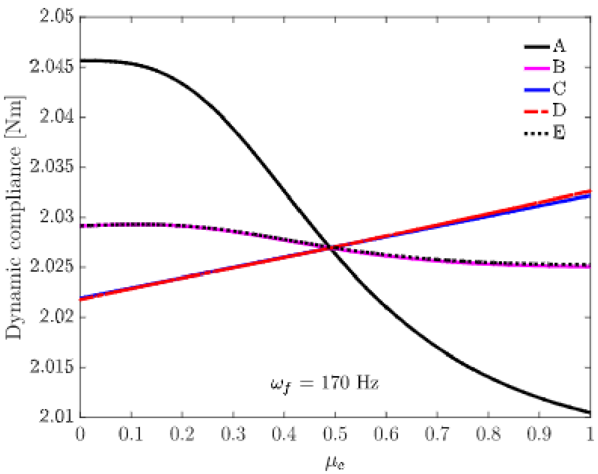
[b] IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

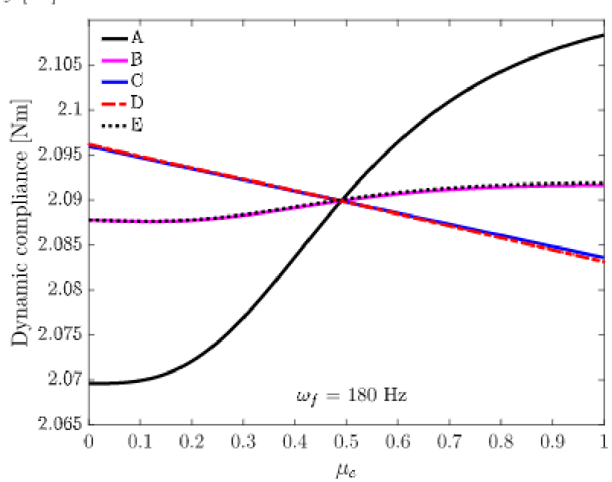


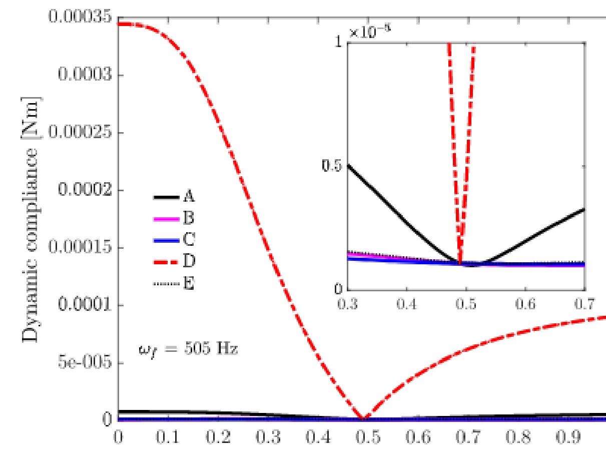
$$C_d = \left|\mathbf{U}^T\mathbf{K}\mathbf{U} + j\Omega\mathbf{U}^T\mathbf{C}\mathbf{U} - \Omega^2\mathbf{U}^T\mathbf{M}\mathbf{U}\right| = \left|C_K + C_C + C_M\right|$$

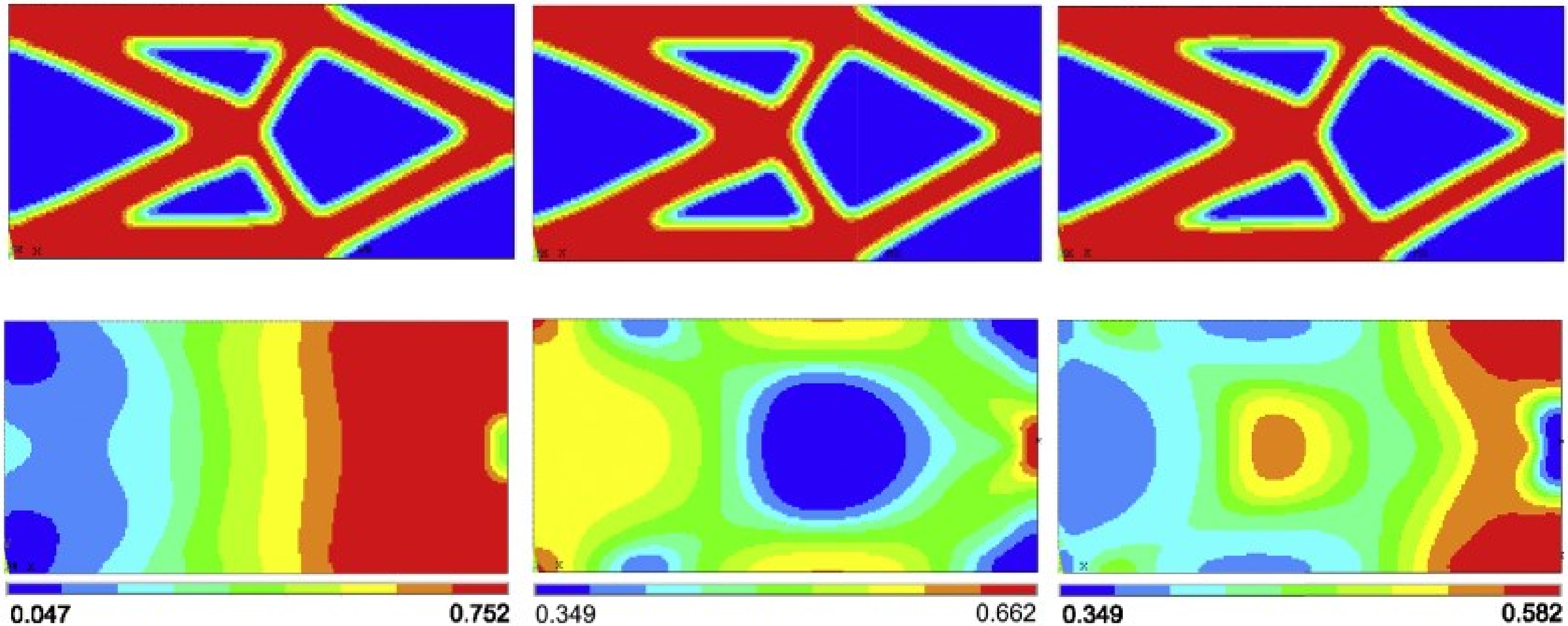








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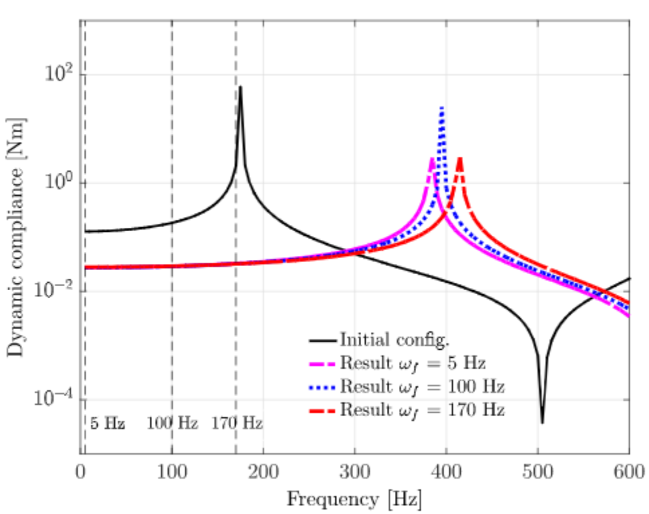
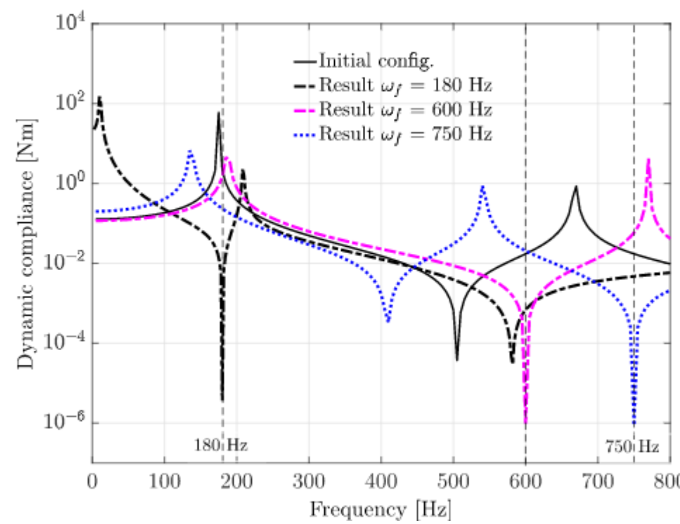
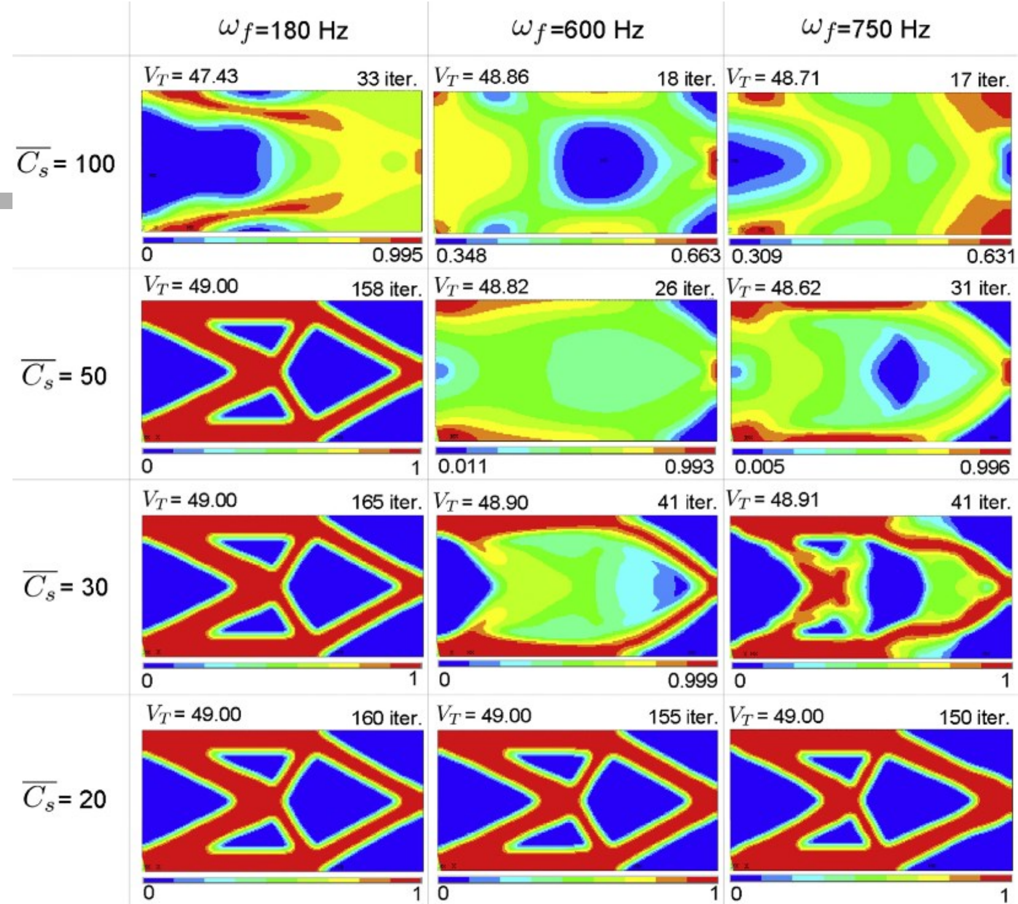
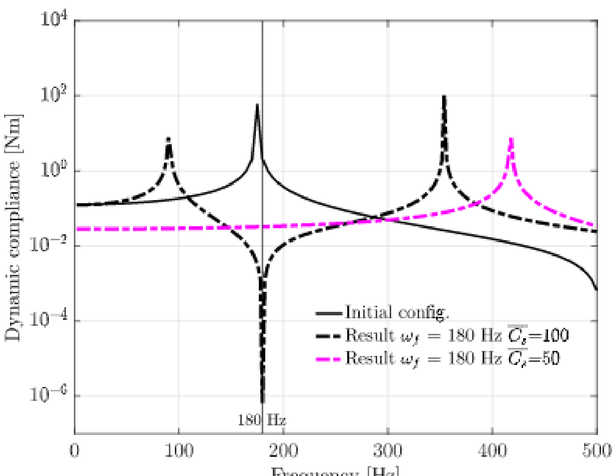
0.752
0.349
0.662
0.349
0.582

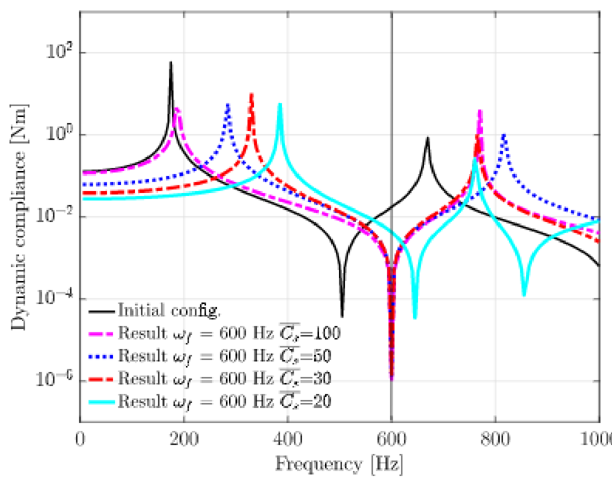

Dynamic compliance [Nm]
Frequency [Hz]
Initial config.
Result ω_f = 5 Hz
Result ω_f = 100 Hz
Result ω_f = 170 Hz
5 Hz
100 Hz
170 Hz

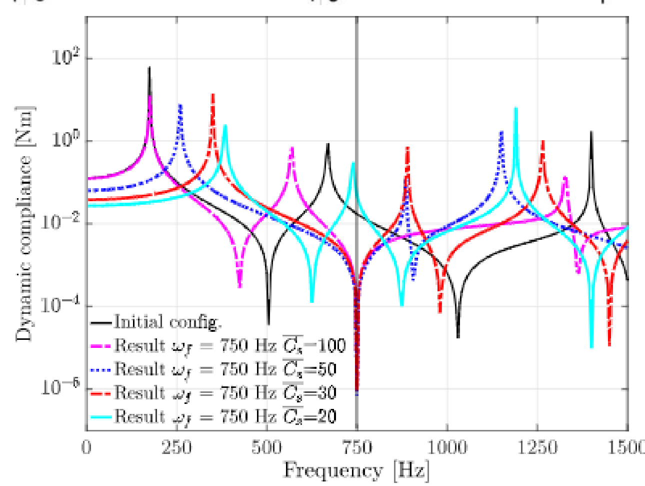

Dynamic compliance [Nm]
Frequency [Hz]
Initial config.
Result ω_f = 180 Hz
Result ω_f = 600 Hz
Result ω_f = 750 Hz
180 Hz
750 Hz

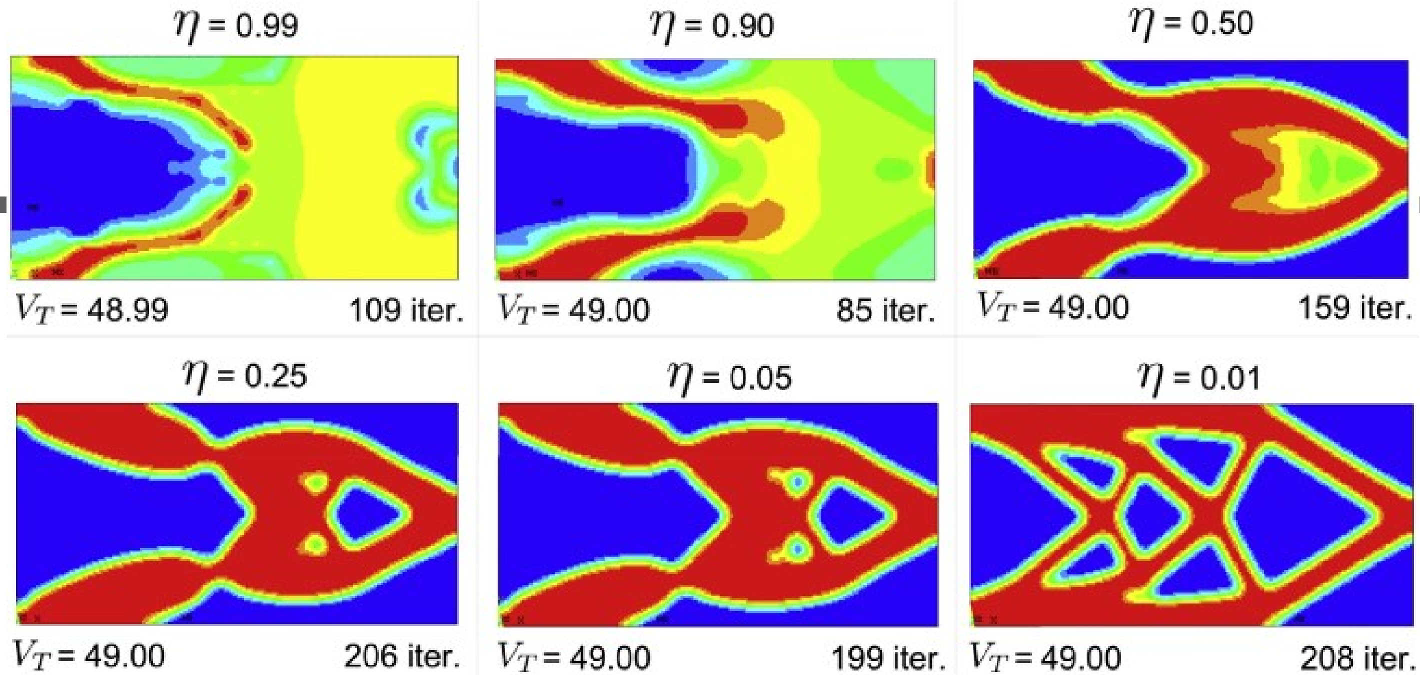
$$
\begin{aligned}
\underset{\boldsymbol{\mu}}{\text{minimize}} \quad & [C_d]_{dB}(\boldsymbol{\mu}, \omega_f), \\
\text{subject to} \quad & \mathbf{K}_D(\boldsymbol{\mu}, \omega_f)\mathbf{U}(\boldsymbol{\mu}, \omega_f) = \mathbf{P}(\omega_f), \\
& C_s(\boldsymbol{\mu}) = 100\,\frac{\frac{1}{2}\mathbf{U}_s^T(\boldsymbol{\mu})\mathbf{K}(\boldsymbol{\mu})\mathbf{U}_s(\boldsymbol{\mu})}{C_0} \le \overline{C_s}, \\
& V_T(\boldsymbol{\mu}) \le V_0, \\
& 0 \le \mu_e \le 1,
\end{aligned}
$$



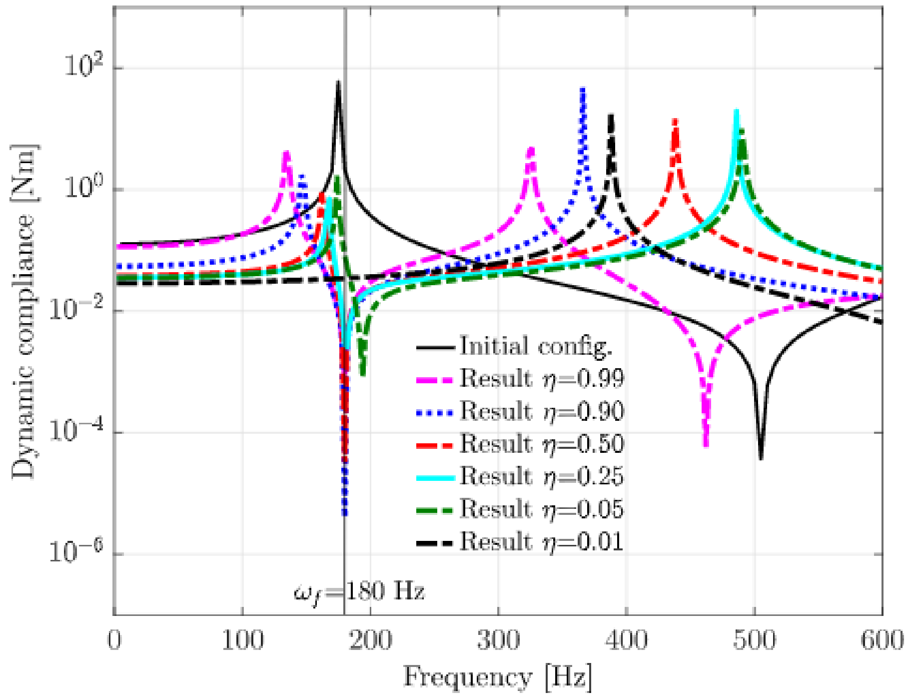






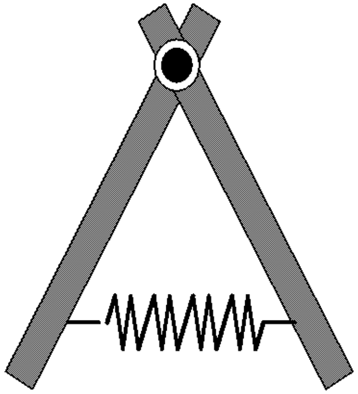


$$
\begin{aligned}
\underset{\mu}{\text{minimize}} \quad & \eta[C_d]_{dB}(\boldsymbol{\mu}, \omega_f) + [1-\eta]C_s(\boldsymbol{\mu}), \\
\text{subject to} \quad & \mathbf{K}_D(\boldsymbol{\mu}, \omega_f)\mathbf{U}(\boldsymbol{\mu}, \omega_f) = \mathbf{P}(\omega_f), \\
& V_T(\boldsymbol{\mu}) \le V_0, \\
& 0 \le \boldsymbol{\mu}(e) \le 1,
\end{aligned}
$$

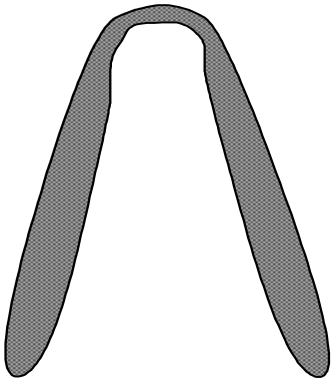


Compliant Mechanism

- Mechanisms which intentionally use the structural fle xibility as a mechanism function
- Kinematics (Flexibility) + Structure (Stiffness)
- Elastic Deformation $\Rightarrow$ Mechanical Function
- Jointless Mechanism : Less Wear, Noise, etc.
- Manufacturing with NO Assembly
  - Micro Machine, MEMS application



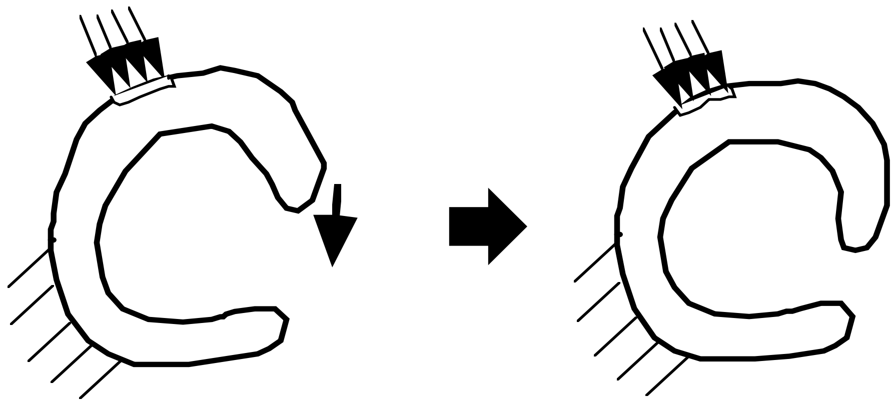
Rigid link mechanism



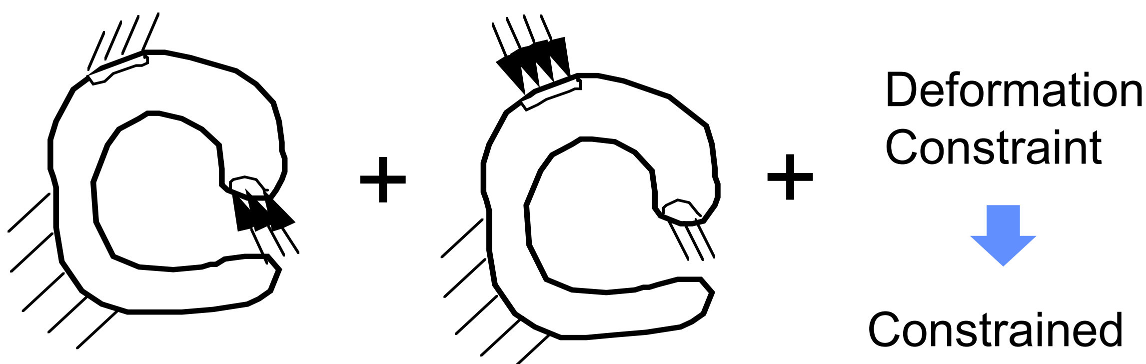
Compliant mechanism

Design of Flexible Structures

- Kinematic function → Flexibility



- Structural function → Stiffness



Reaction force

Applied force

Optimization Problem

Flexibility : Max *Mutual Mean Compliance*

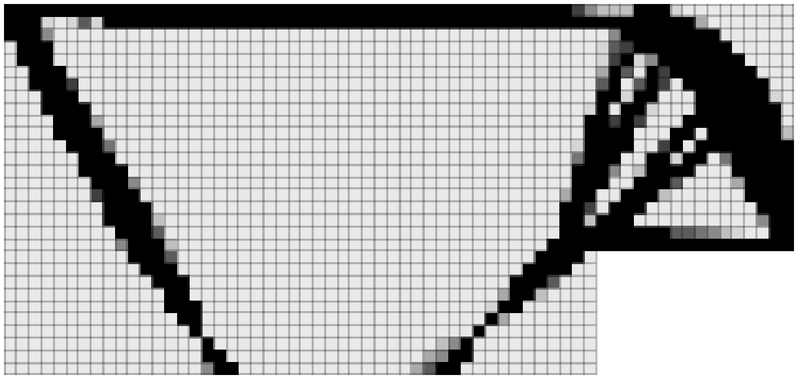
Trade-off

Stiffness : Min $\sum$ *Mean Compliance*

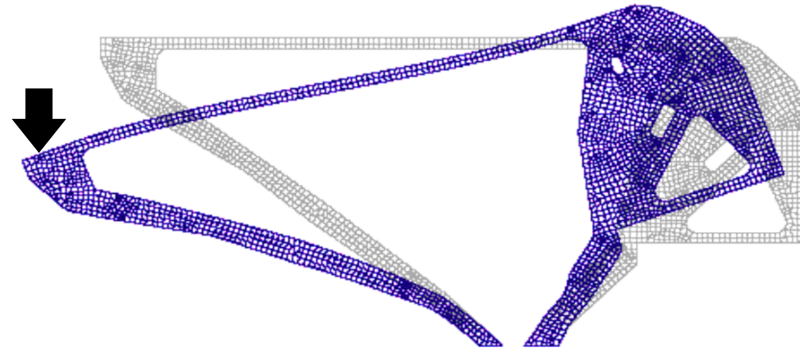
Multi-objective function: $$\underset{design}{\text{Maximize}} \frac{L^2\left(\boldsymbol{u}^1\right)}{wL^3\left(\boldsymbol{u}^3\right)+(1-w)L^4\left(\boldsymbol{u}^4\right)}$$

where *w* is the weighting coefficient such that $0 \le w \le 1$

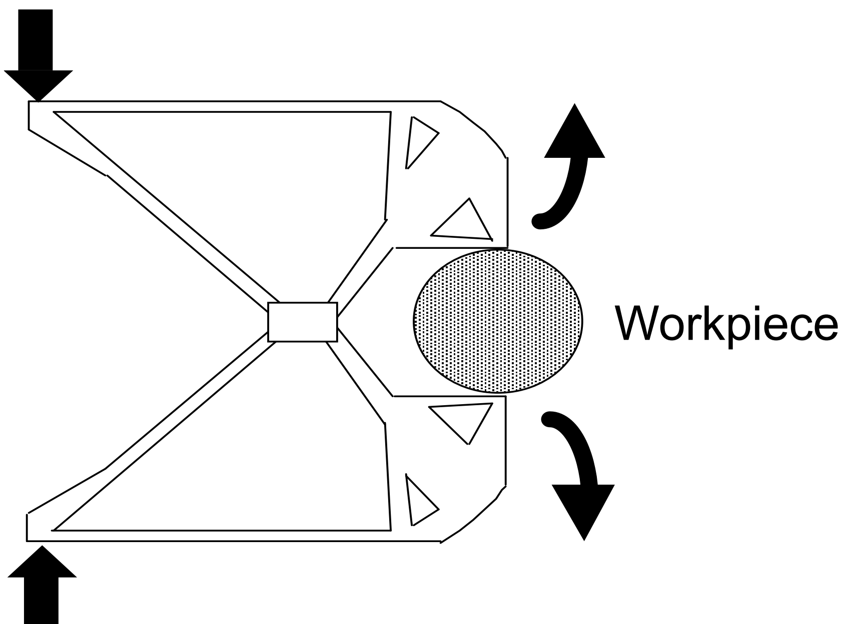
Example: Compliant Clamp

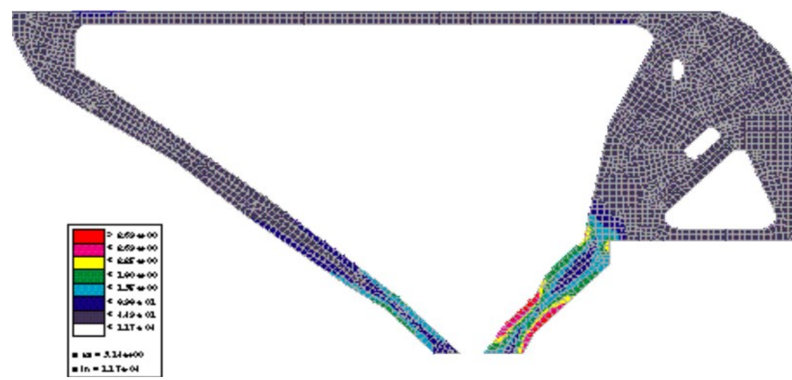


1841 QUAD4 $\Omega_s = 0.25 \times \Omega_d$



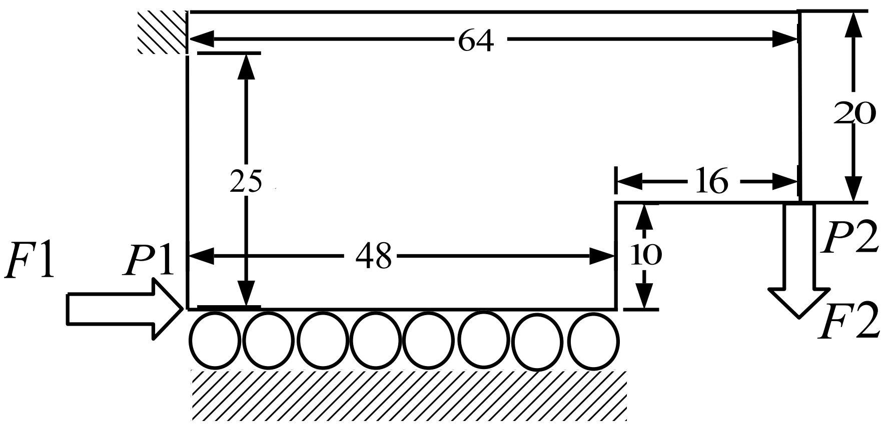
Large displacement analysis



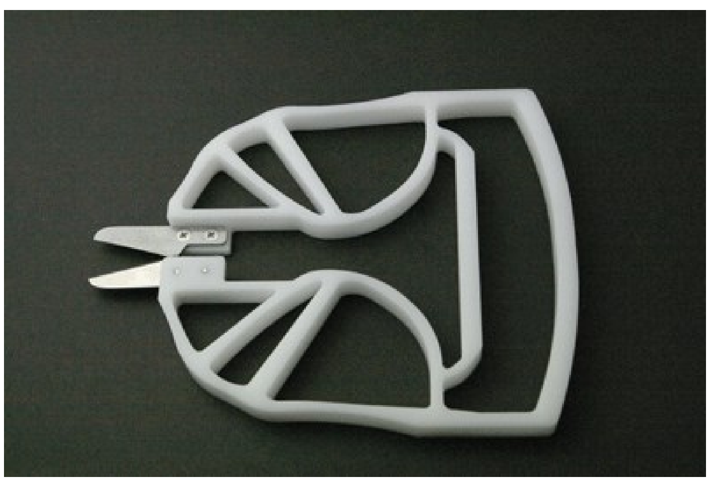


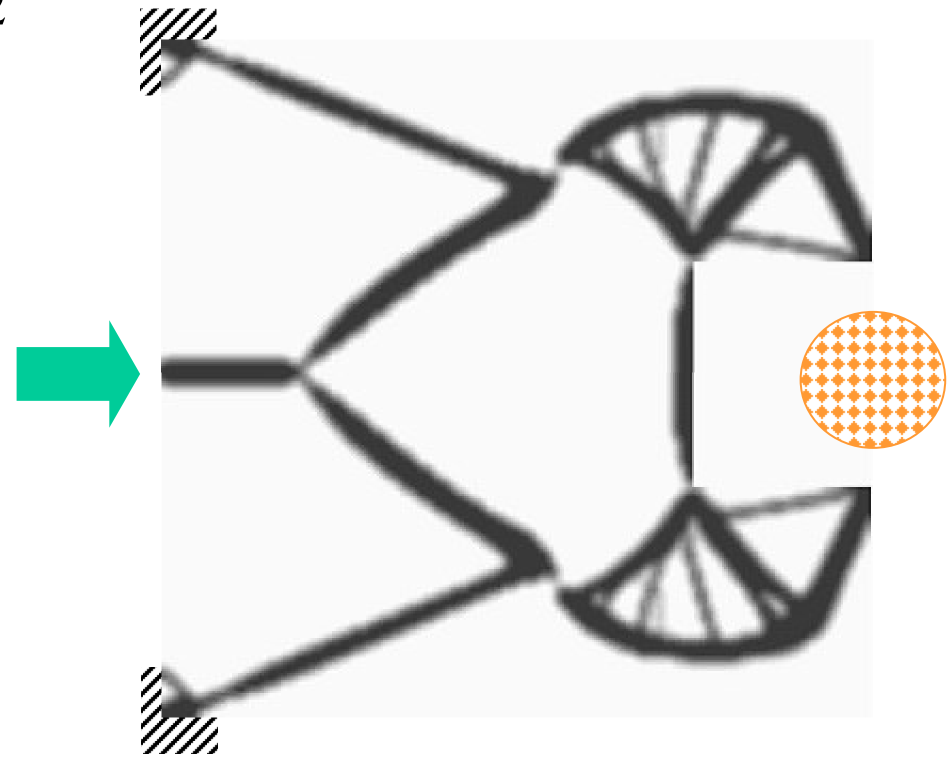
Von-Mises stress distribution

Example: Compliant Gripper



To maximize the displacement in the direction of *F2* at point *P2* when the force is applied at point *P*1.





Comparison of Analogous Properties

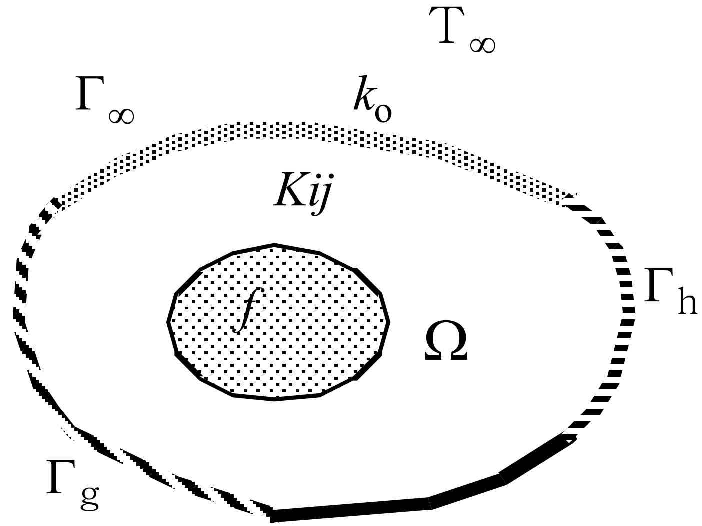
Generic Term	Discipline		
	Elasticity	Heat Conduction	Magnetostatics
Potential function	$\{u\}$	u	$\{A\}$
"Strain"	$\{\varepsilon\}$	$-\{\nabla u\}$	$\{B\}$
"Stress"	$\{\sigma\}$	$\{q\}$	$\{H\}$
Load Density	$\{p\}$	$\{Q\}$	$\{J\}$
Boundary Load	$\{t\}$	$\{q^b\}$	$H \times n$
Definition of Strain	$\{\varepsilon\} = [L]\,\{u\}$	$-\{\nabla u\}$	$\{B\} = \nabla \times \{A\}$
Constitutive Relationship	$\{\sigma\} = [D]\,\{\varepsilon\}$	$\{q\} = -[K]\,\{\nabla u\}$	$\{H\} = [\mu]^{-1}\,[B]$
Potential Energy	$\frac{1}{2}\,\{\sigma\}^T\,\{\varepsilon\}$		$\frac{1}{2}\,\{H\}^T\,\{B\}$
Equilibrium	$\Sigma\,\sigma_{ij,j} = -P_i$	$\nabla \bullet \{q\} = Q$	$\nabla \times \{H\} = \{J\}$
Inertia Loading	$\{p^i\} = -\rho\{u,_{tt}\}$	$Q^s = -\,\rho c u,_t$	

R. H. MacNeal, Finite Elements: Their Design and Performance, Marcel Dekker, 1994

Heat Transfer Problem

Conduction and convection in steady state

$$
\text{(strong form)}\begin{cases}
\dfrac{\partial}{\partial x_i}\left(K_{ij}\dfrac{\partial T}{\partial x_j}\right) = f \quad \text{in } \Omega \\
T = g \quad \text{on } \Gamma_g \\
\left(-K_{ij}\dfrac{\partial T}{\partial x_j}\right)n_i = h_i \quad \text{on } \Gamma_h \\
\left(-K_{ij}\dfrac{\partial T}{\partial x_j}\right)n_i = k_0\left(T - T_\infty\right) \quad \text{on } \Gamma_\infty
\end{cases}
$$



$$
\Rightarrow \text{(weak form)}\begin{cases}
\int_\Omega K_{ij}\dfrac{\partial T}{\partial x_j}\dfrac{\partial \tilde{T}}{\partial x_i}d\Omega - \int_\Omega f\tilde{T}\,d\Omega + \int_{\Gamma_h} h\tilde{T}\,d\Gamma - \int_{\Gamma_\infty} k_0\left(T_\infty - T\right)\tilde{T}\,d\Gamma = 0 \\
\tilde{T} = 0 \quad \text{on } \Gamma_g
\end{cases}
$$

Optimization Problem

$$\left.\begin{array}{l} \text{temperature } T \quad \leftrightarrow \quad \text{displacement } u_i \\ \text{thermal conductivity } K_{ij} \quad \leftrightarrow \quad \text{elasticity } E_{ijkl} \\ \text{heat flux } q_i \quad \leftrightarrow \quad \text{stress } \sigma_{ij} \\ \text{temperature gradient } T_i \quad \leftrightarrow \quad \text{strain } \varepsilon_{ij} \end{array}\right\} \rightarrow \begin{cases} \text{heat flux energy} \leftrightarrow \text{strain energy density} \\ \text{high conductivity structure} \leftrightarrow \text{stiff structure} \end{cases}$$

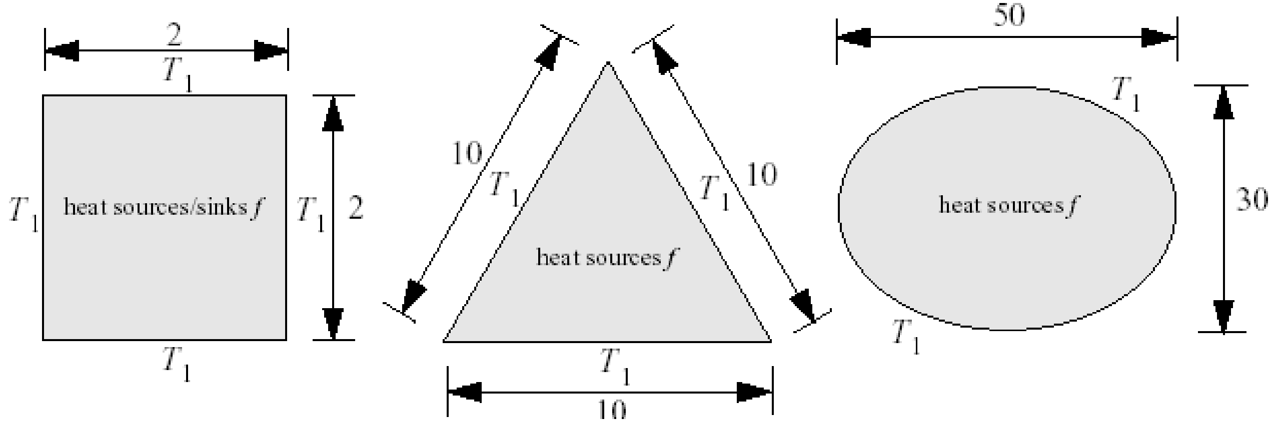
$$\underset{\substack{\textit{design} \\ \text{subject to} \\ \textit{equilibrium} \\ \textit{volume}}}{\text{minimize}} \quad \text{heat flux energy} \Rightarrow \underset{\substack{\textit{design} \\ \text{subject to} \\ \textit{volume}}}{\text{maximize}} \quad \underset{\textit{temperature}}{\text{minimize}} \quad \text{total potential energy}$$

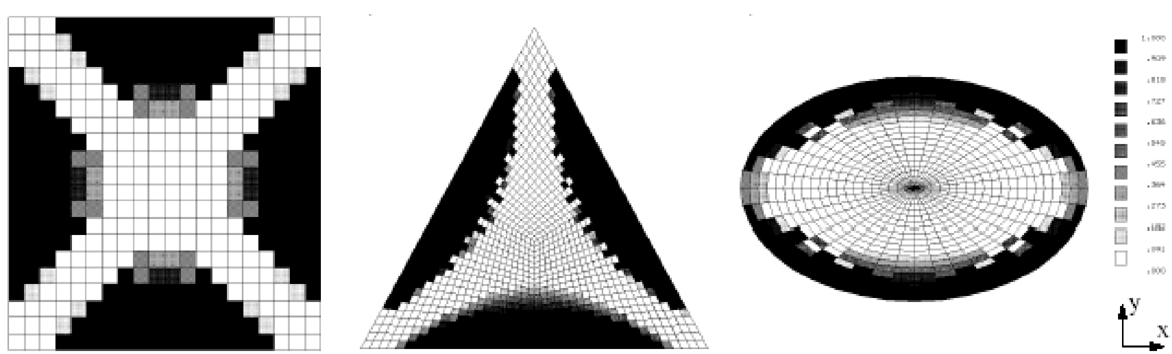
$$\underset{\substack{(a,b,\theta) \\ \text{subject to} \\ \int_\Omega \rho d\Omega \le \Omega_s}}{\text{maximize}} \quad \underset{T \in V}{\text{minimize}} \; F(T)$$

$$F(T) = \frac{1}{2}\int_\Omega K_{ij} \frac{\partial T}{\partial x_j}\frac{\partial T}{\partial x_i} d\Omega - \int_\Omega fT d\Omega + \int_{\Gamma_h} hT d\Gamma + \frac{1}{2}\int_{\Gamma_\infty} k_0 T^2 d\Gamma - \int_{\Gamma_\infty} k_0 T_\infty T d\Gamma$$

Example: Heat Sources and Sinks

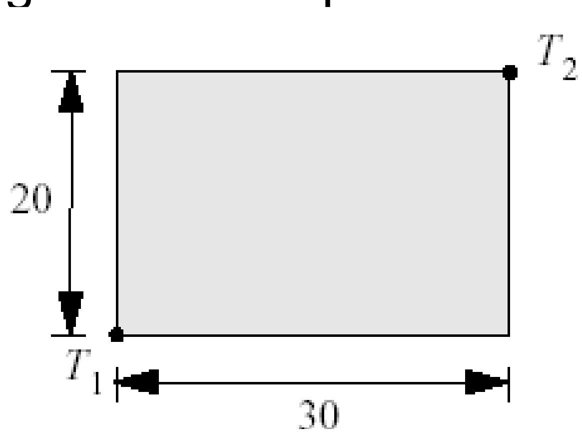
– Heat source: f = 0.2 W/m^2
– Fixed temperature: T_1 = 0 °C
– Material: k_1 = 75 W/m C (white), k_2 = 2 k_1 (black)
– Volume ratio (k_1: k_2) = 1:1
– Measure: high conductivity, integral of $| T - T_1 |$

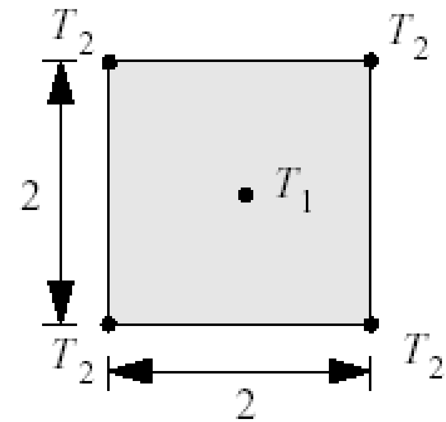


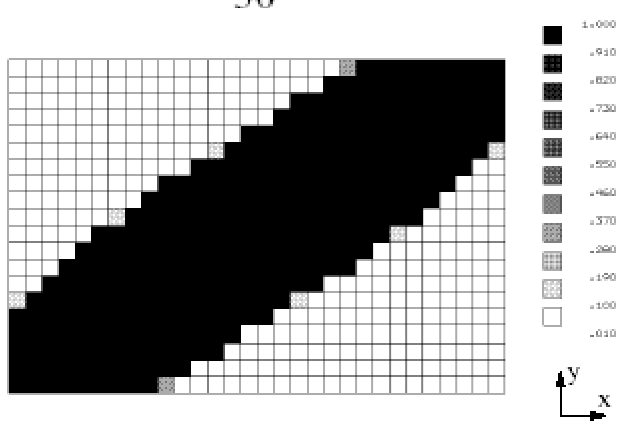


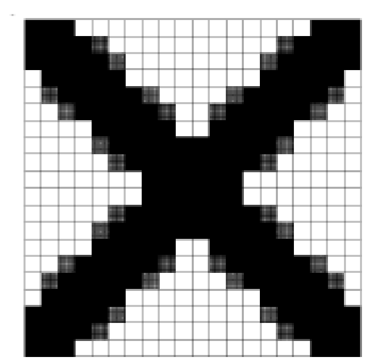
Example: Fixed Temperatures

– Fixed temperature: T_1 = 100 °C, T_2 = 0 °C
– Material: aluminum (k = 236 W/m°C) 30%
– Measure: high conductivity, amount of heat delivered from high to low temperature



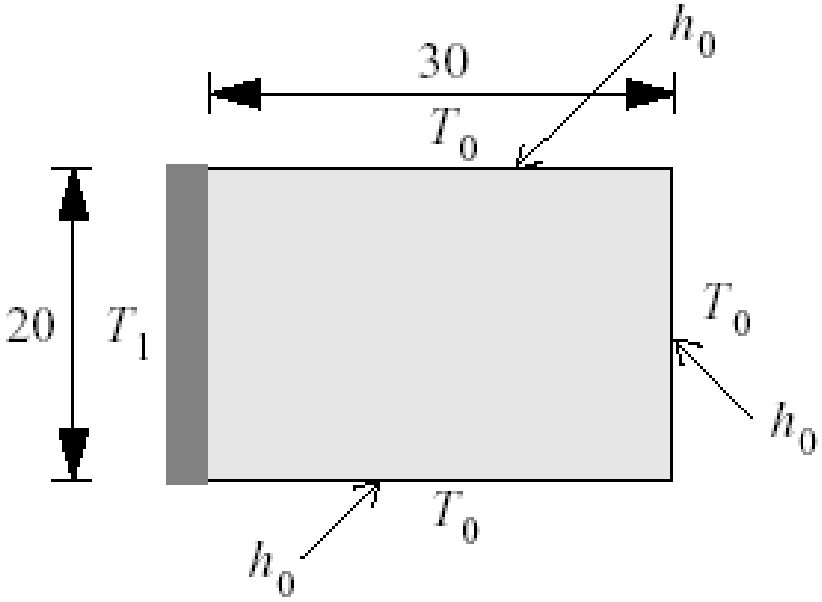


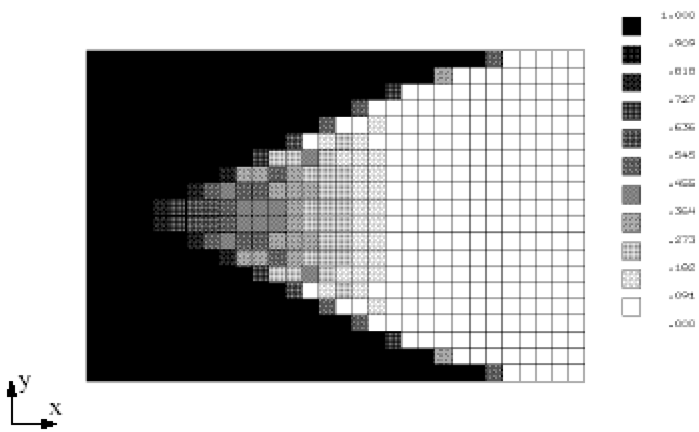




Example: Thermal Convection

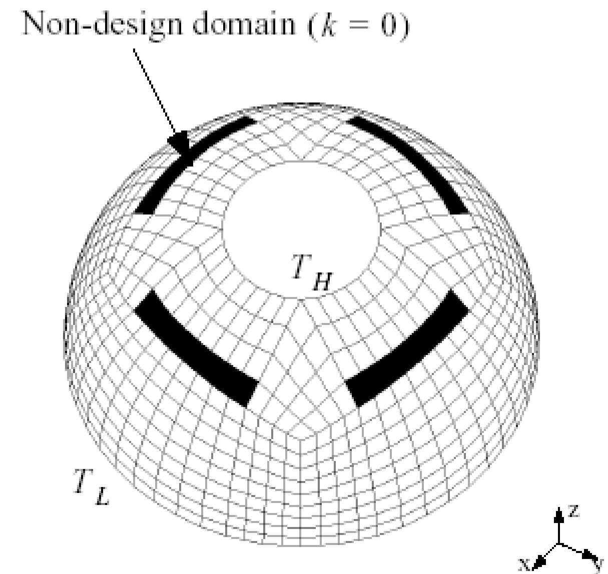
- Fixed temperature: T_1 = 100 °C, T_0 = 25 °C
- Boundary: h_0 = 5.677 W/m^2 °C
- Material: k_1 = 75 W/m°C (white), $k_2 = 2\ k_1$ (black)
- Measure: high conductivity, amount of heat transferred by convection along boundaries

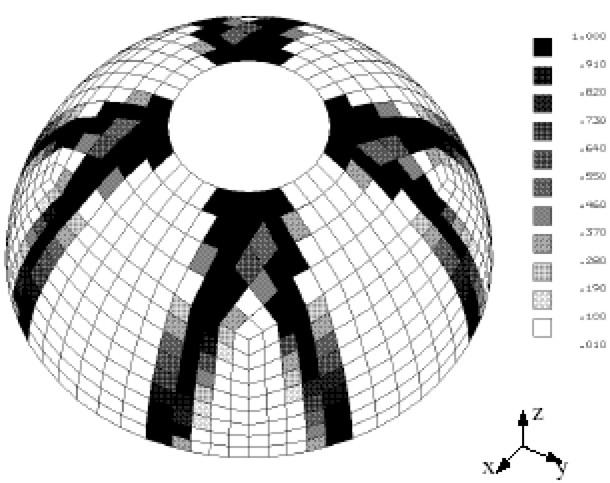


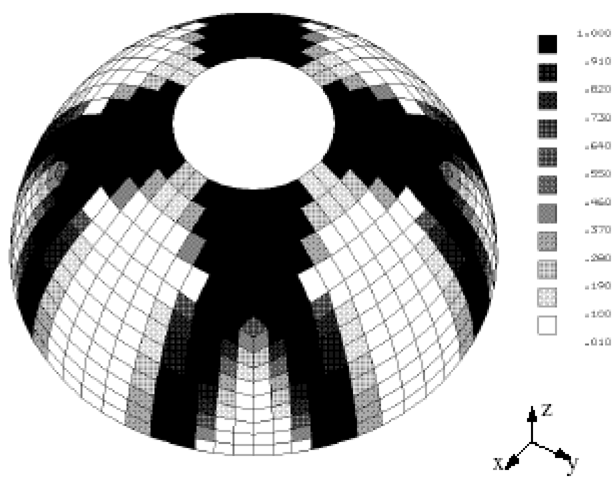


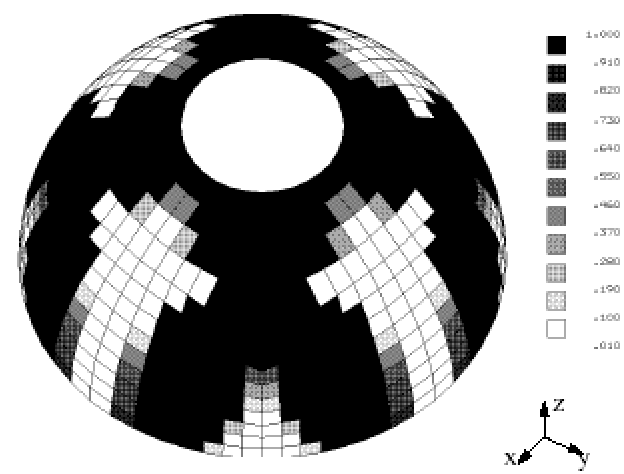
Example: Shell

- Fixed temperature: T_H = 100 °C, T_L = 0 °C
- Material: aluminum (k = 236 W/m°C)
  - 30%, 50%, 70%



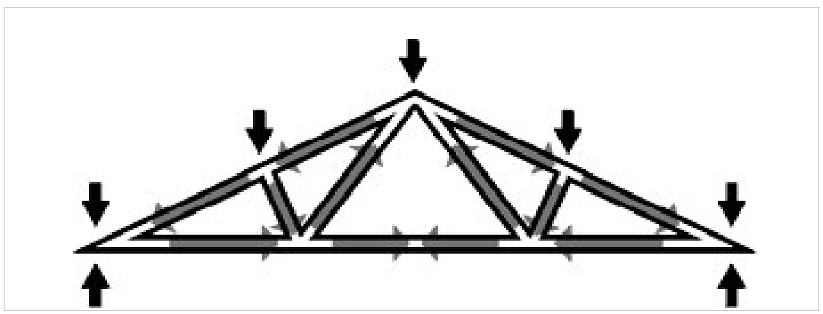




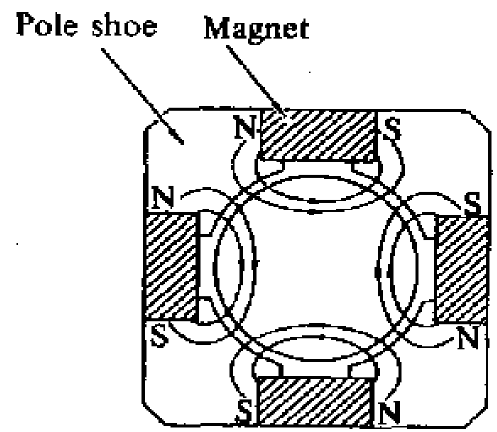


Electromagnetic Problem

– J. Yoo and N. Kikuchi, Topology Optimization in Magnetic Fields Using the Homogenization Design Method, *Int. J. Numer. Meth. Engrg*. 48, pp.1463-1479, 2000



stress distribution



magnetic flux distribution

field	by FEM	stress/flux density	constitutive Eq.
Elastic	$\boldsymbol{Ku} = \boldsymbol{F}$	$\boldsymbol{\varepsilon} = \nabla \boldsymbol{u}$	$\boldsymbol{\sigma} = \boldsymbol{E\varepsilon}$
Magnetic	$\boldsymbol{KA} = \boldsymbol{J}$	$\boldsymbol{B} = \nabla \times \boldsymbol{A}$	$\boldsymbol{H} = \frac{1}{\mu} \boldsymbol{B}$

Optimization Problem

- Magnetic energy

$$W_m = \frac{1}{2}\int_\Omega \mathbf{B}^T \frac{1}{\boldsymbol{\mu}^h}\mathbf{B}d\Omega = \frac{1}{2}\int_\Omega \mathbf{J}\cdot\mathbf{A}d\Omega = \frac{1}{2}NI\varphi$$

where $\mathbf{B}$: magnetic flux density, $\boldsymbol{\mu}^h$: homogenized magnetic permeability

$\mathbf{J}$: current density, $\mathbf{A}$: vector potential, $\mathbf{H}$: magnetic field strength

N : number of turns, I : current, φ : magnetic flux

$$(W_m)_e = \frac{1}{2}\int_{\Omega_e} \mathbf{B}_e{}^T \mathbf{M}_e^h \mathbf{B}_e d\Omega \quad \text{where } \mathbf{M}_e^h : \text{ homogenized permeability matrix}$$

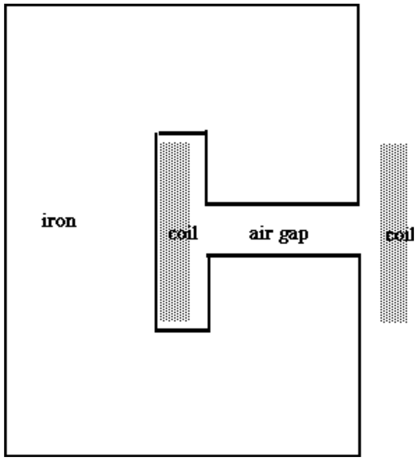
- Maximize magnetic mean compliance = maximize magnetic flux

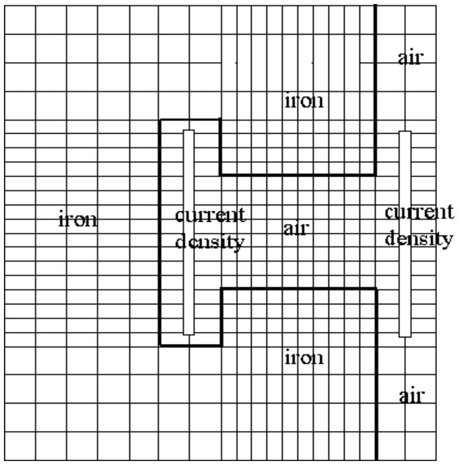
$$\boxed{\begin{array}{ll} \text{maximize} & f_{\text{MMC}} = NI\phi \\ \text{subject to} & \sum_{e=1}^{N} v_e - V \le 0 \end{array}}$$

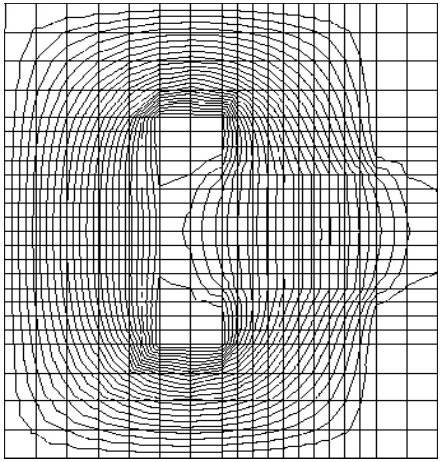
- Sensitivity considering the saturation effect

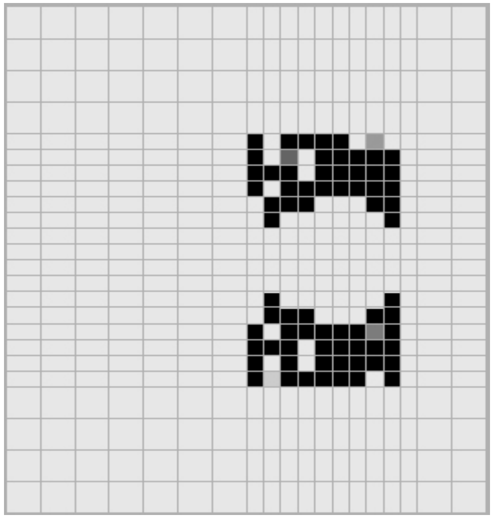
$$\frac{\partial f_{MMC}}{\partial x} = \frac{1}{2}\int_\Omega \mathbf{B}^\mathbf{T}\left[\frac{\partial}{\partial x}\frac{1}{\boldsymbol{\mu}(\mathbf{B})} + \frac{\partial}{\partial \mathbf{B}}\left(\frac{1}{\boldsymbol{\mu}(\mathbf{B})}\right)\frac{\partial \mathbf{B}}{\partial x}\right]\mathbf{B}d\Omega$$

Example: C-core

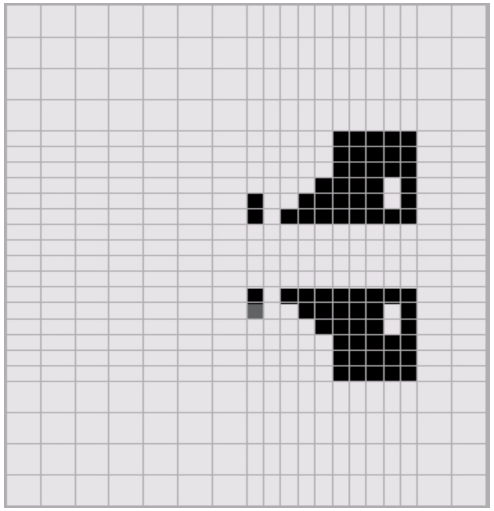








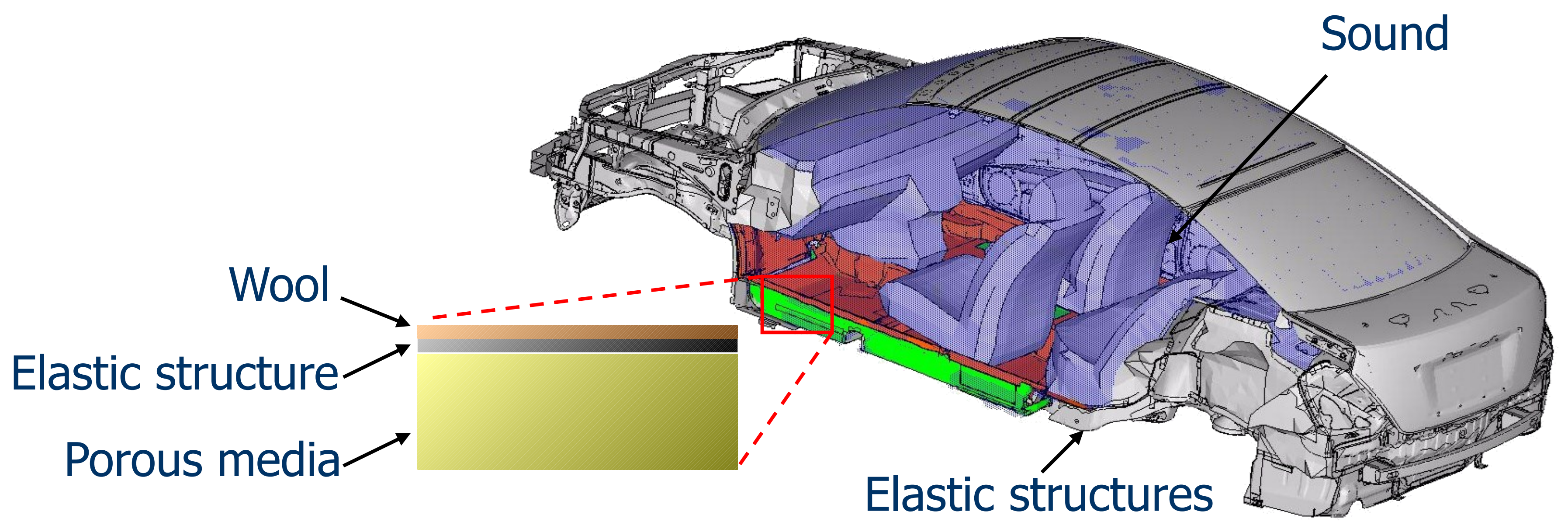
Linear case



Nonlinear case

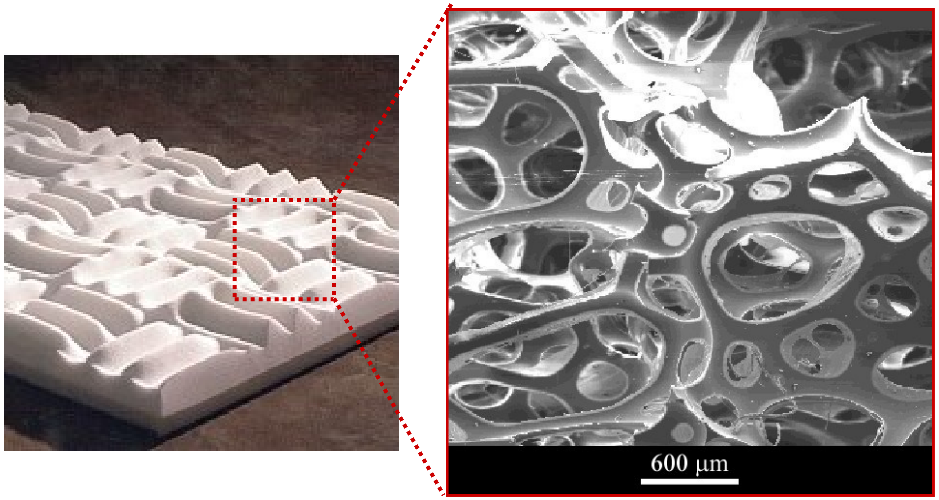
Sound-Vibrations Coupled Problems

- Sound insulation using laminated structures composed of porous media
- To obtain the optimal layout of porous media



Porous Materials

- Two phases material
  - Solid layer and liquid layer
  - Coupled problems with respect to inertias
  - Viscous damping
- Numerical analysis based on Biot's model



Porous media model

Constitutive laws

$$\begin{aligned} \sigma_{ij}^s &= [(P-2N)\varepsilon_{kk}^s + Q\varepsilon_{kk}^f]\delta_{ij} + 2N\varepsilon_{ij}^s \\ \sigma^f &= Q\varepsilon_{kk}^s + R\varepsilon_{kk}^f \end{aligned}$$

Governing equations

$$\begin{aligned} \frac{\partial \sigma_{ij}^s}{\partial x_j} + \omega^2(\rho^{sc}u_i^s + \rho^{cc}u_i^f) &= 0 \\ \frac{\partial \sigma^f}{\partial x_i} + \omega^2(\rho^{cc}u_i^s + \rho^{fc}u_i^f) &= 0 \end{aligned}$$

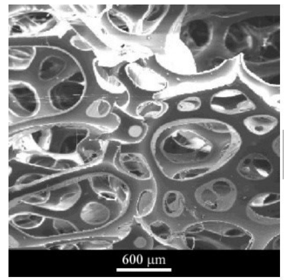
Equivalent mass density

Viscous damping

$$\begin{aligned} \rho^{sc} &= (1-\phi)\rho^s + (\alpha_\infty - 1)\phi\rho^f + \frac{\boxed{\sigma\phi^2 G_j(\omega)}}{j\omega} \\ \rho^{cc} &= -(\alpha_\infty - 1)\phi\rho^f - \frac{\sigma\phi^2 G_j(\omega)}{j\omega} \\ \rho^{fc} &= \phi\rho^f + (\alpha_\infty - 1)\phi\rho^f + \frac{\sigma\phi^2 G_j(\omega)}{j\omega} \end{aligned}$$

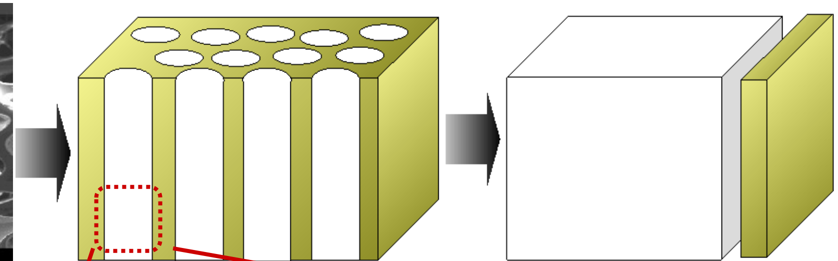
– Use of Biot' model

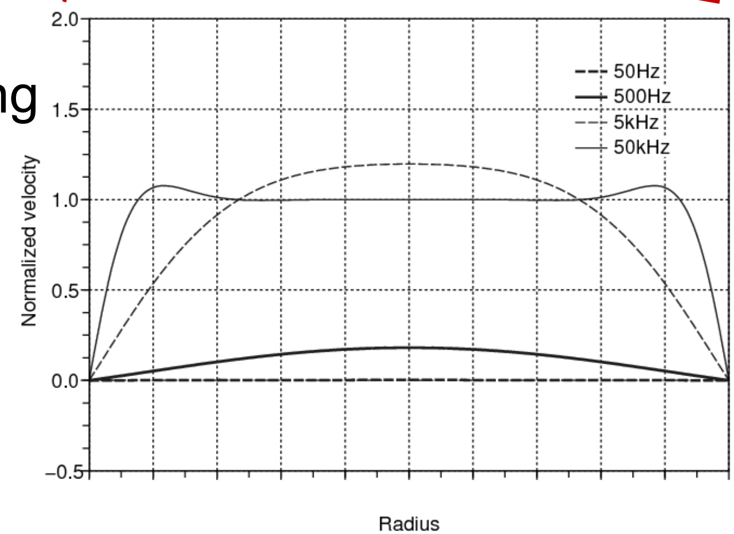
Practical microstructure



Simplified microstructures

Homogenized Properties

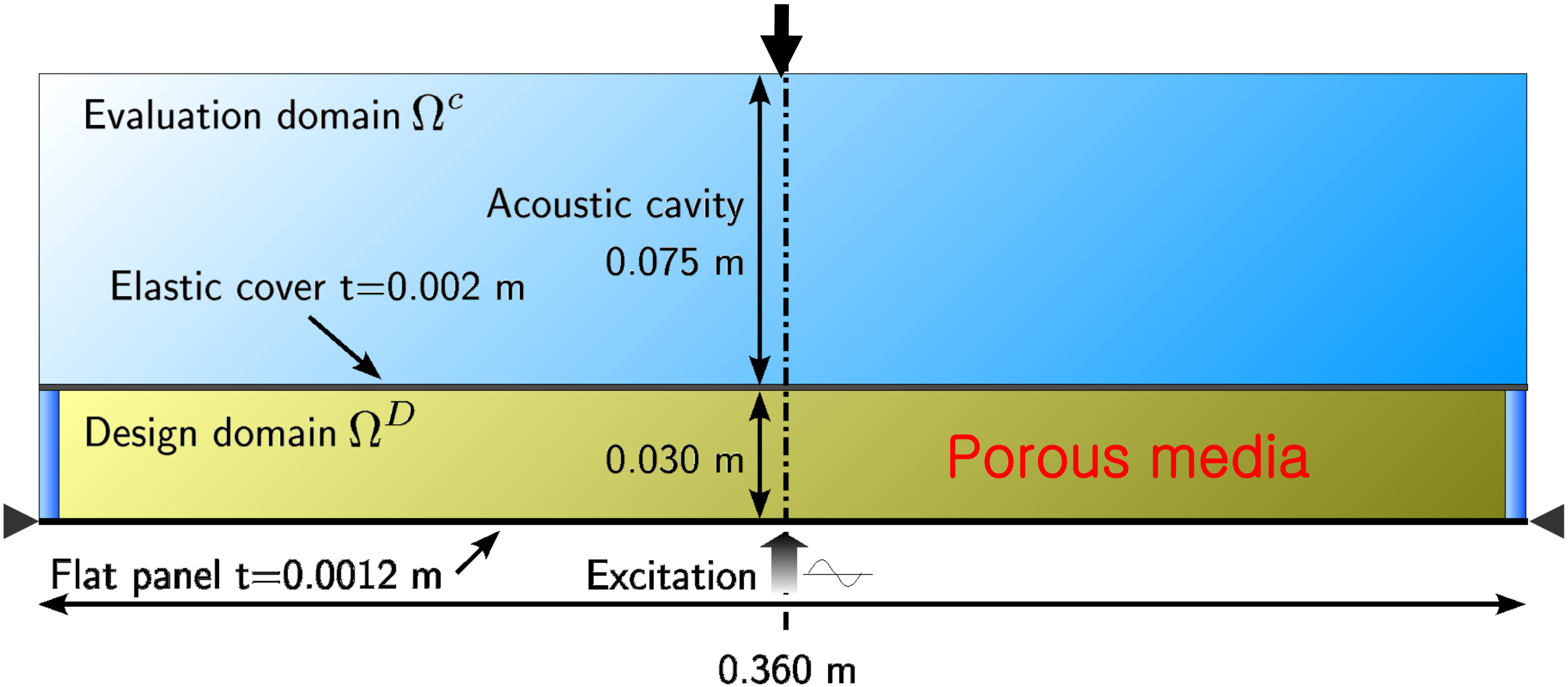




Velocity distributions in microstructures

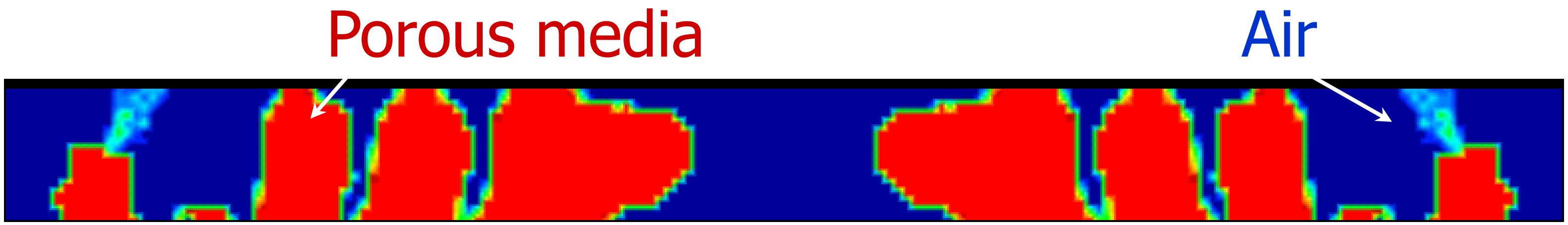
Example

To minimize sound pressure at specified frequency ranges



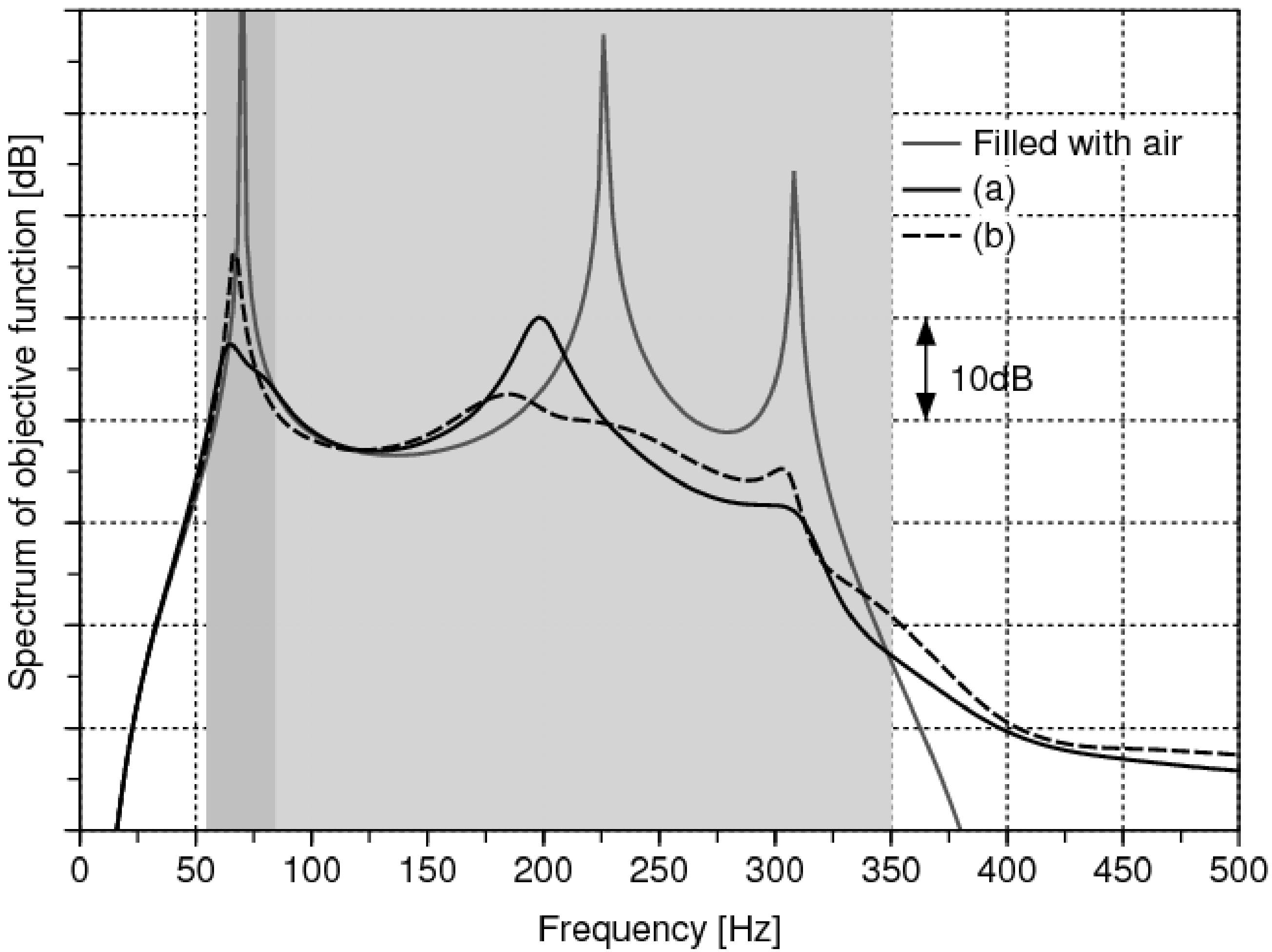
Optimal Configurations

- Volume constraint is set to 25% of total volume
  - (a) From 55 Hz through 85 Hz



  - (b) From 85 Hz through 350 Hz

Sound Pressure Response w.r.t Frequency



Additive Manufacturing

- Produce geometrically complex components layer-by-layer
- Reduce the geometric complexity restrictions imposed on topology optimization
- Make near-full use of the freeform structural evolution of topology optimization

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CSAA

A review of topology optimization for additive manufacturing: Status and challenges

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https://doi.org/10.1007/s00158-018-1994-3

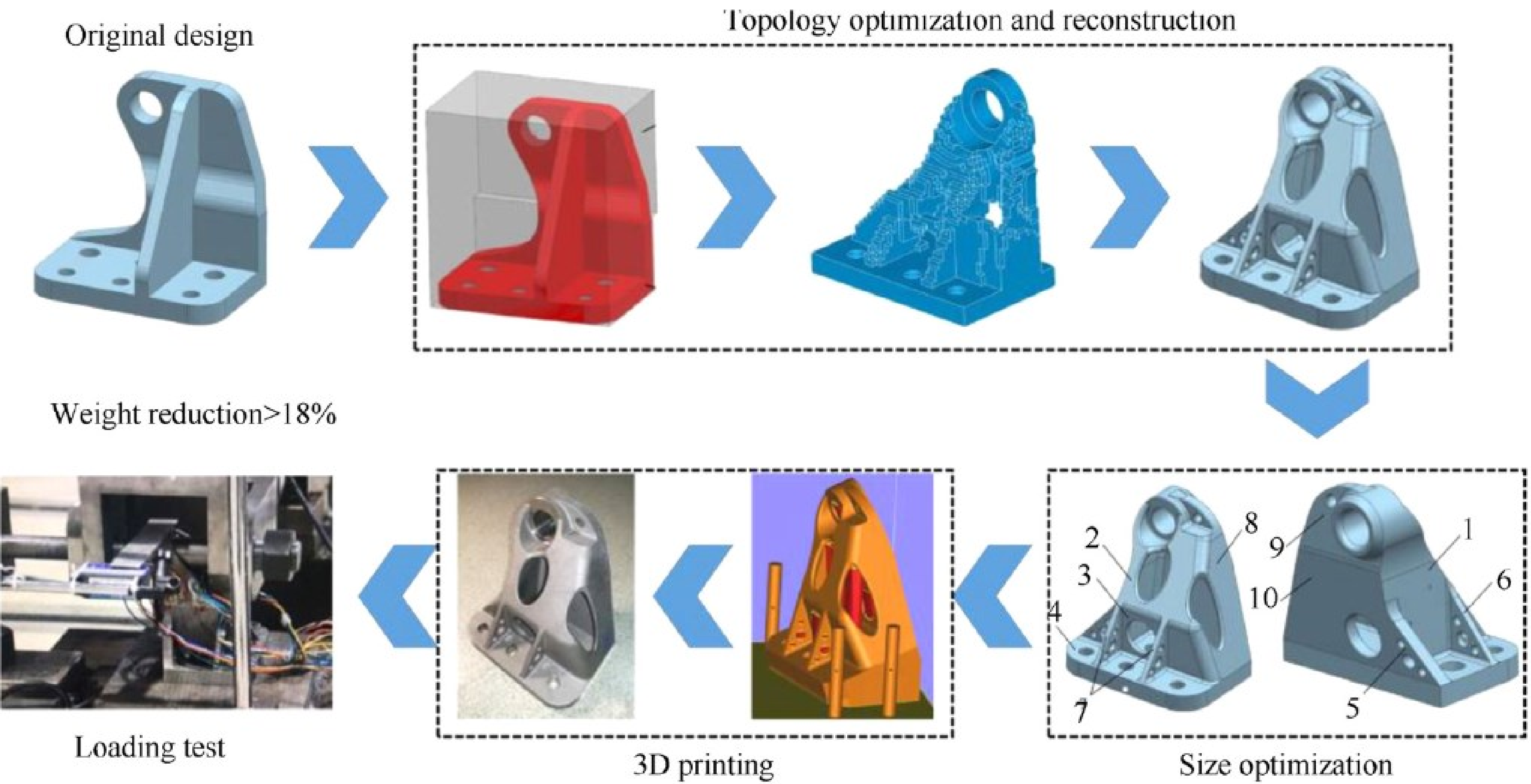
REVIEW ARTICLE

CrossMark

Current and future trends in topology optimization for additive manufacturing

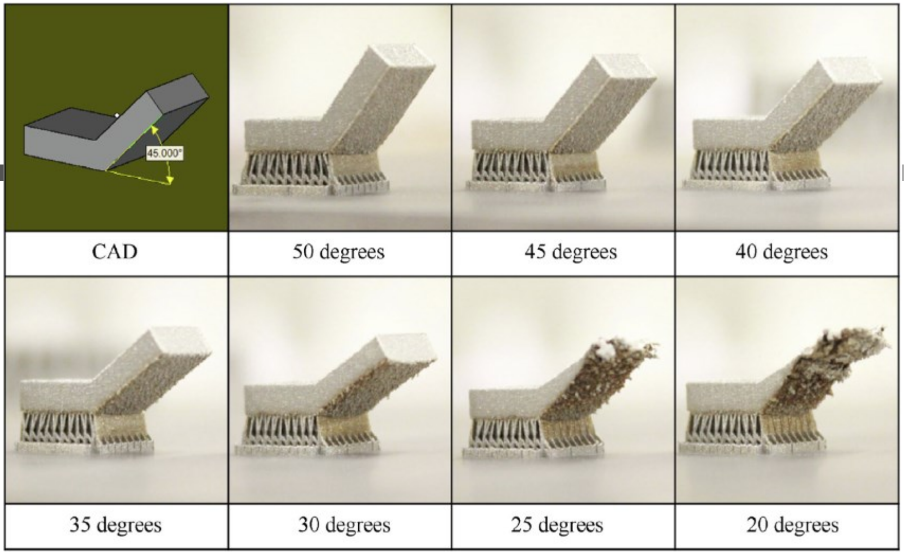
Jikai Liu [1] · Andrew T. Gaynor [2] · Shikui Chen [3] · Zhan Kang [4] · Krishnan Suresh [5] · Akihiro Takezawa [6] · Lei Li [7] · Junji Kato [8] · Jinyuan Tang [9] · Charlie C. L. Wang [10] · Lin Cheng [1] · Xuan Liang [1] · Albert. C. To [1]

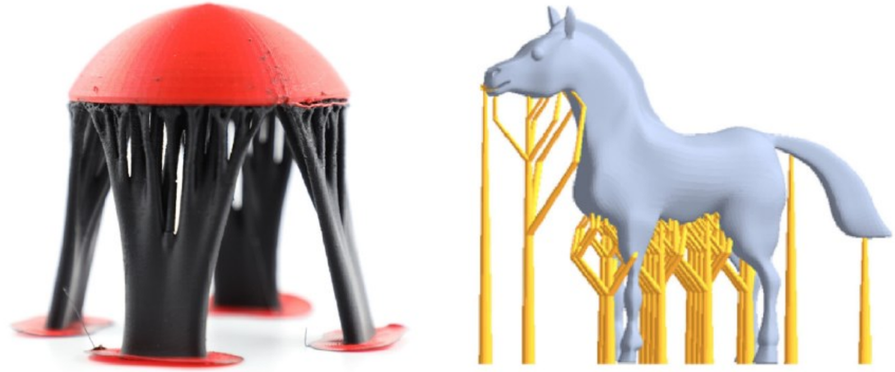
Aerospace bracket designed by topology optimization and manufactured by AM



Additive Manufacturing: Issues

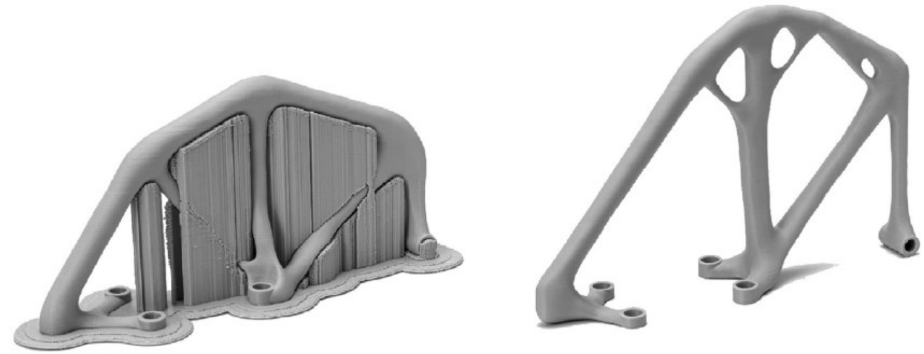
- Support structure design
  - Support slimming
  - Overhang-free topology optimization
- Porous infill design
  - Porous infill optimization
  - Lattice material optimization (meta-material optimization
- Material feature in AM
  - Material anisotropy
  - Microstructure control via topology optimization
- Multi-material and nonlinear topology optimization
  - Multi-material topology optimization
  - Nonlinear (multi-material) topology optimization
  - Topology optimization of structures with specific functionalities
- Robust design incorporating material and manufacturing uncertainties
  - Topology optimization under material uncertainty
  - Topology optimization under manufacturing uncertainty





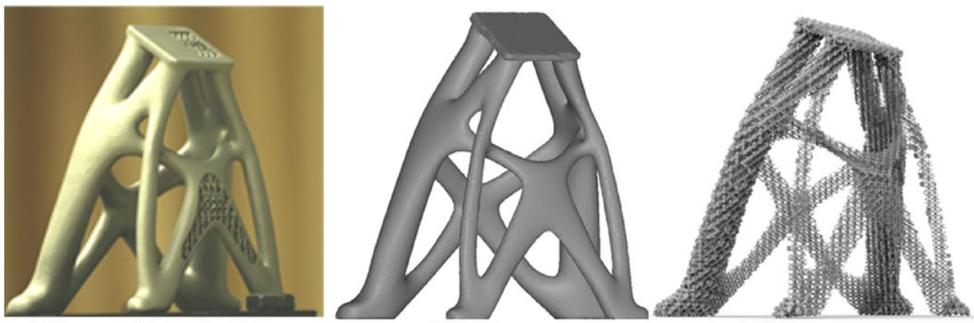
(a) Topologically optimized support[101]　　(b) Tree-like support[102]

Fig. 17 Innovative support structures.



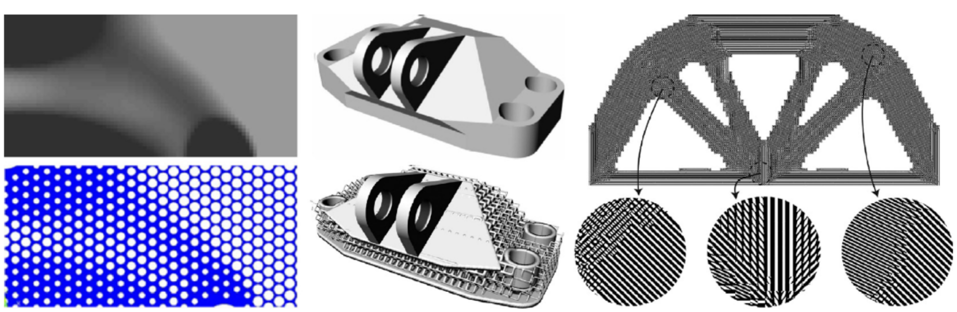
(a) Non-self-support design　　(b) Self-support design

Fig. 18 3D printed topologically optimized industrial frame.[109]



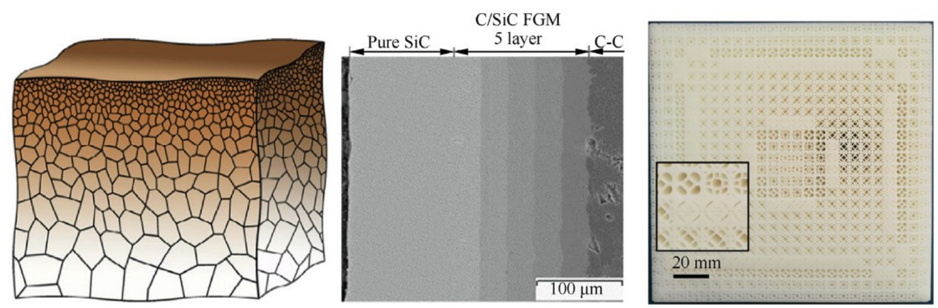
(a) Prototype fabricated by SLM　　(b) Solid structure　　(c) Lattice structure

Fig. 8 A satellite bracket filled with lattice.



(a) Optimized beam infilled with hexagonal lattice[68]　　(b) An engine bracket infilled with strut-based lattice[64]　　(c) Bi-scale design of bridge-type structure[27]

Fig. 9 Some topology optimization examples for hierarchical structures.

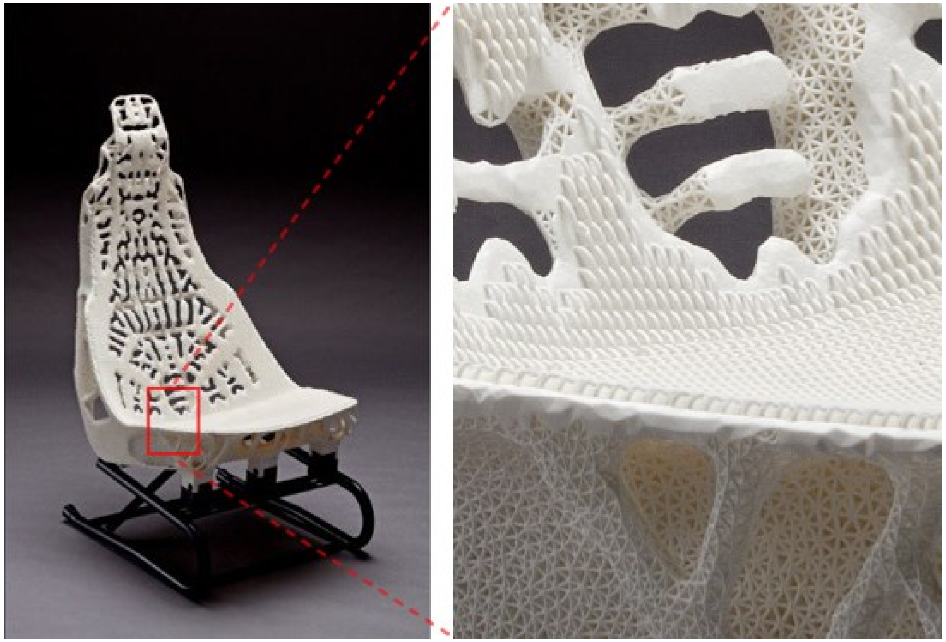


(a) A typical FGM scheme[150]　　(b) Backscattered electron image of C/SiC FGM[149]　　(c) An optimized functionally graded microstructure[151]

Fig. 24 Illustrations of FGMs.

Toyota's Lightweight Car Seat

– Challenge: create such a revolutionizing model, but manipulate and build such a large file
  - apply the 3D geometry at the slice level instead of at the STL level, and save all information about structures and textures as metadata
  - (STL) 250GB (metadata) 36MB
– Reduction: (volume) 72%, (weight) 25→7kg, (heat capacity) 35.4→14.5J/K



https://www.materialise.com/en/cases/materialise-slicing-technology-enables-toyota%E2%80%99s-lightweight-car-seat

Struct Multidisc Optim (2013) 48:1031–1055
DOI 10.1007/s00158-013-0978-6

REVIEW ARTICLE

Topology optimization approaches

A comparative review

Ole Sigmund · Kurt Maute

$$\left.\begin{aligned} \min_{\rho} &: F = F(\mathbf{u}(\rho), \rho) = \int_{\Omega} f(\mathbf{u}(\rho), \rho) dV \\ s.t. &: G_0(\rho) = \int_{\Omega} \rho(\mathbf{x}) dV - V_0 \leq 0 \\ &: G_i(\mathbf{u}(\rho), \rho) \leq 0, \ \ j = 1, \ldots, M \\ &: \rho(\mathbf{x}) = 0 \text{ or } 1, \ \forall \ \mathbf{x} \in \Omega \end{aligned}\right\}$$

$$\downarrow$$

$$\left.\begin{aligned} \min_{\rho\rho} &: F(\mathbf{u}(\rho), \rho) = \sum_i \int_{\Omega_i} f(\mathbf{u}(\rho_i), \rho_i) dV \\ s.t. &: G_0(\rho) = \sum_i v_i \rho_i - V_0 \leq 0 \\ &: G_j(\mathbf{u}(\rho), \rho) \leq 0, \ \ j = 1, \ldots, M \\ &: \rho_i = 0 \text{ or } 1, \ \ i = 1, \ldots, N \end{aligned}\right\}$$

$$\downarrow$$

$$\left.\begin{aligned} \min_{\rho\rho} &: F(\mathbf{u}(\rho), \rho) = \sum_i \int_{\Omega_i} f(\mathbf{u}(\rho_i), \rho_i) dV \\ s.t. &: G_0(\rho) = \sum_i v_i \rho_i - V_0 \leq 0 \\ &: G_j(\mathbf{u}(\rho), \rho) \leq 0, \ \ j = 1, \ldots, M \\ &: 0 \leq \rho_i \leq 1, \ \ i = 1, \ldots, N \end{aligned}\right\}$$

- Topology optimization approaches
  - Density approach
  - Topological derivatives
  - Level set approach
  - Phase field approach
- Discrete approaches
  - Evolutionary approaches
- Lagrangian approaches and combined shape and topology optimization

Comparison of methods

- Use of filtering and smoothing operators
- Convergence and density vs phase field updates
- Local vs global regularization
- Continuous vs. discrete design variables
- Optimizers
- Boundary dependent loads and critical boundary conditions
- Body fitted meshes
- Provision of research codes to the community
- Benchmark problems
- Local constraints
- On the need for level set approaches
- Lagrangian methods

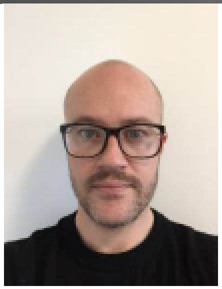
Main Challenges

- Efficiency: large scale 3D problems
- General applicability: arbitrary physics problems
- Multiple constraints
- Complex boundary conditions
- Independence on starting guess
- Few tuning parameters
- Mesh-independent convergence
- Ease of use
- Alternatives to finite element analysis
  - Finite volume methods for compressible flow problems
  - Finite difference methods for nano-optical problems

WCSMO-13: Statistics

- The 13th World Congress of Structural and Multidisciplinary Optimization
- 20th~24th May, 2019 Beijing, China
- 553 presentations (475 oral + 78 poster) in total
  - China(273), Korea(48), Japan(44), USA(43), Germany(35)
- 13 topics
  - Topology Optimization(204), Structural Optimization(40), Robust and Reliability-Based Design Optimization(32), Design Optimization(24), Multidisciplinary Design Optimization(21)

WCSMO-13: SOTA(State-of the Art) Discussion



Niels Aage
Technical University of Denmark, Denmark

Multiphysics & Multiscale design:
Achievements and Current Frontier

Wei Chen
Northwestern University, USA

Machine Learning and Data Driven Techniques:
Status and Opportunities

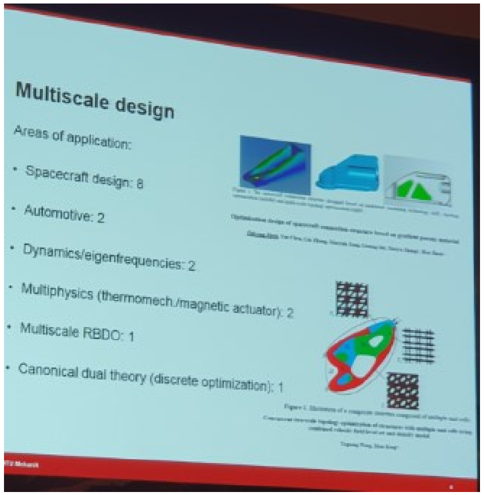
Hai Huang
Beihang University, China

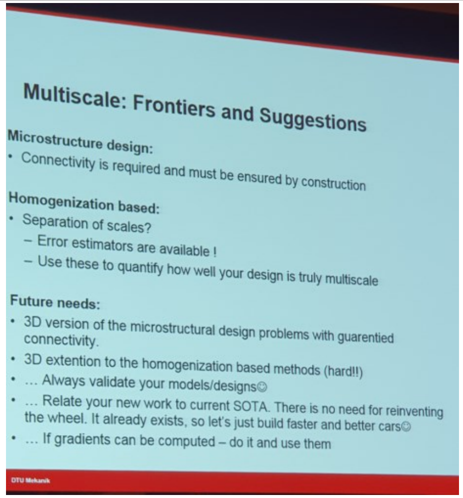
Promote the service of Topology Optimization for Layout Design of Engineering Structural Systems

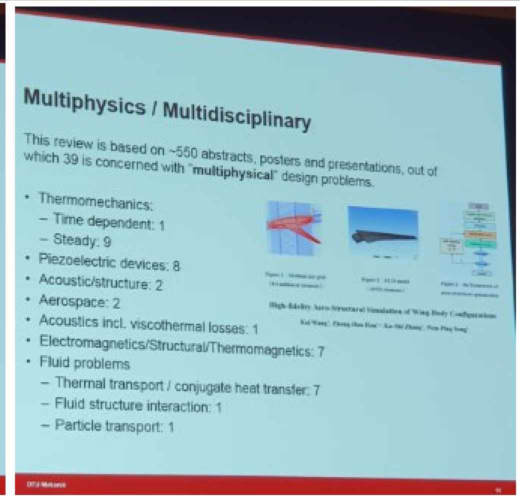
Yoshihiro Kanno
The University of Tokyo, Japan

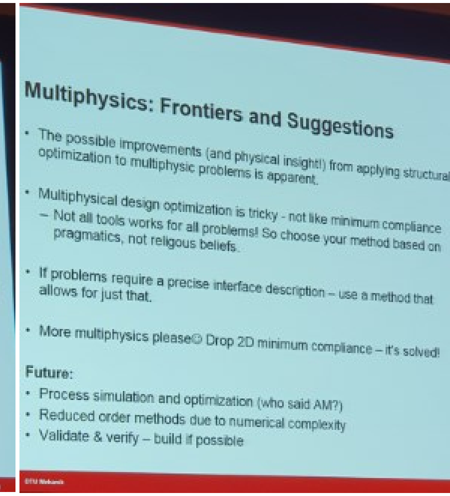
Reliability- and Robustness-Based Design

Multiphysics & Multiscale design: Achievements and Current Frontier





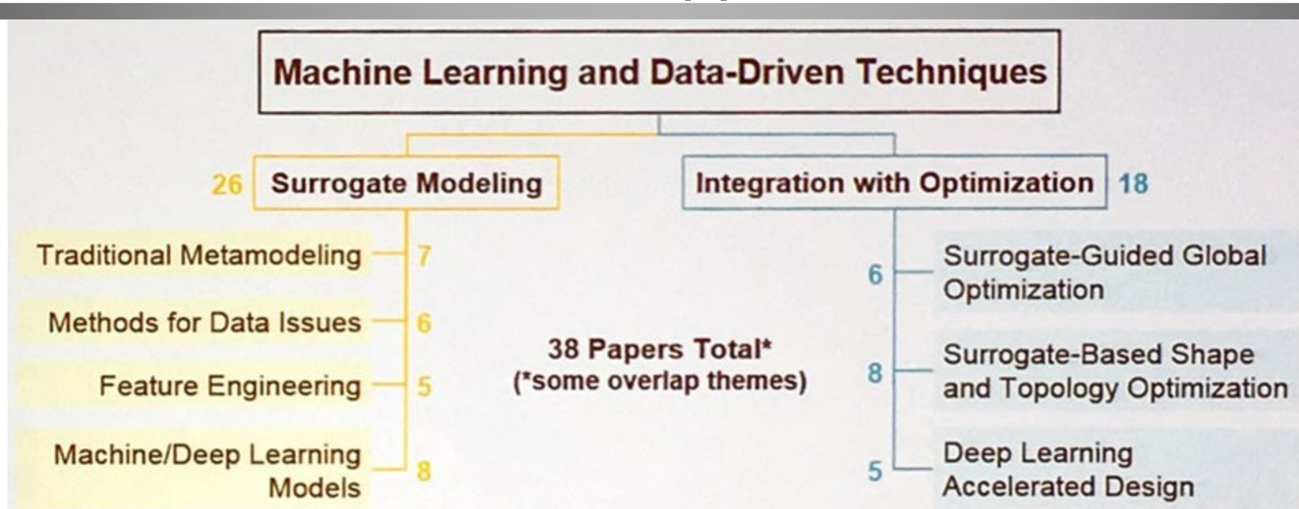




Presentations: multiscales (60), multiphysics (39)

- Discussions
  - Fluid-Structure for large Reynolds number
  - CAD-CAE interaction
  - Benchmarking problem

Machine Learning and Data Driven Techniques: Status and Opportunities



Metamodeling

- Metamodeling will continue to play an important role in SMO with expensive physics-based simulations, for managing information complexity (multiscale/multicomponent/multidiscipline), and for solving inverse problems.
- Choice of metamodeling techniques and sampling decisions need to be integrated and viewed as a resource allocation problem.

Machine learning/deep learning

- Machine learning/dimension reduction helps to gain knowledge and draw insights into physical relations associated with geometry.
- The use of deep learning needs to be justified.
- Physics-based machine learning and transfer learning are needed to make ML practically useful.
- Benefits of using ML-based TO over traditional TO methods need to be further studied (Nonlinear? Multiscale? Hybrid?). Community needs good benchmark problems.

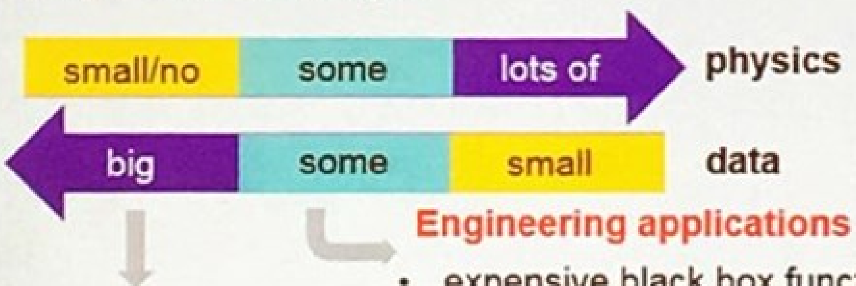
Machine Learning and Data Driven Techniques: Status and Opportunities

Pros

- ML models are fast to evaluate.
- They can capture highly nonlinear behavior.
- They can handle high dimensional inputs such as images.
- No explicit domain knowledge is required.

Cons

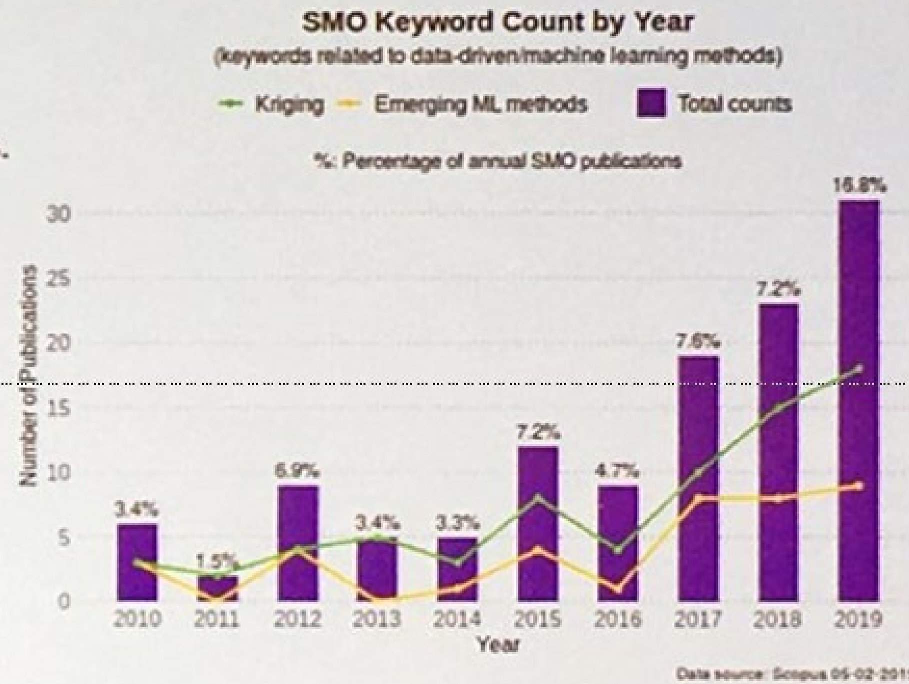
- ML models are difficult to train.
- They are in general only as good as the data.
  - Large amount of high quality data are desired.
- They are hard to interpret.



many CS applications of ML

Engineering applications

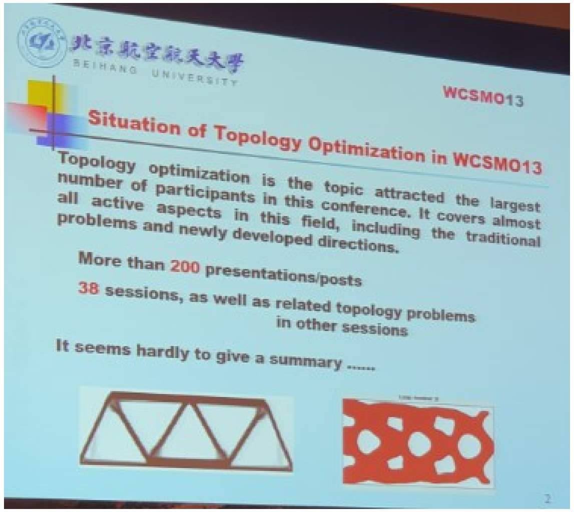
- expensive black box functions
- insufficient data
- some known physics



Research on applying data-driven/machine learning methods in SMO is growing in recent years.

*Up to 05/02/2019, SMO has 184 publications in 2019.

Promote the service of Topology Optimization for Layout Design of Engineering Structural Systems

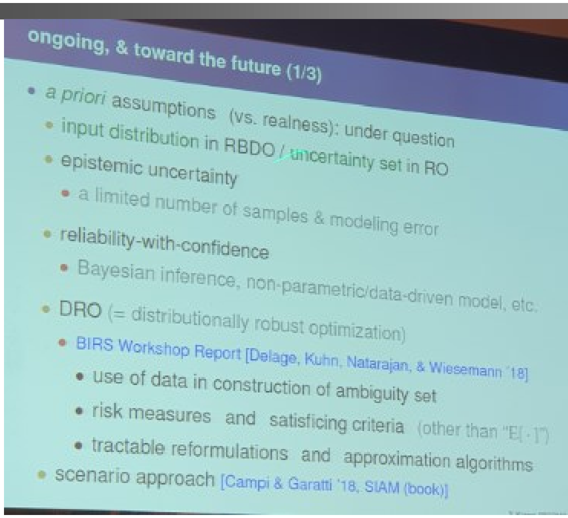


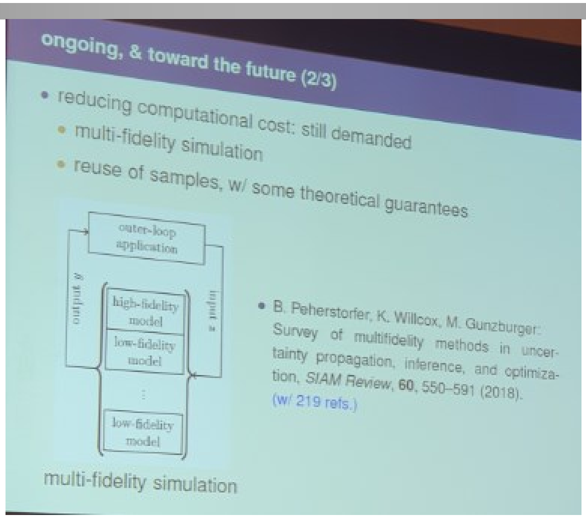
Presentations: TO (200+ presentations, 38 sessions)

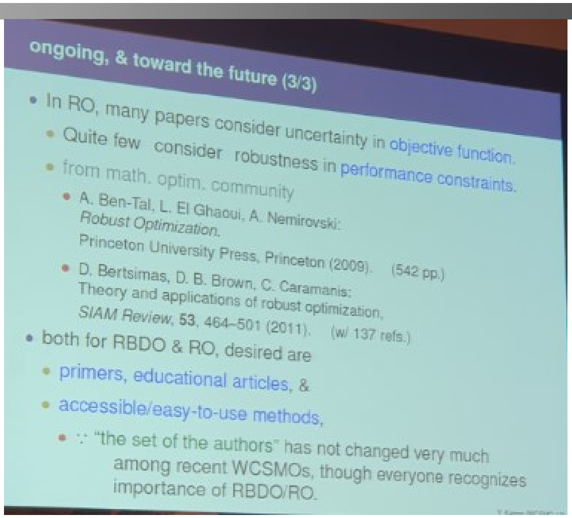
AM (60+), Explicit (30+), Multiscale(30+), Stress (20+), Large scale (20+), {IGA, ML, MMTO, Multiphysics, Shell, Mathematical/Numerical} (10+)

- Discussions
  - Stress problem
  - Benchmarking problem

Reliability and Robustness Based Design







Presentations: 70 (East Asia 47)

- Discussions
  - Only a few group
  - Modeling uncertainty