COMSOL CONFERENCE 2016 SHANGHAI

同濟大學 TONGJI UNIVERSITY

LUMPED ELEMENT MULTIMODE MODELING BALANCED-ARMATURE RECEIVER WITH COMSOL

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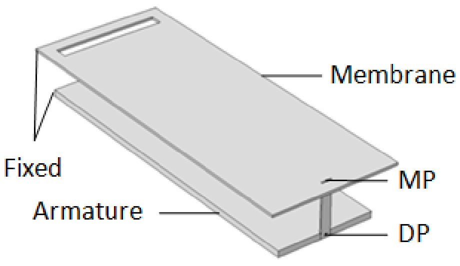
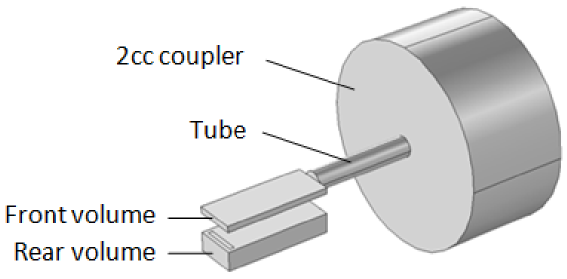
1 Background| Significance

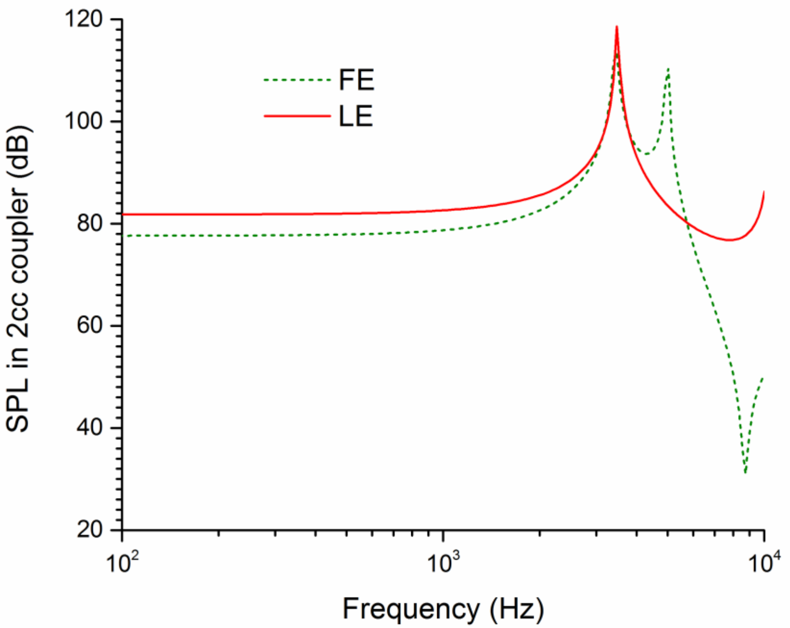
Lumped element (LE) models normally used for balanced-armature receiver (BAR) are mainly based on the fundamental mode of its mechanical structure. For the lack of higher-order modes, they may be insufficient to predict the system of BAR.



(a) Mechanical domain



(b) Acoustic domain



1 Background| Known solutions

FE aided LE modeling method

Disadvantage: time-consuming, complicated, not conveniently applied to engineering application

Full FE modeling method

Disadvantage: time-consuming, not applied to engineering application

Integrated FE-LE modeling method

Disadvantage: improved but still a little time-consuming, not applied to engineering application

1 Background| Proposed solution

Step1

MDOF → SDOF

Decoupled the discretized MDOF mechanical structure of BAR into a set of SDOF systems.

Step2

Mode truncation

using the criterion of energy norm.

Mode selection

with DC gains.

Step3

Development of LE multimode model for BAR

using the determined dominant modes.

2 Review of modal analysis

Input :
Original continuous mechanical structure

1. **Input:** Original continuous mechanical structure

2. **Discretized into MDOF undamped vibration system**

$$-\omega^2 \mathbf{M}\mathbf{X}(\omega) + \mathbf{K}\mathbf{X}(\omega) = \mathbf{F}(\omega)$$

3. **Eigenvalues and eigenvectors**

$$\mathbf{K}\boldsymbol{\varphi}_r = {\omega_r}^2 \mathbf{M}\boldsymbol{\varphi}_r$$

4. **Diagonalization i.e. decompostion, MDOF→SDOFs**

$$([k_r] - \omega^2 [m_r])\mathbf{Q} = \boldsymbol{\Phi}^T \mathbf{F}(\omega)$$

$$[k_r] = \boldsymbol{\Phi}^T \mathbf{K} \boldsymbol{\Phi} \text{ and } [m_r] = \boldsymbol{\Phi}^T \mathbf{M} \boldsymbol{\Phi}$$

$$\mathbf{Q} = [q_1(\omega) \quad q_2(\omega) \quad \cdots \quad q_N(\omega)]^{\mathrm{T}}$$

5. **Response based on mode superposition**

$$x_l(\omega) = \sum_{r=1}^{N} \phi_{lr} q_r \qquad q_r = \frac{\phi_{pr} f_p(\omega)}{k_r - \omega^2 m_r}$$

6. **Output:** Equivalent LE parameters of SDOF

$$k_{er} = \frac{k_r}{\phi_{lr}\phi_{pr}} \qquad m_{er} = \frac{m_r}{\phi_{lr}\phi_{pr}}$$

$$f_{er} = f_p(\omega)$$

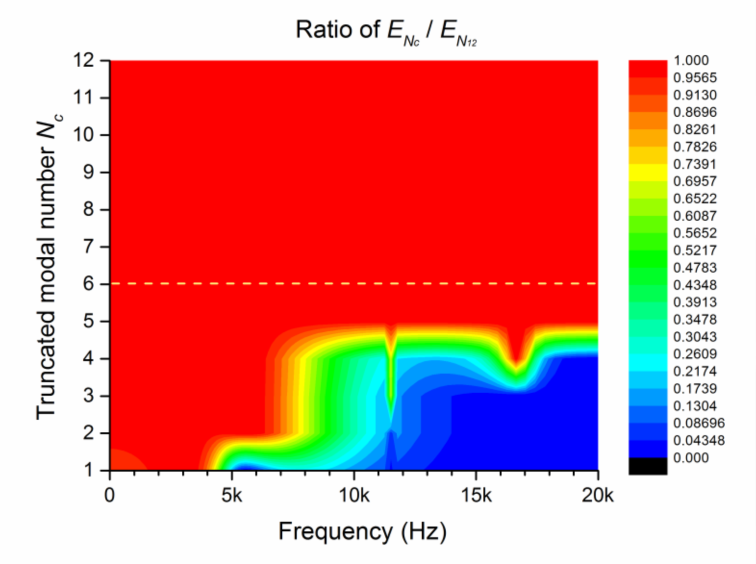
Output:
Equivalent LE parameters of SDOF

3 LE multimode parameters | Mode truncation and selection

Mode truncation based on the criterion of energy norms: **first 6 modes should be enough**

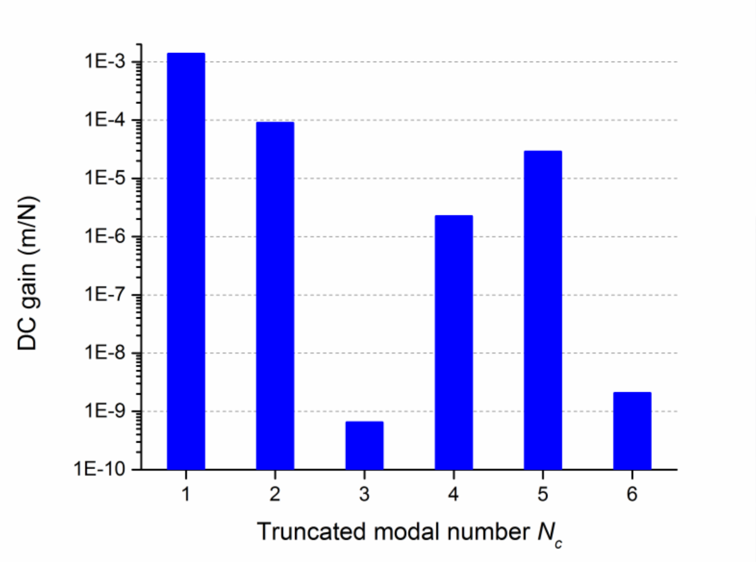
$$E_{N_c} = \left\|\mathbf{J}_{N_c}\right\|^2 + \left\|\mathbf{J}^*_{N_c}\right\|^2$$

$$\left\|\mathbf{J}_{N_c}\right\| = \sqrt{\frac{1}{2}\sum_{i=1}^{N_c} k_i {q_i}^2} \quad \left\|\mathbf{J}^*_{N_c}\right\| = \sqrt{\frac{1}{2}\sum_{i=1}^{N_c} m_i {q_i}^2}$$



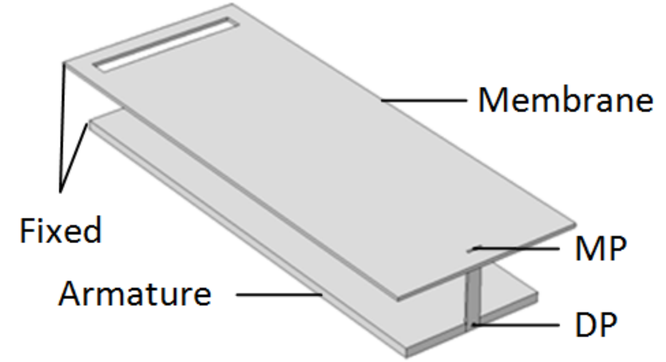
Mode selection with DC gains: **1st, 2nd, 4th, and 5th are dominant**

$$(\text{DC gain})_r = \frac{\phi_{pr}\phi_{lr}}{k_r}$$



3 LE multimode parameters | Equivalent parameters of selected modes

Equivalent LE multimode parameters for the mechanical structure of BAR are determined in terms of the measure point (MP) and input point (DP).



Mechanical domain of BAR

Equivalent parameters of the four dominant modes with respect to MP.

Selected mode	Resonance (Hz)	m_{er} (kg)	k_{er} (N/m)	Load gain
1^{st} mode: M1	2,958	2.11E-06	727	1
2^{rd} mode: M2	5,568	9.15E-06	11,191	1
4^{th} mode: M4	16,694	4.07E-05	447,796	1
5^{th} mode: M5	20,724	2.05E-06	34,810	1

4 LE multimode modeling

Two equations for mechanical and acoustic domains

$$F_{em,r} = \left(j\omega m_{er} + \frac{1}{j\omega/k_{er}}\right) v_{MP,r}$$

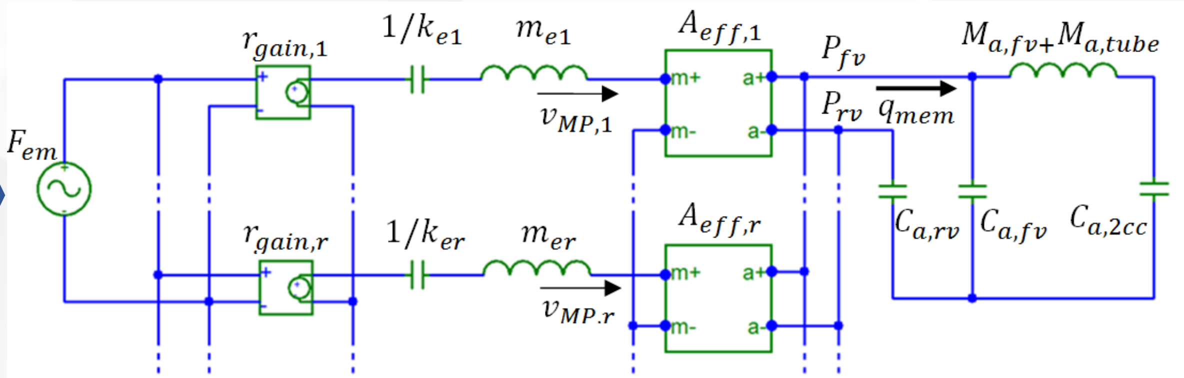
$$P = Z_a q_{mem}$$

Coupling relations between two domains

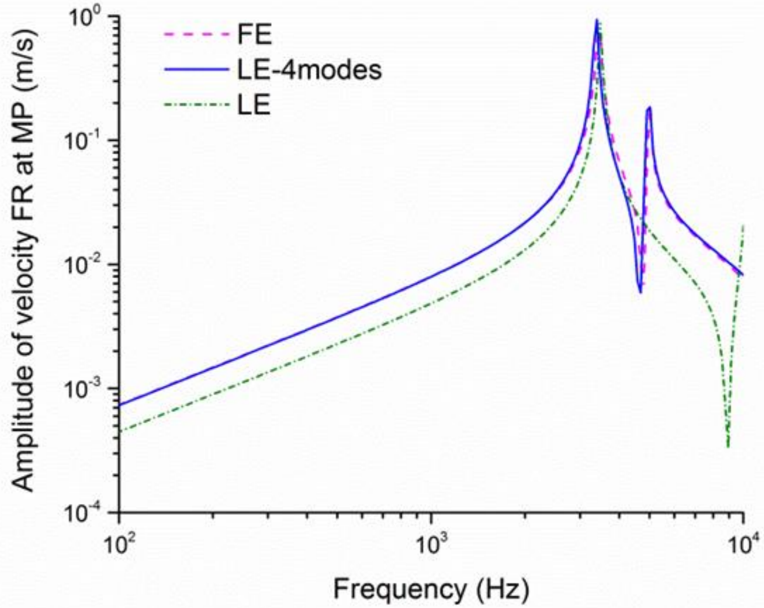
$$q_{mem,r} = A_{eff,r} v_{MP,r}$$

$$F_{mem,r} = (P_{fv} - P_{rv}) A_{eff,r}$$

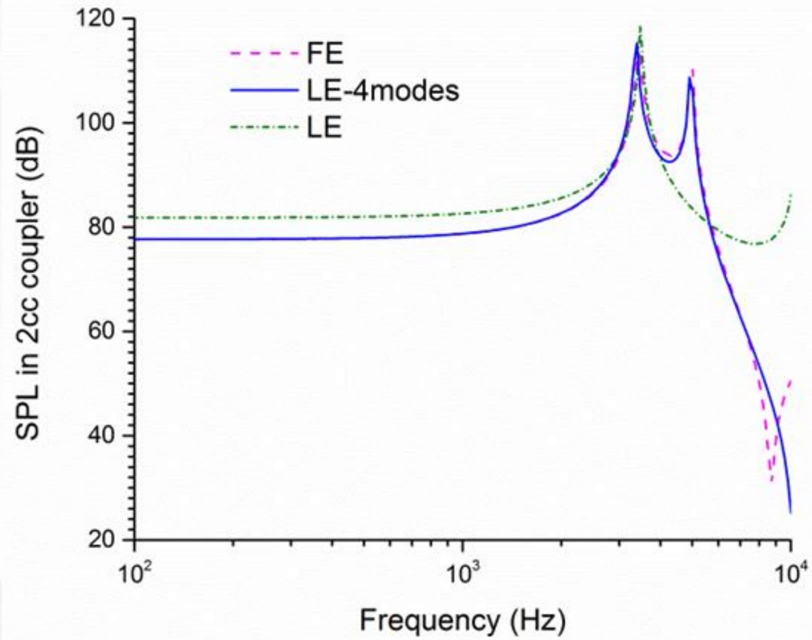
Equivalent circuit of LE multimode model for BAR



5 Results and analysis| Compare with full FE model



(a) Velocity at MP



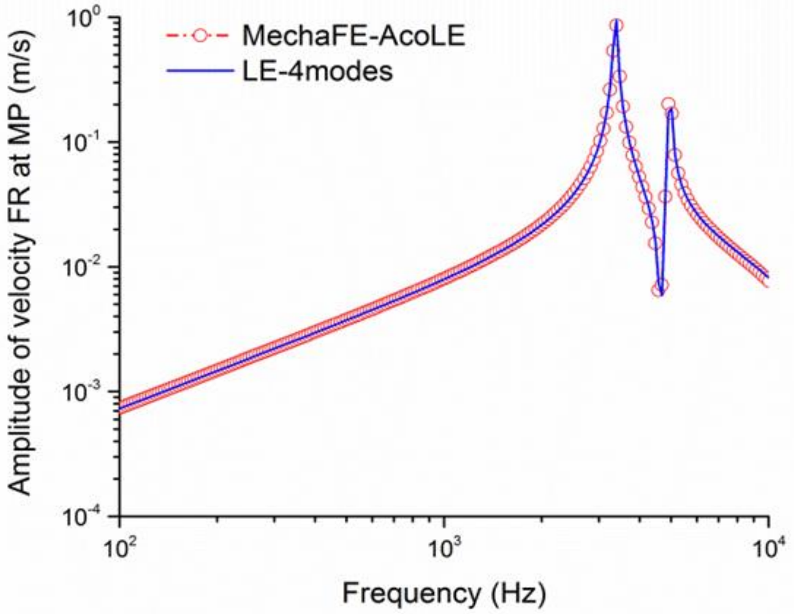
(b) SPL in the 2cc coupler

LE multimode model Vs. **Full FE model**: velocity at MP agrees well over the whole concerned frequency range; SPL in the 2cc coupler agrees well up to 8 kHz.

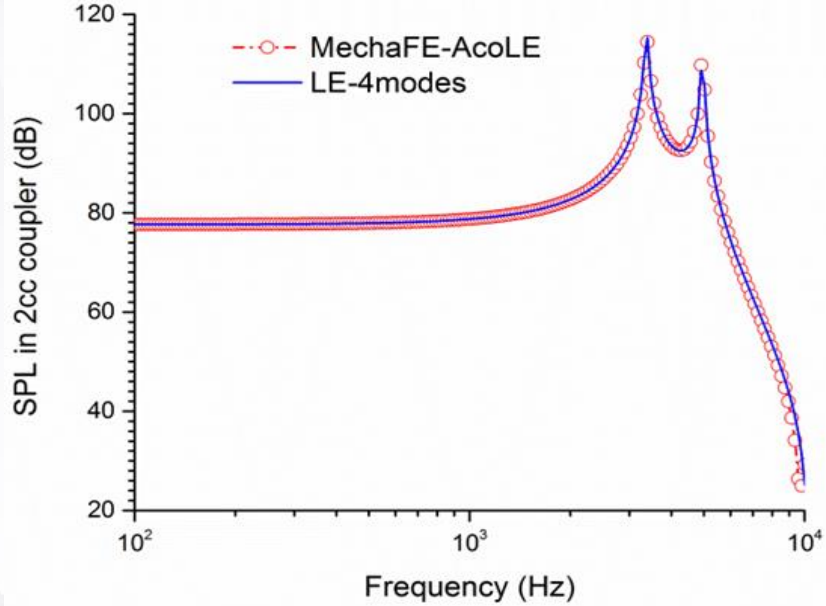
Commonly used LE model Vs. **Full FE model**: apparently deviated from the FE model for both the velocity and the SPL response.

Proved : The developed LE multimode model is more accurate than the LE model.

5 Results and analysis|
Compare with integrated FE-LE model



(a) Velocity at MP



(b) SPL in the 2cc coupler

LE multimode Vs. **Integrated FE-LE models**:

Response: In substantial agreement.

Time consuming (PC with 4-core 3.3 GHz of CPU and 8 GB of RAM):

LE multimode model (**79 seconds** including the modal analysis) **<<** integrated FE-LE model (**3,409 seconds**)

Proved: Efficiency is highly improved.

6 Conclusion and Suggestion

Conclusion

Developed LE multimode model for BAR:

- As effective as integrated FE-LE model .
- Efficiency of computation is highly improved.
- More reliable than LE model by referring to full FE model.
- Engineering application becomes as simple as LE model.

Suggestion

- Adding the electromagnetic field, the dampings.
- Including lumped multimode modeling of the acoustic domain.
- Used for developing other types of transducers.

THANKS