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In-Ear Energy Harvesting : Harvester Design and Validation (Part II)

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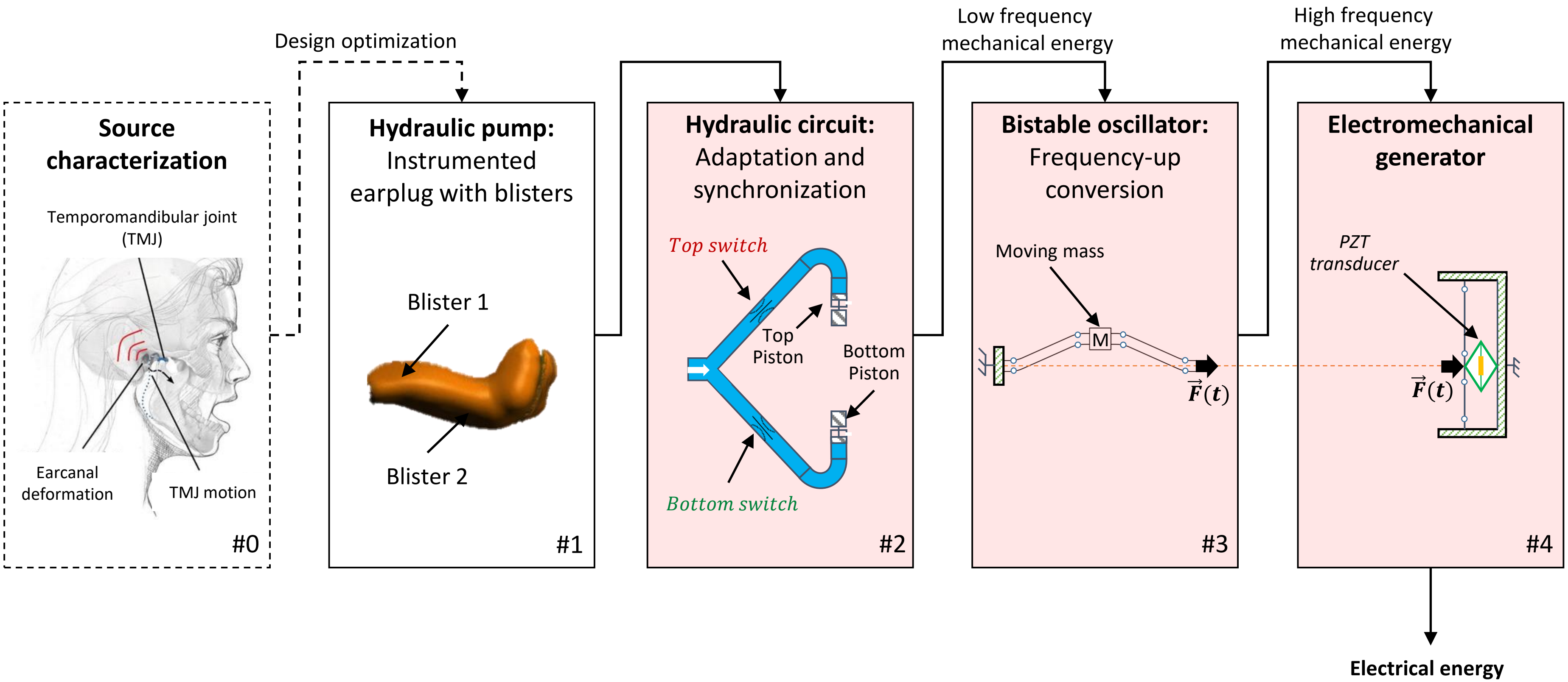
Graphical abstract



Keywords: Ear; energy harvesting; generators; frequency-up; bistable oscillator; hydraulic transmission; passive hydraulic switches;

Abstract

The earcanal mechanical deformation induced by the temporomandibular joint movement constitutes a promising source of energy to power in-ear devices (hearing aids, communication earpieces, etc.). The large morphological variability of the human earcanal and its intrinsic dynamic characteristics - with displacement frequencies below 1.5 Hz with average volume variation of 60 mm^3 - motivate the development of non-conventional dedicated energy harvesting methods. This paper demonstrates the concept and design of a modular hydraulic-piezoelectric self-actuated frequency up conversion micromachine for energy harvesting. The mechanical energy is conveyed using a liquid-filled custom fitted earplug, which can be considered as a hydraulic pump. A dedicated hydraulic circuit drives two micro-pistons (MP) while ensuring the impedance matching between the earplug available pressure and swept volume and the MP required displacement and force. These MP actuate a mechanical oscillator associated to a piezoelectric transducer allowing the low frequency mechanical excitation to be efficiently converted into electric energy through frequency up-conversion. An innovative mechanical feedback selects the actuated MP depending on the mechanical oscillator position. By doing this, each jaw motion can be harvested. A complete theoretical multiphysics model of the machine has been established for the design and evaluation of the potential of the proposed approach. Global analytical and refined FEM approaches have been combined to integrate the fluid and mechanical behaviors. Based on simulation and preliminary experimental data, the harvested energy is expected to be 10 µJ for one jaw closing, with a theoretical 50 % end-to-end conversion efficiency.

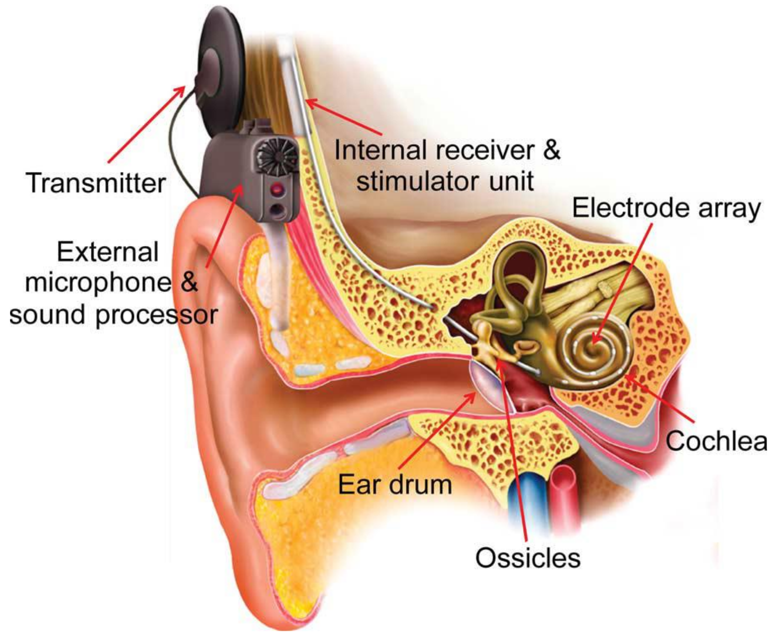
Keywords: Ear; energy harvesting; generators; frequency-up; bistable oscillator; hydraulic transmission; passive hydraulic switches;

Need for energy supply around ears

Daily energy consumption ≈ 72 J

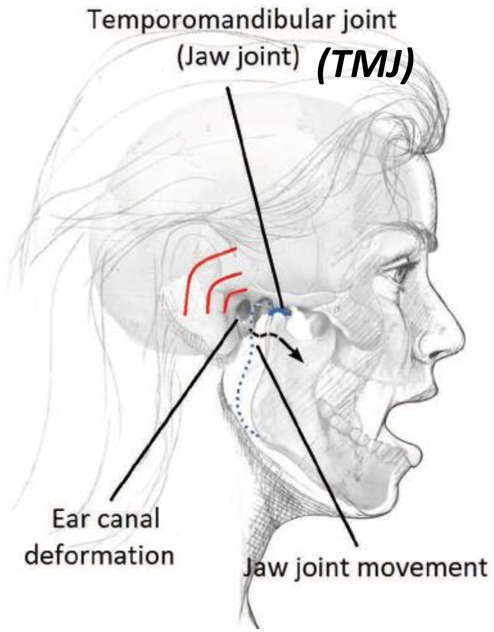
ReSound hearing aid
LYNX Quattro model [1]

Daily energy consumption ≈ 21 J



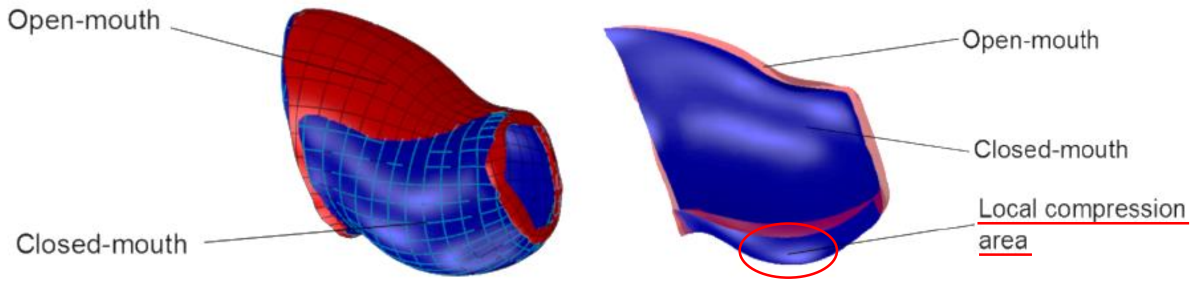
Block diagram of a conventional cochlear implant [M. Yip & al., 2015 [2]].

Earcanal = energy source

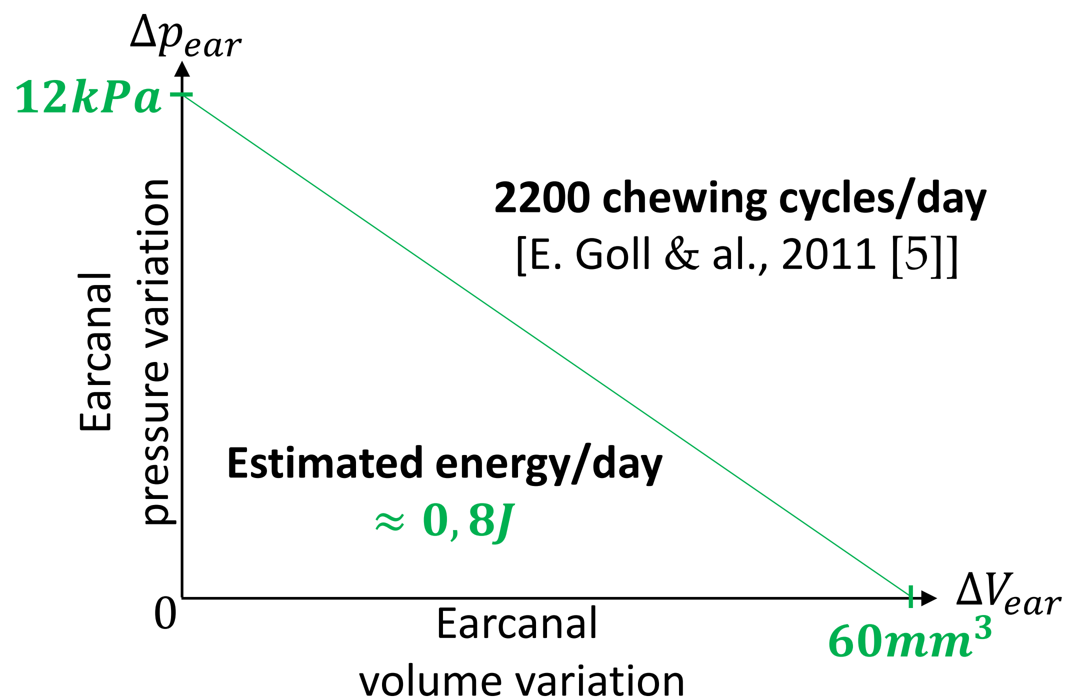


[A. Delnavaz & J. Voix, 2016 [3]]

CRITIAS NSERC-EERS INDUSTRIAL RESEARCH CHAIR IN IN-EAR TECHNOLOGY



[J. Carioli & al., 2016 [4]]



Introduction

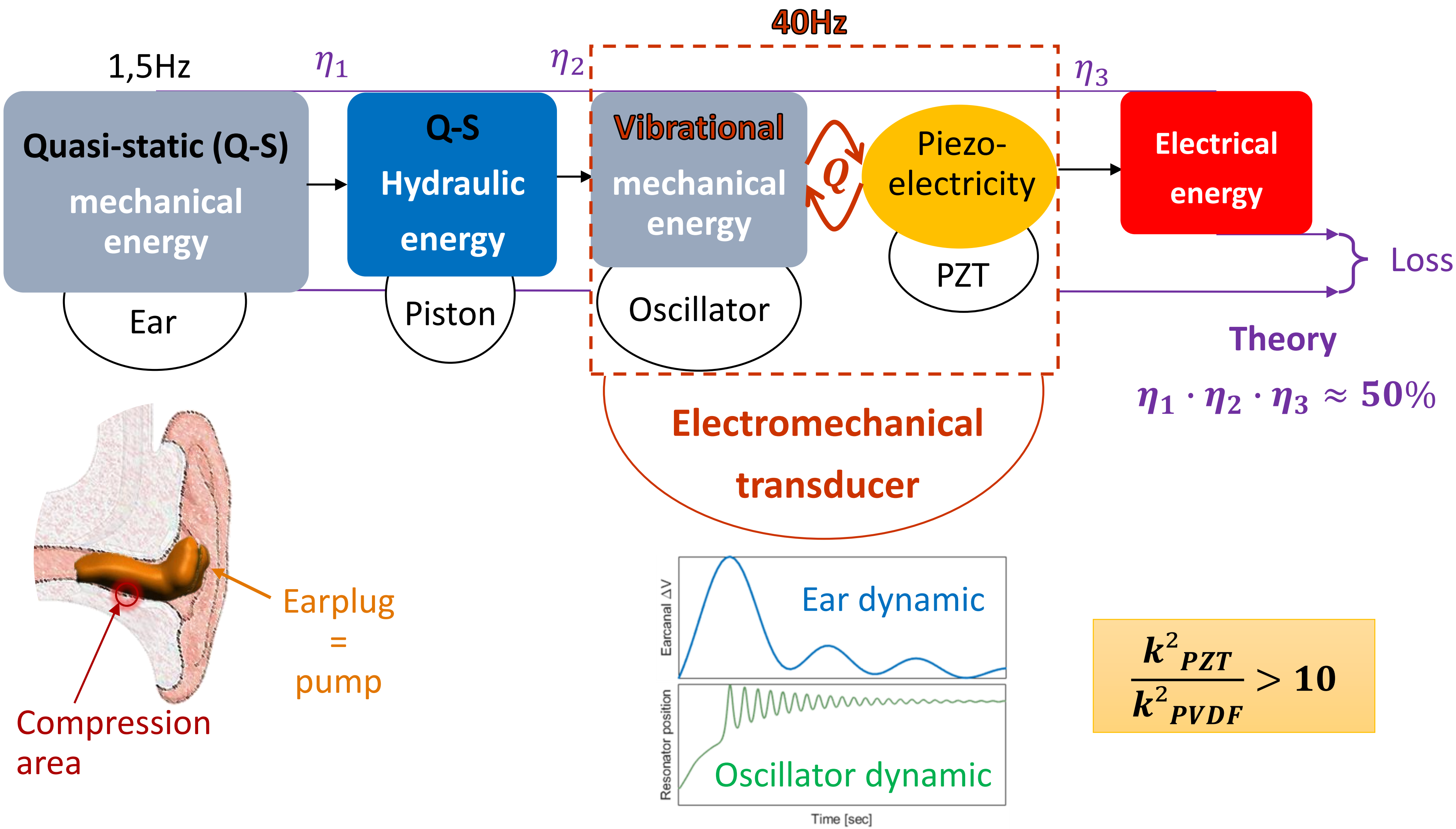
I. Harvesting strategy

II. System presentation : Specifications and design

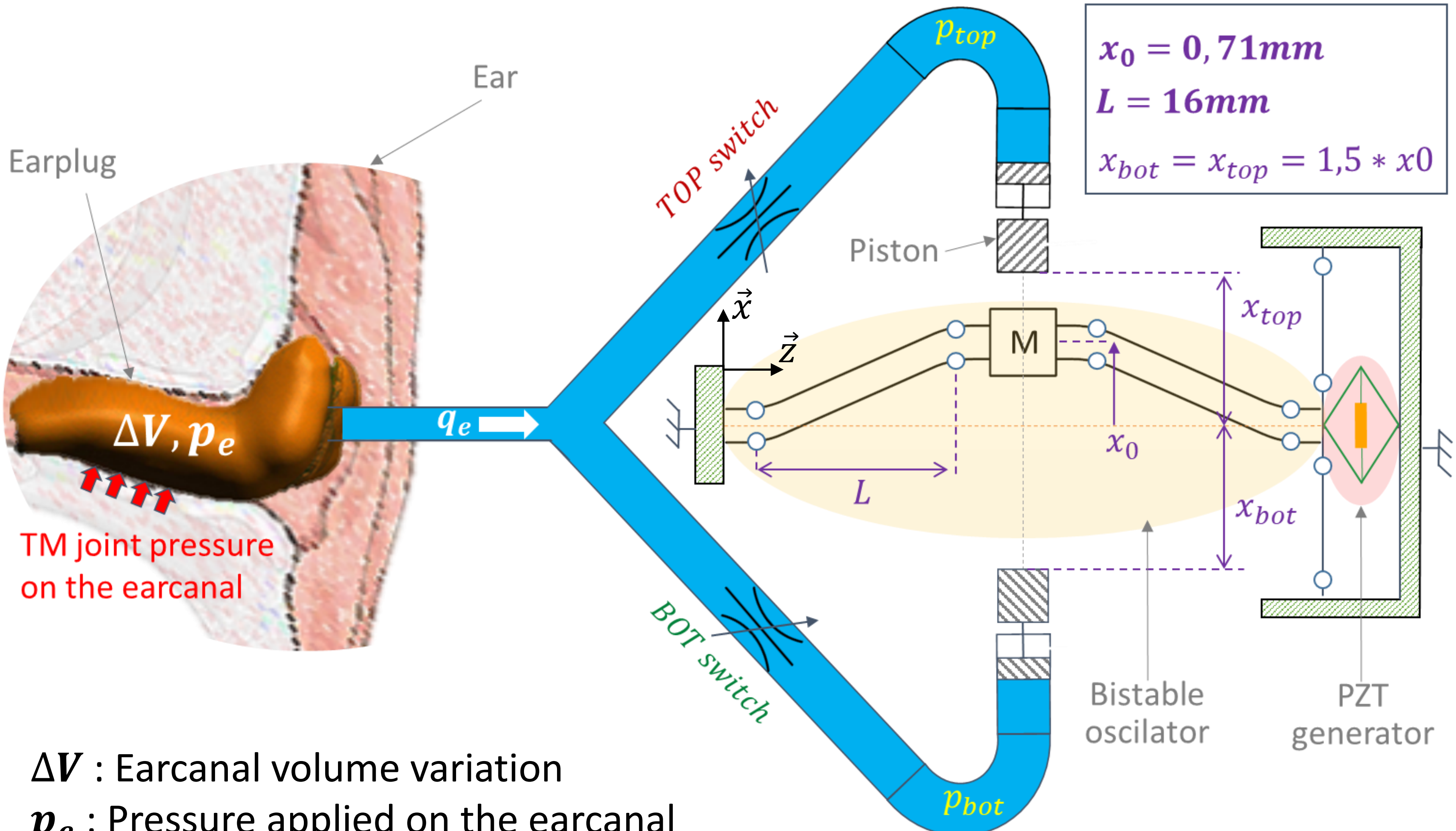
III. Multiphysic system simulations

IV. Experimental characterizations

Energy harvesting strategy



Global system overview

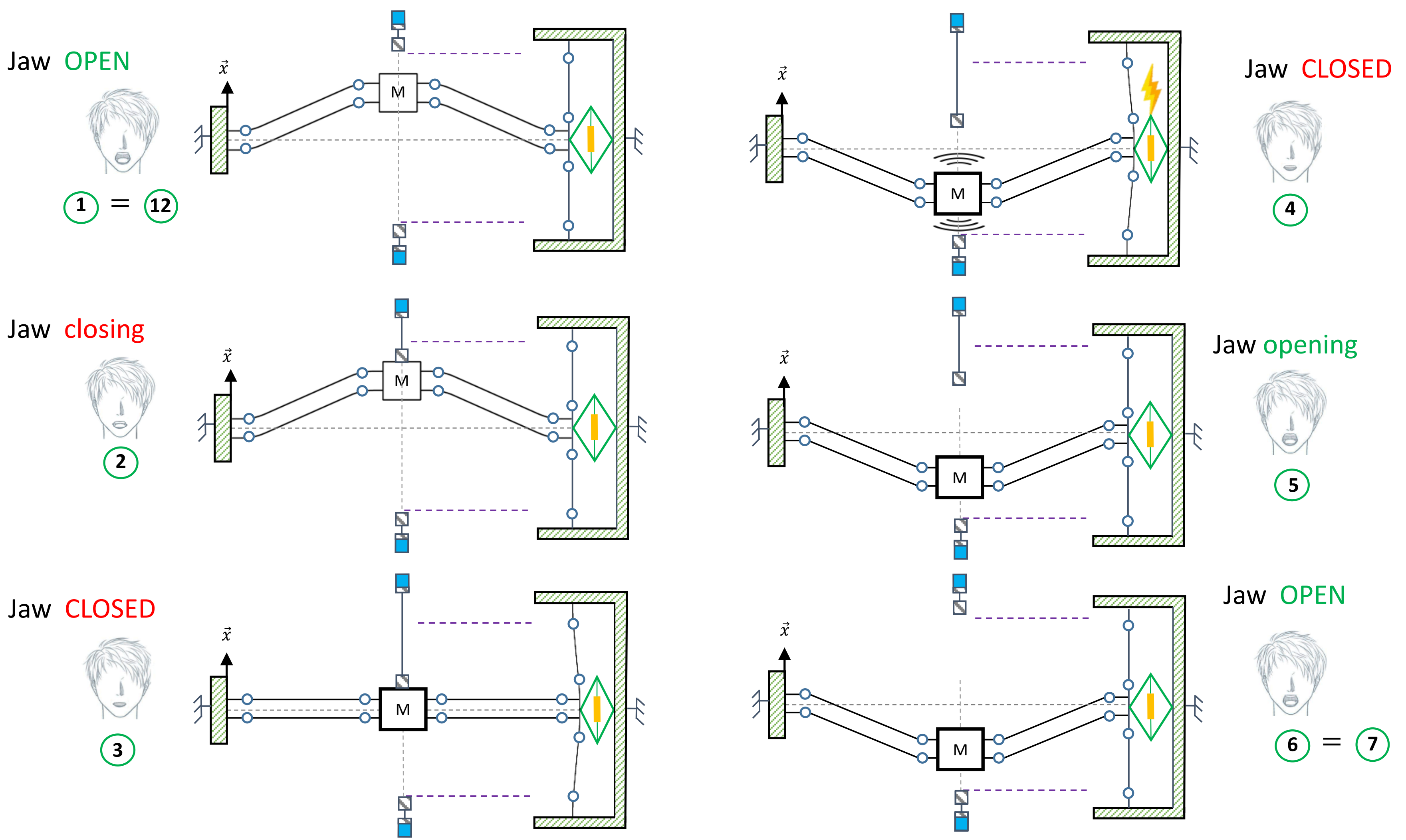


ΔV : Earcanal volume variation

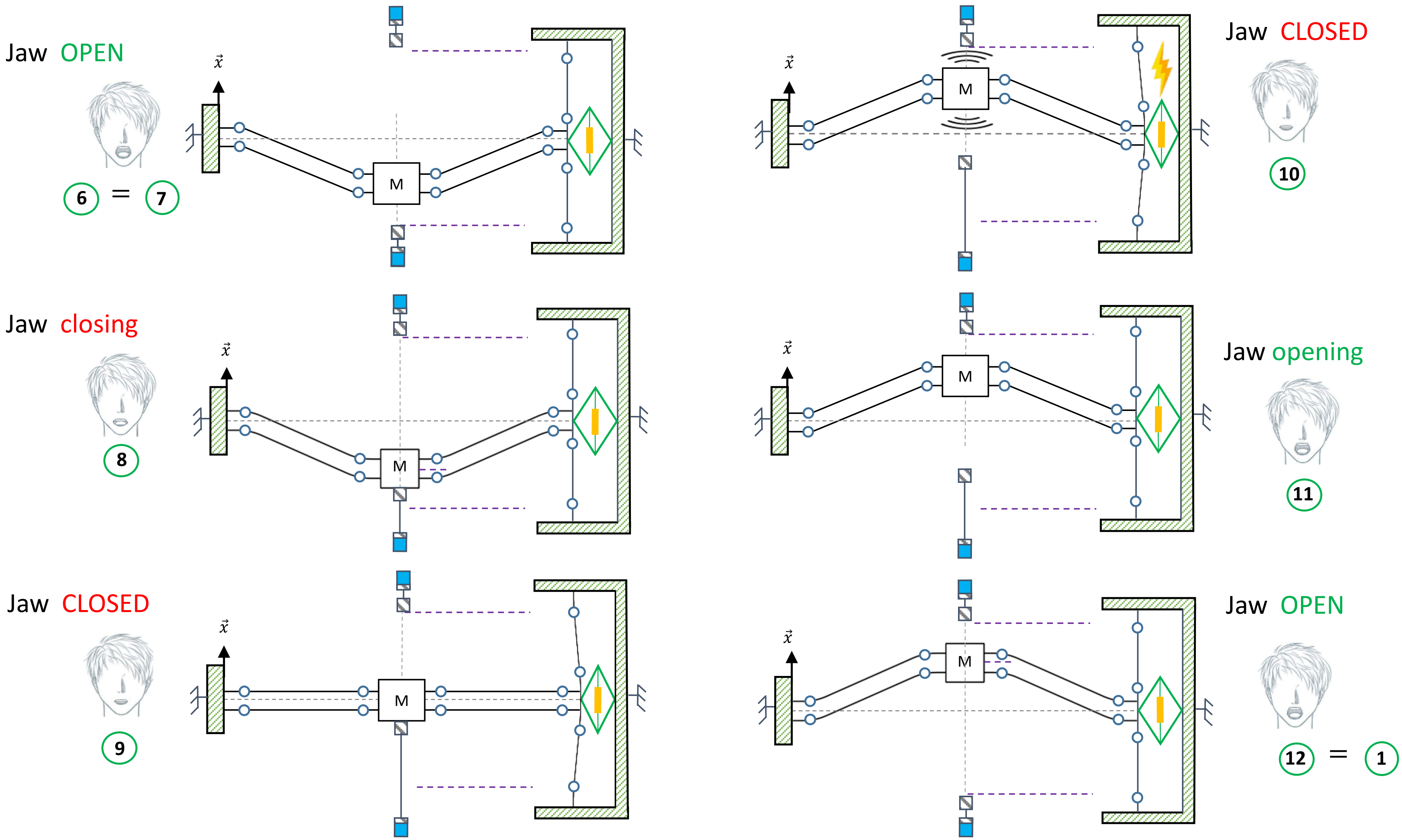
p_e : Pressure applied on the earcanal

q_e : Earplug fluid flow rate

System operation dynamics: Upward actuation



System operation dynamics : Downward actuation



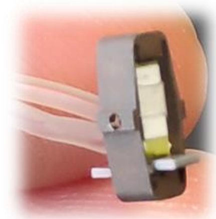
Design specifications

Space requirements

$3 \cdot L < 70mm$

Transducer choice

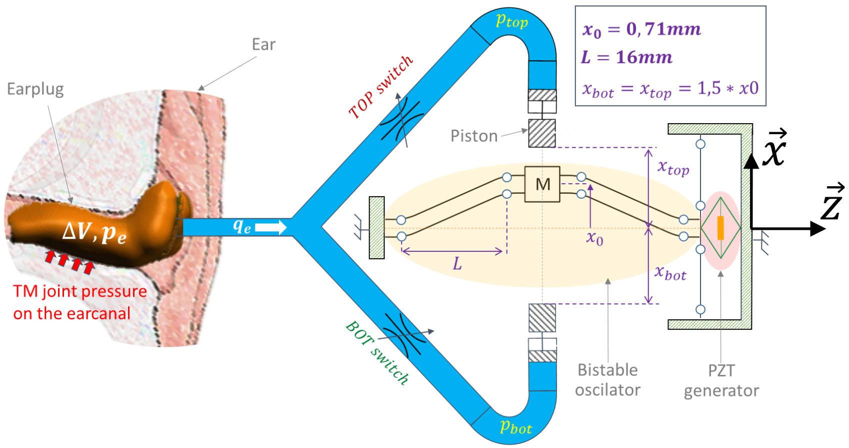
CEDRAT TECHNOLOGIES
Innovation in Mechatronics



K : $Stiffness$

C_0 : $Capacity$

k_e^2 : $EM\ coupling$



$$I = \left(\sqrt{k_e^2 \cdot K \cdot C_0}\right) \cdot \frac{x_M \cdot \dot{x}_M}{L} - C_0 \cdot U_p$$

Generated power : $P = U_p \cdot I$

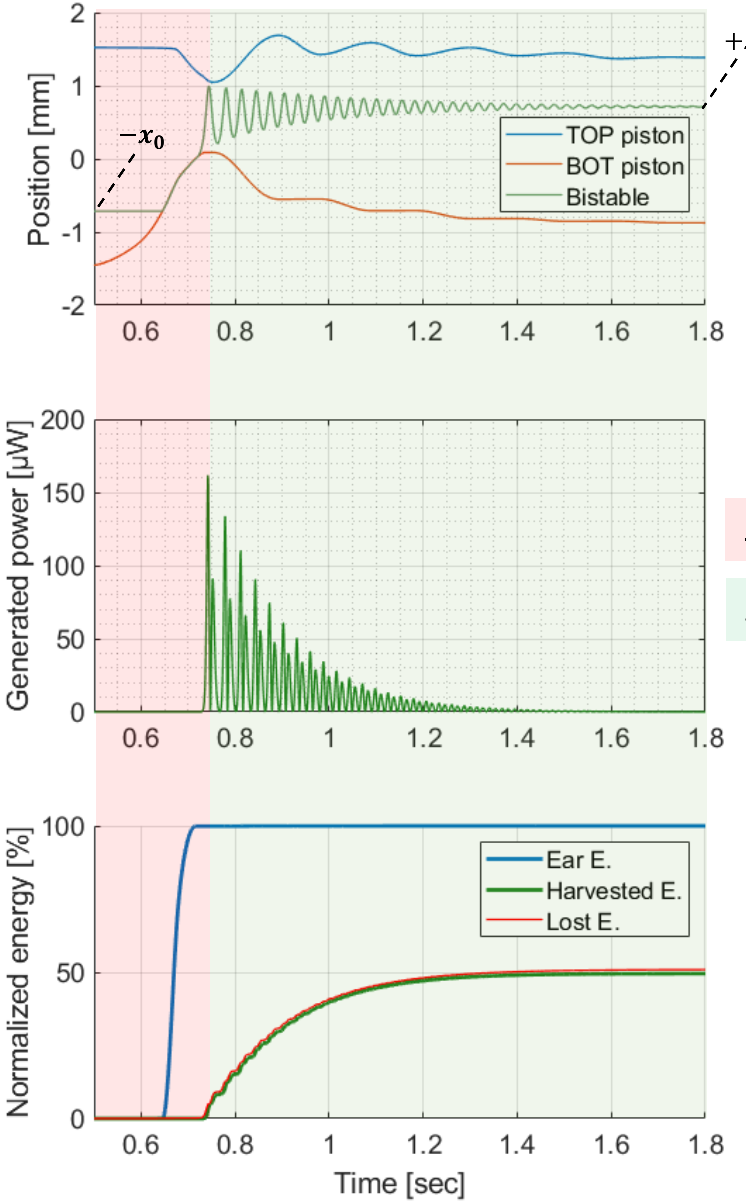
Buckling level

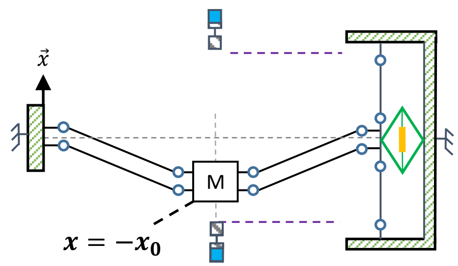
$$p_{ear(comfort)} = \frac{\dfrac{2 \cdot K \cdot x_{0(max)}^3}{3 \cdot \sqrt{3} \cdot L^2}}{S_{piston}}$$

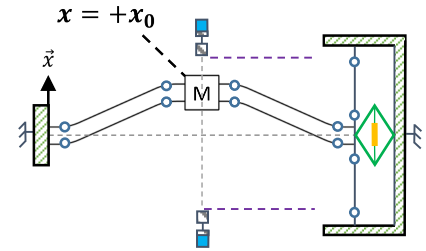
Pistons

$$S_{piston} \cdot 1,5 \cdot x_{0(max)} < \Delta V_{ear}$$

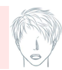
Multiphysics system simulation







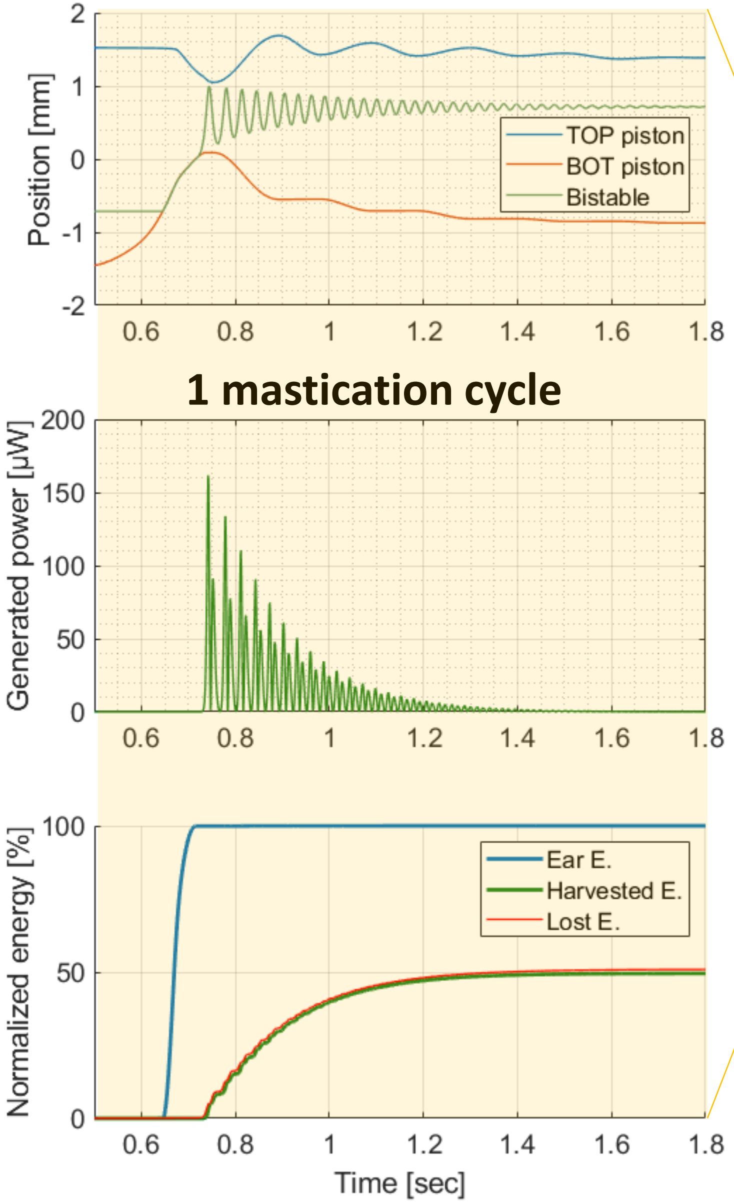
Jaw closing

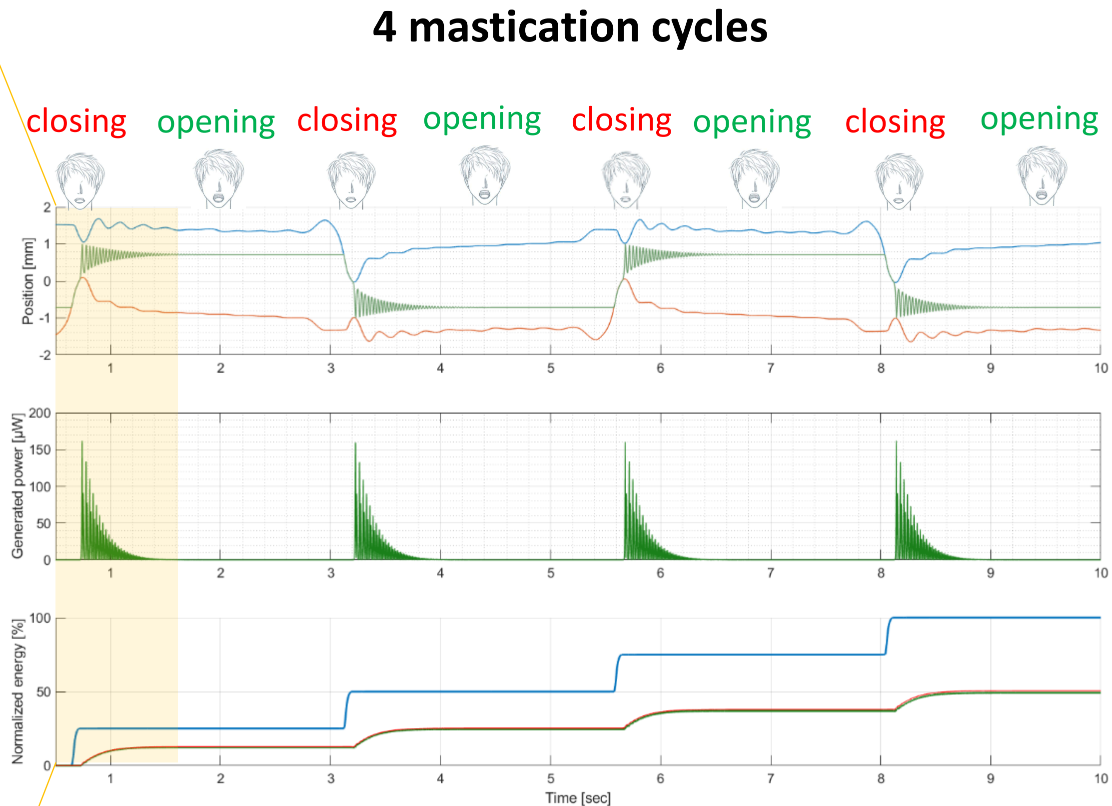


Jaw opening

Theoretical efficiency ≈ 50%

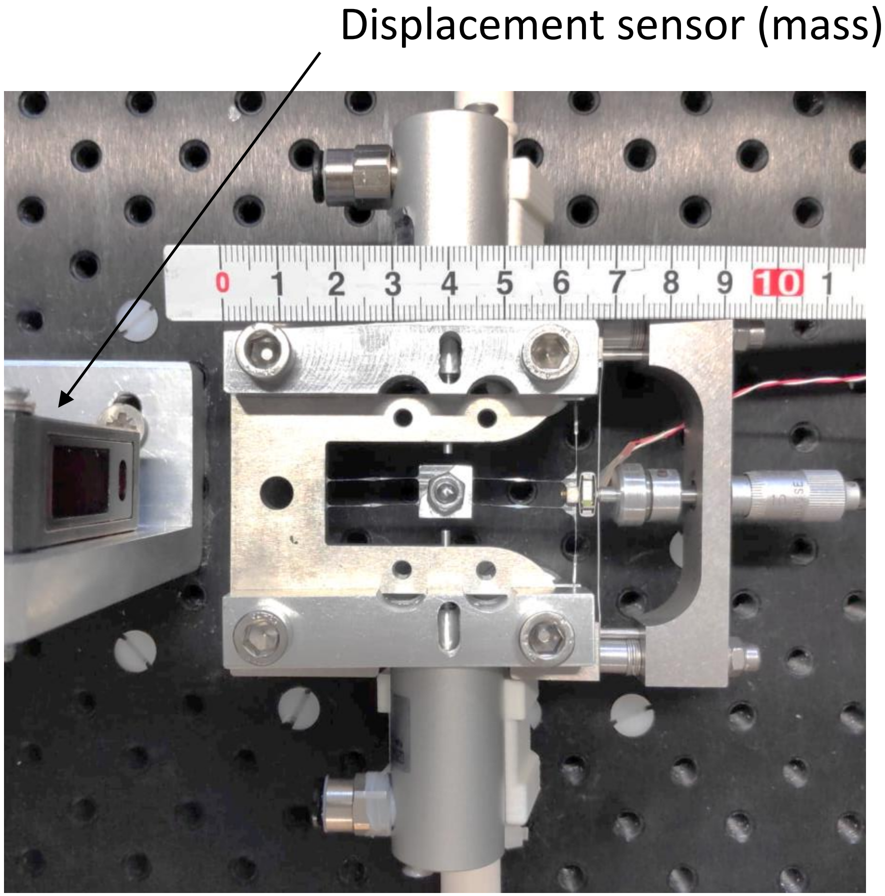
Multiphysics system simulation

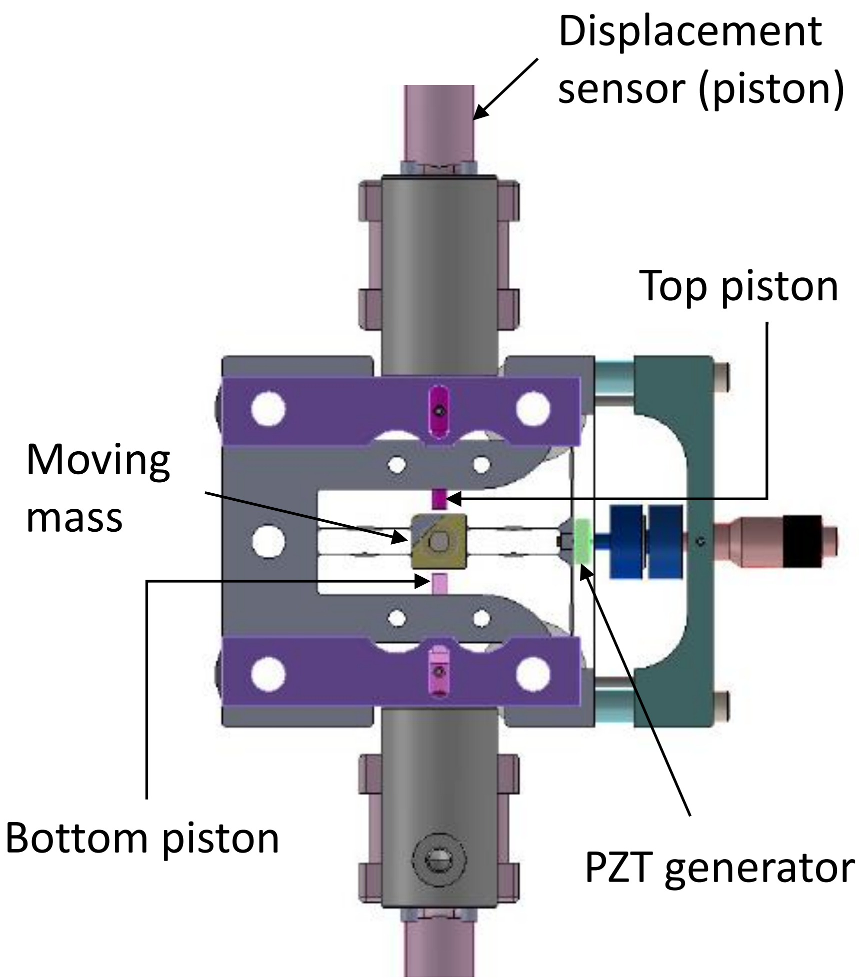




Theoretical efficiency ≈ 50%

Oscillator with the generator



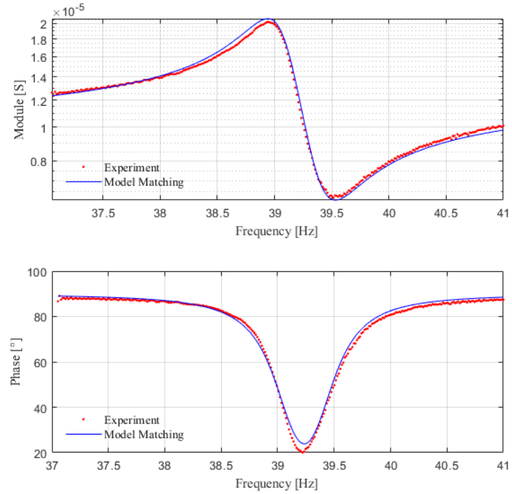


Experimental characterizations : Resonator behavior

Test conditions

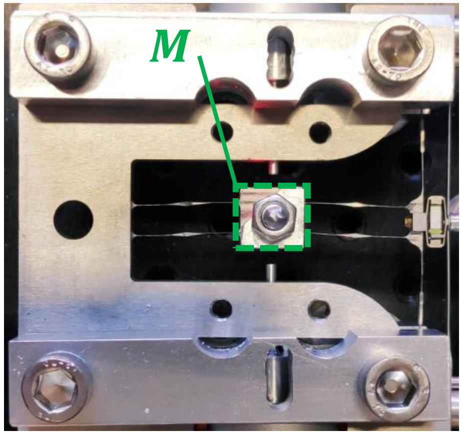
- Bistable buckled (x_0 **unknown**)
- Small displacements
- Initially at a stable position

Impedance Frequency Response

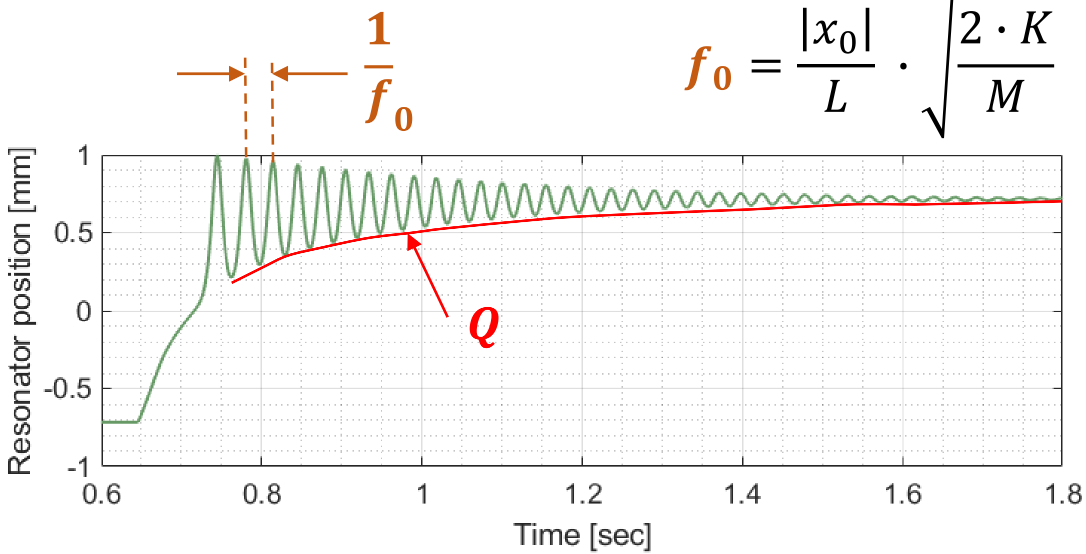


Experimental results

- EM coupling coefficient: $\boldsymbol{k_e^2 = 1,6\%}$
- Quality factor: $\boldsymbol{Q = 78}$
- Resonance frequency: $\boldsymbol{f_0 = 39Hz}$
- Mass on the oscillator : $\boldsymbol{M = 5,88g}$

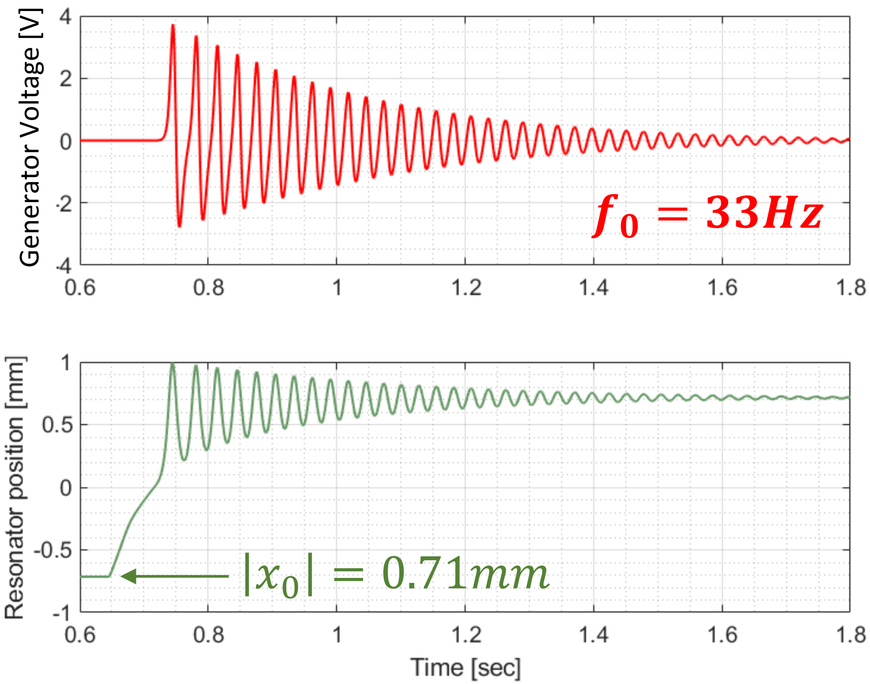


$$f_0 = \frac{|x_0|}{L} \cdot \sqrt{\frac{2 \cdot K}{M}}$$

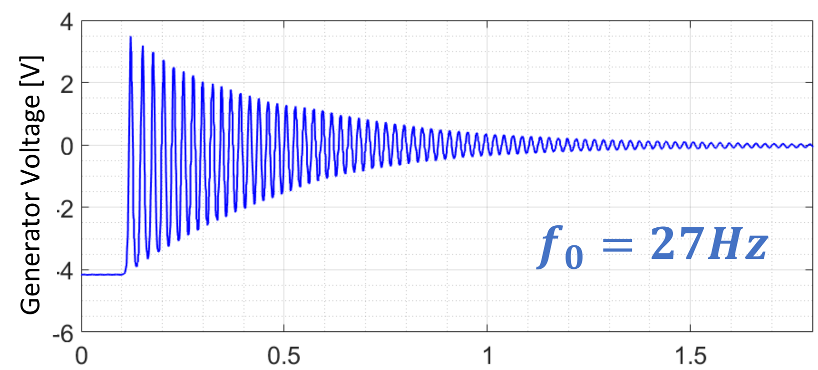


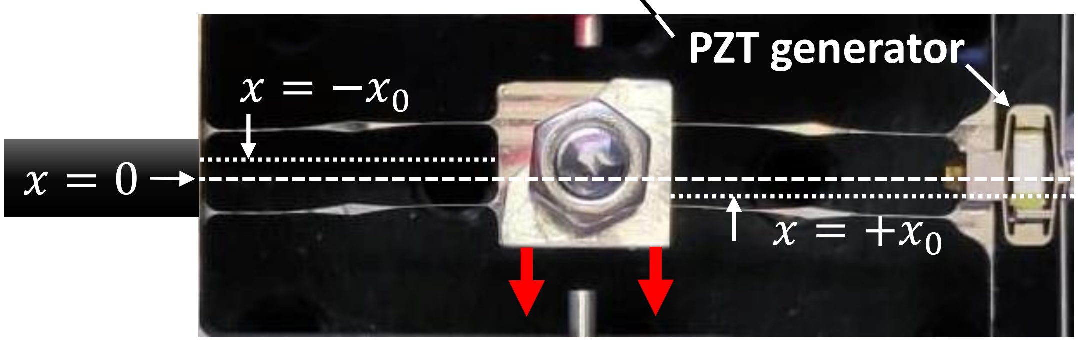
Experimental characterizations: Generator behavior

Theoretical model



Expérimental $|x_0| \approx 0.58mm$





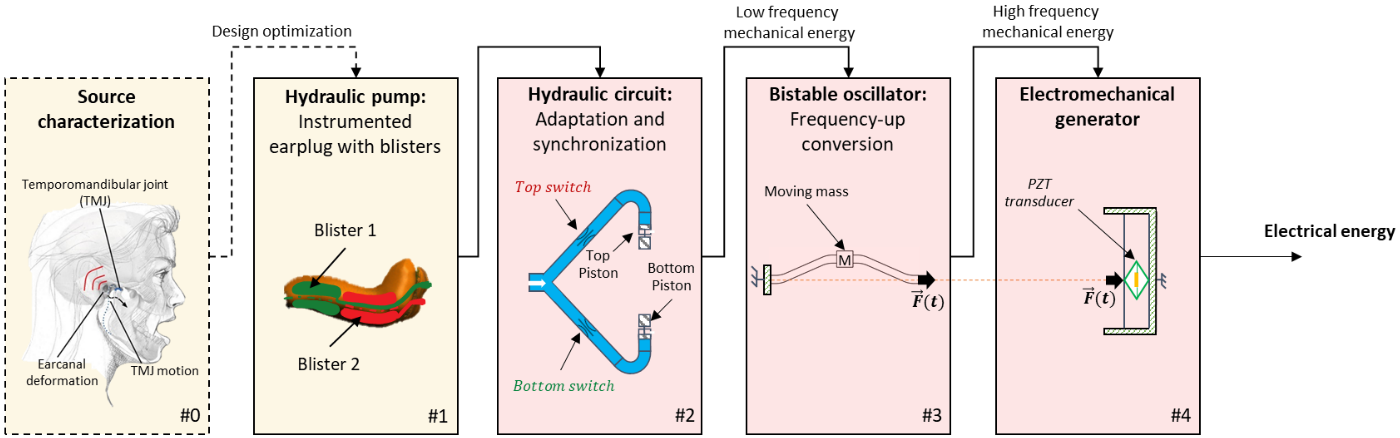
$$f_0 = \frac{|x_0|}{L} \cdot \sqrt{\frac{2 \cdot K}{M}}$$

CONCLUSION

- Designed system : Hydraulics + Oscillator & generator ✔
- Experimental results in accordance with multiphysic model
  - Oscillator & generator ✔
  - Hydraulics
- **Application for patent [US Provisional Patent Application 63/173,463 (2021) [6]]**

PERSPECTIVES

- Run the complete system : Self actuated experimental prototype
- Implement the instrumented earplug and the harvesting prototype together



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[4] Carioli, J., Delnavaz, A., Zednik, R. J., & Voix, J.. Power capacity from earcanal dynamic motion. *AIP Advances*, *6*(12), 2016.

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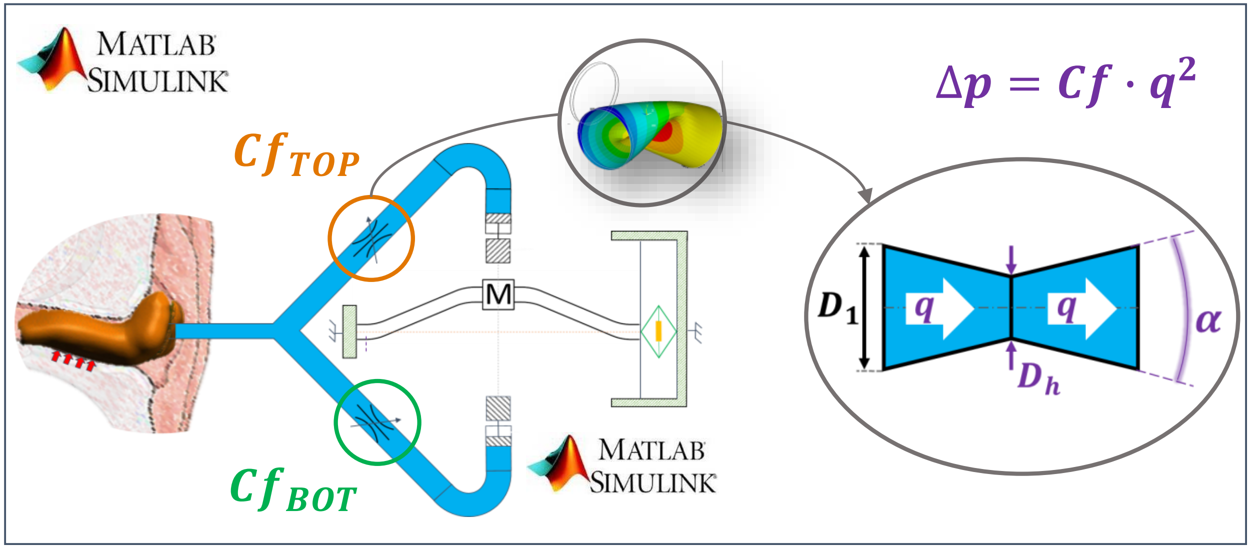
Patent application related to the present work :

[6] ENERGY HARVESTER DEVICE USING DYNAMIC MOTION AND METHOD THEREOF (Méthode et dispositif de grappillage énergétique à base de micro-pompe hydraulique : utilisation intra-auriculaire). US Provisional Patent Application 63/173,463 (2021)

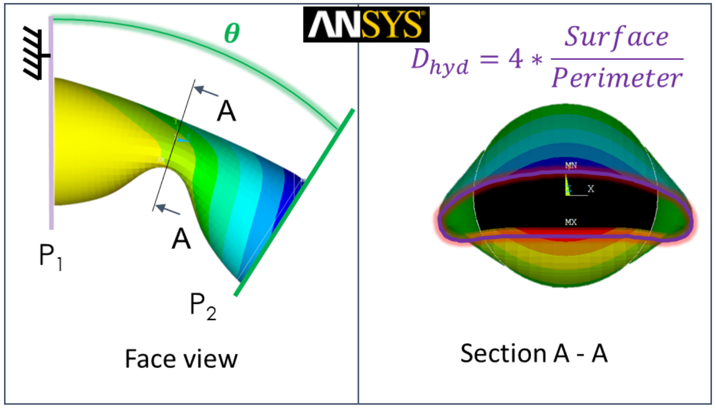
DESIGN OF THE HYDRAULIC SWITCHS

PHASE 1 : find Δp

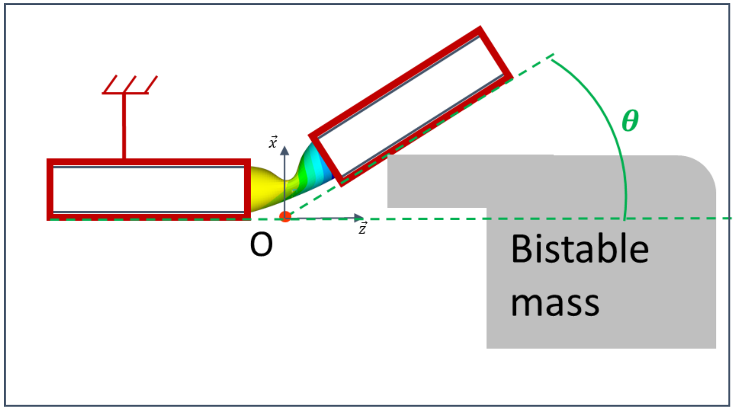


- Cf: Pressure loss coefficient
- D_h : Hydraulic diameter
- α : Enclosed angle
- q : Fluid mass flow
- x_{bis} : Bistable position

PHASE 2 : find θ



PHASE 3 : Integrate the switch



BISTABLE CYCLING MECHANISM