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Hydraulic valves design for the operation of an in-ear energy harvesting system

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***Abstract*— This paper demonstrates the concept and design of a hydraulic-piezoelectric self-actuated frequency up conversion system for energy harvesting. Two pistons actuate a bistable oscillator associated to a piezoelectric transducer allowing a low frequency hydraulic excitation to be efficiently converted into electric energy. An innovative concept of hydraulic passive valves based on flexible tube buckling is presented.**

I. INTRODUCTION - THE ERCANAL AS ENERGY SOURCE

Hearing aids, Bluetooth earphones, cochlear implants or other wearables need to be supplied in energy for longtime and improved use. As a complement to the batteries, it may be possible to provide electrical energy by harvesting it from the human body itself [1]. The figure 1 shows how, during functions such as mastication, the jaw temporomandibular joint (TMJ) activities deform the earcanal [2]. By using a liquid filled custom-fit earplug, the CRITIAS team has evaluated the earcanal volume variation caused by the TMJ activities.

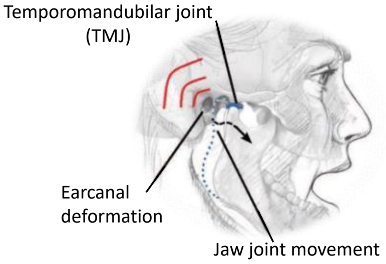

FIGURE 1. TMJ AND EAR CANAL DYNAMIC MOTION DURING THE MOUTH OPENING AND CLOSING MOVEMENT [2]

They estimated a mean volume variation of $\Delta V \approx 60mm^3$, depending on the subject, and an chewing frequency of $1.57Hz$. The following work introduce a hydraulic-piezoelectric frequency up conversion system aiming at harvesting the energy produced by the earcanal deflection.

II. HARVESTER CONCEPT, DESIGN AND SPECIFICATIONS

The figure 3 shows a schematic view of the harvester. The mechanical energy is captured using a liquid filled custom-fit earplug, which can be considered as a positive displacement hydraulic pump. A hydraulic circuit composed of a pressure amplifier and two hydraulic valves (HV) allows to drive two micro-pistons. They actuate a bistable oscillator (BO) associated to a piezoelectric transducer allowing the low frequency excitation to be efficiently converted into electric energy through frequency-up conversion [3].

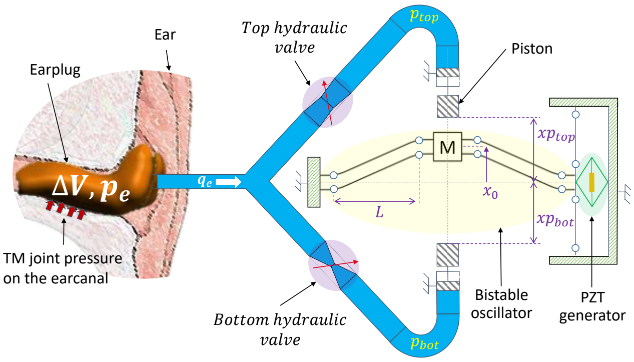

FIGURE 2. SCHEMATIC OF THE HARVESTER SYSTEM

During the actuation phase, the active piston (AP) pushes the BO mass, initially resting at one stable position, until it reaches its unstable position at $x = 0$ (fig. 2). Then comes the harvesting phase during which the mass oscillates around the other BO equilibrium position.

The two synchronized HV allow the pistons to act alternatively on the mass to generate a backward and forward run for two jaw movements. The HV are driven by the BO mass motion, their operation is based on flexible tubes bending in order to take advantage of the section area collapse and the rotational stiffness decrease when the buckling occurs. The following of this work will focus on the operation, modelling and characterization of the HV.

III. HYDRAULIC VALVES DESIGN

Each HV is designed following four iterative phases (0, 1, 2, 3) three of which are illustrated in figure 3. The tube material is silicon to limit the stiffness and the induced additional force applied on the BO mass.

0- HV specifications

In order to ensure that the earplug delivers the fluid to the AP only, the other ("close") HV has to generate enough flow resistance during the actuation phase to prevent fluid flow. This resistance should result in a significantly higher pressure loss, than through the "open" HV. A complete theoretical multiphysics model of the system has been established for design and evaluation of the potential of the proposed approach. A first Matlab - Simulink simulation revealed the pressure loss ΔP_{sw} needed in the "close" HV for the system to be operated properly by the TMJ activities.

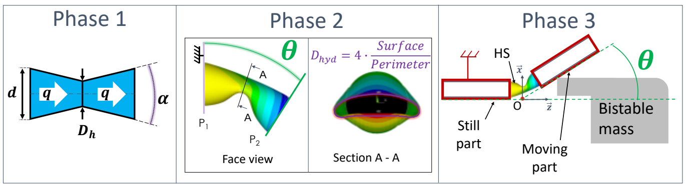

FIGURE 3. ILLUSTRATION OF THE PHASES 1.2 AND 3 FOR THE HV

1- Analytical modeling for prior-design

The pressure loss trough the buckled section of the bent valve is thought to be close to the analytical model established by A.H. Gibson [5,6] for a contracture, followed by an expansion (fig. 3 - 1). This loss is directly related to the hydraulic diameter D_h of a cross section. The equation (1) was obtained by adapting the A.H. Gibson formulas to our case. It establishes the relationship between the singular pressure loss coefficient and D_h. The evolution of the cone angle α during the tube bending being complex to determine, it was preliminary fixed to 45°. Likewise, the correction factor K_{cor} will be determined experimentally and was set to 1 for the preliminary design.

$$Cf = K_{corr} \cdot \frac{\rho}{\pi^2 \cdot D_h^4} \cdot \left(6{,}4 \cdot \left(1 - \frac{D_h^2}{d^2}\right)^{0.75} + 20{,}8 \cdot \left(1 - \frac{D_h^2}{d^2}\right)^2\right) \cdot \sin\left(\frac{\alpha}{2}\right) \qquad (1)$$

Cf : $Pressure\ loss\ coefficient\ [Pa.\sec^2.m^{-6}]$
K_{cor}: $Corection\ factor\ [\text{ø}]$
D_h : $Hydraulic\ diameter\ of\ the\ buckled\ area\ [m]$
ρ : $Density\ of\ the\ fluid\ [kg.m^{-3}]$
d : $Tubing\ diameter\ before\ and\ after\ the\ buckled\ area\ [m]$
α : $Contraction - enlargement\ angle\ [deg]$

We fixed the tube diameter d to 4mm. From the target value of ΔP_{sw} (phase 0), we determine the evolution of the hydraulic diameter D_h during the BO mass motion and the tube bending accordingly. D_h has to drop to $D_{h,min} = 2.4mm$ while the tube is under maximum bending angle.

2- Finite Element (FE) Analysis

A FE model has been established with ANSYS as illustrated in figure 3-2. The rotation angle θ was imposed by the supposedly rigid right hand side section of the tube. We obtained $\theta_{min} = 50°$ in order to reach $D_{h,min}$. Furthermore, the FE model allowed the added rotational stiffness to be evaluated. It was proved to be negligible compared to the BO actual stiffness.

3- HV integration in the system

Knowing the angle θ_{min}, the phase 3 illustration on figure 3 shows how the tube is associated to the BO mass.

The dry friction losses were estimated knowing both the tube and the BO mass materials. The position of the tube with respect to the BO mass was chosen to fulfill the whole rotational angle range.

IV. NUMERICAL VALIDATION OF THE SYSTEM OPERATION

The complete system simulation results with the designed HV is presented on figure 4. The actuation phase occurs while the TMJ is closing. The mechanical to electrical conversion occurs after the BO mass crosses the $x = 0$ position and vibrates around the opposite stable position of the oscillator.

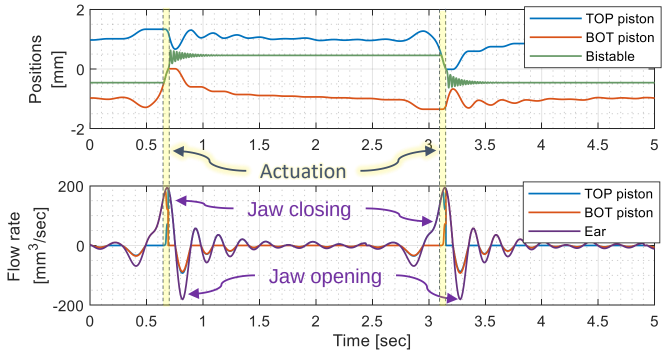

FIGURE 4. SYSTEM SIMULATION WITH INTEGRATED HV

The HVs properly assure the direction of the liquid flow to the one piston at the first TMJ motion and to the other piston at the next motion. The cycle then continues alternatively. The device is expected to harvest 8.5µJ for one jaw closing, at peak to peak power up to 200µW. 84% end to end conversion efficiency underlines the relevance of using such a system. Assuming that the average human does 2200 chewing cycles per day [7], we could harvest about 19mJ/day, per ear.

V. CONCLUSION

We introduce a new energy harvester for the mechanical deformation of the earcanal, induced by the TMJ activities. We present the new concept of HV based on alternative flexible tube buckling. These are designed and implemented to operate a BO associated to a piezoelectric converter. A complete multiphysic model shows that the harvester periodic motion is correctly managed by the designed HV. Experimental comparison with the numerical model is ongoing.

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