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# An irreversible port-Hamiltonian model for a class of piezoelectric actuators ⋆

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**Abstract:** An irreversible port-Hamiltonian system formulation of a class of piezoelectric actuator with non-negligible entropy increase is proposed. The proposed model encompasses the hysteresis and the irreversible thermodynamic changes due to mechanical friction, electrical resistance and heat exchange between the actuator and the environment. The electromechanical dynamic of the actuator is modeled using a non-linear resistive-capacitive-inductor circuit coupled with a mass-spring-damper system, while the non-linear hysteresis is characterized using hysterons. The thermodynamic behavior of the model is constructed by making the electromechanical coupling temperature dependent, and by characterizing the entropy produced by the irreversible phenomena. By means of numerical simulations it is shown that the proposed model is capable of reproducing the expected behaviors and is in line with reported experimental results.



*Keywords:* Port-Hamiltonian system, Piezoelectric Actuator, Non-linear systems, Irreversible Thermodynamics, Hysteresis

## 1. INTRODUCTION

Piezoelectric actuators are multi-physical system frequently used in micro/nano robotic applications (Rakotondrabe and Le Gorrec, 2010; Haddab et al., 2000; Agnus et al., 2003; Huang et al., 2005; Rakotondrabe et al., 2009) because of their small size, high resolution, high bandwidth and high force density. It is well known that piezoelectric actuators exhibit hysteresis in their dynamics, which is due to irreversible thermodynamic phenomena. An important aspect to consider in automatic control applications, such as position tracking or force control, is to compensate for the non-linear behavior caused by the hysteresis. This is a widely investigated subject and various models have been proposed for piezo actuators, as for instance Prandtl-Ishlinskii (Rakotondrabe and Le Gorrec, 2010; Ghafarirad et al., 2015), Preisach (Ge and Jouaneh, 1995; Ping Ge and Musa Jouaneh, 1996; Zsurzsan et al., 2015), Bouc-Wen (Rakotondrabe, 2010; Habineza et al., 2015), generalized Maxwell resistive-capacitive model (Goldfarb and Celanovic, 1997) or models based on hysterons (Karnopp, 1983; Ramirez et al., 2018). Using models of the hysteresis its non-linear effects have been compensated using for instance the inverse model in cascade with an electromechanical actuator model (Rakotondrabe and Le Gorrec, 2010; Ghafarirad et al., 2015; Rakotondrabe, 2010; Habineza et al., 2015). Other approach is to use sensors to measure and compensate the non-linear behavior, but the integration in nano/micro applications is complicated given how expensive and bulky sensing elements for these applications are (Liseli et al., 2019). The irreversible thermodynamic phenomena in piezoelectric actuators are mainly due to internal mechanical friction, inelastic deformations, electrical resistance and heat transfer with the surroundings. For certain applications the performance of the actuator is highly sensitive to temperature changes (Rakotondrabe et al., 2007; Rakotondrabe and Ivan, 2010; Habineza et al., 2016; Al Janaideh et al., 2019), hence in addition to characterizing the hysteresis a thermodynamic model has to be considered to characterize the temperature of the actuator.

Irreversible port-Hamiltonian systems (IPHS) (Ramirez et al., 2013a,b) are an extension of port-Hamiltonian systems (Duindam et al., 2009; Ortega et al., 2001) which encompasses the first and second principle of the thermodynamics, i.e., conservation of energy and irreversible entropy production, as structural properties. This class of multi-physical systems has been used to model lumped and distributed irreversible thermodynamic systems and its passive properties to design non-linear controllers (Ramirez et al., 2016).

In this paper we propose an IPHS formulation of a class of piezoelectric actuator with non-negligible entropy increase where the non-linear hysteresis behavior is characterized using hysterons (Karnopp, 1983; Ramirez et al., 2018). The model encompasses the hysteresis and the irreversible thermodynamic changes due to mechanical friction, electrical resistance and heat exchange between the actuator and the environment. The electromechanical part of the model is based on the model develop by Goldfarb and

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Celanovic (1997), while the thermodynamic part of the model is constructed by making the electro-mechanical coupling temperature dependent, and by characterizing the entropy produced by the irreversible phenomena. The proposed model is adequate for non-linear control techniques that exploits the passivity property of the IPHS (van der Schaft, 2000; Ortega et al., 2002) and we expect that this model will be useful for control purposes. The paper is organized as follows. Section 2 presents the IPHS framework. In Section 3 the proposed IPHS model of a class of piezoelectric actuator is given. Section 4 evaluates the proposed model numerically and shows that it is in accordance with the reported literature. Finally in Section 5 some conclusions and lines of future work are presented.

## 2. IRREVERSIBLE PORT-HAMILTONIAN SYSTEMS

IPHS (Ramirez et al., 2013a,b) are an extension of PHS (Duindam et al., 2009; Ortega et al., 2001, 2002) that encompasses the first and second principles of thermodynamics (conservation of the internal energy and the irreversible creation of entropy).

*Definition 1.* An IPHS is defined by the dynamic equation (Ramirez et al., 2013a,b)

$$\dot{x} = J_{ir}\left(x, \tfrac{\partial U}{\partial x}\right) \frac{\partial U}{\partial x}(x) + g\left(x, \tfrac{\partial U}{\partial x}\right) u(t) \tag{1}$$

$$y = g\left(x, \tfrac{\partial U}{\partial x}\right)^T \frac{\partial U}{\partial x}(x) \tag{2}$$

where $x \in \mathbb{R}^n$ is the state variable, $U : C^\infty(\mathbb{R}^n) \to \mathbb{R}$ is the Hamiltonian function, $S : C^\infty(\mathbb{R}^n) \to \mathbb{R}$ represents the entropy, the matrix $J_{ir}$ is skew-symmetric and is defined by

$$J_{ir} = J_0(x) + R\left(x, \tfrac{\partial U}{\partial x}\right) J \tag{3}$$

with $J_0(x)$ and $J$, skew-symmetric matrices of dimension $n$. Furthermore, $S(x)$ is a Casimir function of $J_0(x)$, $R\left(x, \frac{\partial U}{\partial x}\right)$ is the product of a positive definite function $\gamma$ and the Poisson bracket defined by $J$ of the entropy $S$ and the Hamiltonian $U$

$$R\left(x, \tfrac{\partial U}{\partial x}\right) = \gamma\left(x, \tfrac{\partial U}{\partial x}\right) \{S, U\}_J \tag{4}$$

where $\{S, U\}_J = \frac{\partial S}{\partial x}^T J \frac{\partial U}{\partial x}$ and $\gamma\left(x, \frac{\partial U}{\partial x}\right) \geq 0$ is a non-linear positive function of the states and co-states. $u \in \mathbb{R}^m$ is the external input and $g\left(x, \frac{\partial U}{\partial x}\right) \in \mathbb{R}^{n\times m}$ is the input map.

The total energy balance is $\dot{U} = y^T u$, implying that (1) is a lossless system with supply rate $y^T u$, expressing the first principle of thermodynamics. The entropy balance is on the other hand

$$\dot{S} = \gamma\{S, U\}_J^2 + y_s^T u = \sigma_s + y_s^T u \tag{5}$$

where $\sigma_s(x) \geq 0$ is the internal entropy production and $y_s = g^T \frac{\partial U}{\partial x}$ is an entropy conjugated output. In the absence of some external input, i.e., $u = 0$, the entropy balance reads $\dot{S} = \sigma_s \geq 0$ in accordance with the second principle of thermodynamics.

## 3. THE PIEZOELECTRIC ACTUATOR AS IPHS

The proposed electro-mechanical part of the model of the piezo actuator is shown in Fig.1. This model is based on the work of Goldfarb and Celanovic (1997), where a

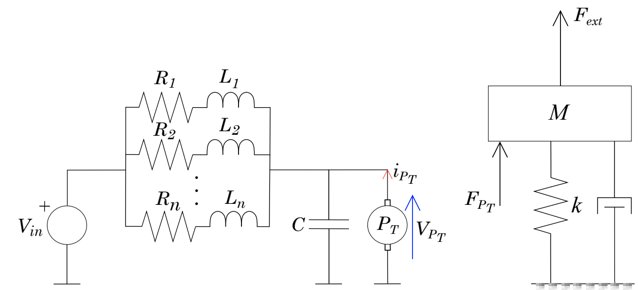


Fig. 1. Piezoelectric actuator model

lumped-parameter model of a piezoelectric stack actuator is represented by an electrical subsystem with a nonlinear hysteresis element and a mechanical subsystem. The electrical and mechanical domains are coupled through a transducer element $P_T$. Different to the model in Goldfarb and Celanovic (1997), we model the hysteresis by the interconnection of hysterons (Karnopp, 1983; Ramirez et al., 2018). The hysteron consists in the interconnection of two types of physical elements, an energy storage element and a resistive element which characterize the basic phenomena of the hysteresis. The interconnection of several hysterons allows to construct complex and more accurate hysteresis curves. The main reason to use hysterons to represent the hysteresis is that it is a passive approach, allowing incorporate the hysteresis as an energy preserving interconnection with the rest of the system (Karnopp, 1983; Ramirez et al., 2018). In the following subsections we present the model of each physical subdomain before giving the complete thermo-electro-mechanical model the piezo actuator.

### 3.1 Mechanical Domain

The mechanical part of the piezoelectric actuator is represented by a mass-spring-damper system with parameters $M$, $k$ and $d$ respectively. The interconnection relations for the forces and velocities are $F_M = -F_k - F_d + F_{P_T} + F_{ext}$ and $v_M = v_d = \dot{q}$ where $F_M$ is the force over the mass, $F_k$ is the elastic force from the spring, $F_d$ is the damping force, $F_{ext}$ is an external force and $F_{P_T}$ is the force produced by electro-mechanical coupling, $v_M$ and $v_s$ are the velocities of the damper and the mass respectively and $q$ is the tip displacement of the piezoelectric actuator. The spring and damper are assumed to be linear. Thus, the constitutive laws of the energy storage elements can be expressed as $F_e = k(q - q_l)$, $F_d = dv_d$, and $v_M = \frac{p}{M}$, where $q_l$ is the displacement of the spring in rest position and $p$ the kinetic momentum. Taking as state variables the pair $(q, p)$ the dynamic equations of this subsystem are

$$\dot{q} = \frac{p}{M}$$
$$\dot{p} = -k(q - q_l) - d\frac{p}{M} + F_{P_T} + F_{ext}$$

### 3.2 Electrical Domain

The electrical part of the piezoelectric model is composed by a voltage source, which is the input of the system, a capacitor of capacitance $C$ and $r$ hysterons, each composed by a resistance and an inductor in series. The interconnection relations are $V_{R_j} + V_{L_j} + V_C = V_{in}$, $V_{R_j} + V_{L_j} = V_{R_k} + V_{L_k}$ for $j \neq k$ and $i_C = \sum_{j=1}^{n} i_{h_j} - i_{P_T}$, where

$j,k=\{1,2,\cdots,r\}$; $V_{R_j}$, $V_{L_j}$ and $V_C$ are the voltage of the $j$-th resistance, $j$-th inductor and capacitor respectively; $i_C$, $i_{h_j}$ and $i_{P_T}$ are the currents through the capacitor, $j$-th hysteron and the transducer respectively. The constitutive laws for the energy storage elements are considered linear, $i_{L_j}=\frac{\phi_{L_j}}{L_j}$ and $V_C=\frac{Q_C}{C}$, where $i_{L_j}$ is the current through the $j$-th inductor, $\phi_{L_j}$ the electromagnetic flux of the $j$-th inductor, $Q_C$ is the charge stored in the capacitor, $L_j$ is the inductance of the $j$-th inductor and $C$ is the capacitance. The $r$ resistances are non-linear with constitutive law $V_{R_j}=w_j(i_{R_j},T)$ where $w_j(\cdot,T)$ is a non-linear, non-smooth operator satisfying the dissipation relation

$$V_{R_j}i_{R_j}=w_j(i_{R_j},T)i_{R_j}=\sigma_{h_j}\geq 0$$

where $\sigma_{h_j}$ corresponds to the internal entropy production of the $j$-th hysteron. From the interconnection equations the following set of state equations are obtained

$$\dot{Q}_C=\sum_{j=1}^{r}\frac{\phi_{L_j}}{L_j}-i_{P_T}$$

$$\dot{\phi}_{L_j}=V_{in}-\frac{Q_C}{C}-w_j\left(\frac{\phi_{L_j}}{L_j},T\right)$$

### 3.3 Thermodynamic Domain

We consider that the piezoelectric actuator is a thermodynamic system that exchanges heat with its environment. Denoting by $S$ the total entropy of the system, the entropy balance is given by $\dot{S}=\sigma+\dot{S}_{en}$ where $\sigma$ represents the internal entropy production and $\dot{S}_{en}$ the entropy exchanges with the environment which is modeled as $\dot{S}_{en}=\lambda\left(\frac{T_e(t)}{T(S)}-1\right)$, where $\lambda$ denotes the Fourier's heat conduction coefficient and $T_e(t)$ is the temperature of the environment. The constitutive relation considered for the temperature is $T(S)=T_0e^{\frac{S}{c_0}}$ where $T_0$ and $c_0$ are constants (Ramirez et al., 2013b). To obtain $\sigma$ we consider the total energy function of the interconnected system

$$U=\frac{1}{2}\frac{Q_C^2}{C}+\frac{1}{2}\sum_{j=1}^{r}\frac{\phi_{L_j}^2}{L_j}+\frac{1}{2}\frac{p^2}{M}+\frac{1}{2}k(q-q_l)^2+f_h(S) \quad (6)$$

where $f_h(S)$ is some smooth function of the entropy which is yet to be deduced. Assuming that there are no external inputs, i.e., $F_{ext}=0$, $V_{in}=0$, and $T_e=T$, which implies $\dot{S}_{en}=0$, the time variation of (6) is

$$\dot{U}=-\sum_{j=1}^{r}\frac{\phi_{L_j}}{L_j}w_j\left(\frac{\phi_{L_j}}{L_j},T\right)-d\left(\frac{p}{M}\right)^2+\frac{\partial U}{\partial S}\dot{S}$$

from were we obtain

$$\sigma=\frac{1}{T}\left(\sum_{j=1}^{r}\frac{\phi_{L_j}}{L_j}w_j\left(\frac{\phi_{L_j}}{L_j},T\right)+d\left(\frac{p}{M}\right)^2\right)=\sum_{j=1}^{r}\sigma_{h_j}+\sigma_d\geq 0 \quad (7)$$

where $\sigma_{h_j}$ and $\sigma_d$ correspond respectively to the internal entropy production of the $j$-th hysteron and the damper. The entropy balance is given by

$$\dot{S}=\sum_{j=1}^{r}\sigma_{h_j}+\sigma_d+\lambda\left(\frac{T_e(t)}{T(S)}-1\right) \quad (8)$$

### 3.4 IPHS Representation

In order to define the coupling relation between the thermal-electrical-mechanical we assume the following.

*Assumption 2.* The three domains are interconnected through the hysterons by the non-linear resistances and by the transducer element $P_T$ as follows

$$V_{R_j}=w_j(i_{R_j},T)$$

where $w_j(i_{R_j},T)$ is an operator that depends on the temperature $T$ but is applied to the current $i_{R_j}$. Furthermore the transducer is temperature modulated, and defined by the following power preserving relations

$$F_{P_T}=\alpha(T)V_{P_T}=\alpha(T)V_C,\quad i_{P_T}=\alpha(T)v_{P_T}=\alpha(T)v_M$$

where $\alpha$ is the electro-mechanical transducer ratio which depends on the temperature $T$ of the piezoelectric actuator.

Using Assumption 2 together with the balance equations deduced in the previous subsections,

$$\dot{q}=\tfrac{p}{M} \quad (9)$$

$$\dot{p}=-k(q-q_l)-d\tfrac{p}{M}+\alpha\tfrac{Q_C}{C}+F_{ext} \quad (10)$$

$$\dot{Q}_C=\sum_{j=1}^{r}\tfrac{\phi_{L_j}}{L_j}-\alpha\tfrac{p}{M} \quad (11)$$

$$\dot{\phi}_{L_j}=V_{in}-\tfrac{Q_C}{C}-w_j\left(\tfrac{\phi_{L_j}}{L_j},T\right) \quad (12)$$

$$\dot{S}=\sum_{j=1}^{r}\sigma_{h_j}+\sigma_d+\lambda\left(\tfrac{T_e}{T}-1\right) \quad (13)$$

the piezo actuator model allows the IPHS formulation given in the following proposition.

*Proposition 3.* Consider $x=(q,p,Q_c,.,\phi_{L_j},.,S)$ as state vector. Then a IPHS formulation for the thermo-electro-mechanical model of the piezo actuator characterized by (9)-(13) is

$$\dot{x}=\left(J_0+R_dJ_d+\sum_{j=1}^{r}R_jJ_j\right)\frac{\partial U}{\partial x}+gu \quad (14)$$

where the structure matrices are defined as

$$J_0=\begin{bmatrix}0&1&0&0&\cdots&0&0\\-1&0&\alpha(T)&0&\cdots&0&0\\0&-\alpha(T)&0&1&\cdots&1&0\\0&0&-1&0&\cdots&0&0\\\vdots&\vdots&\vdots&\vdots&\ddots&\vdots&\vdots\\0&0&-1&0&\cdots&0&0\\0&0&0&0&\cdots&0&0\end{bmatrix}, \quad (15)$$

$J_d$ and $J_j$ have all their elements equal to zero except for two elements in each matrix, respectively

$$J_{d_{(n,2)}}=1\quad J_{d_{(2,n)}}=-1$$

$$J_{j_{(n,j+3)}}=1\quad J_{j_{(j+3,n)}}=-1$$

The non-linear modulating functions are

$$R_d=\frac{1}{T}d\left(\frac{p}{M}\right)\qquad R_j=\frac{1}{T}w_j\left(\frac{\phi_{L_j}}{L_j},T\right)$$

The input vector is $u^T=(F_{ext},V_{in},\lambda\left(\frac{T_e}{T}-1\right))$, with input mapping

$$g^T=\begin{bmatrix}0&1&0&0&\cdots&0&0\\0&0&0&1&\cdots&1&0\\0&0&0&0&\cdots&0&1\end{bmatrix}$$

and conjugated output $y^T=(\frac{p}{M},\sum_{j=1}^{r}\frac{\phi_{L_j}}{L_j},T)$.

From the proposed model the matrices $J_d$ and $J_k$ represent the interconnection of the dissipative elements (damper and hysterons) and $J_0$ represents the interconnection of the energy preserving elements. Note that $J_0$ depends on $T$ which is a co-energy variable, implying it is a pseudo port-Hamiltonian matrix.

In addition, the thermodynamic driving forces, associated with the damper and $j-th$ hysteron are, respectively, $\{S,U\}_{J_d} = \frac{p}{M}$ and $\{S,U\}_{J_j} = \frac{\phi_j}{L_j}$ while the positive definite modulation functions are $\gamma_d = \frac{d}{T}$ and $\gamma_j = \dfrac{1}{T}w_j(\cdot,T)$.

## 4. NUMERICAL SIMULATIONS

In this section, numerical simulations are performed to verify that the proposed thermodynamic model reproduces the behavior of a piezoelectric actuator when the environment temperature and the frequency of the voltage input vary. Numerical values within standard physical ranges were considered for the electro-mechanical components (Goldfarb and Celanovic, 1997; Thorlabs, 2020) while suitable values were selected for the thermodynamic parameters. The considered parameters are resumed in Table 1. No external mechanical loading has been considered, i.e., $F_{ext} = 0$.

| $M$<br>$3,5\cdot 10^{-3}[kg]$ | $k$<br>$5\cdot 10^{5}[N/m]$ | $d$<br>$4\cdot 10^{2}[N\cdot s/m]$ | $C$<br>$5[\mu F]$ |
|---|---|---|---|
| $L$<br>$1\cdot 10^{-3}[H]$ | $T_0$<br>$296,15[K]$ | $\lambda$<br>$2[W/m^2K]$ | $c_0$<br>$5[K/J]$ |

Table 1. Parameters of the model

### 4.1 Temperature dependent coupling elements

The electro-mechanical transducer ratio $\alpha$, which is by assumption temperature dependent, is defined as

$$\alpha(T) = a\frac{T}{T_0}$$

where $a = 10$ with units $[C/m]$ or $[C/s\cdot kg]$ if it is the electrical to mechanical transducer ratio or mechanical to electrical, respectively. For simplicity two hysterons are used for the simulations. Notice that this is a very low number, and that to achieve complex and more precisely hysteresis curves a larger number of hysterons needs to be employed (Karnopp, 1983). The inductance values are chosen equal for both hysterons and the non-linear resistance operators $w_j(z,T)$ defined as

$$w_j = \begin{cases} \frac{10}{T-T_0}(z-0.5) & z > 0.5 \\ 0 & -0.5 \le z \le 0.5 \\ \frac{10}{T-T_0}(z+0.5) & z < -0.5 \end{cases}$$

Notice that for this particular choice the reference temperature $T_0$ has to be selected lower than the operation range of $T$. Figure 2. shows the curve generated by the chosen non-linear operator for different values of $T$.

### 4.2 Simulations

The hysteresis behavior is shown in Figure 3. A $100[V]$ sinusoidal input voltage at frequency $100[Hz]$ has been considered, i.e., $V_{in} = 100\sin(100\cdot 2\pi t)[V]$, and different values for the external temperature $T_e = \{25,30,35,40\}[°C]$ have been used. It is appreciated that the slope of the hysteresis curve changes when the external temperature changes. This is in accordance with reported results on temperature dependent hysteresis in piezoelectric actuators (Habineza et al., 2016; Al Janaideh et al., 2019). Figure 4 shows static temperature changes when the input voltage frequency $f$ is increased, i.e., $V_{in} = 100\sin(f\cdot 2\pi t)[V]$, for different values of inductance in the hysterons, $L = \{0.1, 0.5, 1, 5,\}\cdot 10^{-3}[H]$. From the reported characteristics of commercial piezoelectric actuators, like the bimorph PB4NB2W from Thorlabs (Thorlabs, 2020), it is expected that the static temperature of the actuator increases as the operation frequency increases. It is observed in Figure 4 that the aforementioned characteristic is achieved for a range of lower frequencies which depend on the value of the parameter $L$. Figure 5 shows the displacement step response when the input voltage is changed from $50[V]$ to $100[V]$ for different external temperature values, $T_e = \{25,30,35,40\}[C]$. The results show that the temperature generates an offset in the static response of the displacement, which is in accordance with reported results (Habineza et al., 2016). Figure

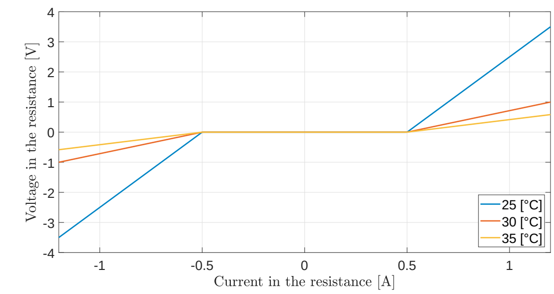

Fig. 2. $w_{T_j}(\cdot)$ operator behavior for different temperatures values

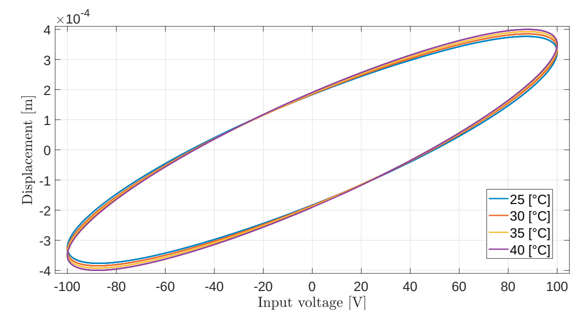

Fig. 3. Hysteresis behavior between voltage and displacement under different temperatures

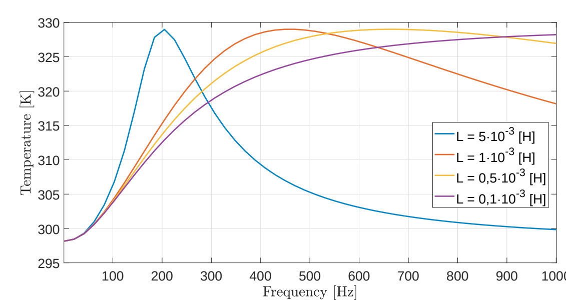

Fig. 4. Static temperature change for different frequency operation

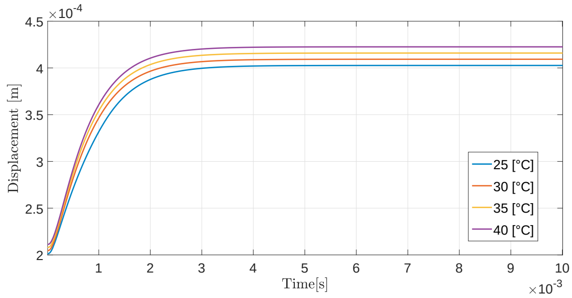


Fig. 5. Step response for different environment temperatures

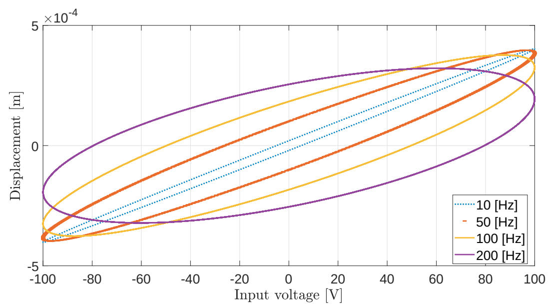


Fig. 6. Change of the hysteresis curve due to the frequency operation

6 shows how the hysteresis curve changes for different voltage frequencies. In this simulation $V_{in} = 100\sin(f \cdot 2\pi t)[V]$ and $f = \{10, 50, 100, 200\}[Hz]$. Notice that the hysteresis curve gets wider and the slope decreases when the frequency is increases, as expected from reported results (Zhu and Rui, 2016; Aljanaideh et al., 2015). These effects are a combination of the ones depicted in Figures 3 and 4.

## 5. CONCLUSION

An irreversible port-Hamiltonian system (IPHS) formulation for a class of piezoelectric actuator with non-negligible entropy increase has been proposed. The proposed model encompasses the hysteresis and the irreversible thermodynamic changes due to mechanical friction, electrical resistance and heat exchange between the actuator and the environment. The electromechanical dynamic of the actuator has been modeled using a non-linear resistive-capacitive-inductor circuit coupled with a mass-spring-damper system, while the non-linear hysteresis has been characterized using hysterons. The thermodynamic behavior of the model has been constructed by making the electro-mechanical coupling temperature dependent, and by characterizing the entropy produced by the irreversible phenomena. By means of numerical simulations it has been shown that the proposed model is capable of reproducing the expected behaviors and that it is in line with reported experimental results. It is interesting to notice that for the numerical simulations only two hysterons were used, strongly limiting the possible dynamics. Since IPHS are passive systems and well suited for non-linear control we expect that the proposed model will be useful for control design. Future work will deal with control design, deduce the number of hysterons to be used in the model and experimental validation.

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