« EMR and inversion-based control of a multi-piezo-actuator system »

Dr. Thanh Hung NGUYEN, Prof. Betty LEMAIRE-SEMAIL,
L2EP, Université Lille 1, France

Prof. Gabriel ABBA,
LCFC, Arts et Métiers ParisTech, France

Assoc. Prof. Christophe GIRAUD-AUDINE,
L2EP, Arts et Métiers ParisTech, France
1. Introduction
   • Context
   • Multi-piezoactuator system

2. EMR of a multi-piezo-actuator system
   • Modeling of mechanical system
   • Modeling of electrical system

3. Inversion-based control of a multi-piezo-actuator system
   • Controlling structure for generation of vibrations
   • Experimental results

4. Conclusion
« Introduction »
Forging is a material manufacturing process by plastic deformation due to the relative movement of the two dies having the product’s form.

→ in the case of metal forging: requires very high force (up to 10 000 kN)

Why must the forging force be reduced?
- Facilitate the process;
- Protect the expensive dies;
- Reduce energy consumption
**Context**

**Traditional methods to reduce forging force**

- **Die lubrication**
  - *Disadvantages*: Additional operations, Geometrical faults

- **Workpiece preheating**
  - *Disadvantages*: Additional operations, Reduced material characteristic

**Vibration assisted forging**

- No additional operations
- Reduce geometrical faults
- Improve material characteristic

---

[Without vibrations](image)  [With vibrations](image)

- Frequency: 20kHz
- Amplitude: 10 μm

[Huang et al.](2002)
Low frequency vibration


[Khan et al] (2013)

Low frequency vibration

- Wave form: progressive wave;
- Frequency: 10Hz;
- Amplitude: few μm;

Reduction gain = \( \frac{\text{Force with vibrations}}{\text{Force without vibrations}} \)
Objective is to generate higher force (by using more than 1 actuator) and to obtain more effective movement (example: progressive wave).

**Applied vibrations’ specifications**

- Vertical vibrations along z in arbitrary form (sinusoidal, triangular, square, ... ) with frequency $< 100$Hz.
- A progressive wave with frequency $< 100$Hz.
- Maximal force: 12000N.

![Diagram of multi-piezo-actuator system]
« EMR and inversion-based control of a multi-piezo-actuator system »

- Multi-piezo-actuator system -

- Multi-stack piezoelectric actuators (max 80µm/5500N)
- Steel ball fixed to each actuator → sphere – plane contact
- Compliant mechanism using 3 flexible beams: zero backlash, friction, wear
- Displacement sensors using Hall effect
« EMR
of a multi-piezo-actuator system »
EMR and inversion-based control of a multi-piezo-actuator system

- Modeling of mechanical system -

Speed and force transmission

\[ \mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & R \\ 0 & 0 & 1 & -\frac{R}{2} \\ 0 & 0 & 1 & -\frac{R}{2} \end{bmatrix} \begin{bmatrix} 0 \\ \frac{R}{2} \\ -\frac{R}{2} \frac{R\sqrt{3}}{2} \\ 0 \end{bmatrix} = A \mathbf{v}_0 \]

\[ \mathbf{v}_0 \mathbf{F}_0 = \mathbf{v}_F \]

\[ \mathbf{F}_0 = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \\ R & -\frac{R}{2} & -\frac{R}{2} \\ 0 & -\frac{R\sqrt{3}}{2} & -\frac{R\sqrt{3}}{2} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = A^T \mathbf{F} \]
« EMR and inversion-based control of a multi-piezo-actuator system »

- Modeling of mechanical system -

\[
\mathbf{M} = \begin{bmatrix}
m_1 & 0 & 0 & 0 & -m_2 & 0 \\
0 & m_1 & 0 & m_2 & 0 & 0 \\
0 & 0 & m_1 & 0 & 0 & 0 \\
-m_2 & 0 & 0 & m_3 & 0 & 0 \\
0 & 0 & 0 & 0 & m_4 & 0 \\
\end{bmatrix}
\]

\[
\mathbf{K} = \begin{bmatrix}
k_1 & 0 & 0 & 0 & -k_2 & 0 \\
0 & k_1 & 0 & k_2 & 0 & 0 \\
0 & 0 & k_5 & 0 & 0 & 0 \\
k_2 & 0 & k_3 & 0 & 0 & 0 \\
-k_2 & 0 & 0 & k_3 & 0 & 0 \\
0 & 0 & 0 & 0 & k_4 & 0 \\
\end{bmatrix}
\]

\[
m_y \ddot{\alpha}_y + k_y \alpha_y = M_y - M_{wpY}
\]

\[
m_x \ddot{\alpha}_x + k_x \alpha_x = M_x - M_{wpX}
\]

\[
m_z \ddot{z} + k_z z = F_z - F_{wp}
\]

Model order reduction
**EMR and inversion-based control of a multi-piezo-actuator system**

- Modeling of electrical system -

**Electrical system’s requirements**

- A three-phase supply with high voltage (up to 1000 V);
- A voltage with variable frequency (from 5 Hz to 100 Hz);

![Diagram of electrical system](image)

Three piezoelectric actuators

Three phase inverter Semikron

![Experiment setup](image)
« EMR and inversion-based control of a multi-piezo-actuator system »

- Modeling of electrical system -

Equivalent mono-phase scheme of electrical supply

The inverter’s average model:

\[ U_m = m(t) U_0 \]
\[ i_0 = m(t) i_b \]

where \( m(t) \): duty cycle

\[ 0 < m(t) < 1 \]

Equivalent scheme for two operating modes

Mode of generating the vibrations

Mode of charging the capacitor \( C_0 \)

\[ \frac{C_0}{m^2} \gg C \]
\[ i_b \approx i_s \]
Diode’s operating diagram

- Diode ON
  - \( i_D > 0 \)
  - \( U_d = 0 \)
- Diode OFF
  - \( i_D = 0 \)
  - \( U_d < 0 \)

\( U_s \): DC voltage
\( U_p \): Actuators’ voltage

Supply system’s EMR

- Voltage supply
- Inductors \( L_s \)
- Parallel connection
- Inverter
- Capacitor \( C_0 \)

Piezoelectric actuators
« EMR and inversion-based control of a multi-piezo-actuator system »

- Modeling of complete system -

Complete system’s EMR

Vibrations along Oz

Rotations around Ox and Oy

\[ \begin{align*}
&U_0, \quad U_m, \quad i_b, \quad U_p, \quad i_c, \quad \vec{v}_p, \quad \vec{v}_m, \quad \vec{F}_k, \quad \vec{F}_w, \quad \vec{F}_w^p, \quad \vec{v}_o, \\
&\text{Electrical system} \quad \text{Piezoelectric actuator + Contact} \quad \text{Lower die + compliant mechanism}
\end{align*} \]
« Inversion-based control of a multi-piezo-actuator system »
EMR and inversion-based control of a multi-piezo-actuator system

- Controlling structure for generation of vibration -

Maximal Control Structure

Practical Control Structure

Simplifications: non-measurable variables $F_s$, $F$, $F_k$ and rigid contacts
« EMR and inversion-based control of a multi-piezo-actuator system »

- Experimental system -

Transfer function

\[
H(z) = \frac{U_p}{U_m} = \frac{1 - \exp(T_s s)^2}{s^2 + \frac{L_b C s^2 + R_b C s + 1}{\omega_f^2 + 2 \frac{s}{\omega_f} + 1}}
\]

Identified model

\[
y(z) = \frac{0, 465z + 0, 465}{z^3 - 0, 1014z^2 + 0, 02796z - 0, 01475} u(z)
\]

Step response of \(d\)-axis

[Graph of step response with labeled lines for reference and measured responses]
EMR and inversion-based control of a multi-piezo-actuator system

- Closed-loop voltage control -

Step response of $dq$-axis voltage

- Measured voltage $U_{dqh}$

- Actuators’ voltage

Generating the vibrations

- A progressive wave of 10Hz
  - $U_d = 30 \text{ V}$, $U_q = 0$
  - $U_{h1} = 130 \text{ V}$

- A vertical vibration of 20Hz
  - Triangular
  - $U_{h2} = 50 \text{ V}$

$U_{dqh}$
EMR and inversion-based control of a multi-piezo-actuator system

- Closed-loop speed control -

Opened loop
Measured speeds at the actuators’ positions

![Graph showing speed responses](image1)

Closed loop
Voltage responses $U_d$, $U_q$

![Graph showing voltage responses](image2)

Response of speeds $v_d$, $v_q$ to step input $U_d$

![Graph showing speed responses](image3)

Step responses $v_d$, $v_q$
« Conclusion »
Results

- Design of a multi-piezo-actuator system
- Modeling and representation by using EMR tool
- Inversion-based control structure and experimental validation

Future work

- Experiments with forging machine
« BIOGRAPHIES AND REFERENCES »
EMR'15, Lille, June 2015

« EMR and inversion-based control of a multi-piezo-actuator system »

- Authors -

Dr. Thanh Hung NGUYEN
L2EP, University Lille 1
PhD in Electrical Engineering at ENSAM (2014)
Research topics: Design, modeling and control of mechatronic systems

Prof. Betty LEMAIRE-SEMAIL
University Lille 1, L2EP, MEGEVH, France
PhD at University of Paris XI, Orsay (1990)
Research topics: EMR, Control, Piezoelectric actuators

Prof. Gabriel ABBA
LCFC, Arts et Métiers ParisTech, Metz, France
PhD in Electronics and Robotics at University of Paris XI, Orsay (1986)
Research topics: Robots, control, actuators

Assoc. Prof. Christophe GIRAUD-AUDINE
L2EP, Arts et Métiers ParisTech, Metz, France
PhD in Electrical Engineering at INP de Toulouse (1998)
Research topics: modelling and control of devices based on piezoelectric and shape memory alloys


