Feedback Loop on a large scale quadrupole prototype

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Overview

-Brief summary of the last presentation in London

-Transfer of the former studies to a large scale prototype:
  - Description of the prototype with appropriate actuators.
  - Results of the active vibration reduction

-Robustness: Development of one frequency tracking in real time

-Technology and location of the instrumentation

-Conclusions

Collaboration with
Strategy of the approach

The Spectrum of disturbances is not a white noise (ground motion, acoustic noise…)

- Some frequencies which are amplified
- All frequencies are independent

Strategy: to control independently every main frequency
**Originalities of the method : the algorithm**

Usually, a classic algorithm (ex : PID), depends on the model of the process:

![Diagram of control system]

It is not a classic algorithm, it is a compensation of the disturbance:

*without knowing the model of the process, only its behaviour at certain frequencies*
Originalities of the method: the signal processing

A non linear problem:

\[ f(t) = \alpha \sin(\omega t + \varphi) \]

(the force to be computed)

Decompose each resonance as a weighted combination of sine and cosine:

(measurement, disturbance, excitation)

\[ f(t) = \alpha \sin(\omega t + \varphi) \Rightarrow f(t) = f_s \sin(\omega t) + f_c \cos(\omega t) \]

where:

\[ f_s = \alpha \cos(\varphi) \]

\[ f_c = \alpha \sin(\varphi) \]
Test the algorithm with a small prototype

Brief summary

Description of the prototype:

- Accelerometer
- Collocation of two piezo-electric patches
- Sensor PZT (bottom)
- The beam in cantilever mode
- Loudspeaker
- Actuator PZT (on top)
Results

Rejection of 6 resonances: (without and with rejection)

Resonances of: - beam
- support
A large scale prototype

Why a new prototype?

-To validate the algorithm on a large scale prototype, whose size, boundary conditions and eigen frequencies are similar to the final focus.

-To validate the micro-computing which:
  - manages noisy low signal with very high resolution
  - computes the appropriate control of the feed-back in a limited time.

-To validate sensors and actuators which are performant, compatible and adapted to the final focus.

-To validate the developed simulation for the prediction.

Movement of a linear mechanical structure < ground motion
A large scale prototype

The mock-up:

- Clamping
- Location of the actuator
- Accelerometers
- The beam in cantilever mode
- The active stabilised table

Dimensions:
- 2.5 m
- 120 mm
- 80 mm
- 2 mm
The actuator: description

Force = 19.3 N
Maximal displacement = 27.8 μm
Resolution = 0.28 nm

The deformation of the PZT patches is amplified by the mechanical structure.

(Produced by Cedrat)
The actuator applies a force in flexion
The actuator applies a force in “proof-mass”
A large scale prototype

Results: rejection of 3 fixed frequencies of disturbances

Efficient vibration rejection
A large scale prototype

**Limitations:**

**Current configuration:** Fast prototyping with XPC Target in a dedicated PC

- Fast prototyping with XPC Target in a dedicated PC
- Ethernet network
- Development PC (host) + Matlab + Simulink
- Dedicated PC (target) + XPC Target Toolboxes
- DSP ("Digital signal processor") of ProDAQ

**Configuration in test:**

- 16 bits with programmable gain
- -24 bits resolution
- Programmable gain…
- Adapted electronic for vibrations
- Possibility to reduce to nanometer scale
- As each frequency is rejected independently, the robustness depends on the estimation of the real value of the disturbance frequency:

Frequency tracking in real time

Signal processing

Mechanical part

sensor

actuator

Algorithm (for one frequency)

signal processing

$y(w_i)$

$y_s(w_i)$

$y_c(w_i)$

signal rebuilding

$f_s(w_i)$

$f_c(w_i)$

$w$

spectral analysis

Frequency tracking: The recursive least squares method
Frequency tracking in real time

Recursive least squares method

Initial Method of “signal processing”:
\[ \hat{y}_i = \hat{y}_s \cdot \sin(wt_i) + \hat{y}_c \cdot \cos(wt_i) \]

Objective:
\[ \hat{y}_i = \hat{y}_s \cdot \sin(\hat{w}t_i) + \hat{y}_c \cdot \cos(\hat{w}t_i) \]
Frequency tracking in real time

Recursive least squares method

Considering the measurement has the following form:

\[ y(t_i) = y_s \cdot \sin(wt_i) + y_c \cdot \cos(wt_i) \]

The criterion to be minimized:

\[
J(y_s, y_c) = \frac{1}{N} \cdot \sum_{i=1}^{N} (y_i - y(t_i))^2 \quad (N : \text{number of samples})
\]

Matrix form:

\[
Y = \begin{pmatrix}
y_1 \\
y_2 \\
\vdots \\
y_N \\
\end{pmatrix} = \begin{pmatrix}
\sin wt_1 & \cos wt_1 \\
\sin wt_2 & \cos wt_2 \\
\vdots & \vdots \\
\sin wt_N & \cos wt_N \\
\end{pmatrix} \begin{pmatrix}
y_s \\
y_c \\
\end{pmatrix}
\]

The matrix \( \hat{M} \) which minimizes the criterion:

\[
\hat{M} = (H^T \cdot H)^{-1} \cdot H^T \cdot Y
\]
Minimizing the criterion \( J \) corresponds to minimizing its derivative by the variables to be estimated:

\[
\frac{\partial J}{\partial \hat{y}_s} = 0 \quad \frac{\partial J}{\partial \hat{y}_c} = 0 \quad \frac{\partial J}{\partial \hat{w}} = 0
\]

Which gives:

\[
\hat{w}_{j+1} = \hat{w}_j - \lambda \frac{\partial J}{\partial \hat{w}}
\]

(\textit{where} \( \lambda \) \textit{is the dynamics of the recursivity})

The ending criterion of the recursivity:

\[
\frac{J(\hat{w}_{(j+1)}) - J(\hat{w}_{(j)})}{J(\hat{w}_{(j)})} < \varepsilon
\]
- External disturbance simulation with a step frequency function (response of a 1st order process):

The loudspeaker generates a step of frequency which simulates, for example, a change of speed of a pump near the final focus.
Experimental results

Frequency tracking in real time

- Without rejection
- With rejection

Efficient rejection if the variation is slow
Location and technology of the instrumentation

Problem: No access to the area to be stabilised

- Where is the optimal location and what technology for the instrumentation?
- What are the effects of a local control on the global movement of the beam?
- How to be sure that the end of the beam is stabilised in real time?
Location and technology of the instrumentation

Small mock-up

The prototype:

Experimental results:

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Sensor</th>
<th>PZT0</th>
<th>PZTM</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT0</td>
<td>PZTM</td>
<td></td>
<td>VG</td>
<td>G</td>
</tr>
<tr>
<td>PZT0</td>
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<td>VG</td>
</tr>
</tbody>
</table>

The rejection always works at the measurement point of the feed-back.
The behaviour of the beam changes with the configuration.
Location and technology of the instrumentation

Numerical simulation of the small mock-up

- Finite elements with ANSYS:

(Collaboration with LMECA)

- “Structural Dynamic Toolbox” is used to process the characteristics of the model under Matlab / Simulink environment:

Simulation of the disturbance

Transfer between 2 PZT

Transfer between a PZT actuator and any node

Feed-back loop
Location and technology of the instrumentation

Numerical simulation of the small mock-up

Example of the simulation:

Configuration of the test:

- Rejection of one disturbance frequency (1st mode of flexion)
- “PZTM top” in actuator / “PZTM bottom” in sensor
- Monitoring simultaneously of:
  - each node of the beam
  - the voltage of each PZT patch
Results:

Numerical simulation of the small mock-up

Location and technology of the instrumentation

Behaviour of the beam (feed-back ON)

Steady state before rejection

End of the beam: less efficient rejection

Measurement point of the rejection: efficient rejection

Beginning of the rejection

End of the beam

Clamping

(1st mode of the beam)
Location and technology of the instrumentation

Large prototype

The prototype:

- Actuator in flexion
- Seismic sensor (accelerometer and velocity sensor)
- Clamping
- Mechanical structure
- Actuators in proof-mass

Clamping | Antinode of 3\textsuperscript{rd} mode | Antinode of 2\textsuperscript{nd} mode | Node of 2\textsuperscript{nd} mode | End of the beam
Location and technology of the instrumentation

Simulation of the large prototype

- Finite elements with SAMCEF:

- Simulation of the entire system:

  - External perturbation
  - Structure
  - Dynamic Response
  - Action of actuators
  - Results from sensors
  - Active Feedback Loop

SAMCEF
MATLAB – Simulink
   XPC target
Conclusions

• Active feedback loop on a large scale prototype

  Validation of the method for the micrometer scale

  Validation of the frequency tracking

  Requirement of an efficient hardware (data acquisition) to get results at nanometer scale

• Choice of the location and the technology of the instrumentation

  First approach with experimental tests

  Requirement of simulation for validation (with accurate updating models)

  Multivariable problem with many sensors and actuators using different technologies