Vibration and mechanical stability — status and perspectives

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**Vibration**: A rapid oscillation of a particle, particles, or elastic solid or surface, back and forth across a central position

*The American Heritage® Science Dictionary*
Outlines

Fundamentals
How to measure nm level of vibration
Ground vibration
Vibration of mechanical structure
Vibration propagation
Beam stability
Vibration investigation
  - Vibration on the EXPH floor
  - Cooling flow induced vibrations
Summary and perspectives
**Fundamentals**

**Temporal domain**

- Temporal velocity (Response to mass drop)

**Frequency domain**

- Fourier transform

**Some terms**

- Window length $t_{\text{win}}$
- Sampling rate (number of samples per second): $f_s = 1/\Delta t$
- Bandwidth: $f < f_{\text{max}} = f_s / C_{\text{Nyquist}}$ ($C_{\text{Nyquist}} \geq 2$)
- Spectral resolution $\Delta f = 1/t_{\text{win}}$

**Graphs**

- Temporal velocity
- Spectral velocity

**Equations**

- $V_{\text{RMS}} = 30.382 \, \mu$m/s
In frequency domain

3 frequency ranges

Low ( \( f < 1 \) Hz)
- Ocean waves
- Micro seismic activities

Intermediate (1<\( f <100 \) Hz)
- Mechanical resonant frequencies
- Traffic, machine operations, water flow, wind,…

High ( \( f >100 \) Hz)
- Generated by small electro-mechanical structures
- Vibro-acoustic
- Much smaller level
Sensors (transducers)

- Geophones (L4C: 285 V/(m/s), sensor noise < 80 pm (RMS) < $d_{RMS-ESRF-Site}/1000$)
- Seismometers (Guralp CMG-3ESP: 0.03 ~ 50 Hz)
- Accelerometers (strong, high-f Vib.)
- Laser vibrometer (d & V, d (>2nm))
- Displacement sensors (capacitive, …)
Data acquisition systems (DAS)

- OROS, RefTek
- Standalone or network
- Dynamical range
  (12 → 16 → 24 bits, 60 → 80 → 120 dB)
- Lowest input range: 17mV, 200mV (RT)
- Internal noise ~ $10^{-7}$: $16 \text{nV (RT)} @ 200\text{mV}$ → $10\text{pm}$ (with geophone L4C)

Data processing systems

- Matlab, SAC, Star,...
- OROS
**Measurement quantities**

<table>
<thead>
<tr>
<th>Displacement</th>
<th>Velocity</th>
<th>Acceleration</th>
</tr>
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<tbody>
<tr>
<td>integration</td>
<td>differentiation</td>
<td></td>
</tr>
<tr>
<td>( *(2\pi f) )</td>
<td>( /(2\pi f) )</td>
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**Spectra of Velocity**
- Flatter than those of displacement, acceleration
- Less dynamic range requirement from DAS
- One operation (integration or differentiation) to obtain displacement or acceleration

Most convenient to measure velocity → geophone widely used
Fundamentals

Measurement quantities

Displacement  \(\int (2\pi f)\)  Velocity  \(\frac{1}{(2\pi f)}\)  Acceleration

3D spectral displacement at the ESRF site
3D spectral velocity at the ESRF site
3D spectral acceleration at the ESRF site

Sensors vs frequency range

- Very low frequency range  \(\rightarrow\) displacement sensors
  (positioning and alignment, ...)
- Intermediate frequency range  \(\rightarrow\) velocity sensors: geophone
  (seismology, geophysics, petroleum exploration, ...)
- High frequency range  \(\rightarrow\) accelerometers
  (industries: auto, aeronautics, ...)

\[ \text{integration: } (2\pi f) \]
\[ \text{differentiation: } \frac{1}{(2\pi f)} \]
**Power Spectrum Density (PSD)**

**Temporal domain**
- Velocity of **unit mass**: \( v(t) \)
- Kinetic energy: \( e(t) = \frac{1}{2} v(t)^2 \)
- RMS of \( v(t) \): \( V_{RMS} = \sqrt{\frac{1}{n} \sum v(t)^2} \)

**Frequency domain**
- Velocity spectrum: \( V(f) \)
- **Power spectrum density**: \( PSD = \frac{1}{2} \frac{V(f)^2}{\Delta f} \) (kinetic energy per unit of frequency interval)

\[ V_{RMS} = 30.385 \, \mu m/s \]

**Power Spectrum Density**

\[ P_{total} = \int PSD \times df \]

\[ V_{RMS} = \sqrt{\int PSD \times df} \]
Fundamentals

Power Spectrum Density (PSD)

- Independent of window length

Spectral displacement (velocity, acceleration): window length $t_{\text{win}}$ dependant

- PSD : independent of window length $t_{\text{win}}$
- PSD is appropriate for vibration spectra comparison
Capacitive sensor test setup

- A moving surface driven by a piezo-actuator generates a controlled displacement
  \[ d(t) = A \sin(2\pi ft) \]
- Capacitive sensor and Laser vibrometer measure simultaneously this controlled displacement
- Tested sensors:
  - LION C7-C (resolution: pp=1.5nm, rms=0.1nm, range 10um)
  - PI Seca (range 20um)
Capacitive sensor test results

- Piezo-actuator generated \( d(nm) \sim 1 \times \sin(2ft) \), \( f=60 \) Hz
- Resonance of the test assembly at 557 Hz → excellent agreement between Laser vibrometer and capacitive sensor
- At \( f=60\)Hz, all sensors measure \( PSD=2.6 \times 10^{-6} \) \( \mu m^2/Hz \), \( \Delta f \sim 0.1\)Hz
  → \( d_{RMS} \sim 0.5 \) nm
  \( d_{peak} \sim 0.7 \) nm
- Consistent with Piezo-actuator delivered displacement
Capacitive sensor test results

In vibration measurements
- Capacitive sensors (PI, Lion) can measure sub-nm (~100pm)
- Laser vibrometer can measure 1 nm when f>10Hz

In static measurements
- Capacitive sensors (PI, Lion) can measure nm-range displacement
- Laser vibrometer can measure 10 nm

Laser vibrometer measurements sensitive to air refractive index variation (temperature, convection). This limits the measurement accuracy of the laser vibrometer.
Ground vibration decreases with increase in frequency:

- Displacement PSD $\sim f^{-4}$
- Spectral displacement $\sim f^{-2}$
Ground vibration

Spectra at ESRF site

- Comparable spectrum in 3D
- A peak at 3Hz (site resonance)
- Vibration varies with time
  - Period of 24H, week
- Typical values (in 1–100 Hz)
  - Day: $d_{pp} = 1 \, \mu m$, $d_{RMS} = 0.3 \, \mu m$
  - Night: $d_{pp} = 0.15 \, \mu m$, $d_{RMS} = 0.05 \, \mu m$

Varies with time
Ground vibration

low frequency motion (0.03-1Hz)

peak-to-peak displacement (µm)

at the ESRF
at Orme des Merisiers
at the SuperACO

Vertical
down

08/10/96 12:00 09/10/96 12:00 10/10/96 12:00 11/10/96 12:00
time (dd/mm/yy hh:mm)

Vertical displacement spectra at 3 sites on 9-Oct-1996

0.07, 0.14 Hz

0.14 Hz
Ground vibration

$d_{2\text{sites in Paris}} = 5 \text{ km}$

$d_{\text{Paris-Grenoble}} = 500 \text{ km}$
Ground vibration

Seismic waves

P-wave
Primary (pressure)

S-wave
Secondary (shear)

Rayleigh wave

Love wave

Body waves

Surface waves
**Seismic waves**

Cross-hole test to determine Soil properties

- Wave emission by hammer shock
- Measurement of wave propagation by geophones
- Determine $P$– and $S$– wave propagation speeds $V_p$ & $V_s$ from measurement results
- Determine soil parameters
  - Poisson’s ratio
    \[ \nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \]
  - Young’s modulus
    \[ E = 2\rho(1+\nu)V_s^2 \]
- $E$: a key parameters for EX2 golden slab design
Earthquake measured at ESRF in 1994

Ground vibration

Earthquake measured at ESRF in 1994

epicenter : Cruseilles near Annecy, about 100 km from Grenoble
Magnitude : 4.5/Richter

dpp (μm)
106
65
84
70
70

P-wave S-wave
time delay of S-wave Δt=15s
→ distance from source ~ 90 km
Earthquakes

Date: 26/12/2005
Time: 07:58:50 (local time)
01:11:50 (at ESRF)
Magnitude: 8.9
Epicentre: west coast of Northern Sumatra
Distance: ~11000 km (surf), ~9100 km, v ~11.7 km/s

Distance effects !!

Date: 03/12/2000
Time: 05:24:00 (local time)
Magnitude: 2.3
Epicentre: Domène, France
distance: 15 ~ 20 km
Ground vibration

Traffic generated vibration

- Main contribution in the vibration noise (period of 24H, week)

Distance effects
- at least 30 m necessary to have limited effects on the ESRF site
Ground vibration

Tramway Line-C extension
(Vibrations influences)

- 1st vibration studies made by ESRF
  - In 1993, UJF campus, SMH
  - In 1999, Fontaine
- Vibration concerns expressed by ESRF and CNRS to Authorities (Prefecture, Mairie, DDE)
- Coordinated studies and meetings
  - Territoire 38
  - Acouplus
  - VibraTec
  - ESRF, CNRS, CEA
- Study made by VibraTec in 2008
Ground vibration

Tramway Line-C extension

Vibration study

- Vibration sources (generated by tramway, measured at 3 m from rail)
- Vibration propagation and attenuation in the soil
- Vibration transmission to the ESRF buildings (EXPH)
Tramway Line-C extension

Results of vibration study

- **Source**: tramway Citadis on recent rail
- **Attenuation rate**: ~ 0.25 dB/m
- Distance between future Line–C rail to ESRF central building: 180 m

→ **Estimated vibrations level** due to future tramway < actual ground vibration level at the ESRF site

- Efforts requested so that the Tramway line–C should not generate higher vibrations than existing ones!
Mass Spring Damper system

(1 DOF system)

Simple model MKC

- Mass: m
- Stiffness of the spring: k
- Damping constant: c (=2\(\gamma\)m)
- Resonant frequency:

\[
 f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{k}{m}}
\]

Transfer function

\[
 FrF = \frac{X}{X_g} = \frac{1}{\omega^2 - \omega_0^2 + j2\gamma\omega_0}
\]
Complex system
(Multi DOF system)

ESRF magnet–girder assembly MGAs

1\textsuperscript{st} mode: lateral rocking due to the deformation of 3 jacks. A global mode
Vibration Damping

Passive damping systems
- Widely used, effective, cheap
- Damping Plate, Damping Pad
- Damping Link
- Tuned Vibration Absorbers (TVA)

Active damping systems
- Some commercial products – active vibration ISOLATION system:
  - TMC stacis (PEL)
  - Halcyonics (OML, ID10, SSL)
  - HWL Sc. Instr.
- Acoustic noise reduction device
- Could be expensive
- Design specific
- Actuator – sensor limitation
High performance in vibration
Insufficient stiffness for static positioning
Damping links for MGA

- Increase stiffness and $f_0$
- Damping factor > 8
Damping links for MGA
(Performance on e-beam)

- Implemented in 2000
- Significant e-beam stability improvement

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>PSD(_{pk})</th>
<th>rms(_{4-12Hz})</th>
</tr>
</thead>
<tbody>
<tr>
<td>noDL</td>
<td>158 (\mu m^2/\text{Hz})</td>
<td>11.7 (\mu m)</td>
</tr>
<tr>
<td>DL</td>
<td>3.2 (\mu m^2/\text{Hz})</td>
<td>49 (\mu m)</td>
</tr>
</tbody>
</table>
Active vibration isolation systems - (TMC Stacis 2100)

- 1st Tested in 2003, in collaboration with CERN
- 1st Installation at ESRF – PEL in 2007
- Tested and commissioned in 2008
- -20 dB (2~40 Hz), -10 dB (1~100 Hz)
- 70 k€ for 3 mounts
**Active vibration isolation systems (Halcyonics)**

- Used in Optical Metrology Lab
- ID10, SSL
- Test results
  - Effective damping above 2 Hz
  - Amplification below 2 Hz
- ~ 7 k€

![Displacement - Longitudinal](image1)

![Transmissivity - Longitudinal](image2)
Vibration propagation

Mechanical → (air) acoustic → ground
(Helicopter flying over Soleil site, 1996)

Spectrogram of vertical acceleration (dB.µm/s^2)

Doppler Effects:
\[
\frac{\Delta f}{f} = \frac{1}{\frac{V_s}{V_{helico}} - \frac{V_{helico}}{V_s}}
\]

V_s: sound speed

\(\Delta f/f \sim 1/8 \rightarrow\)
- \(V_{helico} \sim 42 \text{ m/s}\)
- \(\sim 151 \text{ km/h}\)
The RMS amplitude was reduced

- 10 μm to 2.7 μm (4–12 Hz)
- 12 μm to 4 μm (4–200 Hz)

**dRMS-horizontal (μm) (4–12 Hz)**

This ratio agrees with theoretical estimation:

\[
\frac{RMS_{\text{e-beam}}}{RMS_{\text{quadrupole}}} \approx 30
\]

**PSD of the e-beam and quadrupole when the booster ON or OFF**

\[
\text{ratio} = \frac{PSD_{\text{e-beam}}}{PSD_{\text{quadrupole}}} \approx 1000
\]
### e-beam stability

In the frequency range of 4–200 Hz

- $d_{RMS\text{-horizontal}} = 1 \ \mu m$, (0.25% of horizontal beam size) @ high-$\beta$ section
- $d_{RMS\text{-vertical}} = 0.6 \ \mu m$, (7.5% of vertical beam size) @ low-$\beta$ section

### e-beam stability at the middle of a high-$\beta$ straight section ($\beta_x = 35.4 \ m$)

\[
RMS_{horizontal} = 402 \ \mu m
\]

<table>
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<tr>
<th>$\Delta RMS_{horizontal} (\mu m)$</th>
<th>4-12 Hz</th>
<th>4-200 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>no damping links ($\mu m$)</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>with damping links ($\mu m$)</td>
<td>2.7</td>
<td>4</td>
</tr>
<tr>
<td>damping links + feedback ($\mu m$)</td>
<td>0.28</td>
<td>1</td>
</tr>
</tbody>
</table>

### e-beam stability at the middle of a low-$\beta$ straight section ($\beta_z = 2.5 \ m$)

\[
RMS_{vertical} = 8 \ \mu m
\]

<table>
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<th>4-12 Hz</th>
<th>4-200 Hz</th>
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<tr>
<td>with damping links ($\mu m$)</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>damping links + feedback ($\mu m$)</td>
<td>0.17</td>
<td>0.6</td>
</tr>
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</table>
**X-ray beam stability**

**Example of ID06 Cinel mono**

Correlation between X-ray intensity fluctuation and mechanical vibration
- $F=24.8, 66.2, 70.3, 78.7, 82.8$ Hz
- 1st peak due to vacuum pump 1, other 4 peaks due to pump 2

Remaining peaks $\circ$ probably due to mechanics $\rightarrow$ room for improvement
Example of ID20

Many pumps

Fig. 2 - beamline elements

P4: Photodiode  S1: Att.

P3  P2  EIH

PS: primary slits – S1: secondary slits
Att: attenuator
Photodiode coupled to A/V converter
P1: primary pump mono - P3: scroll pump rotation stage mono
P2 and P3: primary pumps in EIH - P6: Alcatel pump on N2 pipe
P4: primary pump sample in EIH - P7: scroll pump (not shown)
Vibration on the EXPH floor

Various measurements show vibration increases on the EXPH floor

→ A vibration survey campaign on all the EXPH floor carried out during summer 2009
  ➢ 4 geophones (vertical, L4C) placed along each beamline (ID or BM)
  ➢ Measurements period: June–30 to July–21, working time
Results of the vibration on the EXPH floor, in 2009

**ID32**

- EXPH survey – Vertical PSD
Vibration investigations

Pictures of the vibration on the EXPH floor, in 2009

\[ d_{pp} \, (\mu m) \]
\[ (1-100 \, Hz) \]

\[ d_{RMS-\Delta f=2Hz} \, (nm) \]
\[ (1-20 \, Hz) \]

\[ d_{RMS-\Delta f=2Hz} \, (nm) \]
\[ (20-40 \, Hz) \]

\[ d_{RMS-\Delta f=2Hz} \, (nm) \]
\[ (40-60 \, Hz) \]
Picture of the vibration on the EXPH floor, in 2009

EXPH floor vibration - acceleration spectrogram (2009)
Vibration investigations

Vibration on the EXPH floor

Vibration increased during last 10 years:
- Wide band
- High frequencies
- Many peaks

→ Internal vibration noises

Proposal to remedy the situation:
- Sources identification
- Proposition and correction
- Collaboration of all staff to limit vibration generation

Set up a procedure to check some new installations in terms of vibration?
**Cooling flow induced vibrations**

Commonly used cooling fluids at ESRF:
- Water
- Liquid nitrogen
- Gas (Helium, nitrogen, air)

Vibration due to cooling flow
- Increase with flow rate
- Flexible tube, corrugated tube

Cooling flow optimization
- Decrease vibrations
- Save pumping capacity (no need to add additional capacity in EX2)
- Define and regulate necessary flow rate for each component
- Combine serial and parallel connections
Vibration investigations

Cooling flow induced vibrations

Examples

- Machine magnet–girder MGA
- ID24 mirrors
Cooling flow induced vibrations
1st measurement results (ID24 mirror)

- Natural frequencies: 376, 710 Hz
- Water flow in corrugated tube excites the resonant frequencies of the piping system
- Flow rate, \( d_{\text{tube}} \), \( f \rightarrow d_{\text{per}} = 5 \sim 10 \text{ mm} \)
Vibration investigations

Cooling flow induced vibrations
1st measurement results (ID24 mirror)

The 2 peaks at f=376, 710 Hz
- Very high acceleration
- But also spectral displacement comparable to the peak at 3 Hz
Summary and perspectives

Some points on vibration at ESRF
- Ground vibration level
- Slight degradation of stability on the EXPH floor
- X-ray beam vibration stability (>1Hz) can be seriously impacted by internal vibration sources

Proposals:
- Investigation to identify vibration sources in EXPH1
- Investigation on cooling flow induced vibration
- Proposition for improvements
- Call for collaboration of all staff to limit vibrations
- Improve awareness of vibration aspects

Questions
- Shall we set up a procedure to check new installations in terms of vibration?
- Can we reinforce dynamic analysis capability to assist and improve design of new systems?
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BIG
Thank you for your attention!