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Acoustics VTAN01

2. Measurement Techniques

NIKOLAS VARDAXIS
DIVISION OF ENGINEERING ACOUSTICS, LUND UNIVERSITY

Outline

- Introduction
- Signals
- Excitation sources
- Measurement devices
- Errors in measurements
- Examples
- Conclusions

Why do we measure?

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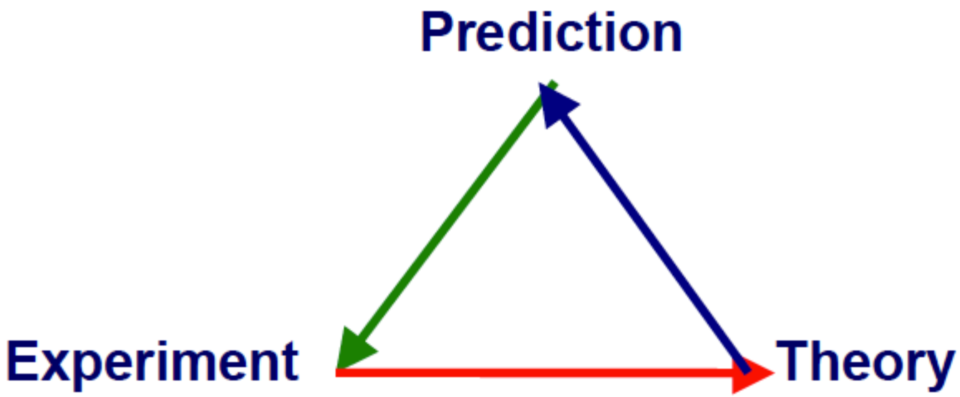
Introduction (I)

- Paradigm of natural sciences

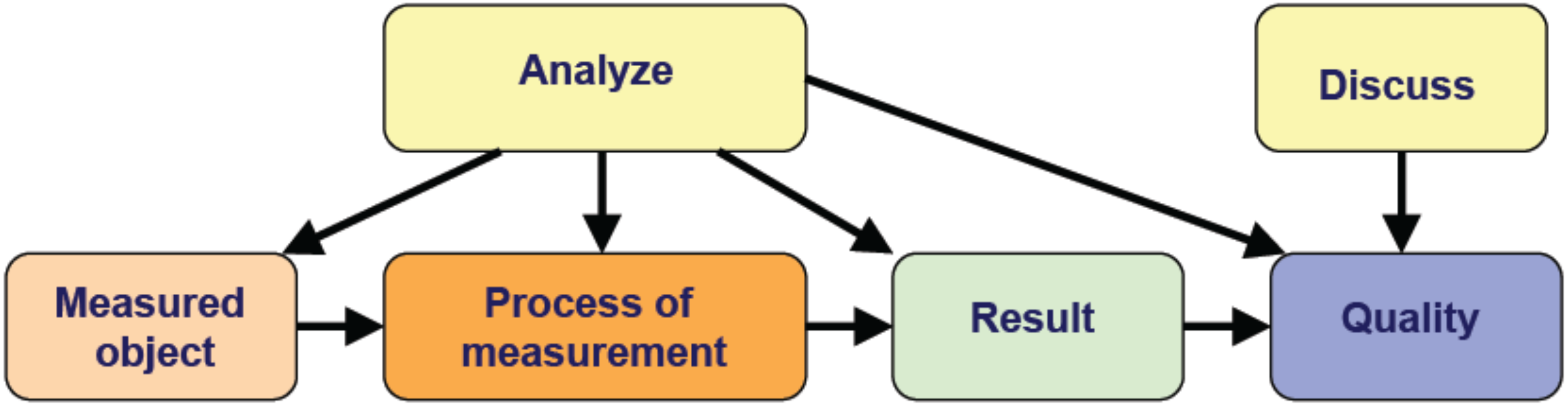


  - Theory: explanained and generalised experimental results
  - Prediction: use theory to predict consequences
  - Experiment: observation / measurement of phenomena

Introduction (II)

Eisenhart [1876-1965]: *"To measure is to assign numerical values to concepts of physical quantities to symbolise the relations which exist between them regarding special properties"*

Introduction (III)



- Experimental process to acquire new knowledge of a "product"
- Planned actions for quantitative comparison of a measurand with an unit
- Measurand: physical quantity to be measured
- Measurement equipment: software, standards, aparatus…

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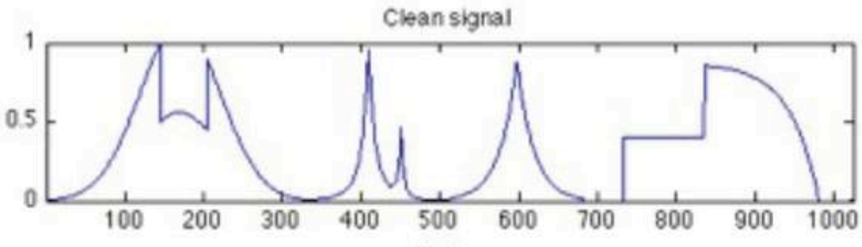
Signals

- Acquisition: voltage-time
  - Unequivocally related to the measurand



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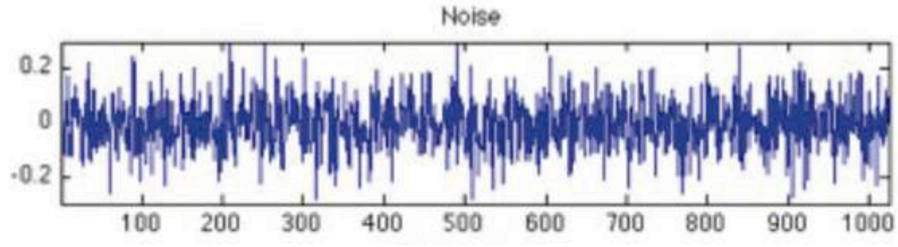
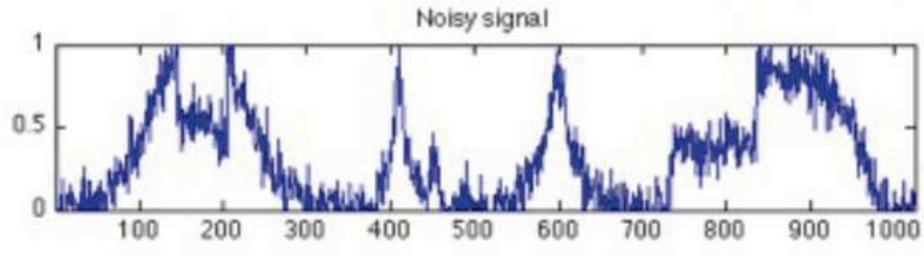


- Noise: changes the smooth signal to a "jagged" curve



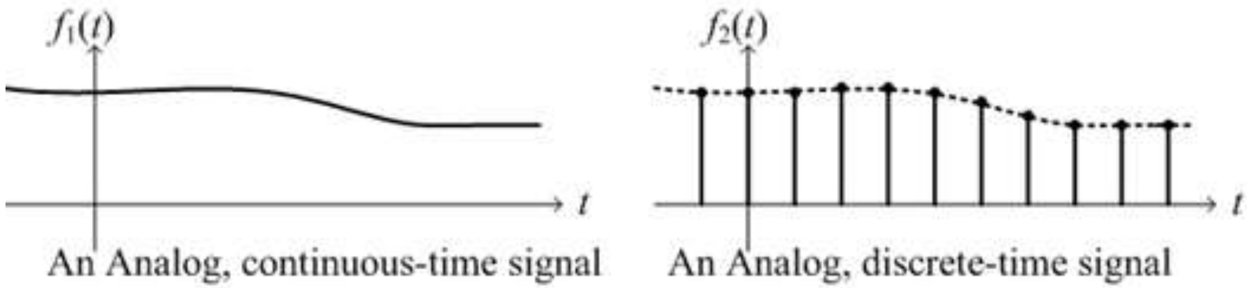
- Signal to noise ratio (SNR)
  - *SNR>1* means *Signal>Noise*
  - Filtering

$$SNR = \frac{P_{signal}}{P_{noise}}$$

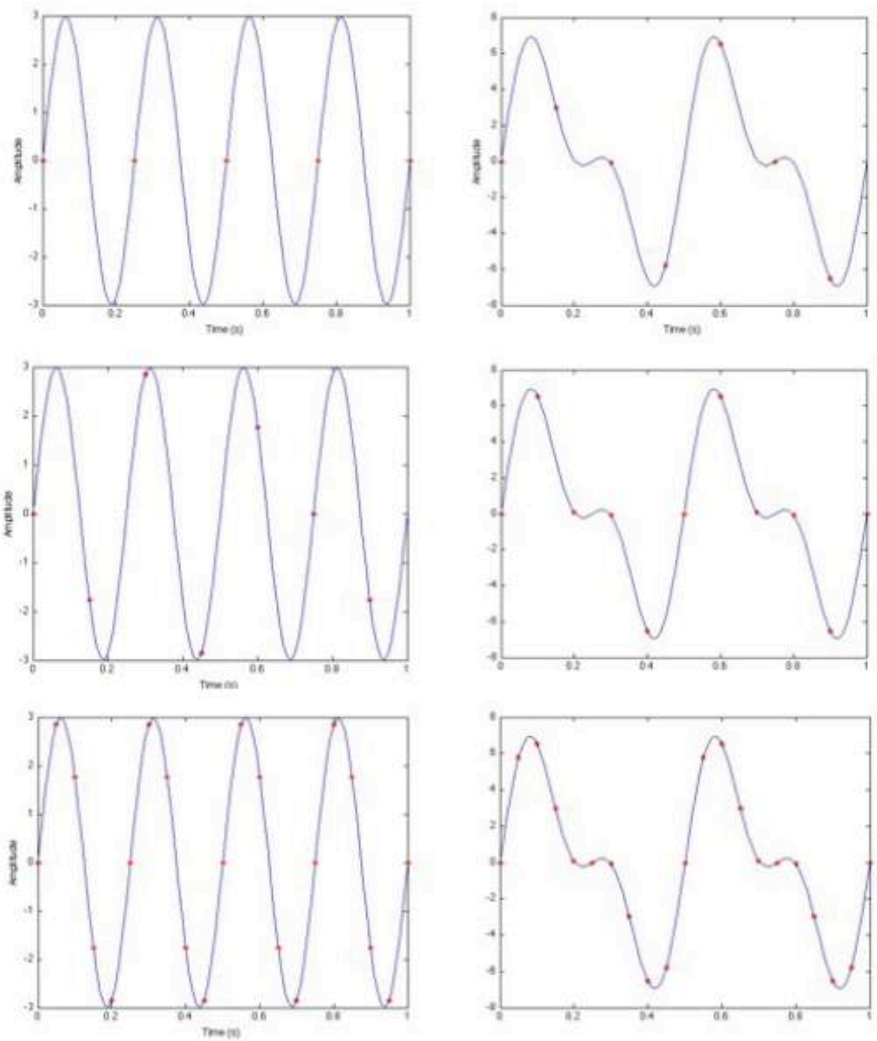
$$SNR_{dB} = 10\log_{10}\frac{P_{signal}}{P_{noise}}$$

Getting ready for the analysis

- To get the signal into a computer, one needs to digitalise it
- Digitalise (also called digitise): conversion from analogue signal to a stream of discrete values (numbers)
- Δt between two consecutive values: given by sampling frequency



Sampling frequency



- The red dots (samples) do not truly represent the signal
- How to select an appropriate sampling frequency?

NYQUIST-SHANNON CRITERION

sampling frequency must be twice the higher frequency in the signal

Nyquist-Shannon sampling criterion

Let *x(t)* be a continuous-time signal and *X(f)* its FT

$$X(f) \overset{Def}{=} \int_{-\infty}^{+\infty} x(t) e^{i2\pi ft} dt$$

x(t) is said to be bandlimited to a one-sided baseband bandwidth, *B*, if:

$$X(f) = 0 \quad \forall \quad |f| > B$$

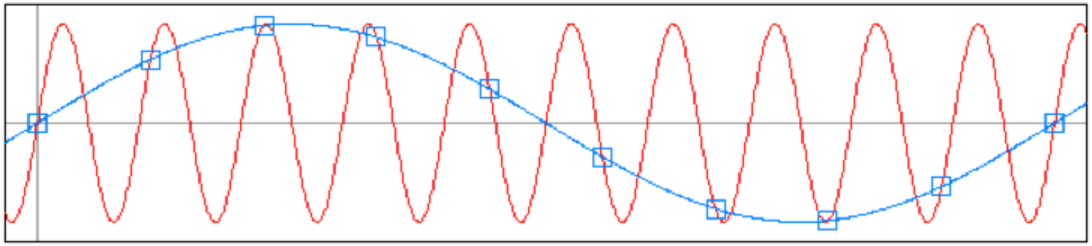
The the sufficient condition for "exact" reconstructability from samples at uniform sample rate is:

$$f_s > 2B \Leftrightarrow B < \frac{f_s}{2} \quad ; \quad T \overset{Def}{=} \frac{1}{f_s}$$

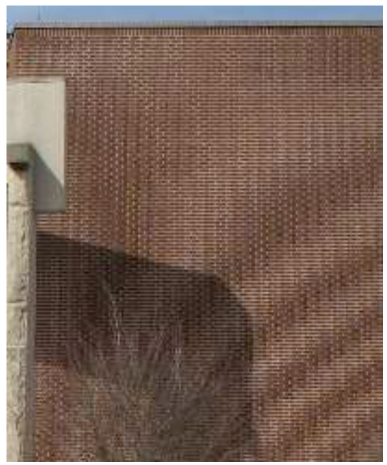
2B is called the Nyquist rate and it is a property of the band-limited signal, while $(f_s/2)$ is called the Nyquist frequency and is a property of the sampling system

Aliasing

- If Nyquist-Shannon criterion is not fulfilled (bad sampling)
  - Two different continuous signals become indistinguishable

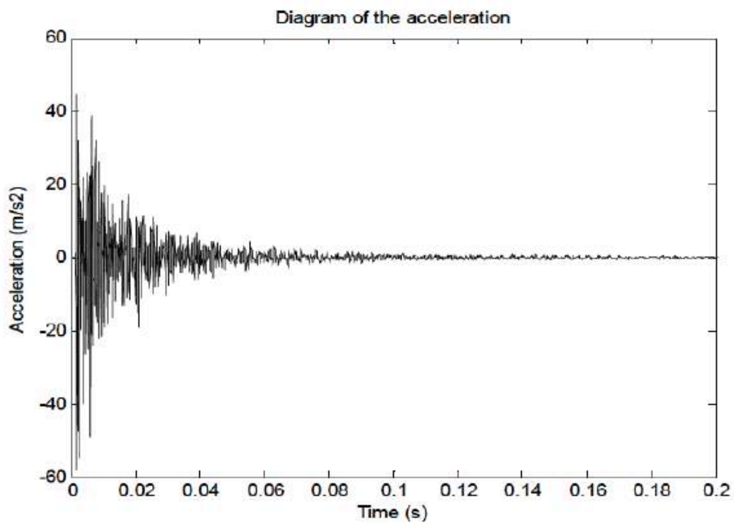


- Example: Helicopter: Stroboscopic effect
- Example: Image aliasing (Sampling / Pixel density wrong)

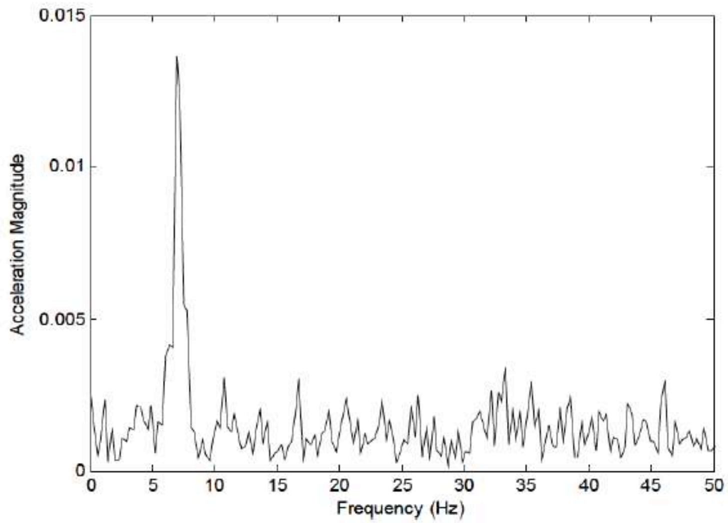


How to analyse the data?

- Waveform: amplitude as a function of time
- Spectrum: frequencies contained in the signal
- Leap between domains: FT
- In practice, software apply FFT



(a) Time domain.



(b) Frequency domain.

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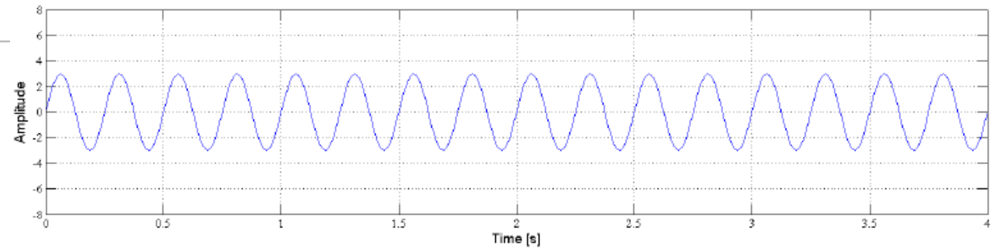
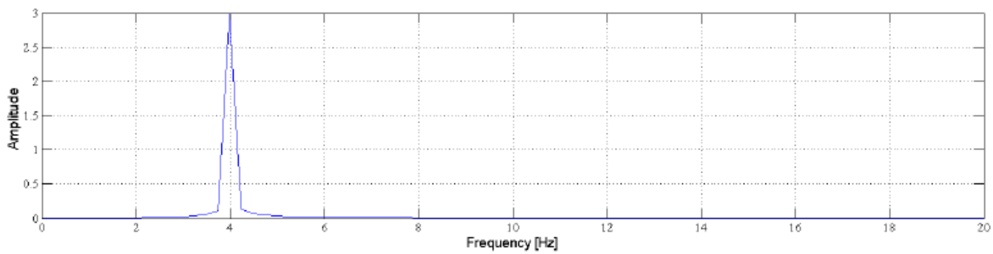
FFT example (Matlab)

```
%Juan Negreira; May 2011
%Calculates the discrete fourier transform of the timedomain signal y(t)
%Y:amplitude of the frequency components
%f:frequencies[Hz]
%Only the unique points are returned ie. f lies in 0 <= f <= Fs/2

%% Introducing the time signal
dt=1/100;
et=4;
xData=0:dt:et;
yData=3*sin(4*2*pi*xData);
%% Calculating the FFT
%Number of points in input data
NFFT=length(yData);
%Nyquist frequency
Fn=1/(xData(2)-xData(1))/2;
%Absolute value of the FRF
FFTY=abs(fft(yData));
NumUniquePts=ceil((NFFT+1)/2);
% fft symmetric, throw away second half
FFTY=FFTY(1:NumUniquePts);
% Take magnitude of Y
Yfft=abs(FFTY);
% Multiply by 2 to take into account the fact that we
% threw out second half of FFTY above
Yfft=Yfft*2;
% Account for endpoint uniqueness
Yfft(1)=Yfft(1)/2;
% We know NFFT is even
Yfft(length(Yfft))=Yfft(length(Yfft))/2;
% Scale the FFT so that it is not a function of the length of y.
Yfft=Yfft/length(yData);
%Frequencies
freq=(0:NumUniquePts-1)*2*Fn/NFFT;
%% Plotting time signal and FFT
subplot(2,1,1)
plot(xData,yData); grid on
axis([0 et -8 8])
xlabel('Time [s]'); ylabel('Amplitude')
subplot(2,1,2)
plot(freq, Yfft);grid on
xlabel('Frequency [Hz]'); ylabel('Amplitude')
```





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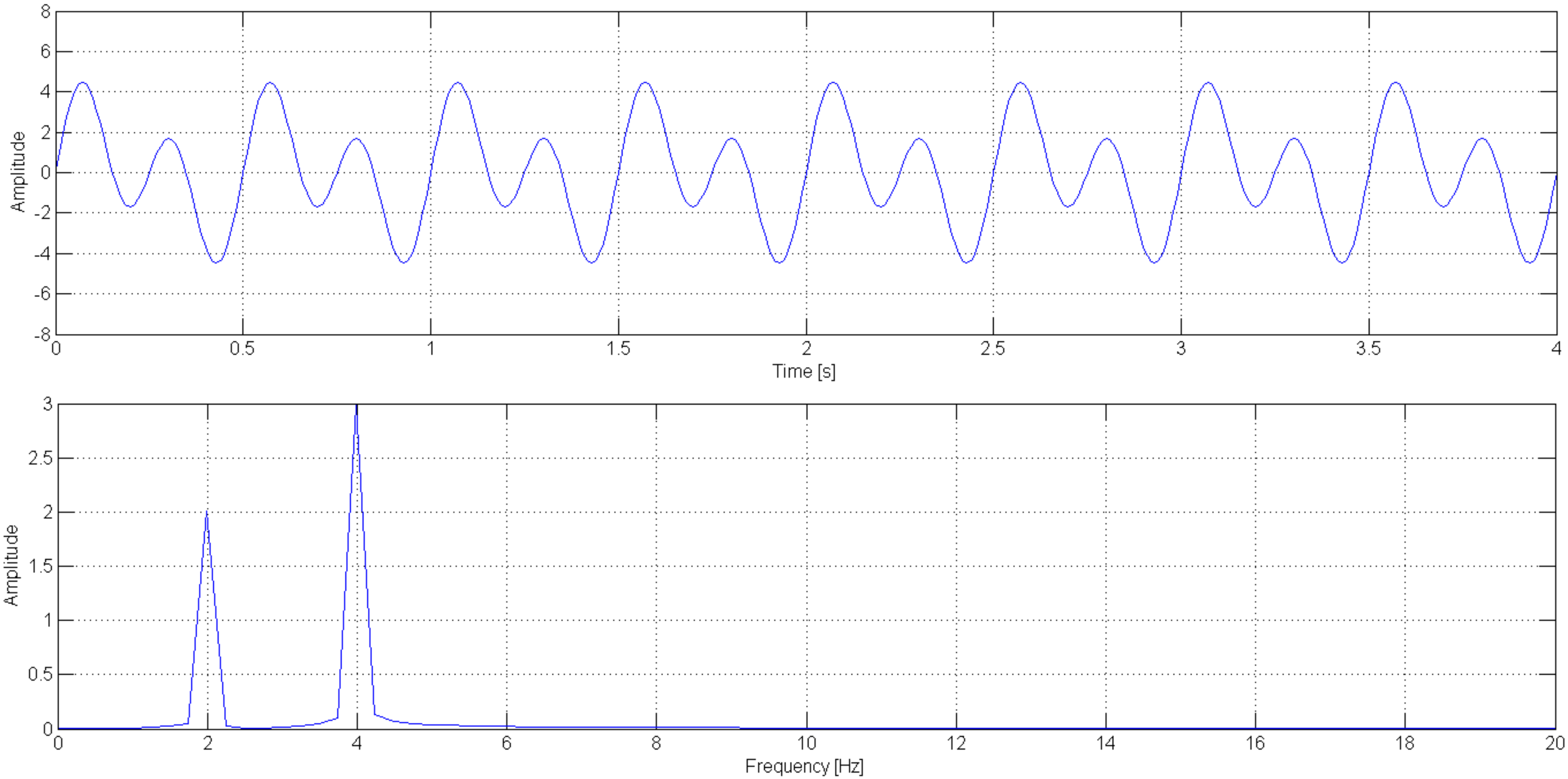
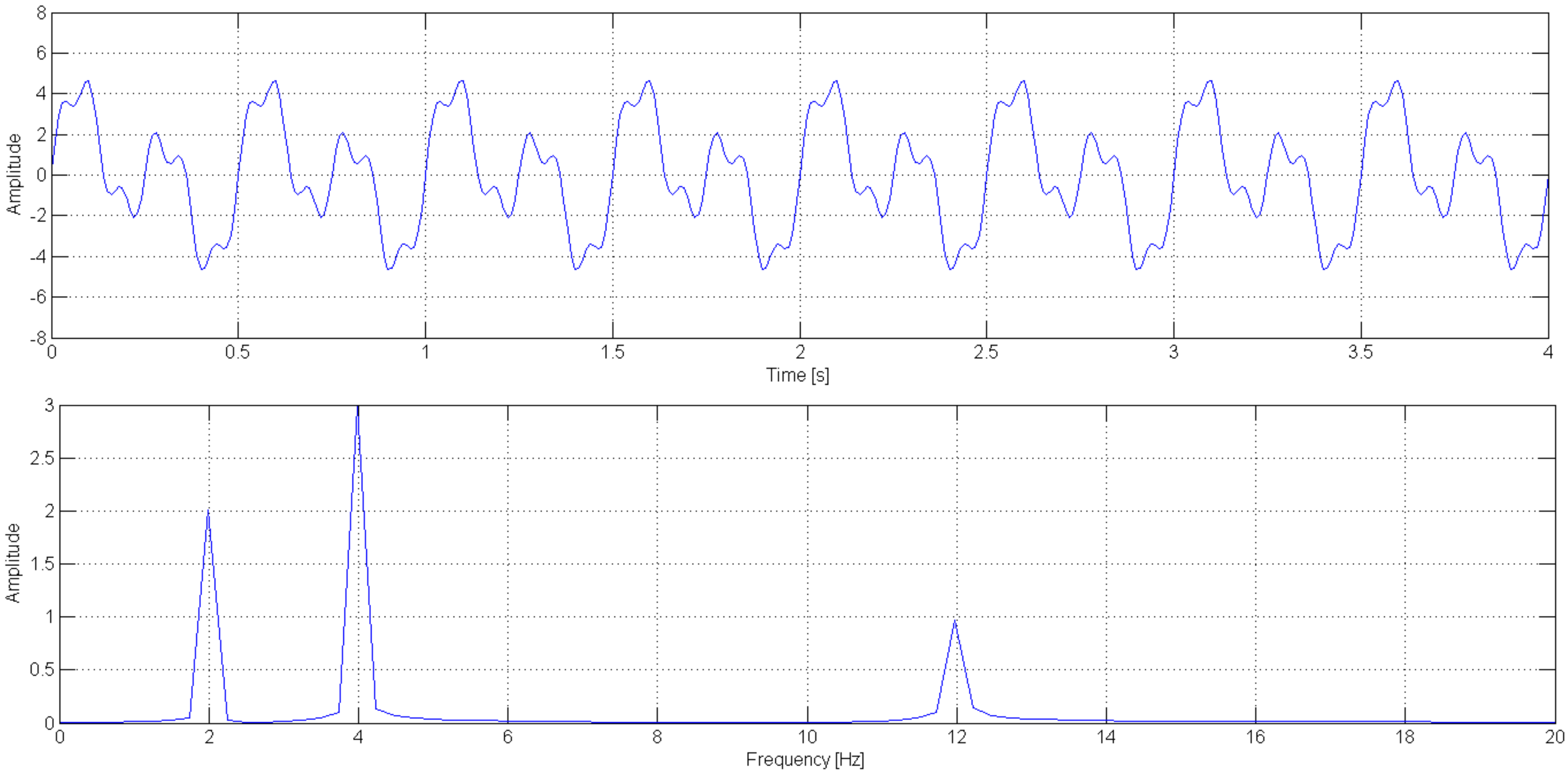
FFT example (Matlab)



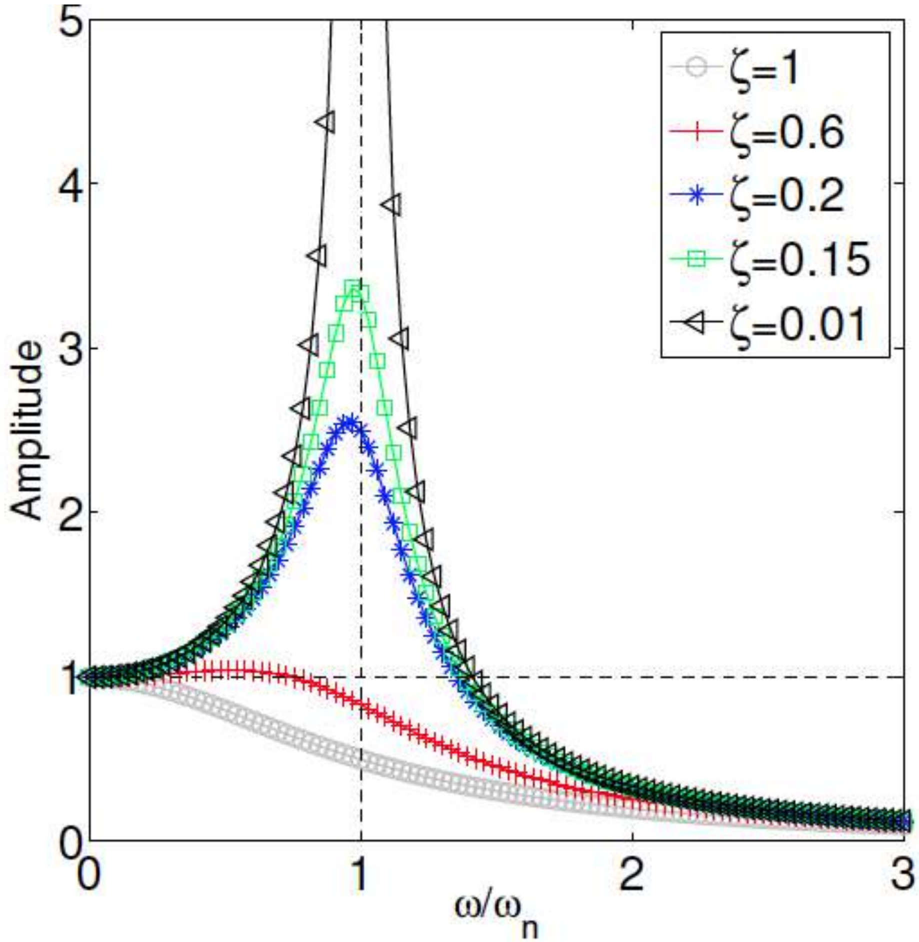
FFT example (Matlab)



- *Example: video*

Resonance

- Resonance (def.):
  - Tendency to oscillate at a greater amplitude at some frequencies
- Depends on:
  - Mass
  - Stiffness
  - Damping
- Examples:
  - Earthquake design
  - Bridges (Tacoma & Spain)
  - Cup
  - Plate (mode shapes)



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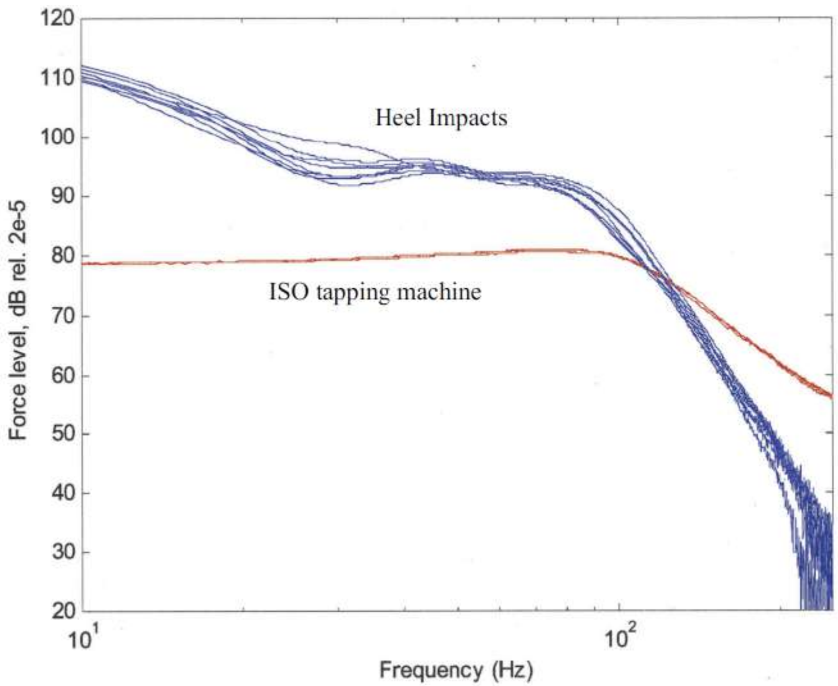
Excitation sources (floor vibrations)

- Standardised
  - Tapping machine
  - Rubber tire



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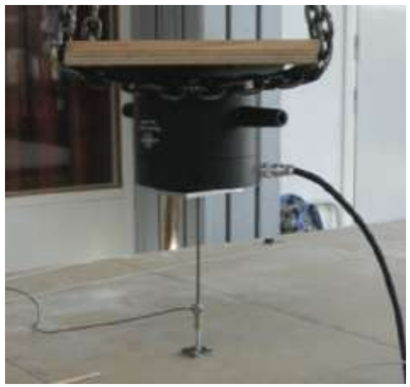
Excitation sources (floor vibrations)

- Standardised
  - Tapping machine
  - Rubber tire
- Non-standardised
  - Shaker
  - Japanese ball
  - Impact hammer
  - Human walking
  - …





Excitation sources (acoustics)

- Standardized
  - Loudspeakers (noise)
- Non-standardized
  - Cap-gun
  - Baby-crying
  - Impulse

Outline

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Sensors and transducers

- Transducers: detection
- Sensors: detect and communicate
  - Parameters:
    - » Sensitivity: “electrical output / mechanical input”, e.g. [mV/ms^{-2}]
    - » Frequency response: sensitivity over whole spectra
    - » Phase response: time delay between input and output
    - » Resolution: smallest input increment reliably detected
    - » Dynamic range: output proportional to input
    - » Saturation: maximum output capability
    - » Weight < 0.1 x weight specimen to be measured
    - » Environmental characteristics: temperature, humidity…
    - » Repeatability / Reproducibility
    - » Eccentricity

Calibration (I)

- What is it?
  - Comparison between the value indicated in a device and a reference known value

- Why calibrate?
  - Repeatability
  - Transference
  - Equipment exchange
  - Fulfillment of quality standards

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Calibration (II)

- Examples:
  - Sound level meter:

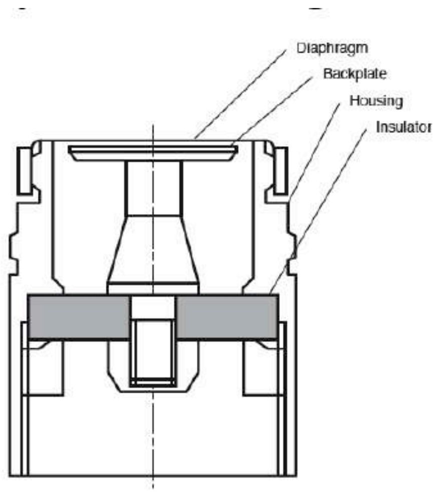
  - Accelerometers:

Microphones (I)

- Acoustical-to-electric transducer (sound → electric signal)
- Scalar pressure sensors with an omnidirectional response

Microphones (II)

- Requirements:
  - Good acoustic and electric performance
  - Minor influence from the environment
  - High stability of sensitivity and frequency response
  - High suitability for measurement
  - Comprehensive specifications and performance description.



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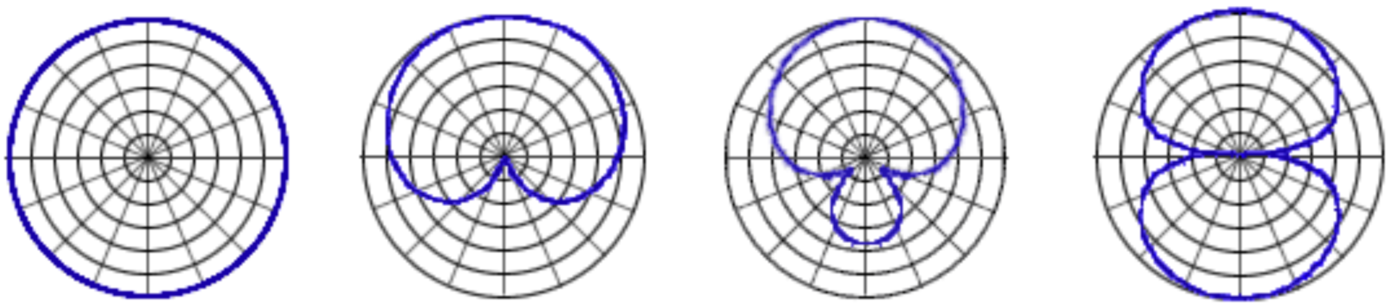
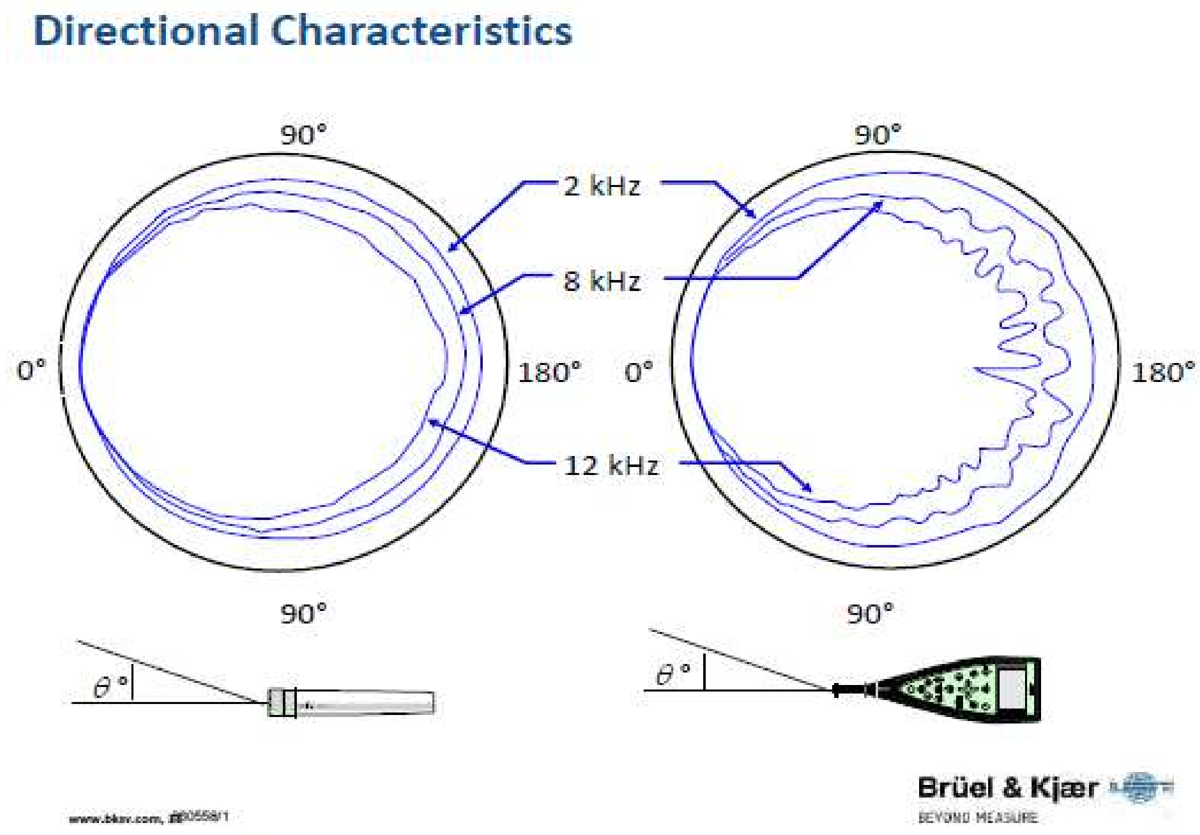
Microphones (III)

Microphones' directionality (polar plots)

- Microphone's sensitivity to sound from various directions
  - Omnidirectional
  - Unidirectional (e.g. cardioid and hypercardioid)
  - Bidirectional

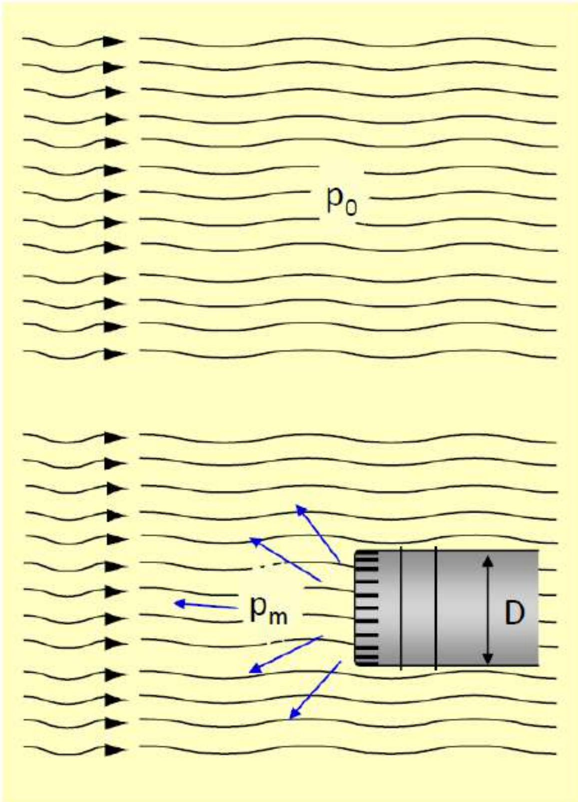


Microphones (IV)

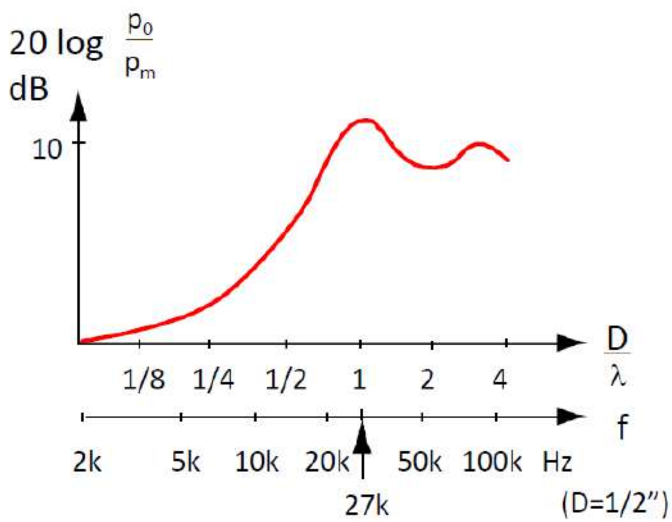


Microphones (V)

Free Field Correction



$$\sqrt{\frac{(5-4\times\cos(\pi\times\text{freq}\times\text{diameter})}{c}}$$



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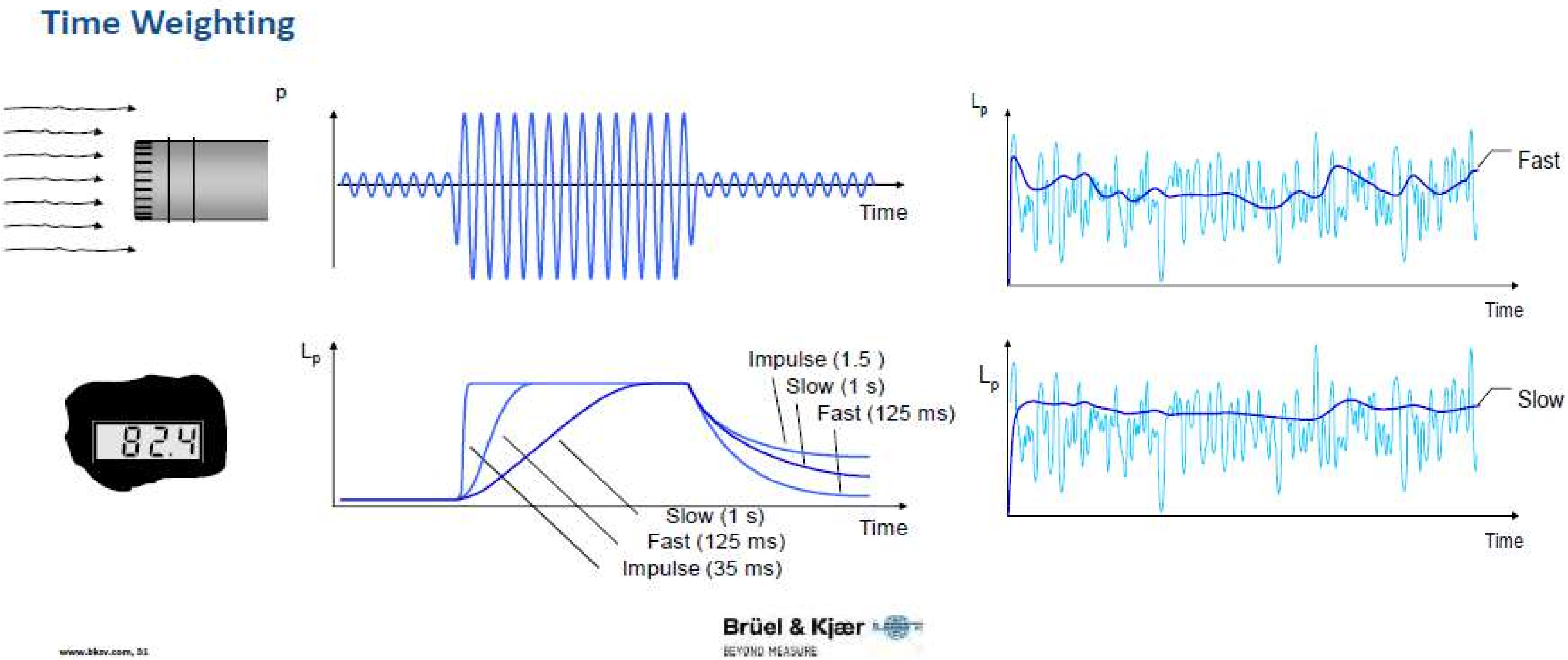
Microphones (VI)



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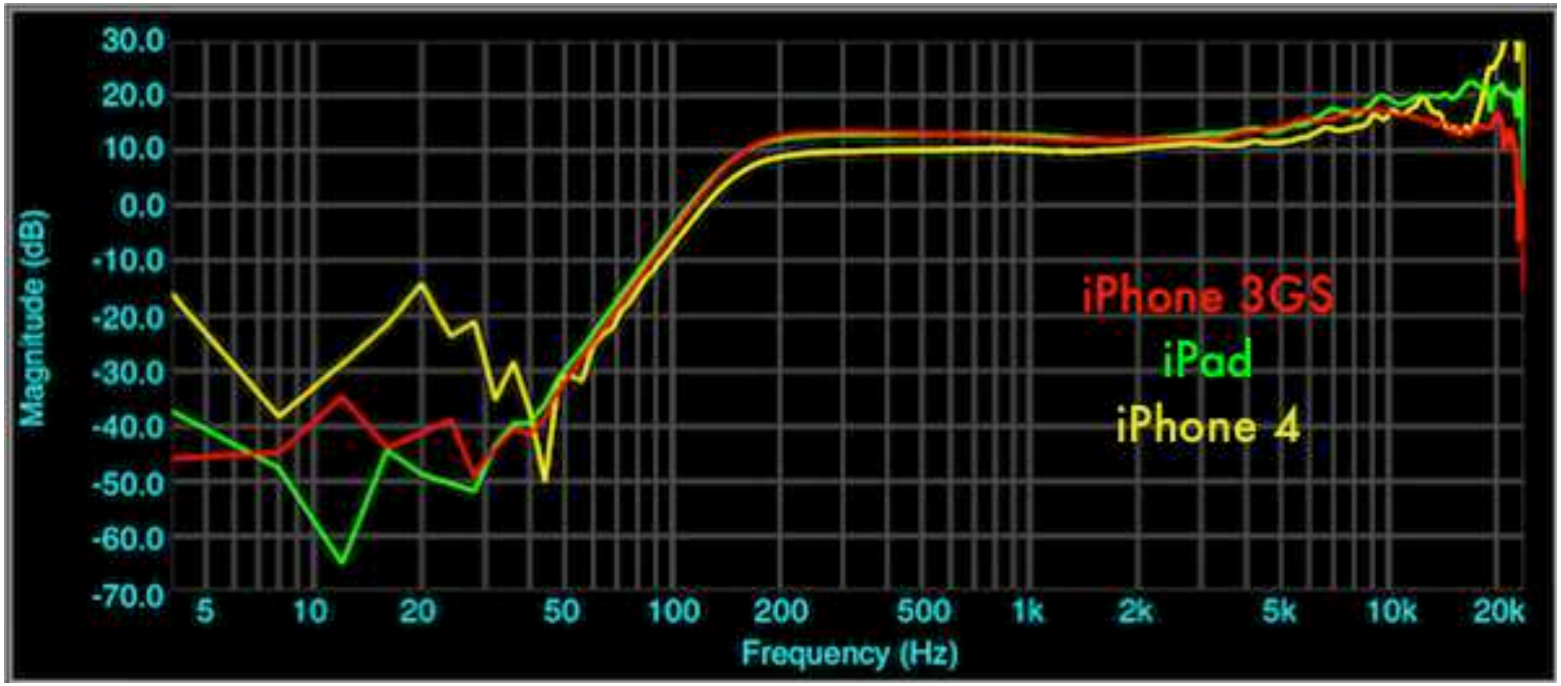
Microphones (VII)

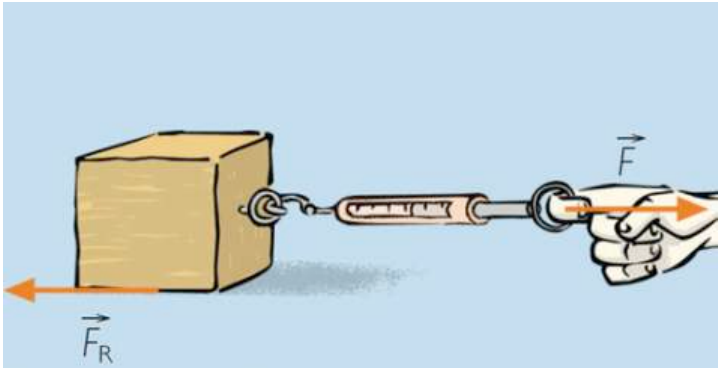
Example: iPhone Built-in Microphone Frequency Response

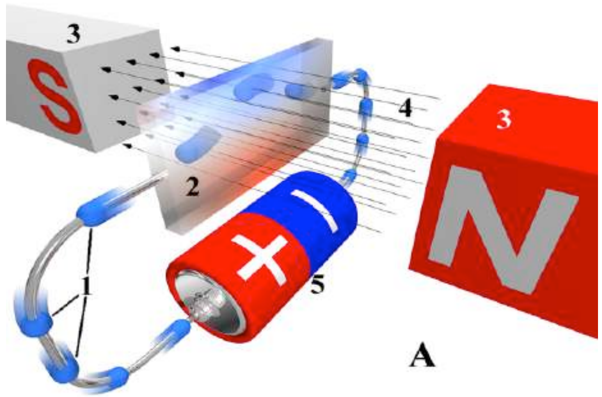


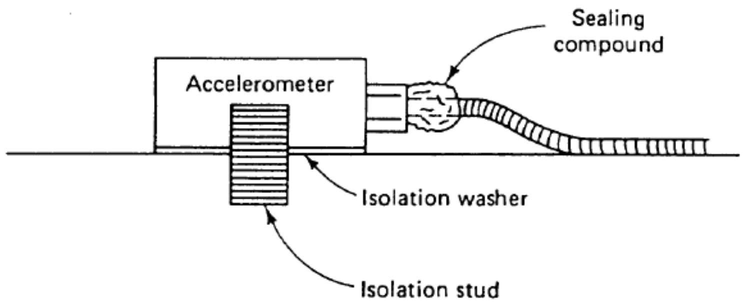
REF: http://blog.faberacoustical.com/2010/ios/iphone/iphone-4-audio-and-frequency-response-limitations/

Accelerometers (I)

- Mechanical, piezoelectric, hall effect, capacitive...







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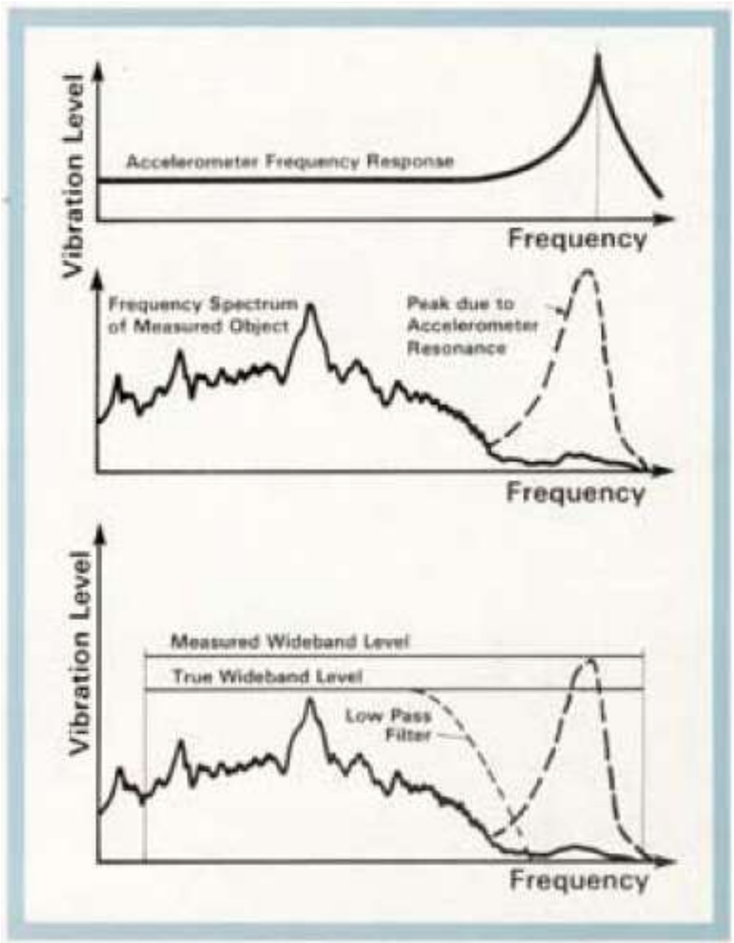
Accelerometers (II)

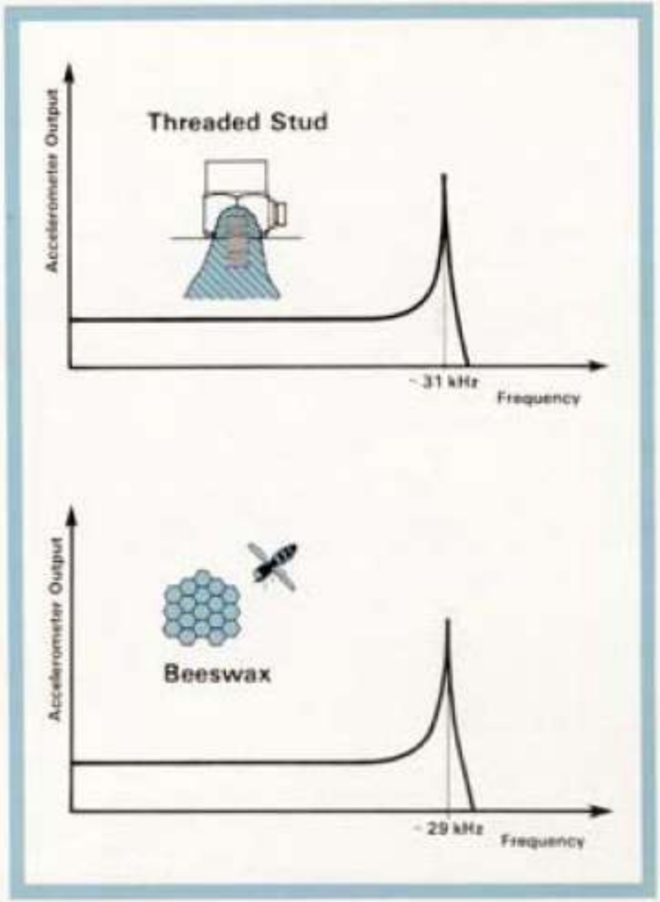
- Avoiding errors due to accelerometer resonance

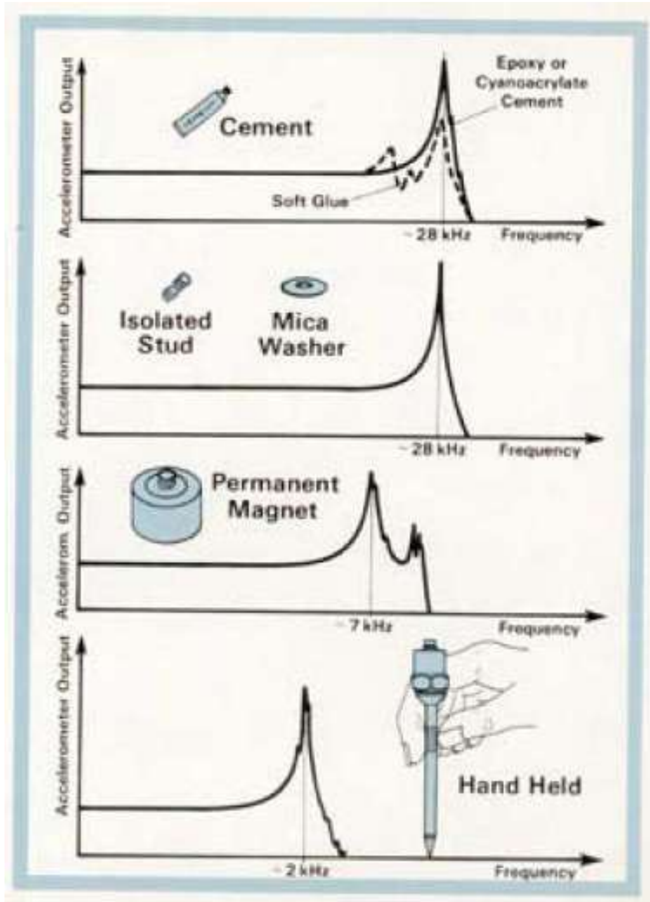


Source: Measuring vibration (B&K)

Accelerometers (III)

- Be aware of the mounting method…



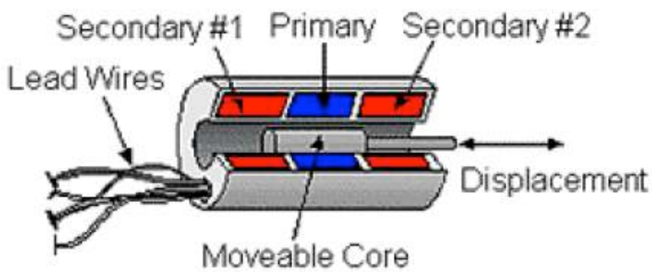


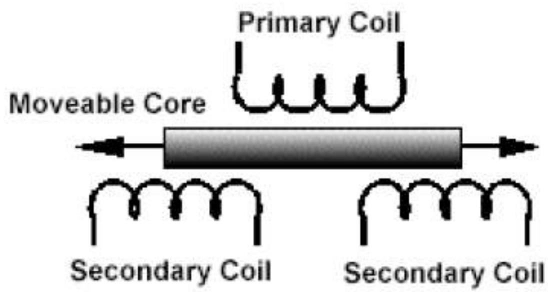
Source: Measuring vibration (B&K)

Others (I)

- Gyroscopes
  - Measure or maintaining orientation
  - Based on conservation of angular momentum

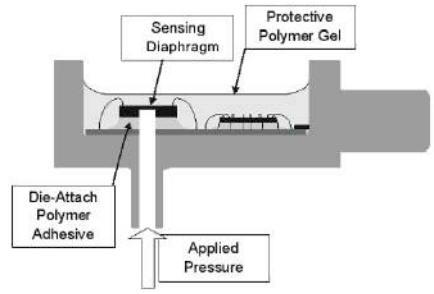
- LVDT sensors
  - Linear Variable Differential Transformers
  - Output voltage proportional to the displacement of the core



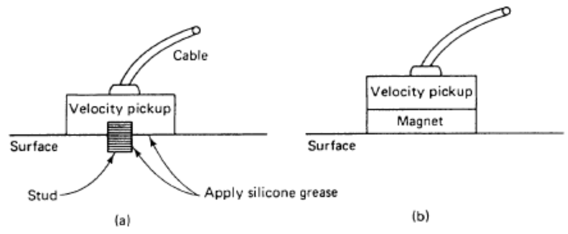


Others (II)

- Pressure sensors
  - Output voltage proportional to the pressure



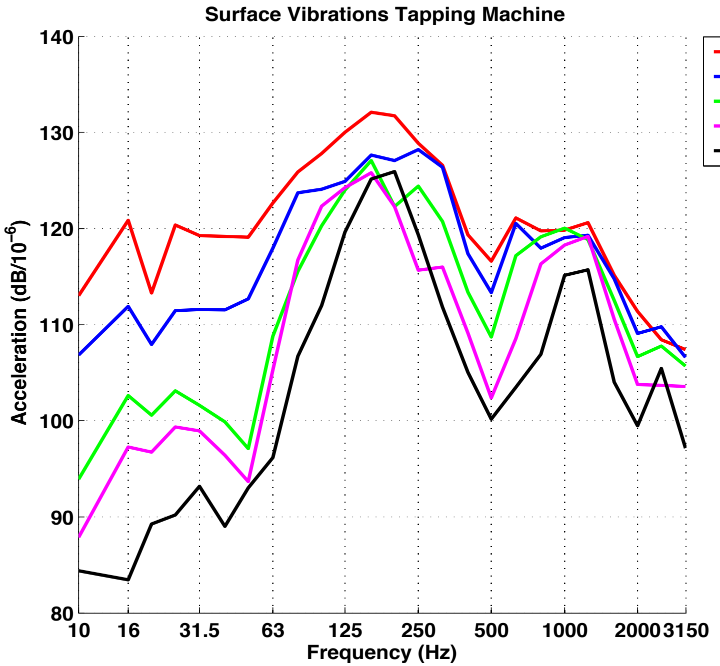
- Interferometers
  - Output voltage if obstacle detected

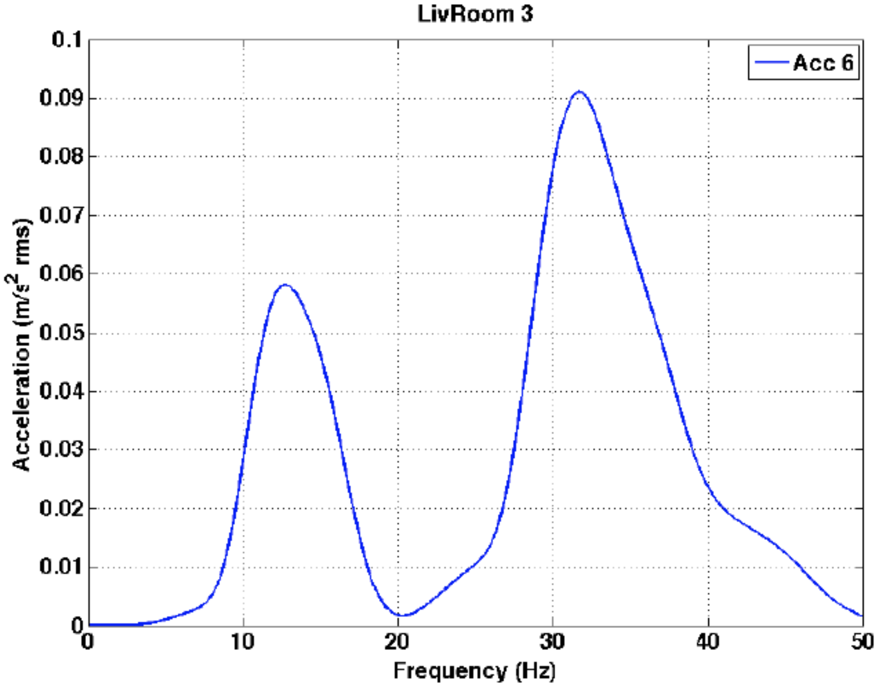


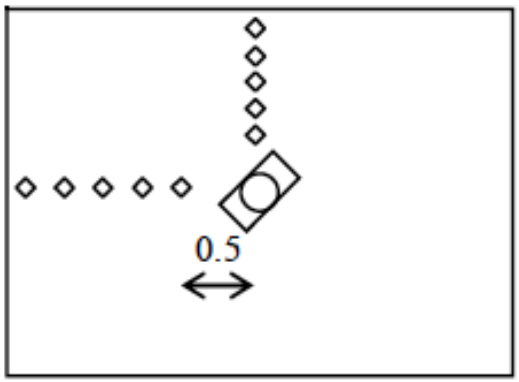
- Velocity pickups
  - Voltage proportional to the relative velocity between elements

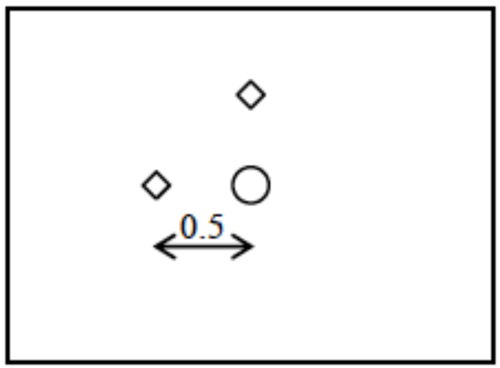
- Smartphones
  - Different sensors

In-situ vibratory measurements (Example)









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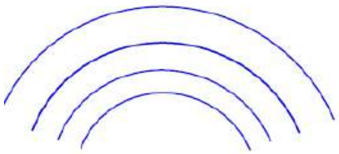
Note / Reminder

Receiver ⟷ Sound Pressure Level

$$L_p = 10 \log_{10} \frac{p^2}{p_o^2}$$

$$p_o = 2 \times 10^{-5} N/m^2$$

$$= 20 \mu Pa$$



Path ⟷ Sound Intensity Level

$$L_i = 10 \log_{10} \frac{I}{I_0}$$

$$I_o = 1 pW/m^2$$

Source ⟷ Sound Power Level

$$L_w = 10 \log_{10} \frac{W}{W_o}$$

$$W_o = 1 pW$$

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- Measurement devices
- Errors in measurements
- Examples
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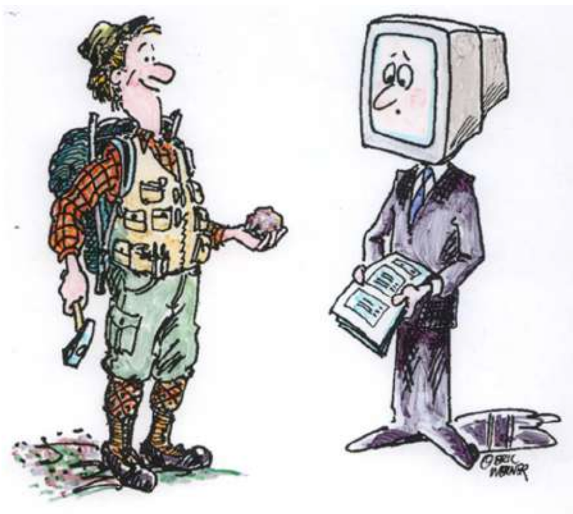
Errors – Introduction

- Ideal measurements: no errors
- Real ones always do
- Clear defined processes to identify every source of error
- Measurement system errors can only be defined in relation to the solution of a real specific measurement task



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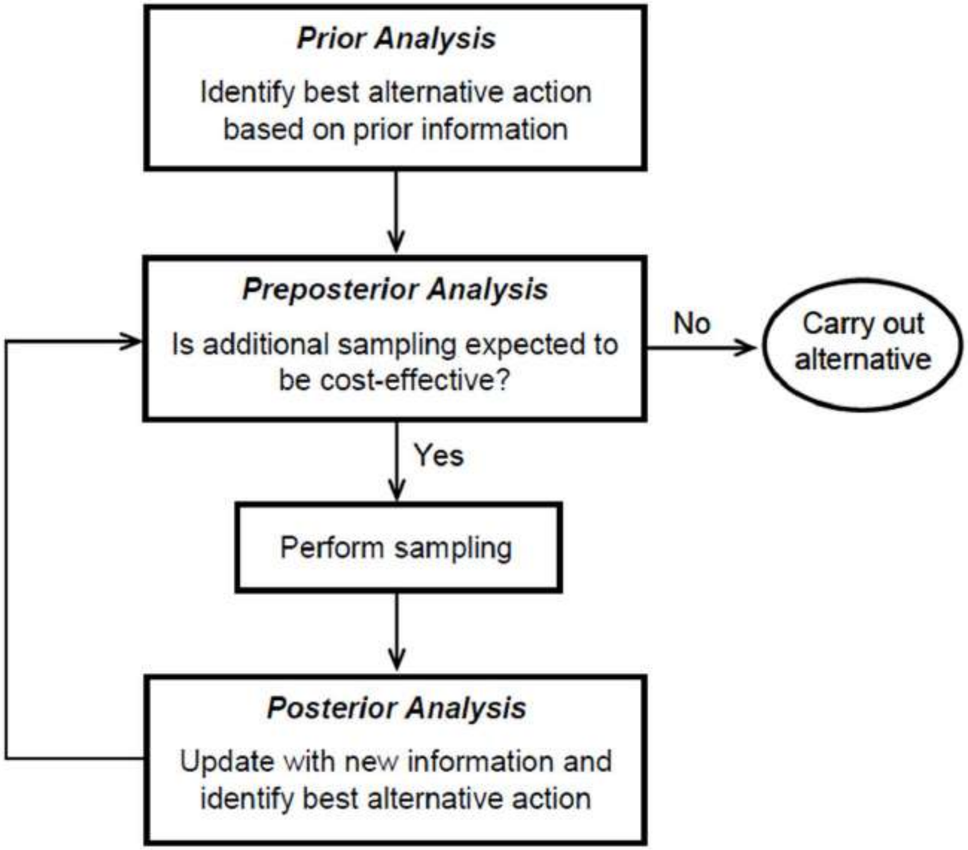
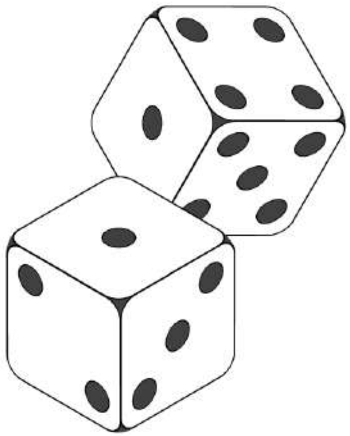
VOI analysis

- Value of Information analysis (VOI)
  - How much do I want to "pay" for my information / output?



Errors in measurements

- Before the measurement:
  - Uncertainty
  - Reliability / Confidence
  - Risk
  - Probability



- After the measurement:
  - Error: $\Delta x = x_{real} - x_{measured}$

NOTE: the concept of error presumes a knowledge of the correct value and it's therefore an abstraction

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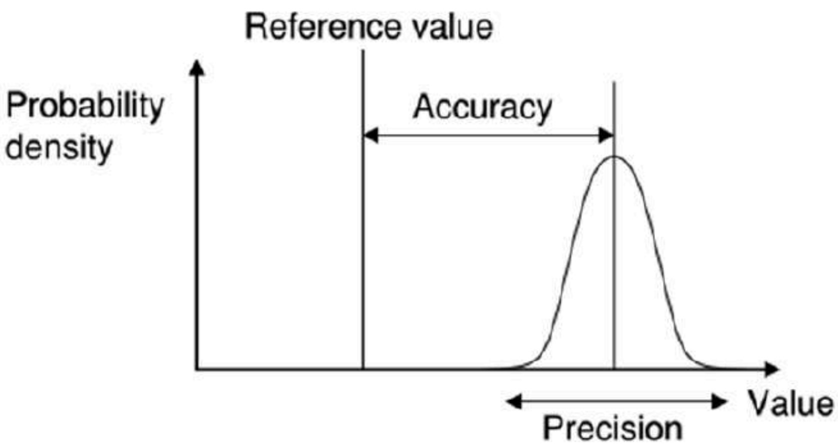
Quality of measurements

- Lack of systematic deviation from a true value: accuracy
- Bias: average deviation from a true value
- Lack of scatter: precision
  - Repeatability (variability when measuring by 1 person)
  - Reproducibility (variability caused by changing operator)



Error “chain”

- Measurement system type. Common errors:
  - Input error
  - Sensor error
  - Signal Transmission error 1
  - Transducer error
  - Signal Transmission error 2
  - Converter error
  - Signal Transmission error 3
  - Computer error
  - Signal Transmission error 4
  - Indication error

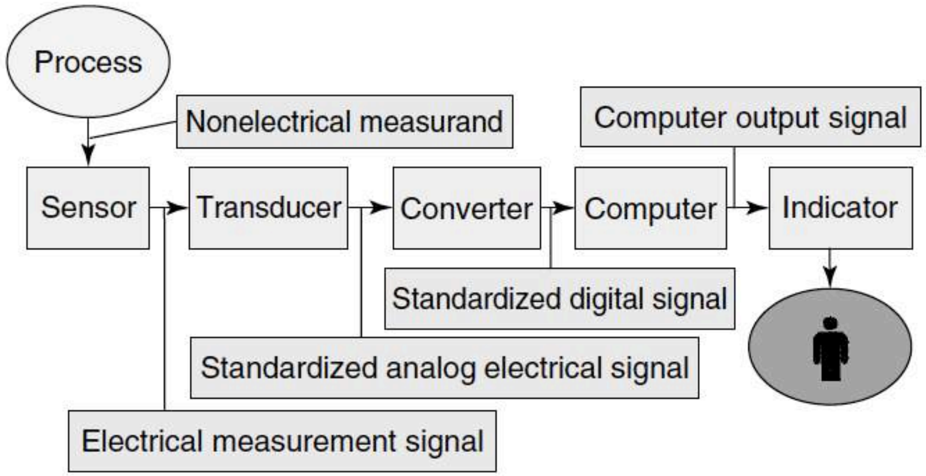
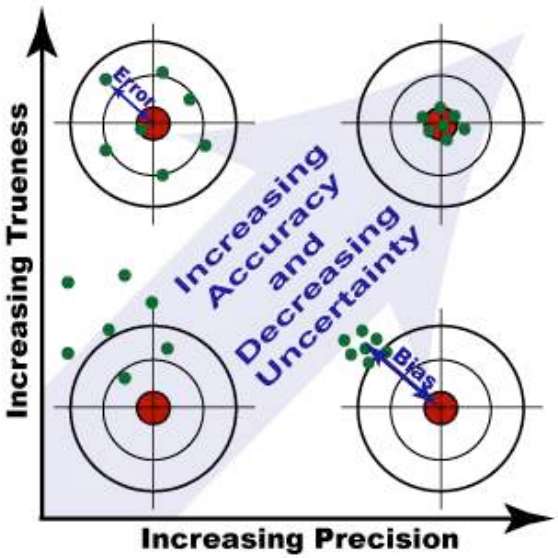


Figure 1. Measurement chain.

Types of errors (I)

- Systematic error (bias)
  - Permanent deflection in same direction from true value
  - It can be corrected
  - Types:
    - » Lack of gauge resolution
    - » Lack of linearity
    - » Drift (time, temperature…)
    - » Hysteresis



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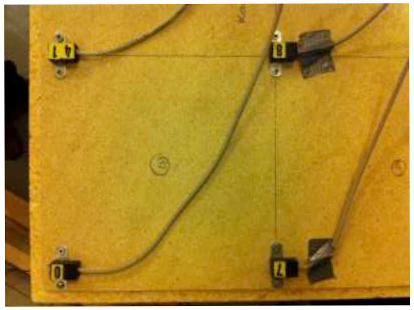
Types of errors (II)

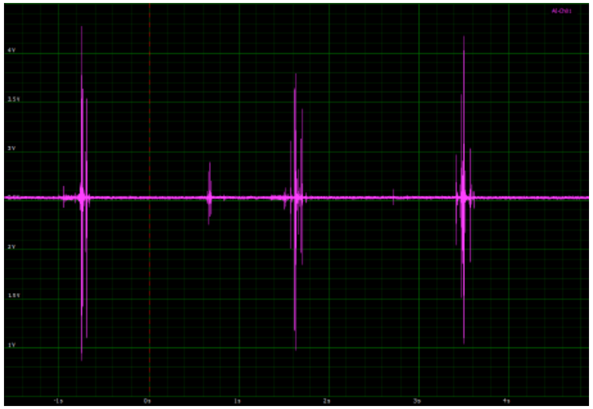
$$X_{true} = X_{measured} + e_{syst} + e_{random}$$

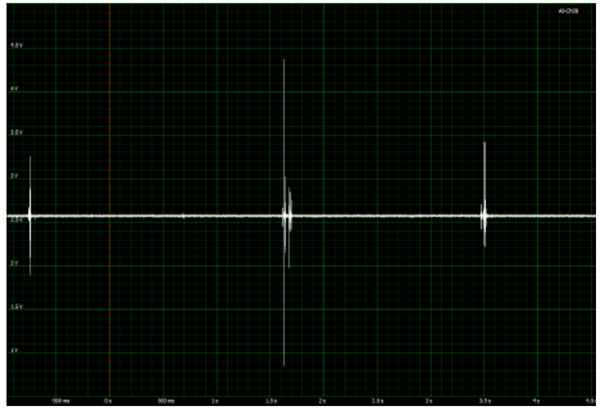
- Gross errors
  - Human mistakes
- Random error
  - Remains after correct gross and systematic errors
    - » It cannot be corrected
  - Short-term scattering of values around a mean value
  - Varies in an unpredictable way
  - Expressed by statistical methods
  - Reasons
    - » Lack of equipment sensitivity
    - » Noise
    - » Imprecise definition

Examples of errors

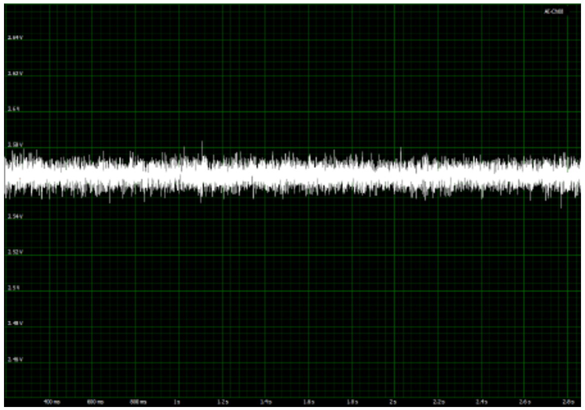
- **Wire error**

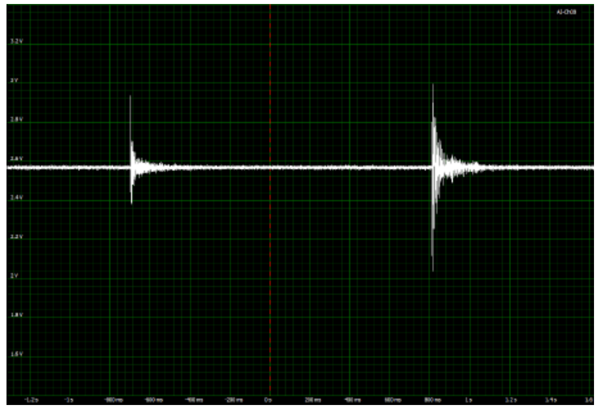




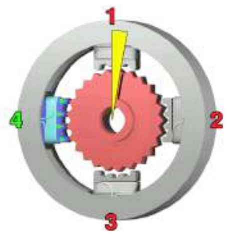


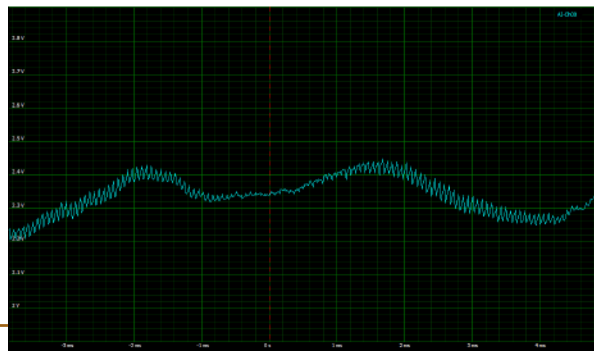
- **Music and external impact**

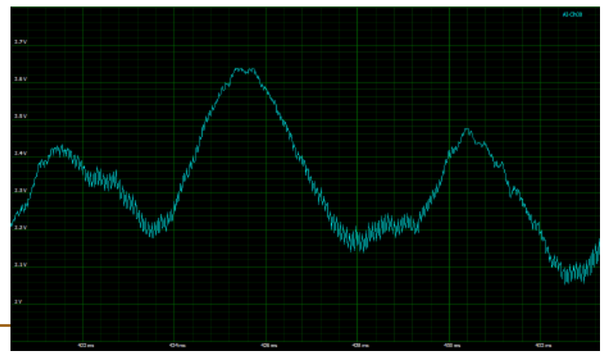




- **Step motor (2/4.5 Hz), harmonic signal?**





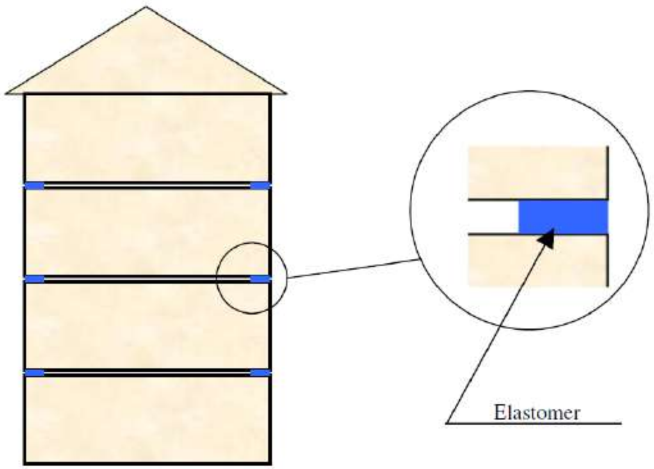


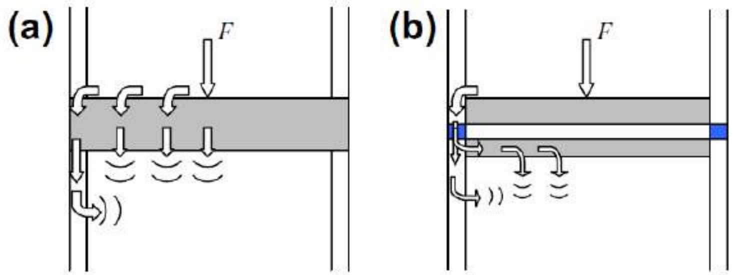
Outline

- Introduction
- Signals
- Excitation sources
- Measurement devices
- Errors in measurements
- **Examples**
- Conclusions

Prefabricated wooden buildings

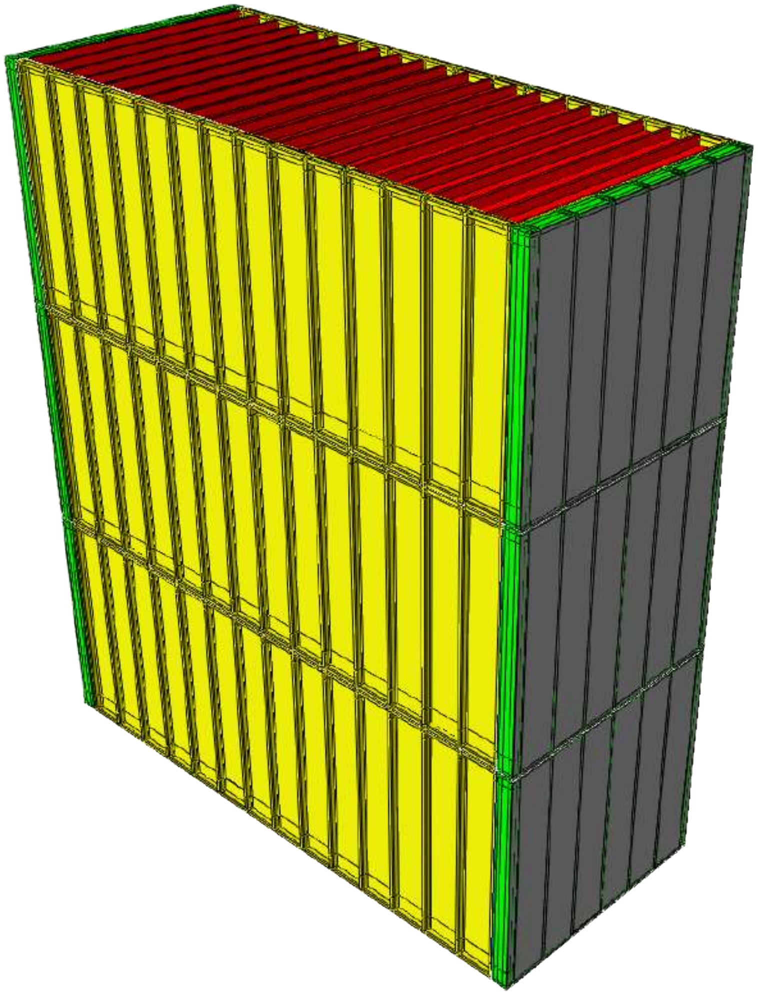
- Timber volume element (TVE)-based building

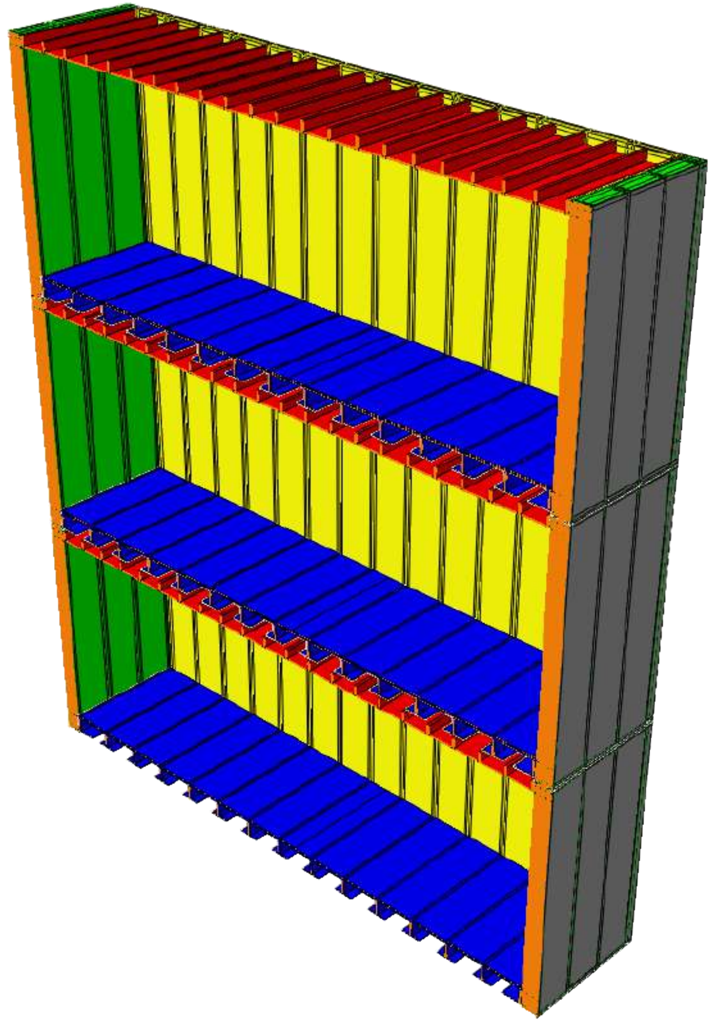




- Method (to develop numerical prediction tools):
  - Calibration FE model with in-situ measurements
  - Modify features in the model

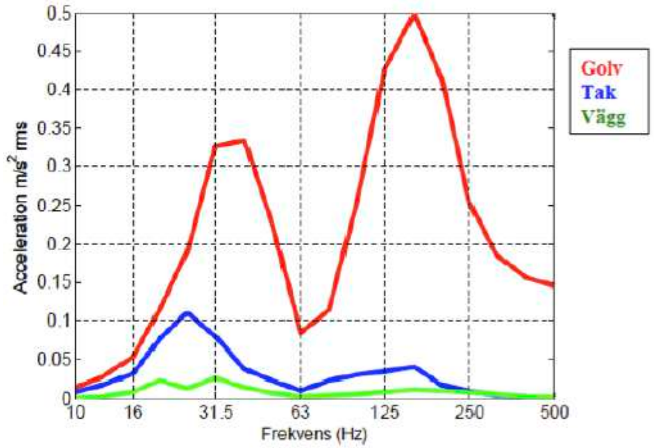
Finite Element model for TVE-based building



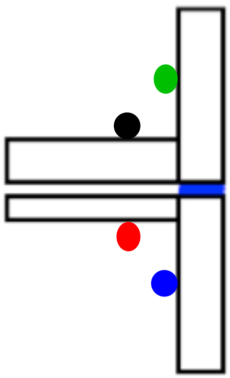


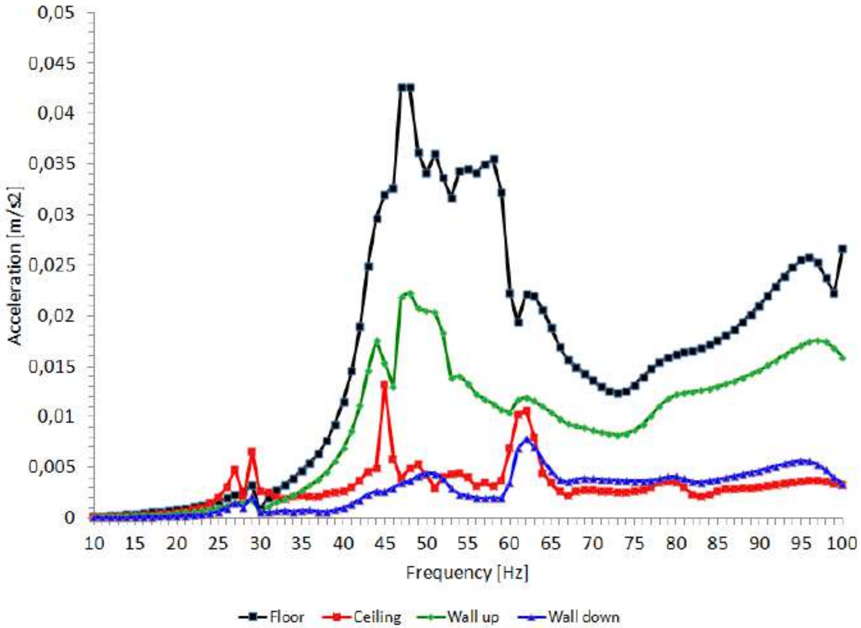
Calibration (preliminary results)

- Measurements



- Simulations





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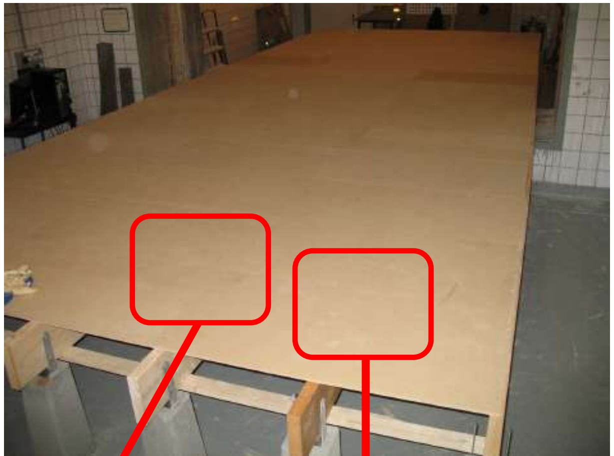
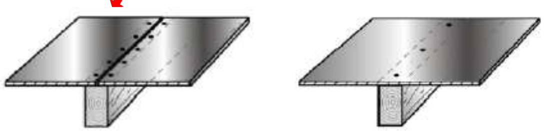
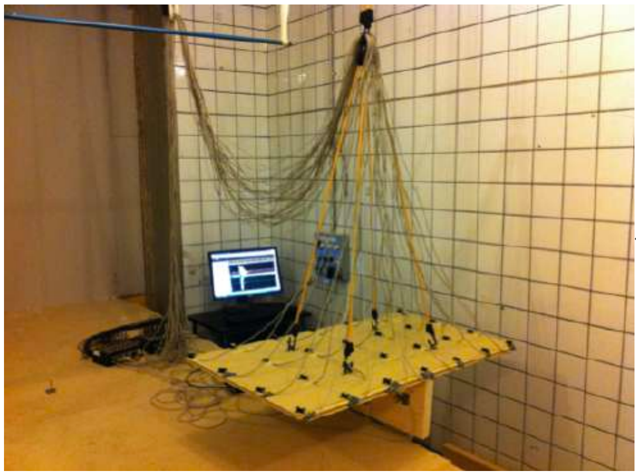
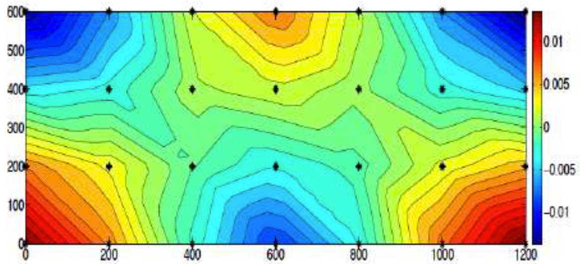
T-junctions



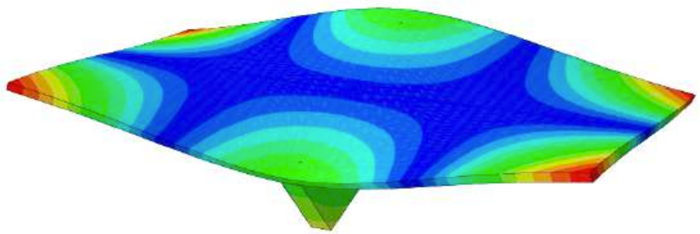




- Influence of the use of glue in lightweight timber junctions
  - Investigate how to model connections



Many transducers and excitation positions! Document everything



Calibration of the FE models with measurements in terms of modal analyses to understand their behaviour

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Outline

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Conclusions

- To measure: acquire knowledge of a new product
  - Analyses prior to measurements
  - Measurement plan based on analyses and purpose
- Signals: frequency and time domain
  - Nyquist-Shannon criterion
  - Resonance
- Excitation sources
- Measurement devices
- Errors
  - Measurements: accompanied by a quality statement
- Document the process (pictures, notes…)

Thank you for your attention!

nikolas.vardaxis@construction.lth.se

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