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Structural dynamic computing (VSMN10) – Measurement techniques

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Outline

Introduction

Signals

Excitation sources

Measurement devices

Errors in measurements

Examples

Conclusions

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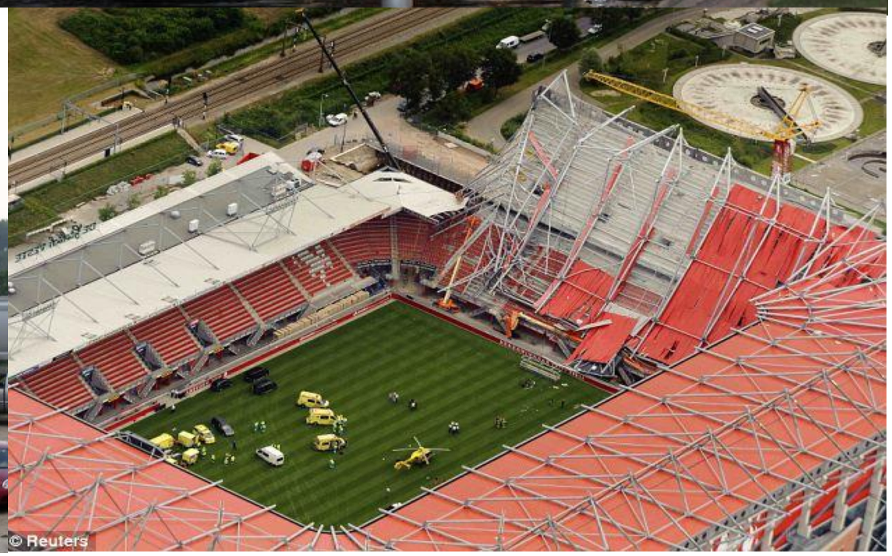
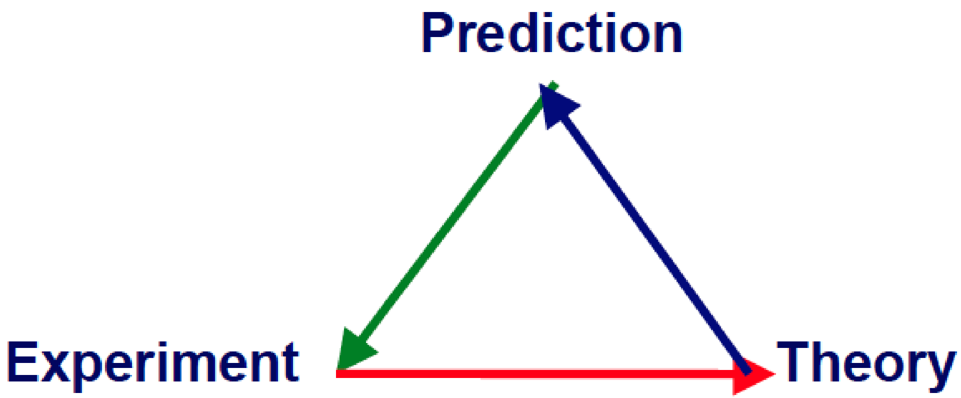
Why do we measure?



Introduction (I)

- Paradigm of natural sciences



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

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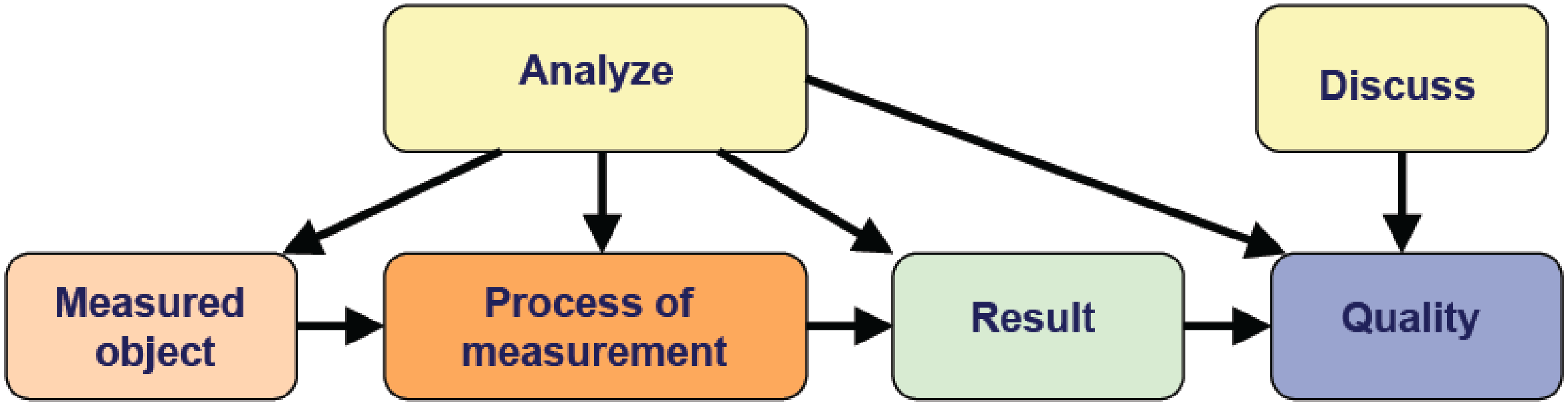
Introduction (II)

Eisenhart [1876-1965]: "*To measure is to assign* <u>*numerical values*</u> *to* <u>*concepts*</u> *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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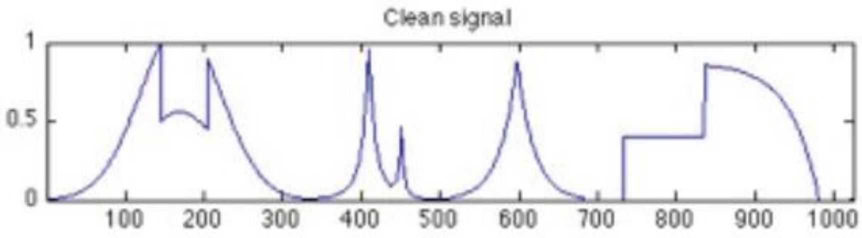
Signals

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



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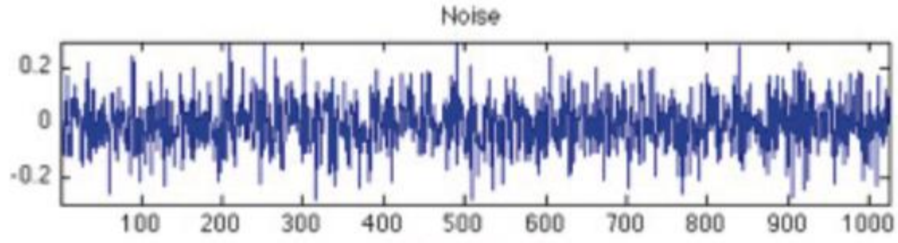
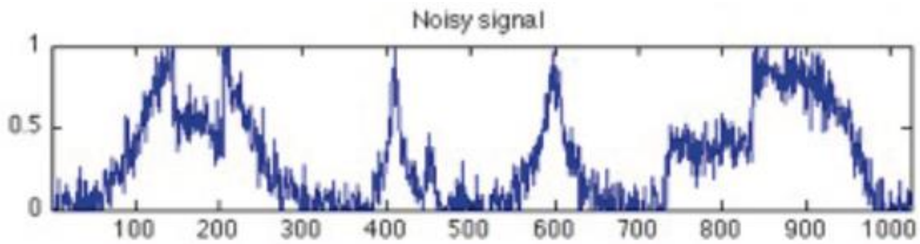


- Noise: changes the smooth signal to a "jagged" curve



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

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

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

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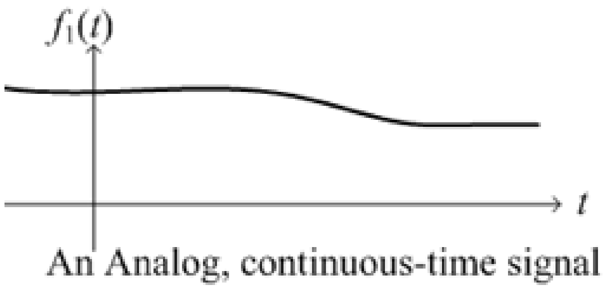
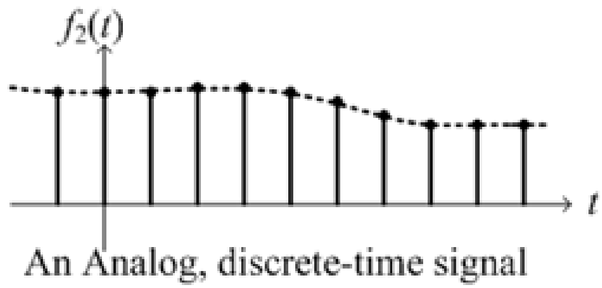
Getting ready for the analysis

- 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





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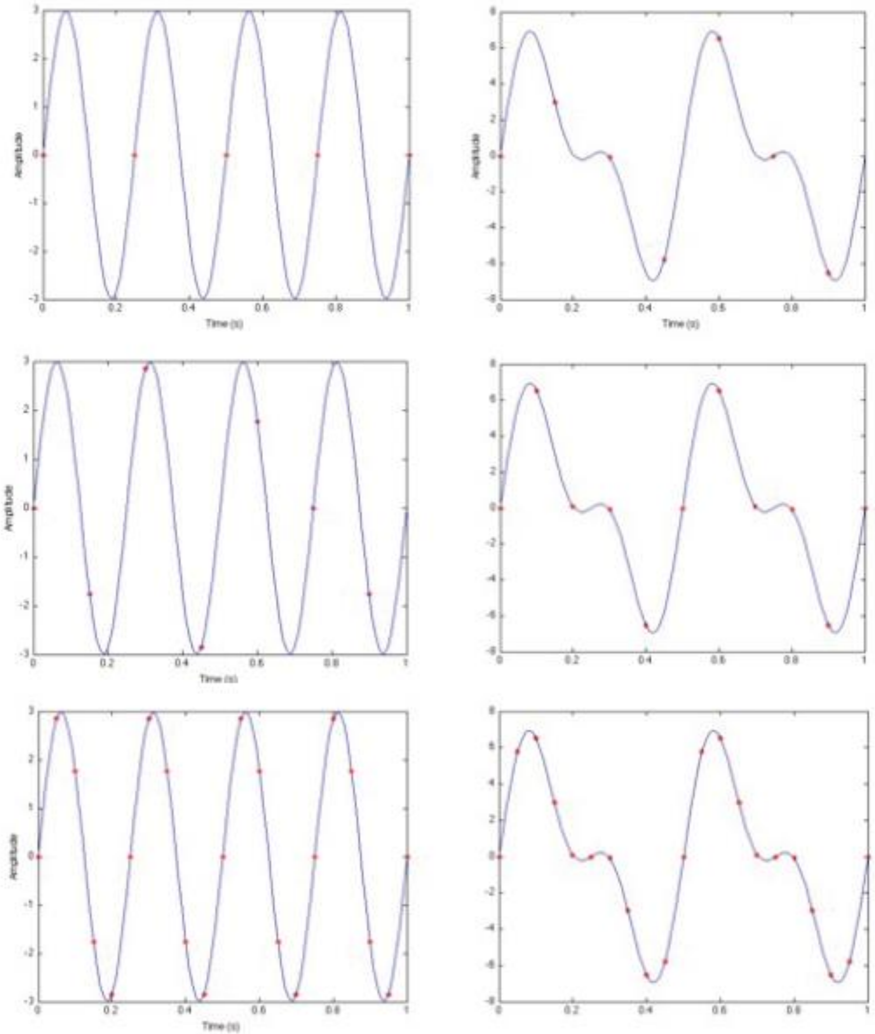
Sampling frequency



- 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

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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:

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

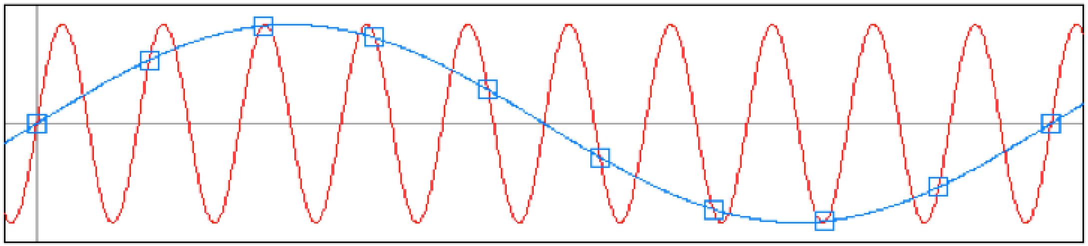
The the sufficient condition for "exact" reconstructability from samples at uniform sample rate is:

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

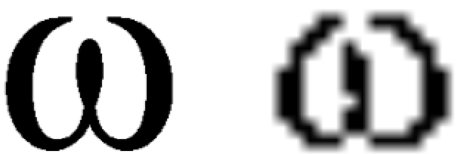
2B is called the Nyquist rate and it is a property of the band-limited signal, while ($f_s/2$) is called the Nyquist frequency and is a property of the sampling system

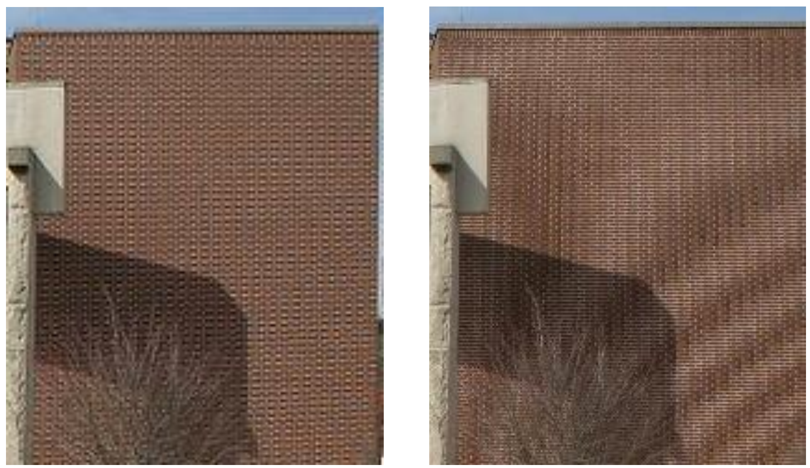
Aliasing

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



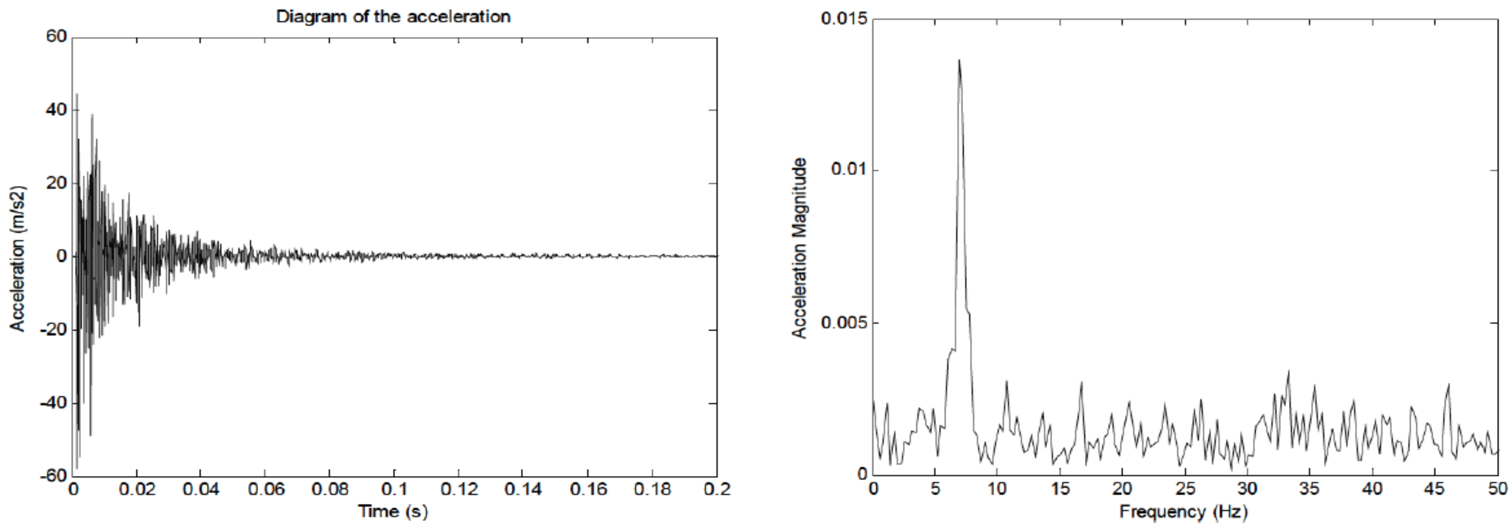
- Example: Helicopter: Stroboscopic effect
- Example: Image aliasing (Sampling / Pixel density wrong)





How to analyse the data?

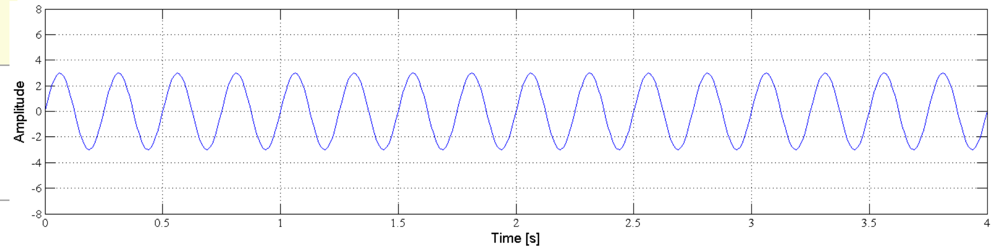
- Waveform: amplitude as a function of time
- Spectrum: frequencies contained in the signal
- Leap between domains: FT
- In practice, software apply FFT

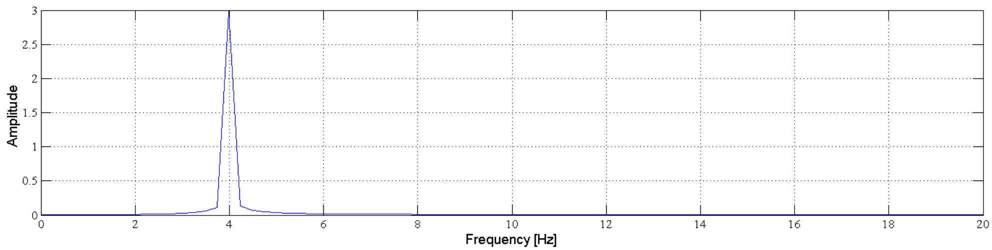


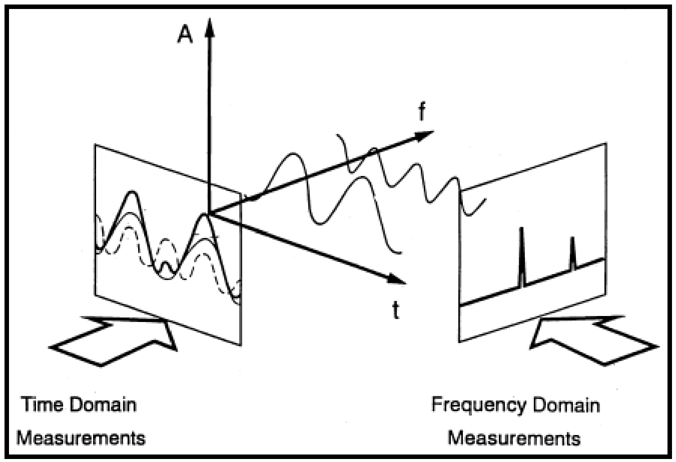
(a) Time domain. (b) Frequency domain.

FFT example (Matlab)

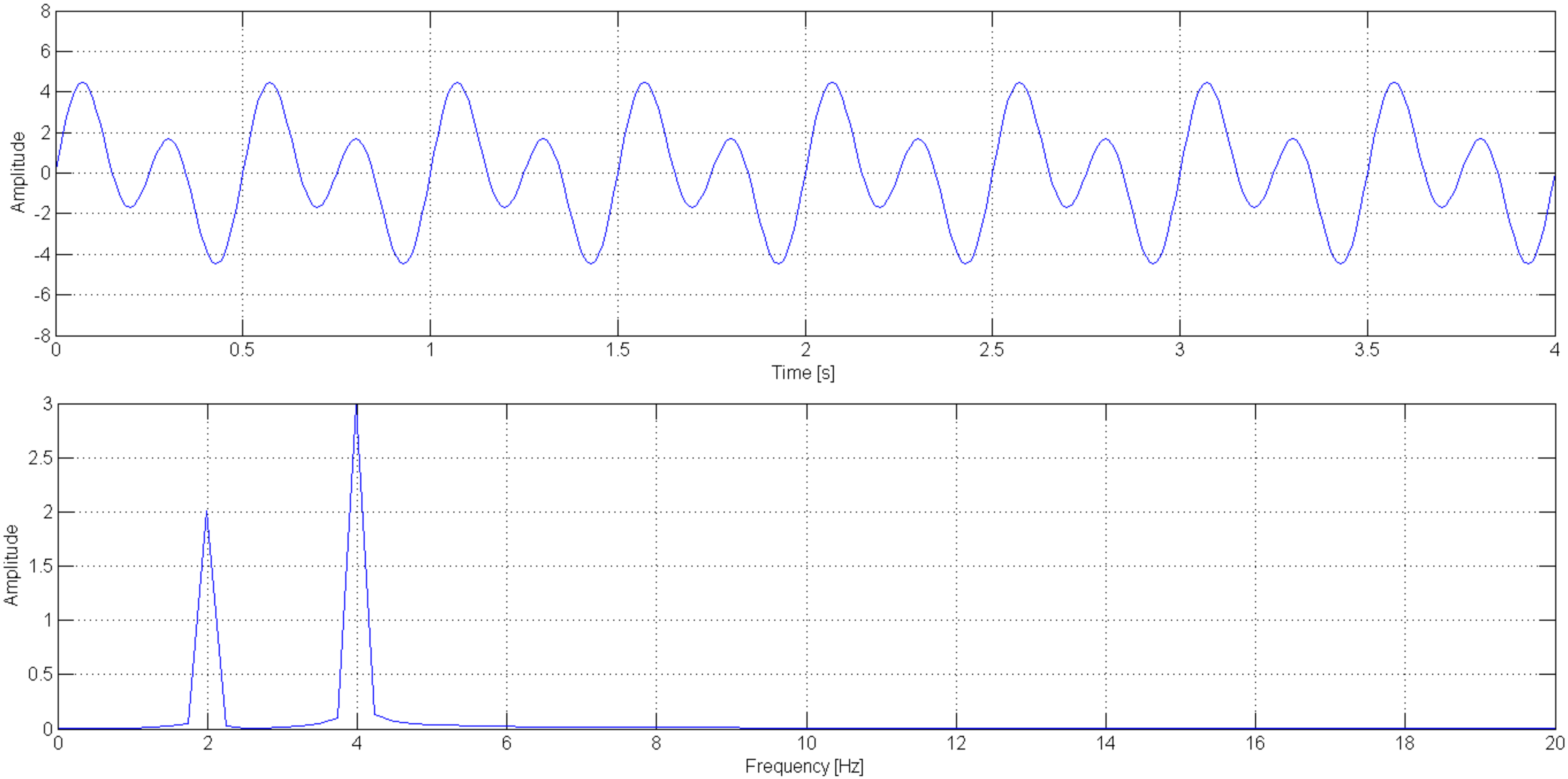
```
%Juan Negreira; May 2011
%Calculates the discrete fourier transform of the timedomain signal y(t)
%Y:amplitude of the frequency components
%f:frequencies[Hz]
%Only the unique points are returned ie. f lies in 0 <= f <= Fs/2

%% 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')
```



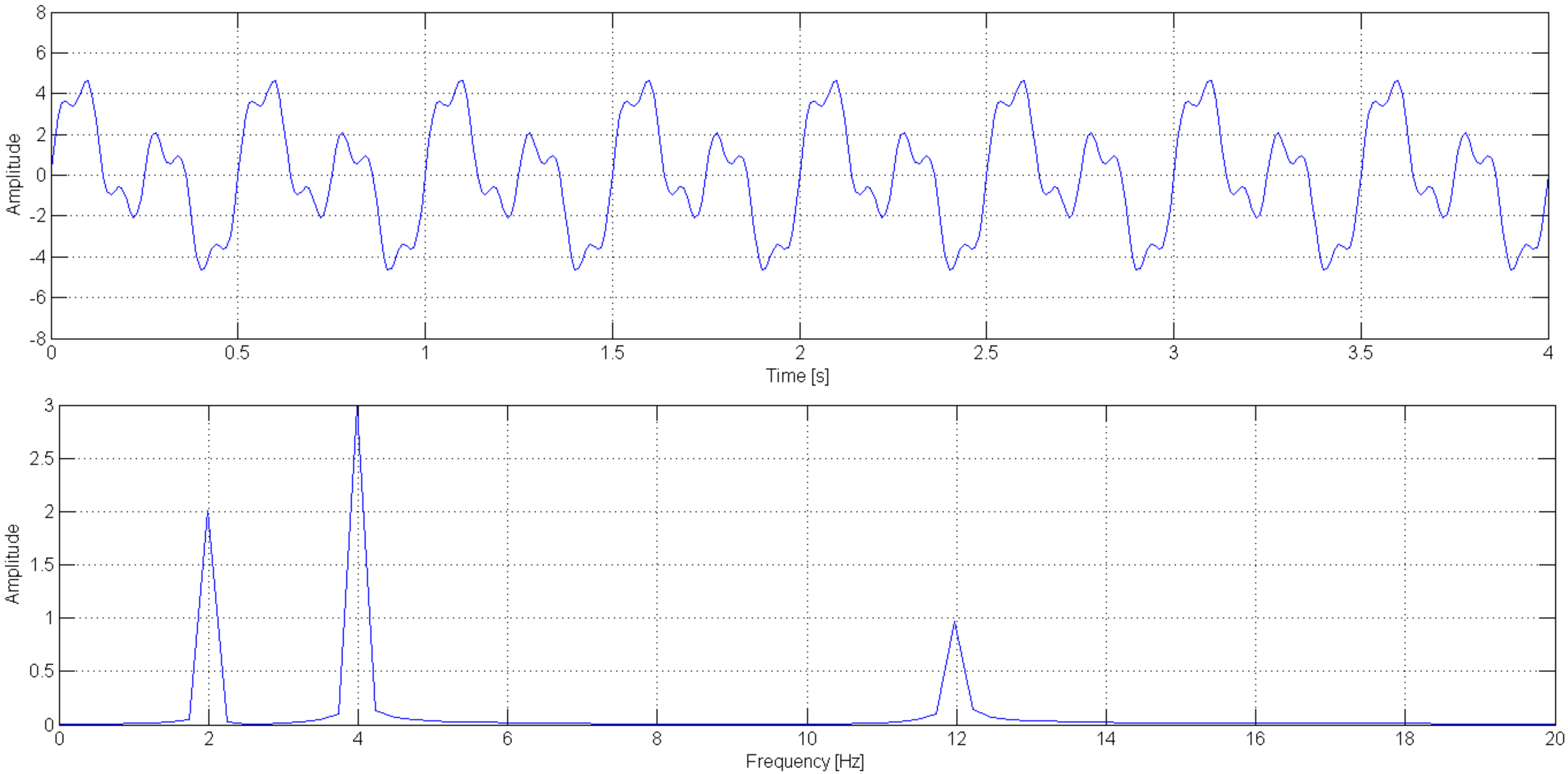




FFT example (Matlab)



FFT example (Matlab)



- *Example: video*

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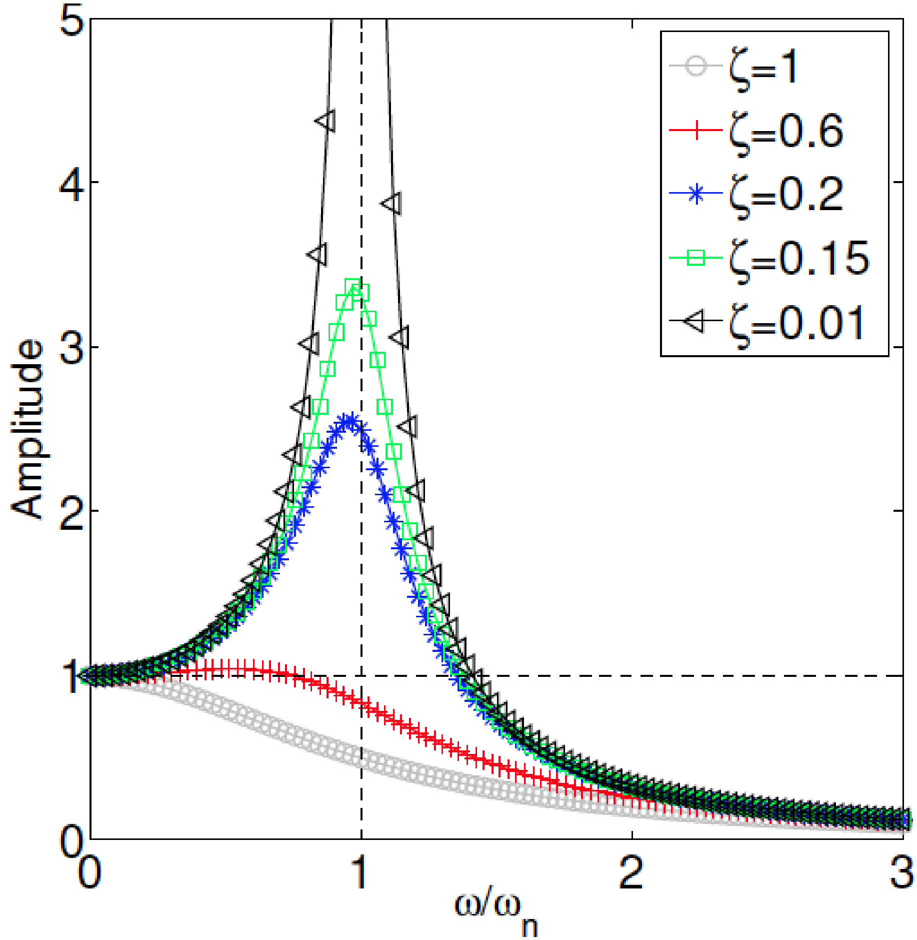
Resonance

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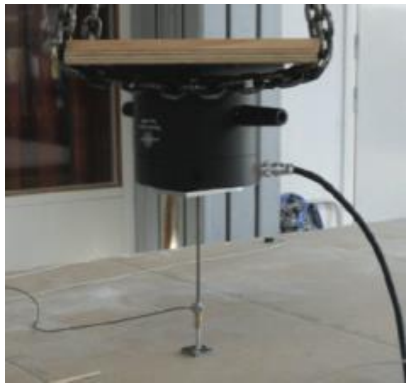
- Signals
- Excitation sources
- Measurement devices
- Errors in measurements
- Examples
- Conclusions

Excitation sources (floor vibrations)

- Standardised
  - Tapping machine
  - Rubber tire

- Non-standardised
  - Shaker
  - Japanese ball
  - Impact hammer
  - Human walking
  - …





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Excitation sources (acoustics)

- Standardised
  - Loudspeakers (noise)
- Non-standardised
  - Cap-gun
  - Baby-crying
  - Impulse

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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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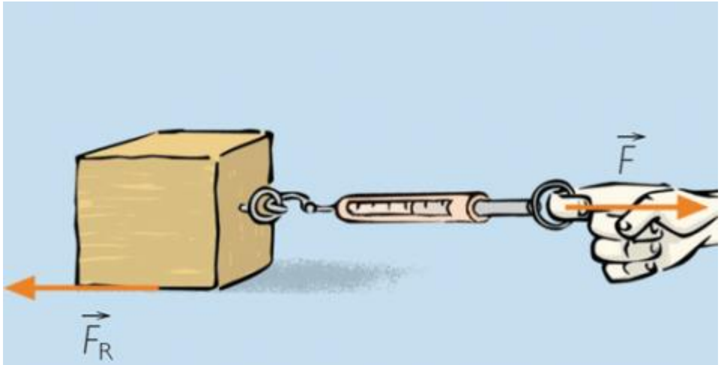
Calibration (II)

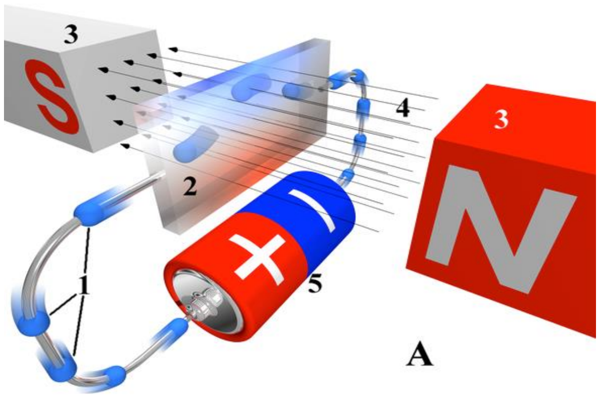
- Examples:
  - Sound level meter:

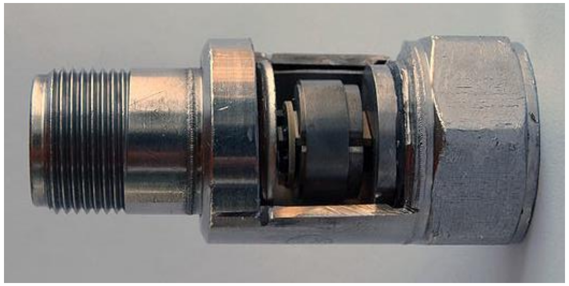
  - Accelerometers:

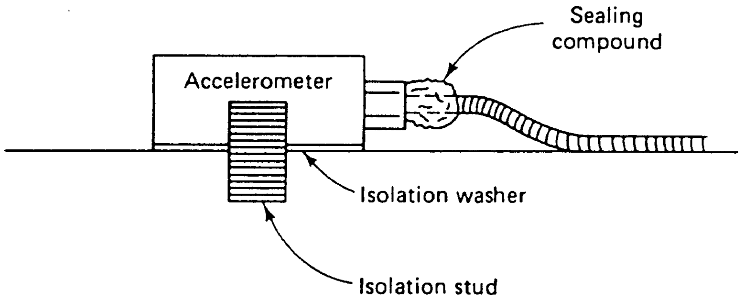
Accelerometers

- Mechanical, piezoelectric, hall effect, capacitive…









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We measure FRFs…

- In general, FRF = transfer function, i.e.:
  - Contains system information
  - Independent of outer conditions

$$H_{ij}(\omega) = \frac{\tilde{s}_i(\omega)}{\tilde{s}_j(\omega)} = \frac{\text{output}}{\text{input}}$$

- Different FRFs can be obtained depending on the measured quantity

Measured quantity	FRF	
Acceleration (a)	Accelerance = $N_{dyn}(\omega)$ = a/F	Dynamic Mass = $M_{dyn}(\omega)$ = F/a
Velocity (v)	Mobility/admitance = $Y(\omega)$ = v/F	Impedance = $Z(\omega)$ = F/v
Displacement (u)	Receptance/compliance = $C_{dyn}(\omega)$= u/F	Dynamic stiffness = $K_{dyn}(\omega)$ = F/u

$$C_{dyn}(\omega) = \frac{\tilde{u}(\omega)}{F_{driv}(\omega)} = \frac{1}{(K - M\omega^2) + Ri\omega}$$

$$K_{dyn}(\omega) = C_{dyn}(\omega)^{-1} = -M\omega^2 + Ri\omega + K$$

Microphones

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

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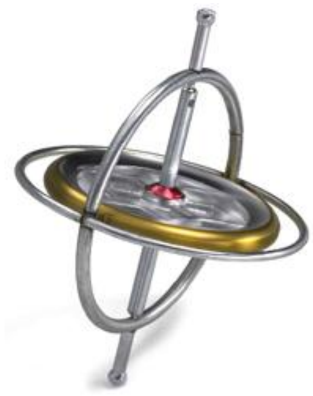
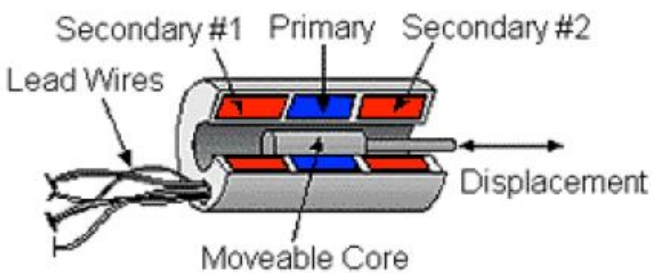
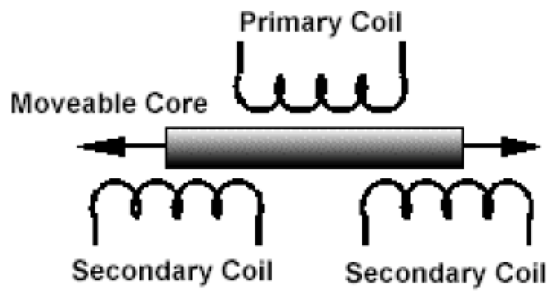
Others (I)

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



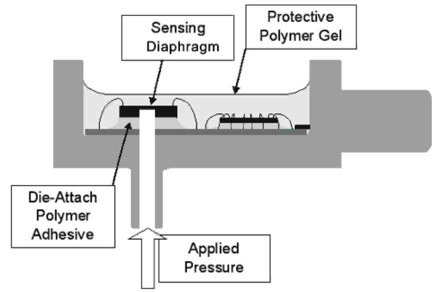
- LVDT sensors
  - Linear Variable Differential Transformers
  - Output voltage proportional to the displacement of the core



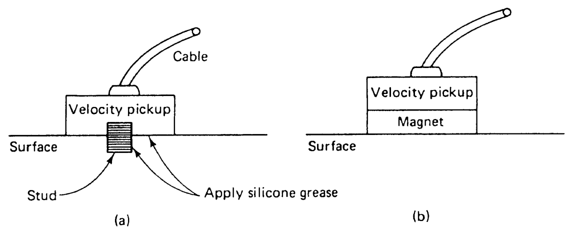


Others (II)

- 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

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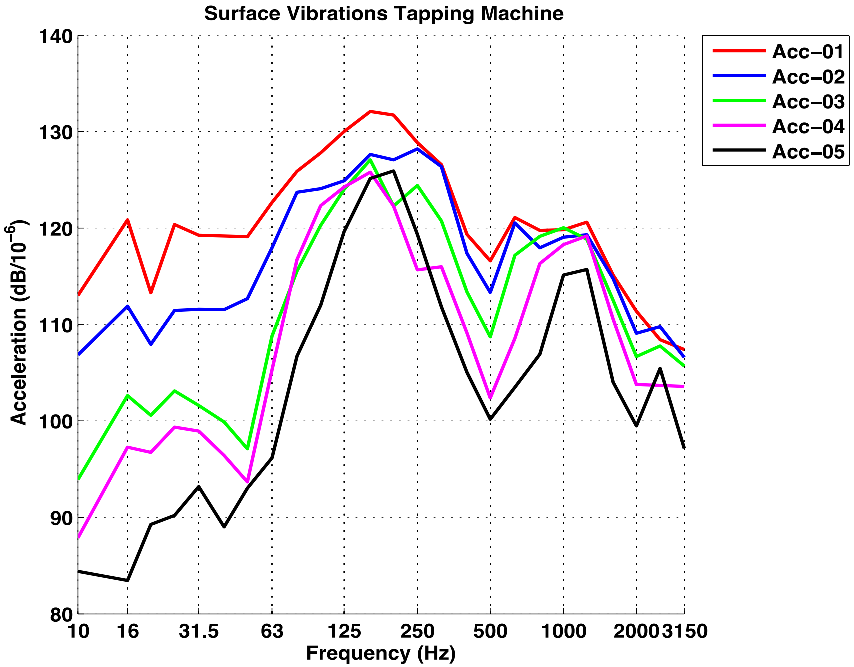
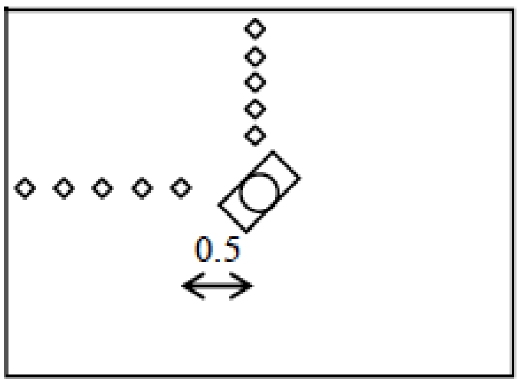
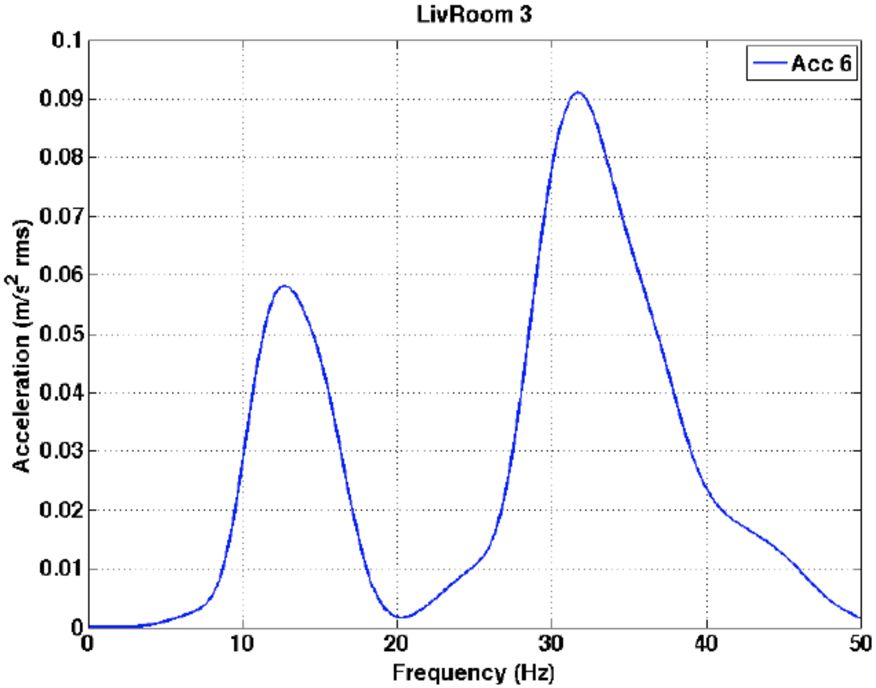
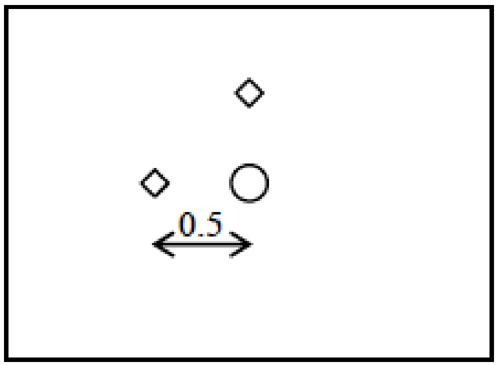
In-situ vibratory measurements (I)





In-situ vibratory measurements (II)





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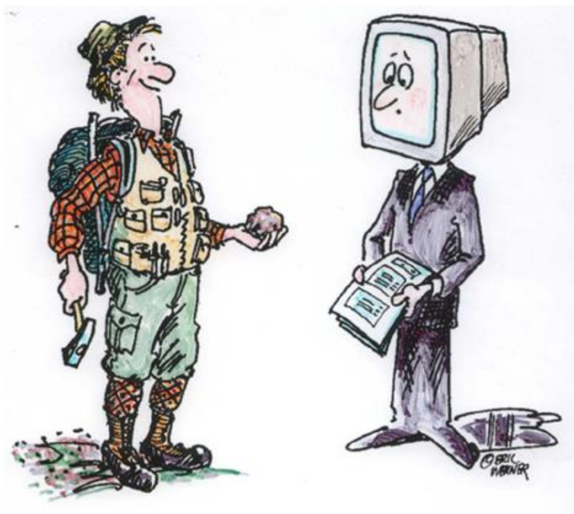
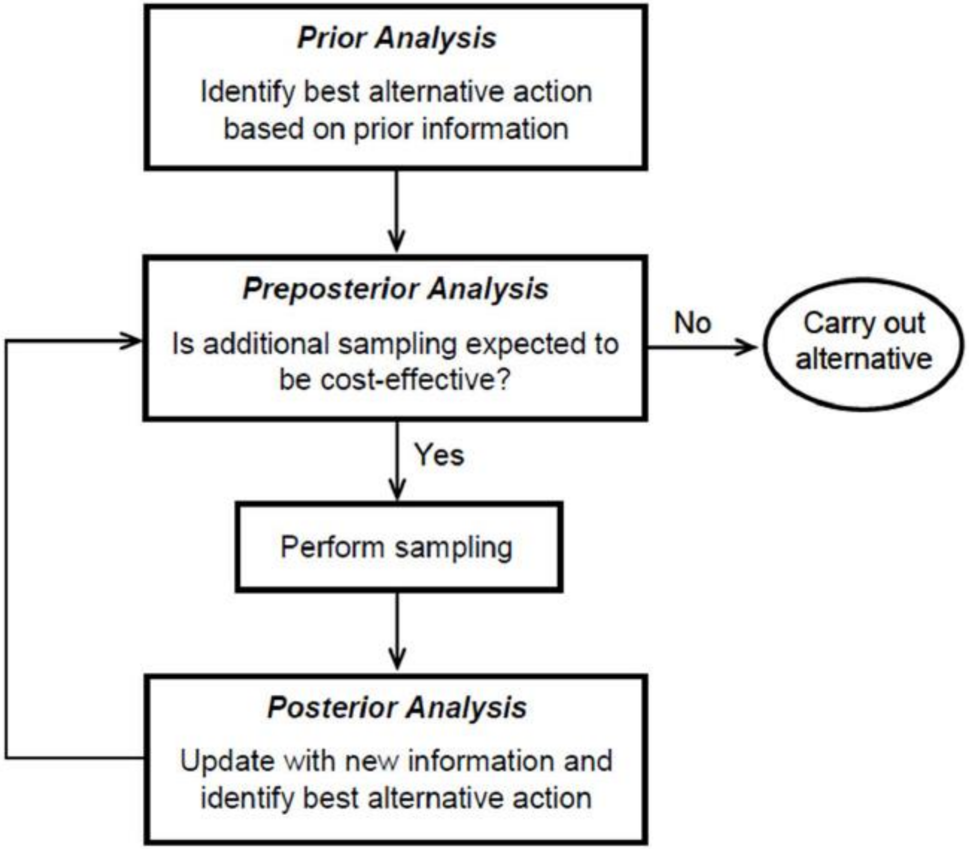
Errors – Introduction

- 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



VoIA (I)

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



VoIA (II)

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

1.234 m

1.234 m ± 0.017 m

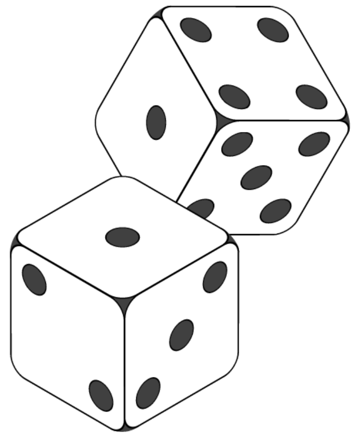
2 000 000 €

?

The issue of scale…

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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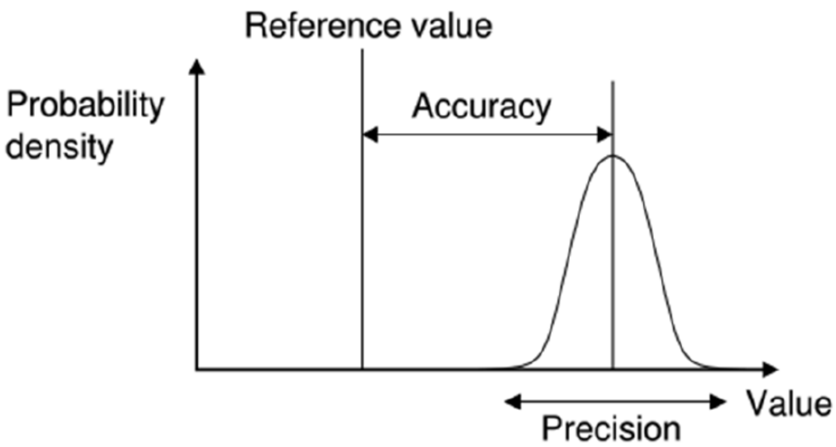
Quality of measurements

- 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)



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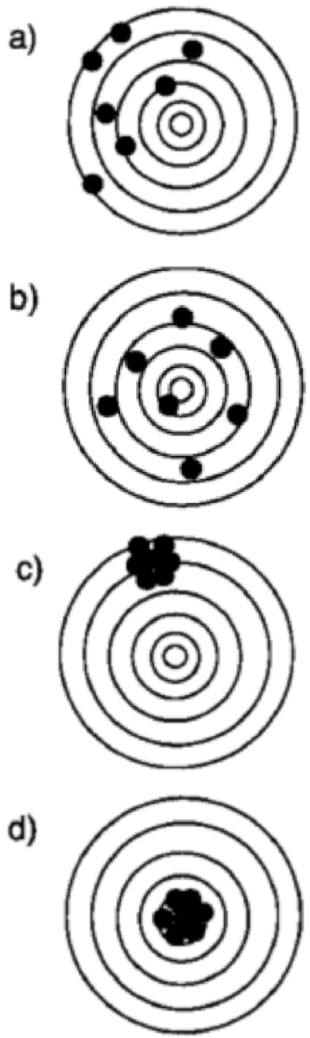
Accuracy / Bias / Precision



Accuracy = Bias + Precision

a) high bias + low precision = low accuracy

b) low bias + low precision = low accuracy

c) high bias + high precision = low accuracy

d) low bias + high precision = high accuracy

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

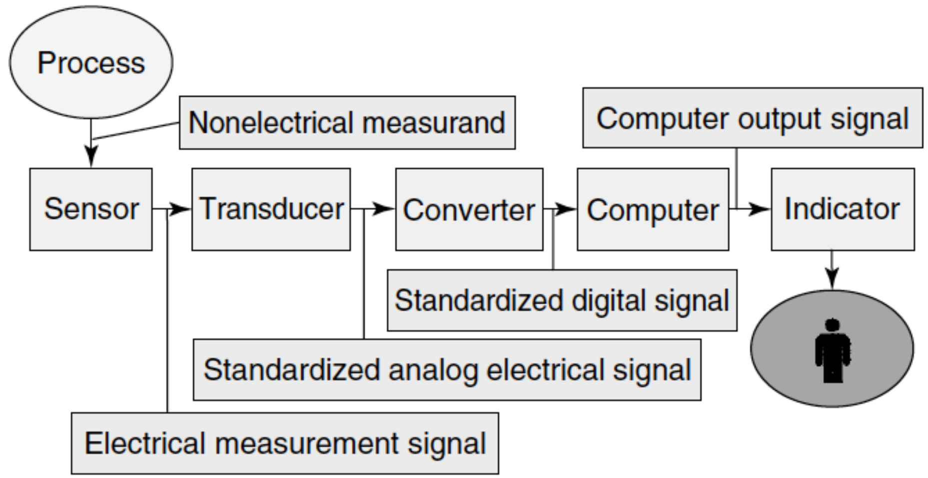
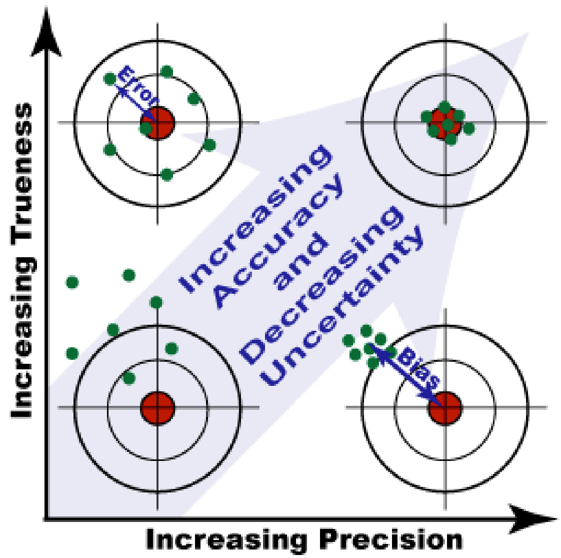


Figure 1. Measurement chain.

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



Types of errors (II)

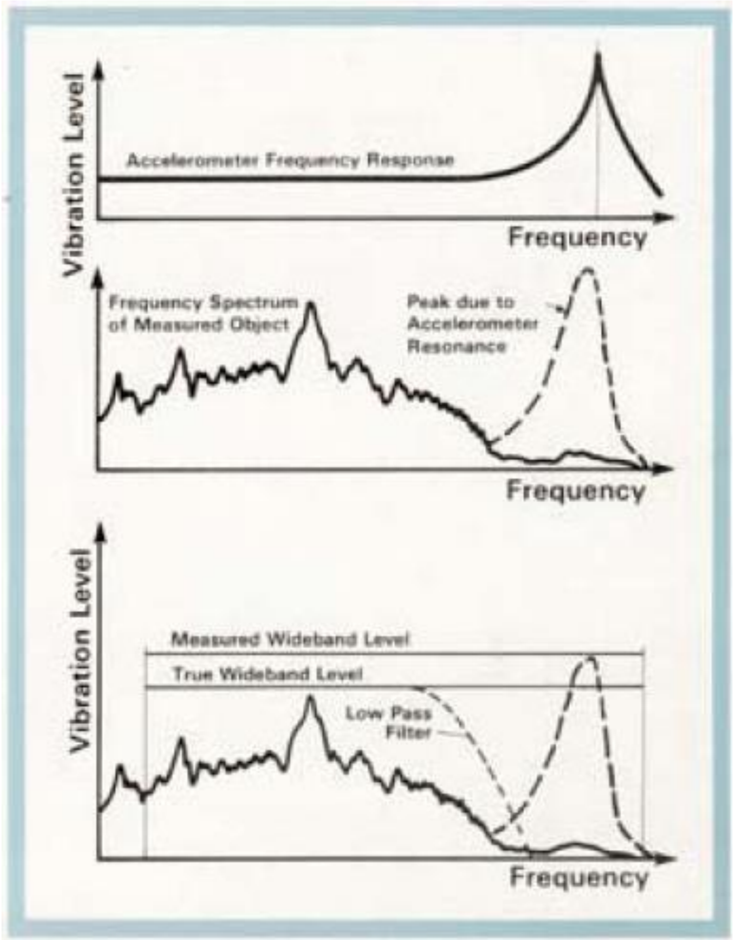
- Gross errors
  - Human mistakes

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

- 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

Errors with accelerometers (I)

- Avoiding errors due to accelerometer resonance



Source: Measuring vibration (B&K)

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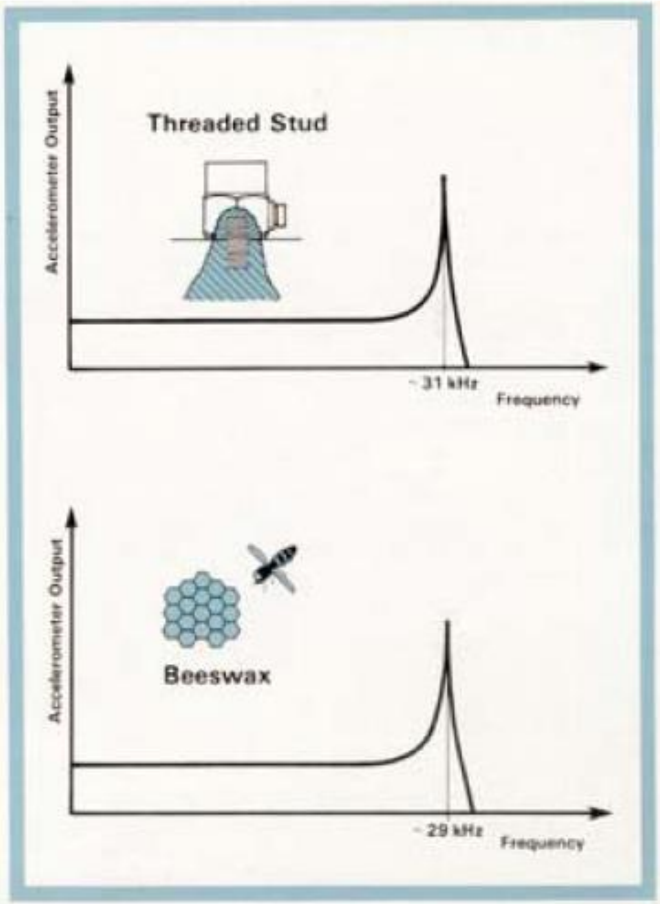
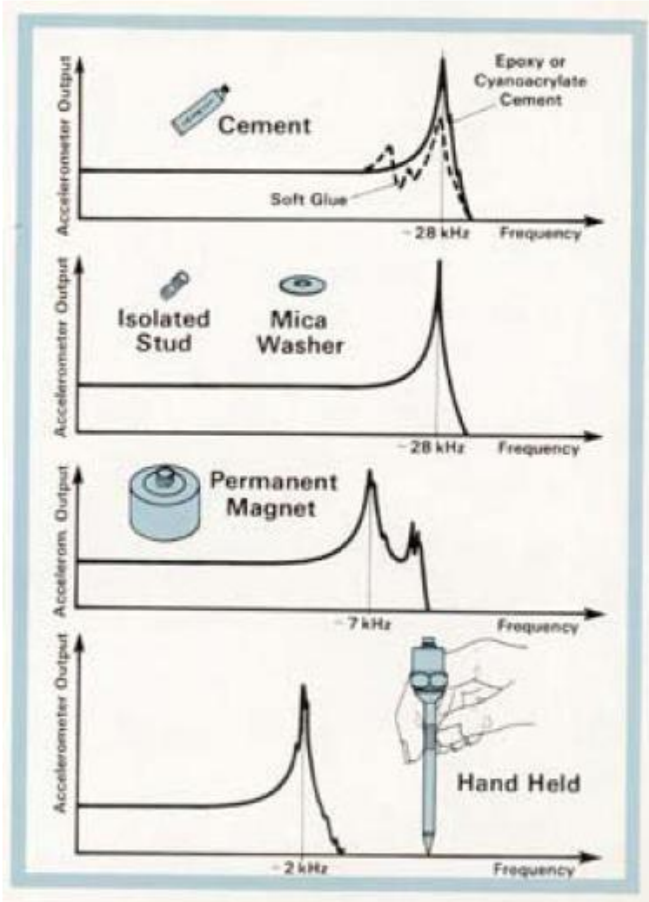
Errors with accelerometers (II)

- Be aware of the mounting method…





Source: Measuring vibration (B&K)

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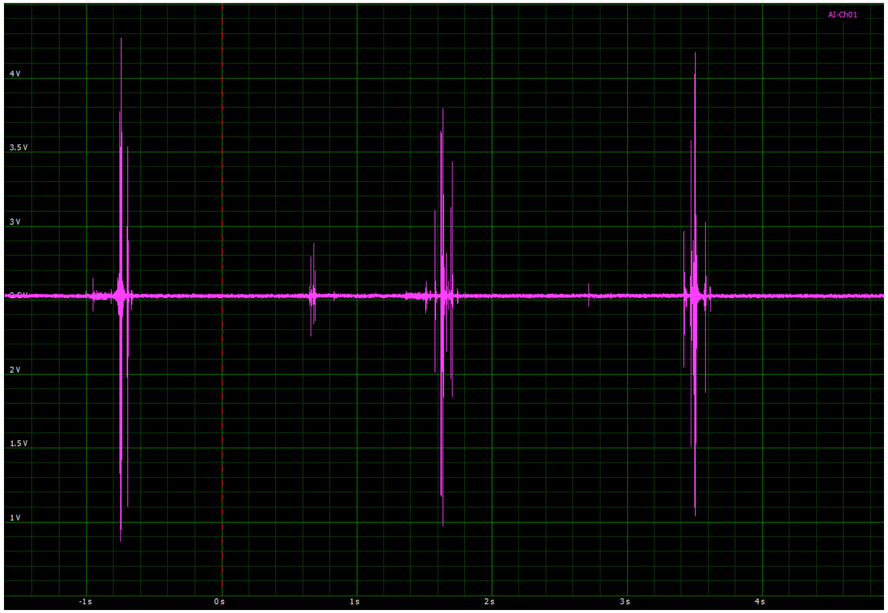
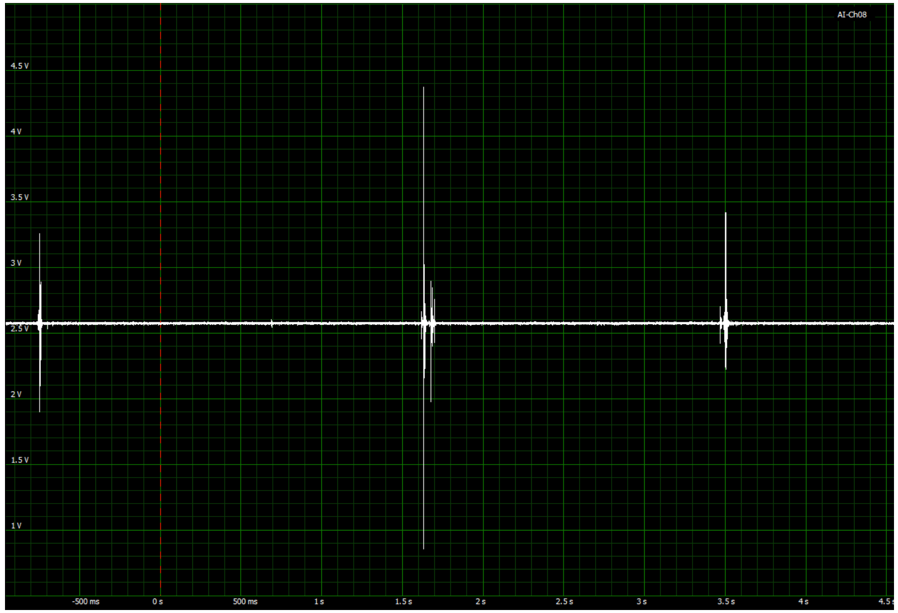
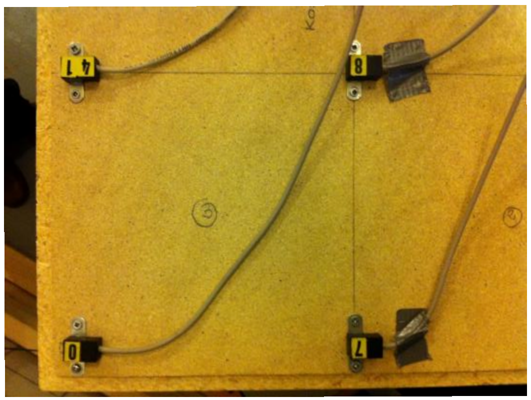
Errors with accelerometers (III)

- Wire error







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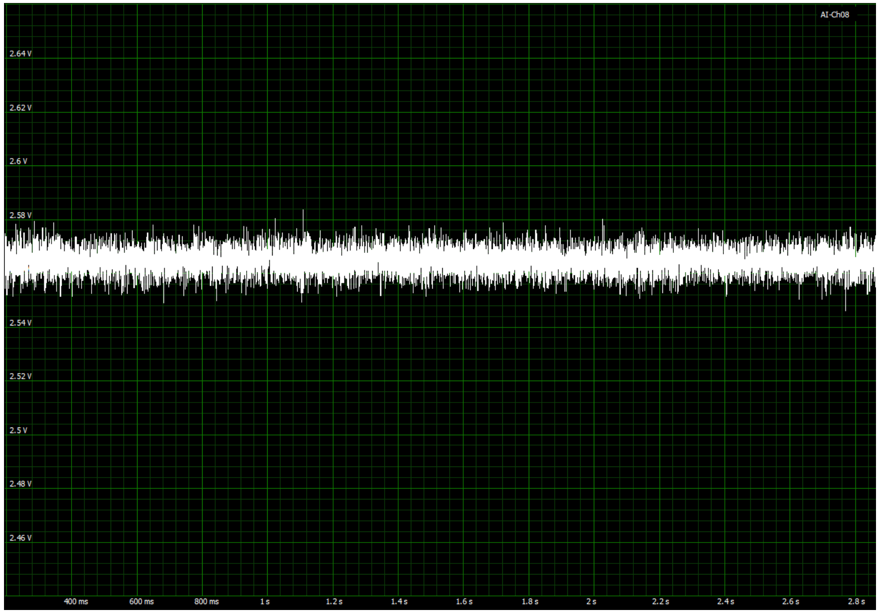
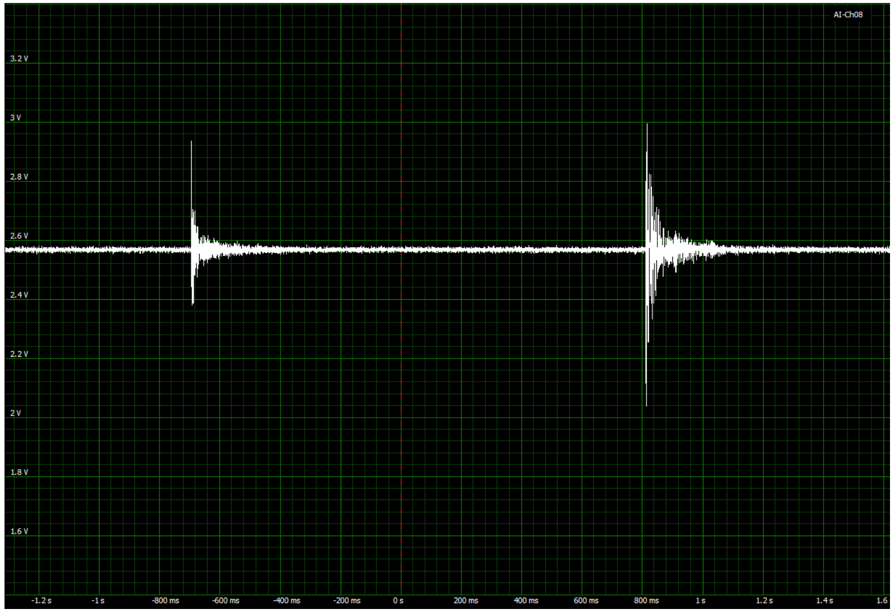
Examples of errors (I)

- Music and external impact





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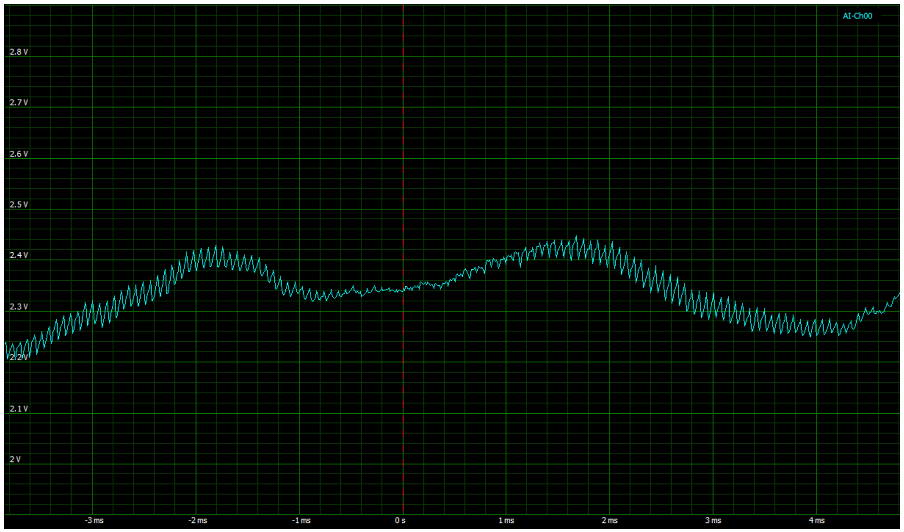
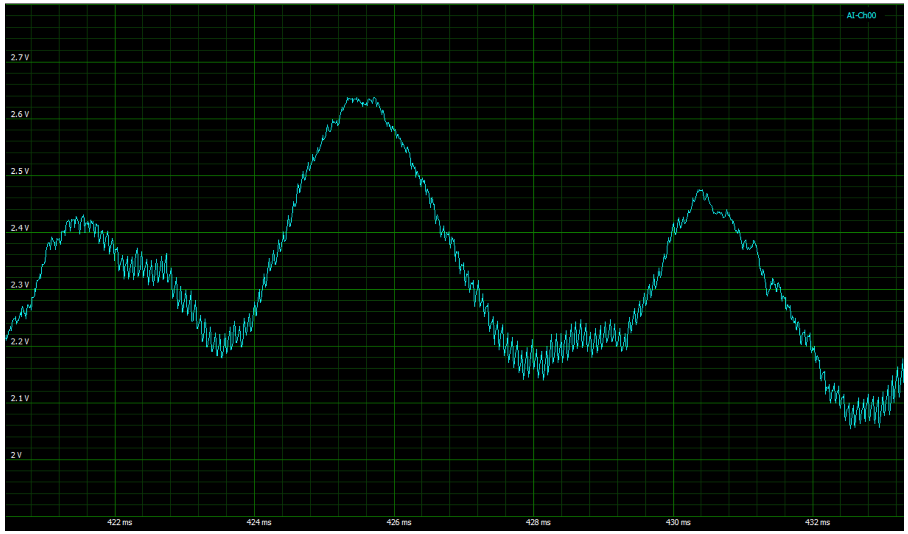
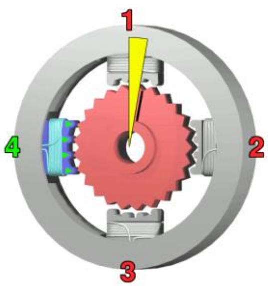
Examples of errors (II)

- Step motor (2 Hz / 4.5 Hz)
  - Harmonic signal?







Outline

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

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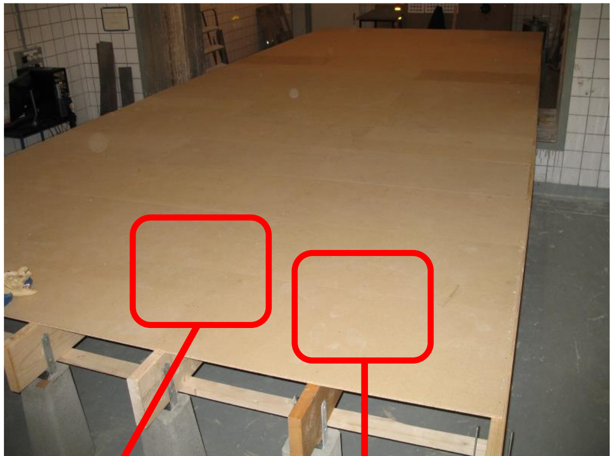
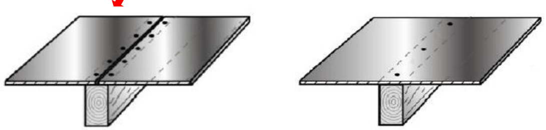
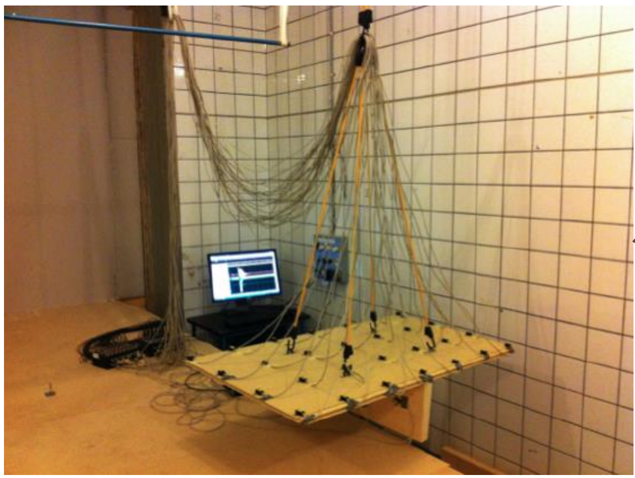
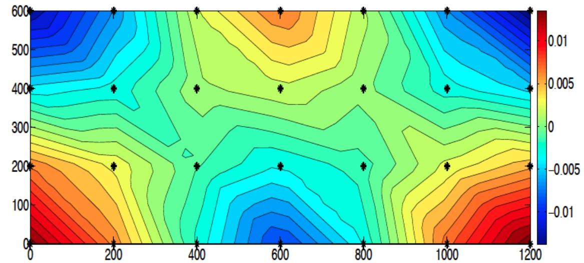
T-junctions



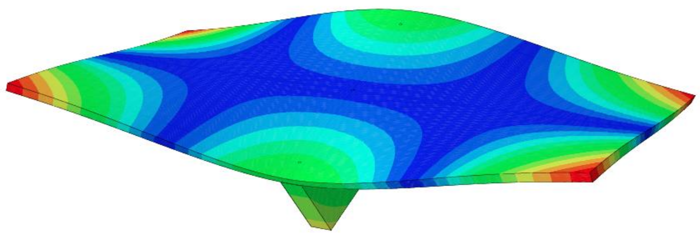




- Influence of the use of glue in lightweight timber junctions
  - Investigate how to model connections



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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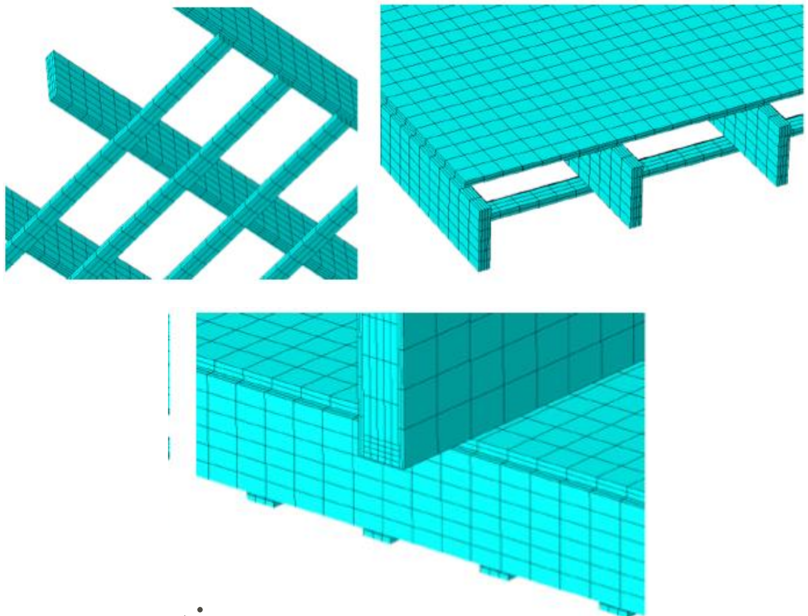
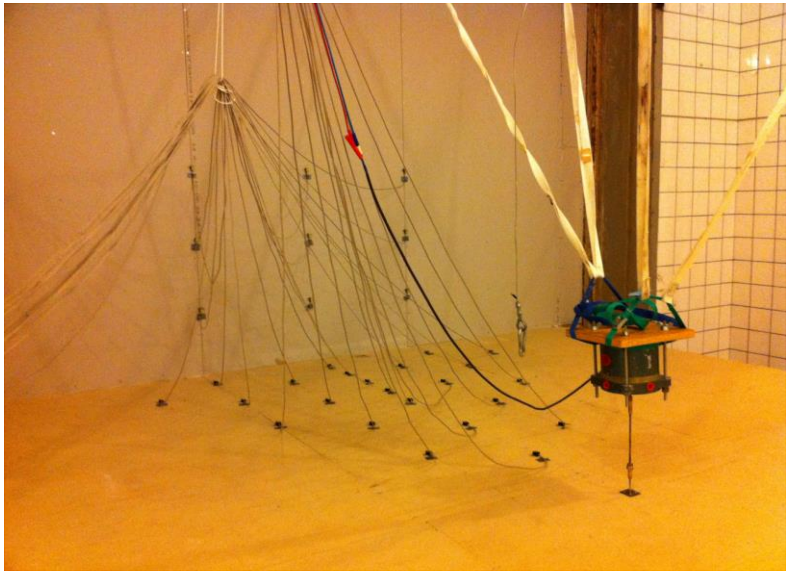
Wall-floor building element (I)

- Wall-floor element:
  - Dimensions: 9.3 x 3.6 m^2
  - Connections: glue and screws

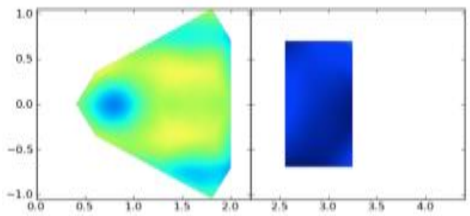


- Investigation of reflection and transmission properties
  - Gain knowledge towards FE modelling

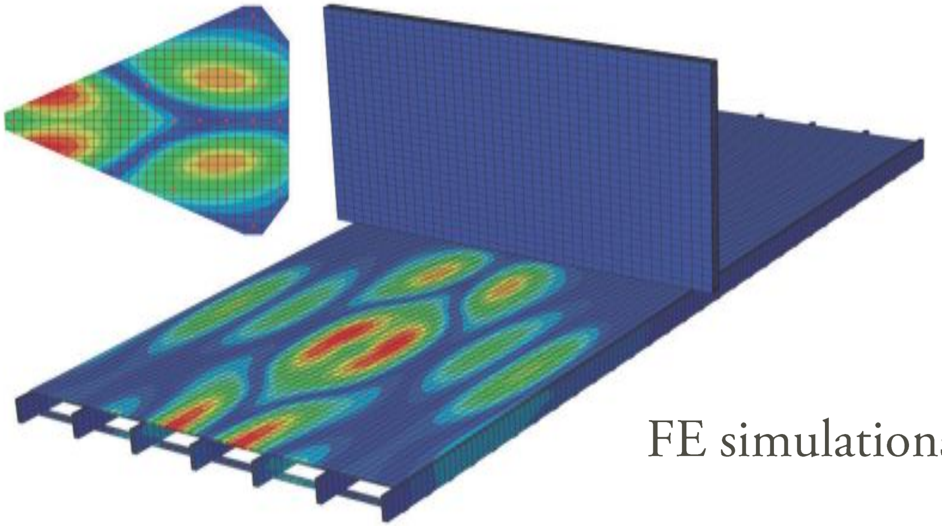
Wall-floor building element (II)



Many transducers and
excitation positions!
Document everything



Measurements



FE simulations

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Psycho-vibratory investigation of timber floors

- Subjective: 31 subjects / 5 floors
  - Walking
  - Seated
- Objective measurements

- 310 data files (subjective)
- 30 data files (objective)
- Always planned actions!!

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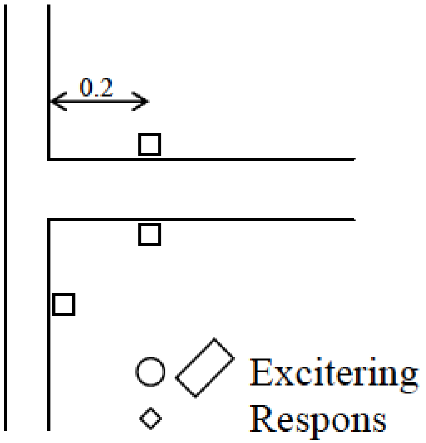
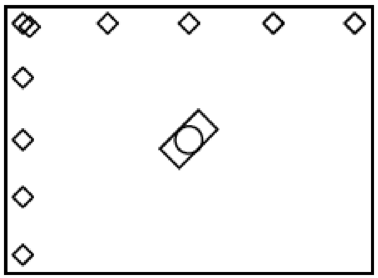
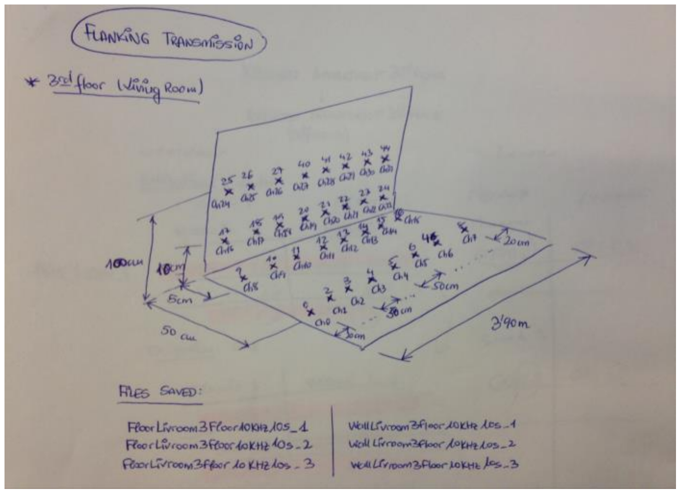
Flanking transmission

Many transducers and
excitation positions!
Document everything







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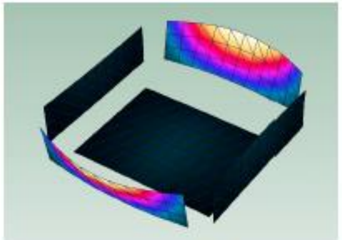
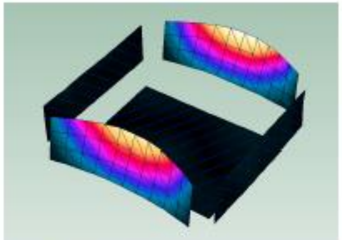
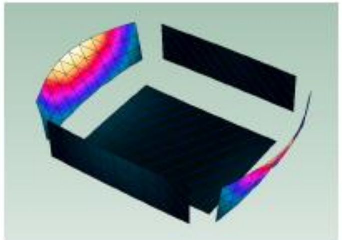
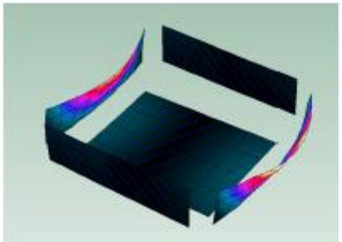
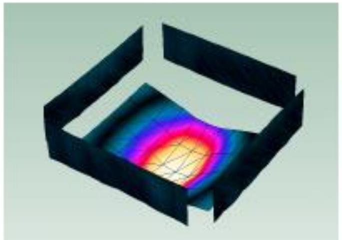
EMA of a TVE mockup

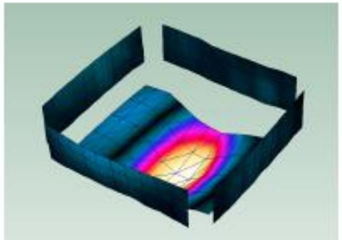

(a) 1st mode shape.

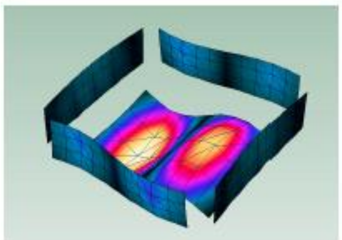

(b) 2nd mode shape.

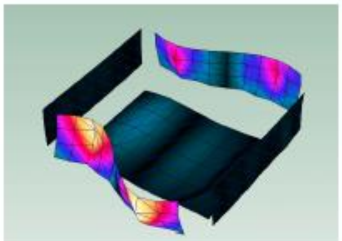

(c) 3rd mode shape.

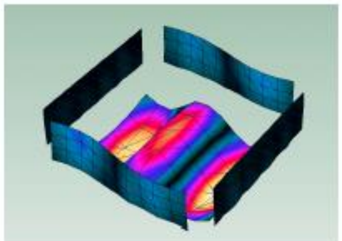

(d) 4th mode shape.


(e) 5th mode shape.


(f) 6th mode shape.


(g) 7th mode shape.


(h) 8th mode shape.


(i) 9th mode shape.

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!

juan.negreira@construction.lth.se

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