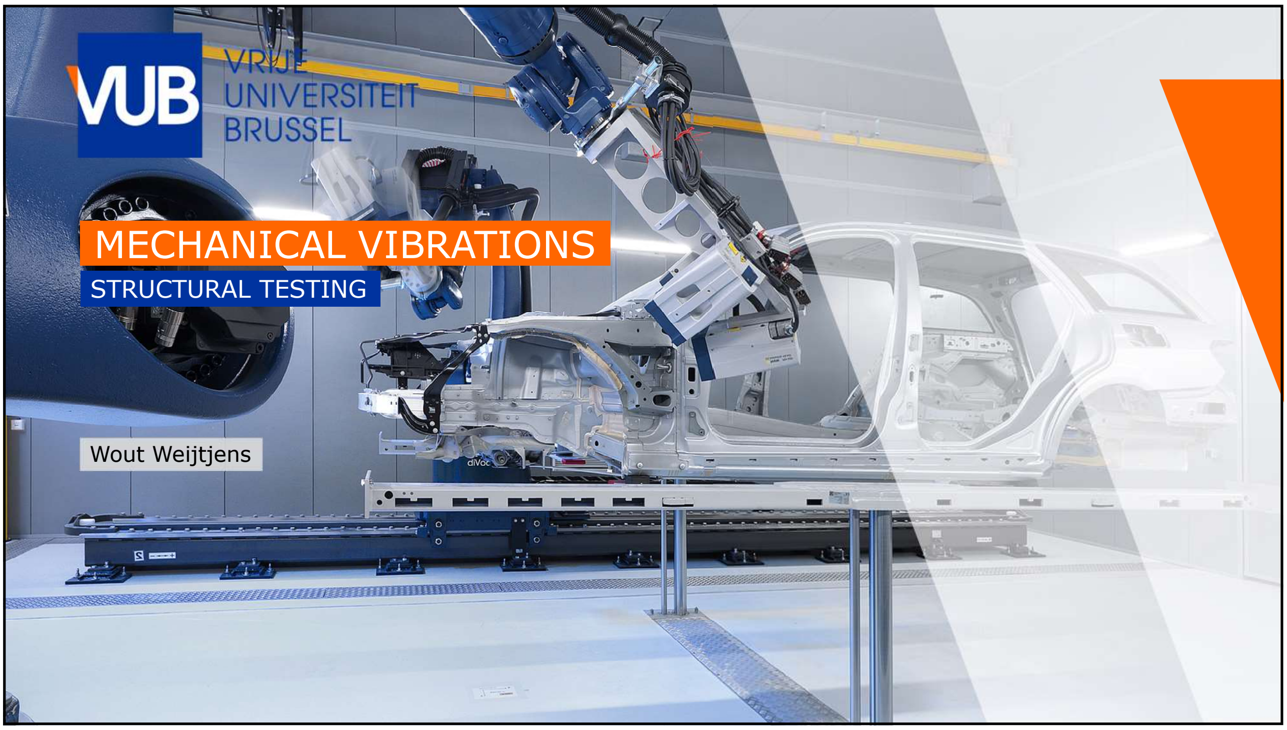


MECHANICAL VIBRATIONS
STRUCTURAL TESTING

Wout Weijtjens

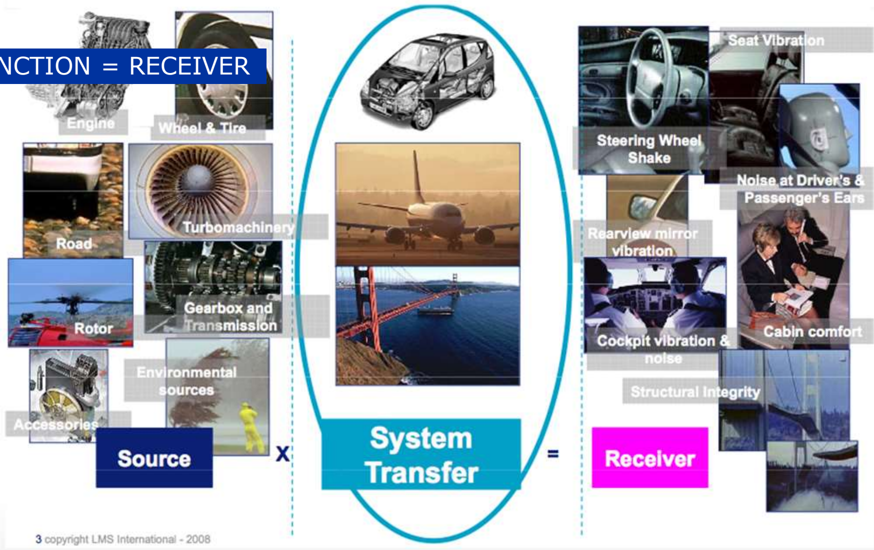
1

BASIC MODEL
SOURCE X TRANSFER FUNCTION = RECEIVER

Any noise or vibration perceived by the receiver is the product of a Source passing a System.

Want to increase passenger comfort?

Either you remove the source, or you optimise the transfer : **System analysis**



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3

BASIC MODEL

SOURCE X TRANSFER FUNCTION = RECEIVER

Known force

$\vec{F}(\omega)$

X

Transfer function

H (ω)

The big unknown

=

Recorded response

$\vec{X}(\omega)$

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MODAL TESTING

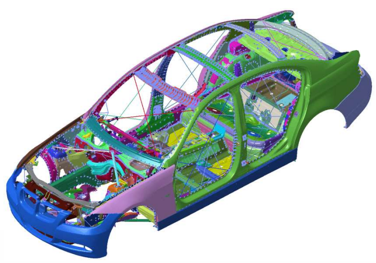
WHY?

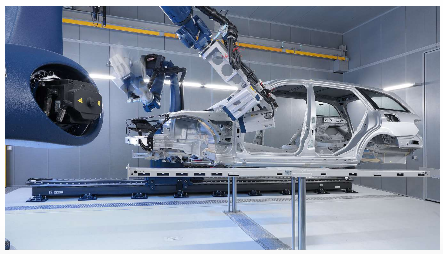
In many applications we can rely on high fidelity FE models, to design our structures.

We can compute the transfer function ahead of fabrication.
Don't we know the transfer function computationaly?

But FE models are never perfect so we need:

- **Model validation**: Proofing that what was assumed in design holds in the real world
- **Model updating**: feeding back real world data back into the FE code to improve it





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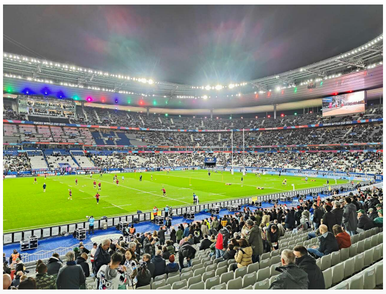
MODAL TESTING

WHY?

In many applications we can rely on high fidelity FE models, to design our structures.

In other applications, we might never have had a high fidelity FE model to begin with.

Or at least not with **Dynamics** in mind!



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So how can we **experimentally** determine the transfer function of a real world structure?

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MODAL TESTING
TOPICS TODAY

What is Experimental modal analysis **(EMA)**?

Design of experiment:

- Setting up the specimen of interest
- Strategy : roving input or output?
- Required hardware:
  - Response measurements
  - Controlled excitations

Objective: to collect all required data to experimentally determine the transfer function.

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EXPERIMENTAL MODAL ANALSYIS
GETTING THE MODAL PARAMETERS FROM MEASUREMENTS

- The main objective of Experimental Modal Analysis is to **Experimentally determine transfer function of the system of interest**
- Often this extended to determine the **modal parameters** from the collected measurements
  - Resonance frequencies and damping values of the observed modes
  - Mode shapes of the modes of interest

$$F(\omega) \times H(\omega) = X(\omega)$$

To do so: **Experimental modal analysis will measure the response X(ω) to a controlled/measured input force F(ω)**

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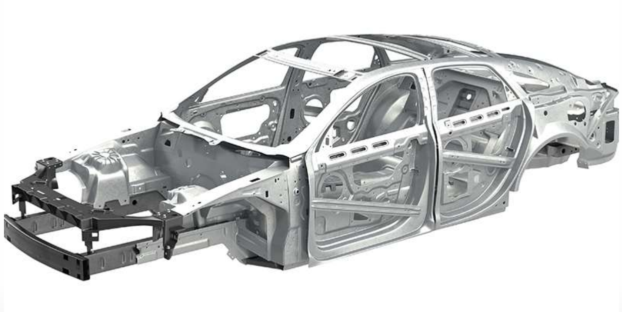
DESIGNING A MODAL TEST

THE PERFECT SETUP

How would we define the best setup?
Well ideally the modal test setup should not alter the structural dynamics of interest.



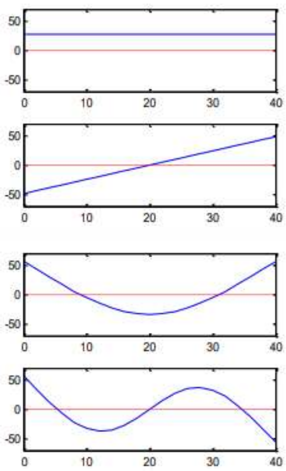
DESIGNING A MODAL TEST

THE IDEAL TEST

Consider our structure is a simple beam *floating in space*

The modes of this system are

- The 6 Rigid body modes (X,Y,Z, Yaw, Roll, Pitch)
- The structural dynamics modes (a.k.a. flexible modes)
  - Infinite number
  - These are of interest



DESIGNING A MODAL TEST

THE IDEAL TEST

Off course we can not have our specimen floating in space, it has to be mounted in a way.

The way the item is suspended will have an impact on the dynamic behavior.

The more rigid, the more the test setup becomes a 'boundary condition'

Preference for a 'Free-Free' setup, as close as possible to 'floating in space'

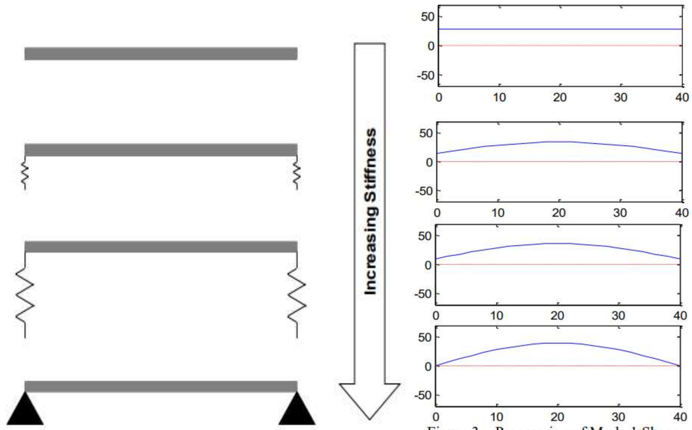


Figure 3 – Progression of Mode 1 Shape

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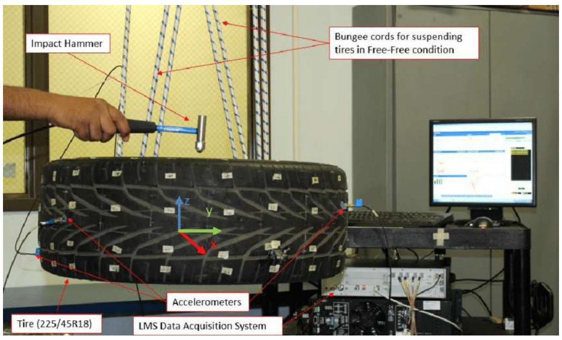
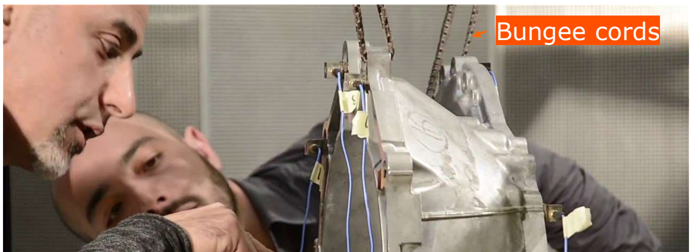
DESIGNING A MODAL TEST

FREE FREE SETUP





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DESIGNING A MODAL TEST

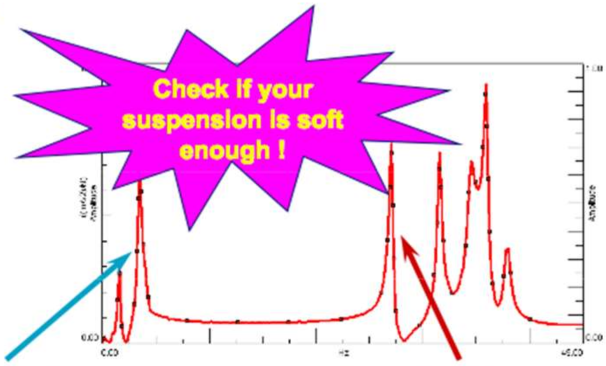
FREE FREE SETUP

Typically (almost) achieved using

- Soft springs, elastic cord, long flexible suspension
- Soft cushion to support structure

Rule of thumb :

- Rigid body modes should be well seperated from flexible modes



Rigid body mode frequency < 10 % of first flexible mode

STRATEGIES TO MODAL TESTING

TRANSFER FUNCTION

The transfer function **H(ω)** is 2 Dimensional. For an N-DOF system its dimensions are N x N.

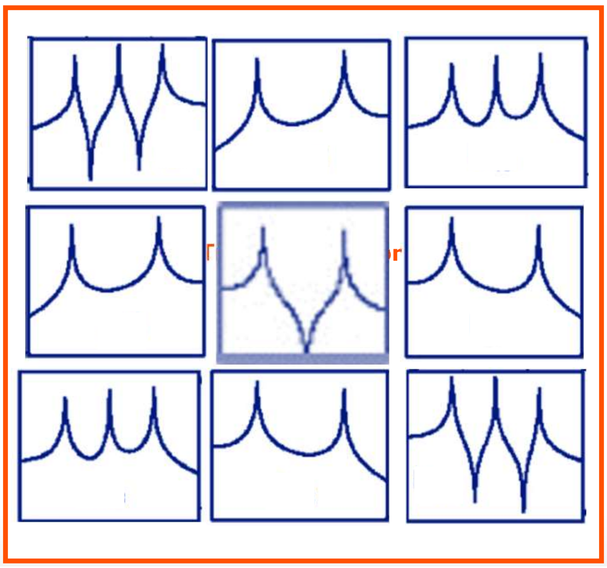
i.e. there is a transfer function between each input and each output location

But we don't have to measure all N² transfer functions because of the **reciprocity of the system,** i.e. the transfer function is symmetric

$$H_{ij}(\omega) = H_{ji}(\omega)$$

It is sufficient to measure an all elements in single row *i* or to measure all elements in a single *j*.

Yes, also those on the other rows and columns



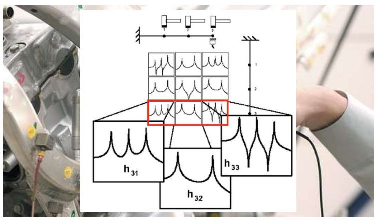
STRATEGY
ROVING INPUT / FIXED INPUT

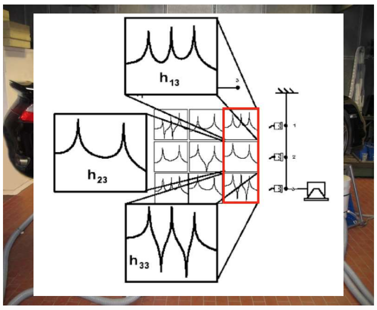
Roving input :

- vary input location, have fixed output locations
- Modal hammer approach

Fixed input :

- Have fixed input location, typically a shaker
- Consider multiple output locations:
  - Multiple accelerometers
  - Laser Doppler Vibrometer (LDV)
  - *Image based techniques (e.g. Digital image correlation)*





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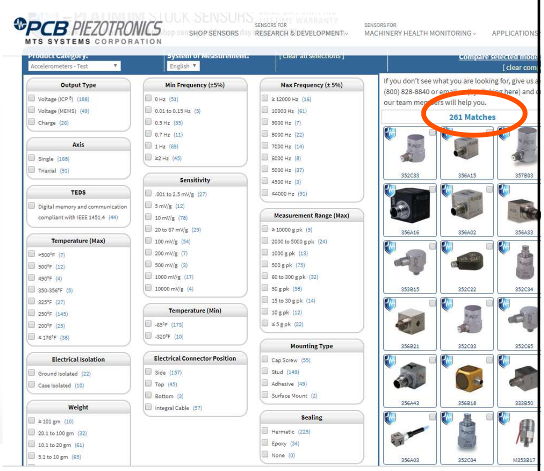
OUTPUT MEASUREMENTS
ACCELEROMETER

- Three most common technologies available
  - MEMS : more widespread technology, also in e.g. phones
  - Piëzo – electric (ICP) : typical for lab experiments
  - *Force balance : Very sensitive, but bulky and expensive typical for civil applications*
- General specifications to consider :**Does it match my application?**
  - Frequency band : Does it match my application
    - For ICP *Rule-of-Thumb* the bigger the sensor the better its performance at lower frequency bands
    - MEMS can go to 0Hz, thus can measure gravity, from tri-axial you can determine orientation
  - Tri-axial or not?
  - Sensitivity and/or Signal to Noise ratio



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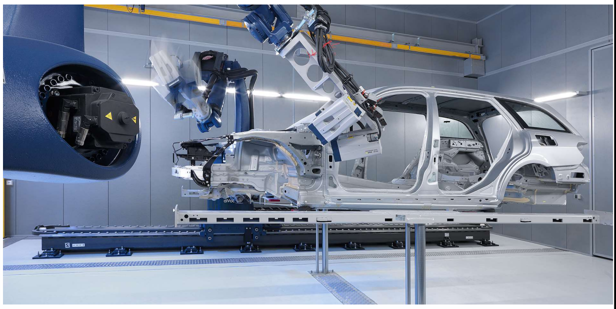
OUTPUT MEASUREMENTS

LASER DOPPLER VIBROMETER

- Alternative to the accelerometer, does not introduce added mass
- Measures vibration based on the Doppler effect
- Can be used as a roving output measurements by pointing the laser at different points on the structure
  - Fixed Input – Roving Output



INPUT MEASUREMENTS (F)

ROVING INPUT : IMPULSE HAMMER

- Modal or impulse hammer is a instrumented hammer
- Typically relies on Piëzo-electric technology
- Limited hardware required
  - 1 Hammer & 1 accelerometer (more is possible)
- Flexible, suitable for many applications
  - Different sizes
  - Different heads
- Some ‘handiness’ required to avoid *Double impacts*
  - *But on the other hand is that really an issue?*

Large number of points, fast assessment

INPUT MEASUREMENTS (F)

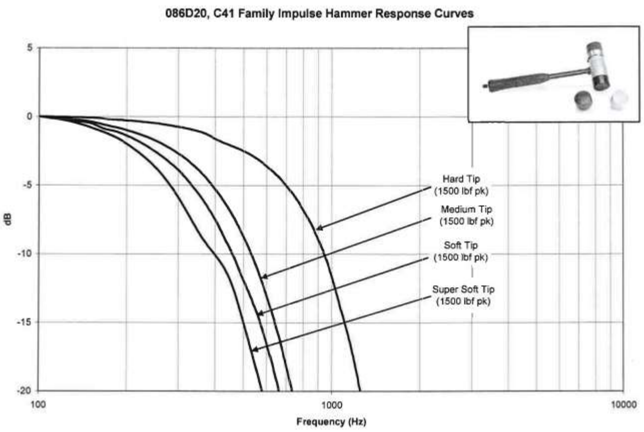
IMPULSE HAMMER : DIFFERENT HEADS

Different materials of the head allow to have different frequency spectra to excite

The softer the head, the longer the impact duration and smaller the bandwidth of the excitation.

Why?

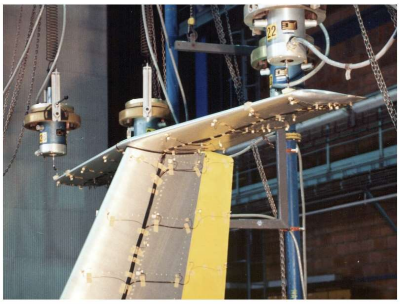
- More energy in the band of interest
- Avoid issues, i.e. non-linearities at higher frequencies



INPUT MEASUREMENTS (F)

SHAKER

- Typically electrodynamic shaker (can be hydraulic for demanding sizes)
- More controlled input excitation, deterministic. Can basically be any signal that you like (**and we will get back to this!**)
- Setup consists out of one or more shakers, and then as many output measurements as you like.
- Can be done at different sizes, but you can imagine the cost



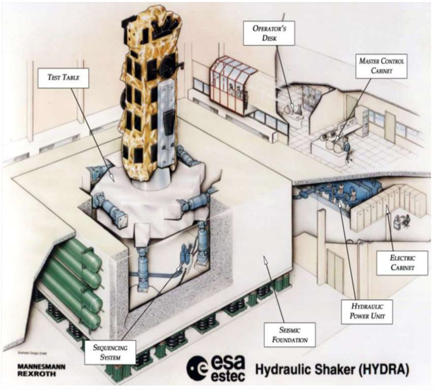
INPUT MEASUREMENTS (F)

SHAKER : IN EVERY SIZE

Example the HYDRA

ESA (ESTEC)

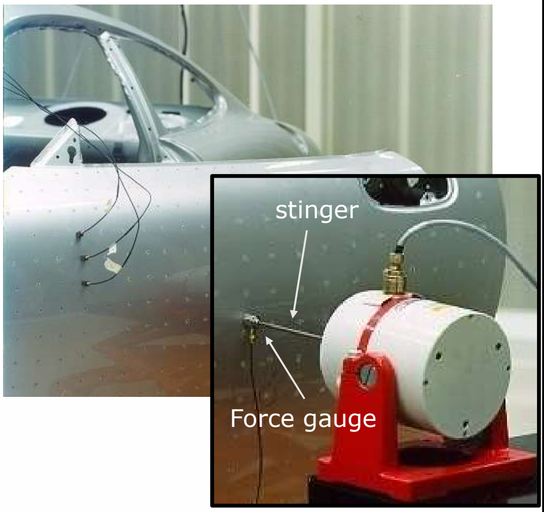
A 6DOF shake table



INPUT MEASUREMENTS (F)

SHAKER

- The shaker is connected to the structure using a slender rod, so-called ‘stinger’
  - Ensure that the excitation is only along the shaker excitation direction
    - High axial stiffness
    - Low transvers and bending stiffness
- Actual force measured using force gauge/cell
- Multiple shakers can be used
  - Energy distribution over (larger) structures
  - 3D – excitation in X,Y,Z direction
  - Multi-reference measurements



INPUT MEASUREMENTS (F)

MODAL HAMMER OR SHAKER

Hammer

- Low cost : hammer + 1 accelerometer
- No physical connection = no dynamic interaction
- Only single accelerometer adding mass
- Only impact /impulse inputs
- Short setup time, experiment time proportional to the number of locations
- Poor for non-linear structures

Shaker

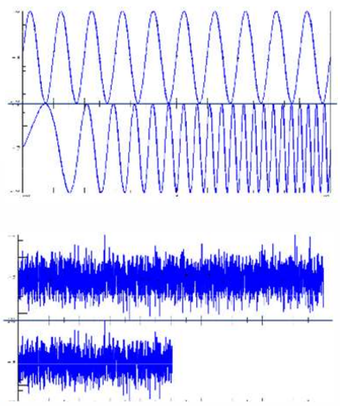
- High cost : expensive shaker + multiple sensors
- Shaker is connected to the system, can influence dynamics.
- Added mass effect of the large number of accelerometers
- Controlled input, can be designed for optimal properties. Improved repeatability and Signal to Noise ratio
- Longer setup time, shorter experiment time. Once installed bigger range of tests
- Can be used for non-linear structures

SETTING UP THE SHAKER

CHOOSING INPUT SIGNAL FOR THE SHAKER

Typical input signals for shakers are :

- Normal mode excitation : single frequency sine at resonance frequencies
- Stepped or swept sine : sine-wave with varying frequency over time
- Random : i.e. *white* noise
- Burst random : i.e. *white* noise but limited in time



CHOOSING INPUT SIGNAL FOR THE SHAKER

NORMAL MODE

Excite the structure with single sine at resonance frequency, with *tuned* input force combination (typically with several shakers), to have a single mode in resonance.

Oldest method, very accurate but very time-consuming

Get a physical *feel* of the mode

All energy of the shakers goes into a single mode of vibration

Still preferred method in **Ground vibration testing** of aircraft

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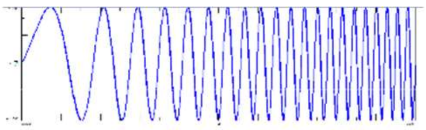
CHOOSING INPUT SIGNAL FOR THE SHAKER

SWEPT SINE



A swept sine (or chirp) is a sine with a continuously varying frequency, it contains all frequencies. A stepped sine is similar, but has discrete frequencies, preferably matching the frequency lines of the final spectrum.

- Still sinusoidal -> All energy in a single frequency at a time, resulting in a better S/N ratio
- Covers entire frequency range -> single test compared to multiple tests in normal mode
- Very controlled signal (known properties) -> Useful to quantify to non-linear behaviour
- Periodical signal -> can be designed to minimize leakage

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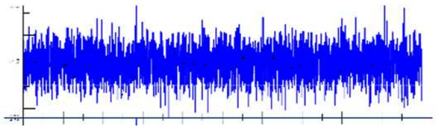
CHOOSING INPUT SIGNAL FOR THE SHAKER
RANDOM

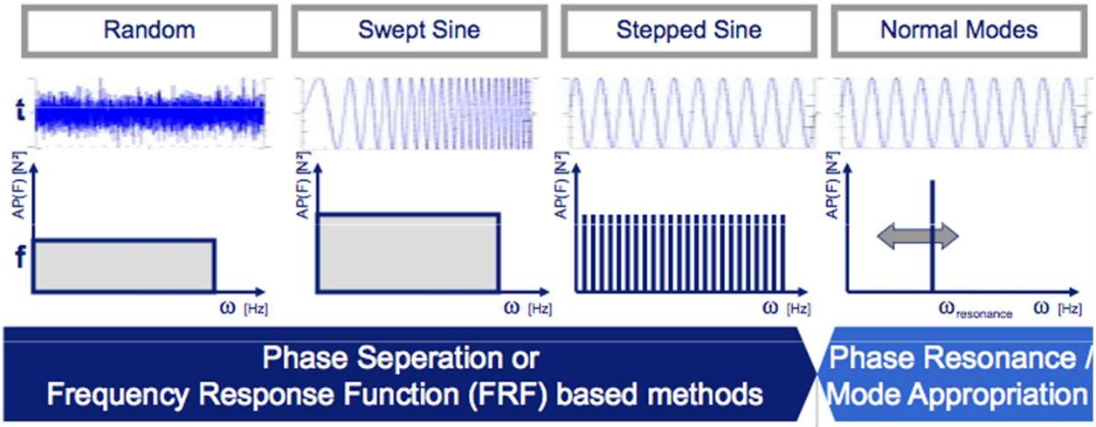


Random noise is a 'white noise' signal and thus covers all frequencies at the same time

- Most 'natural' excitation
- All at once, fast but implies lower energy in each frequency. Might not be sufficient for heavy test subjects.

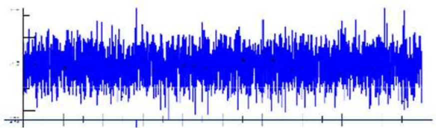
But… inherently implies leakage.

CHOOSING INPUT SIGNAL FOR THE SHAKER
SPECTRAL CONTENT



CHOOSING INPUT SIGNAL FOR THE SHAKER

RANDOM



Random noise is a 'white noise' signal and thus covers all frequencies at the same time

- Most 'natural' excitation
- All at once, fast but implies lower energy in each frequency. Might not be sufficient for heavy test subjects.

But… inherently implies leakage.

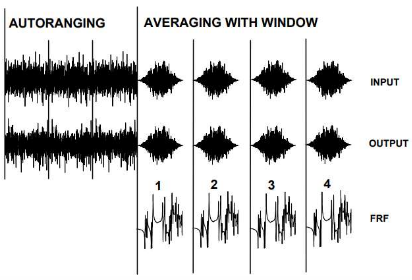
CHOOSING INPUT SIGNAL FOR THE SHAKER

RANDOM

Using Random implies the need for a window as there is no guarantee that the signal at the windows outer edges are continuous.

Typically the **Hanning** window is applied to both input and output.

Hanning window inherently distorts the signal, the effect is irreversible!

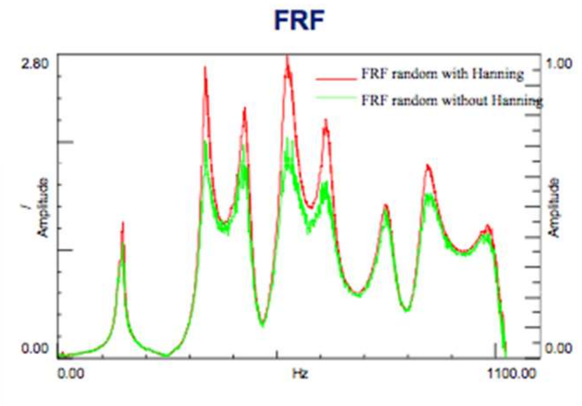


CHOOSING INPUT SIGNAL FOR THE SHAKER

RANDOM

Comparison of random with and without Hanning window after **40 averages**.

Applying the Hanning window reduces leakage and results in a better representation of the actual system.



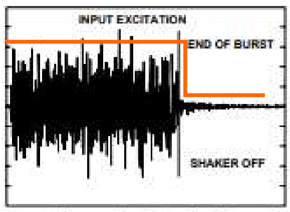
CHOOSING INPUT SIGNAL FOR THE SHAKER

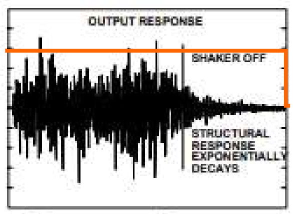
BURST RANDOM

Idea : random signal of limited duration (e.g. 50% of measurement duration)

Allow for signal to decay after burst, natural anti-leakage prevention. But sacrifices S/N ratio

Apply rectangular windows. Limited effect on signal.





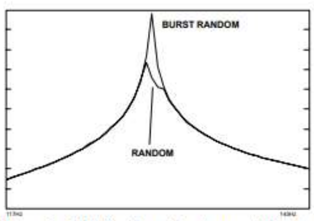


Figure 6 - FRF for Burst Random and Random

CHOOSING INPUT SIGNAL FOR THE SHAKER

CONCLUSION

So which signal do we choose? Best to play to the strengths of using a shaker

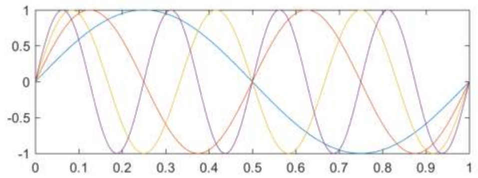
- Easy to repeat experiment
  - Large number of averages is not an issue
- Freedom to choose an optimal signal
  - Replicate real world conditions (when relevant)
  - Avoid leakage, rather than mitigate with windows
- Target energy where we want it to be
  - Heavy structure : swept/stepped sine or normal mode

But maybe none of the aforementioned ones!

CHOOSING INPUT SIGNAL FOR THE SHAKER

EPILOGUE

What if we can engineer a signal that is like random but without leakage!



Summing up sines that are perfectly adjusted to the measurement window.

> No leakage!

CHOOSING INPUT SIGNAL FOR THE SHAKER

MULTISINE

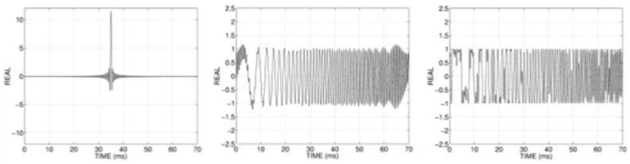
The main variables in the composition of multisines are the **amplitude** and the **phase** of each additional sine.

Signals can be engineered to optimize desired properties.

In the examples to the right this is CF : the Crest Factor.

$$\text{multisine} = \sum_{k=1}^{F} A_k \cos(k\omega_1 \cdot t + \phi_k)$$

$$CF = \frac{PEAK}{RMS}$$



- **Zero phase**
  - CF = 16
- **Schroeder phase**
  - CF = 1.70
- **L-infinity algorithm**
  - CF = 1.40

$\phi_k = 0$

$\phi_k = -\frac{\pi k(k-1)}{F}$

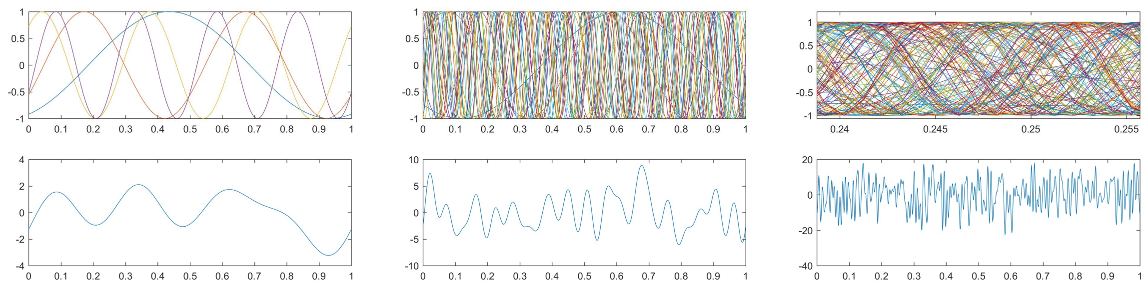
$F = 128, A_k$ = constant

CHOOSING INPUT SIGNAL FOR THE SHAKER

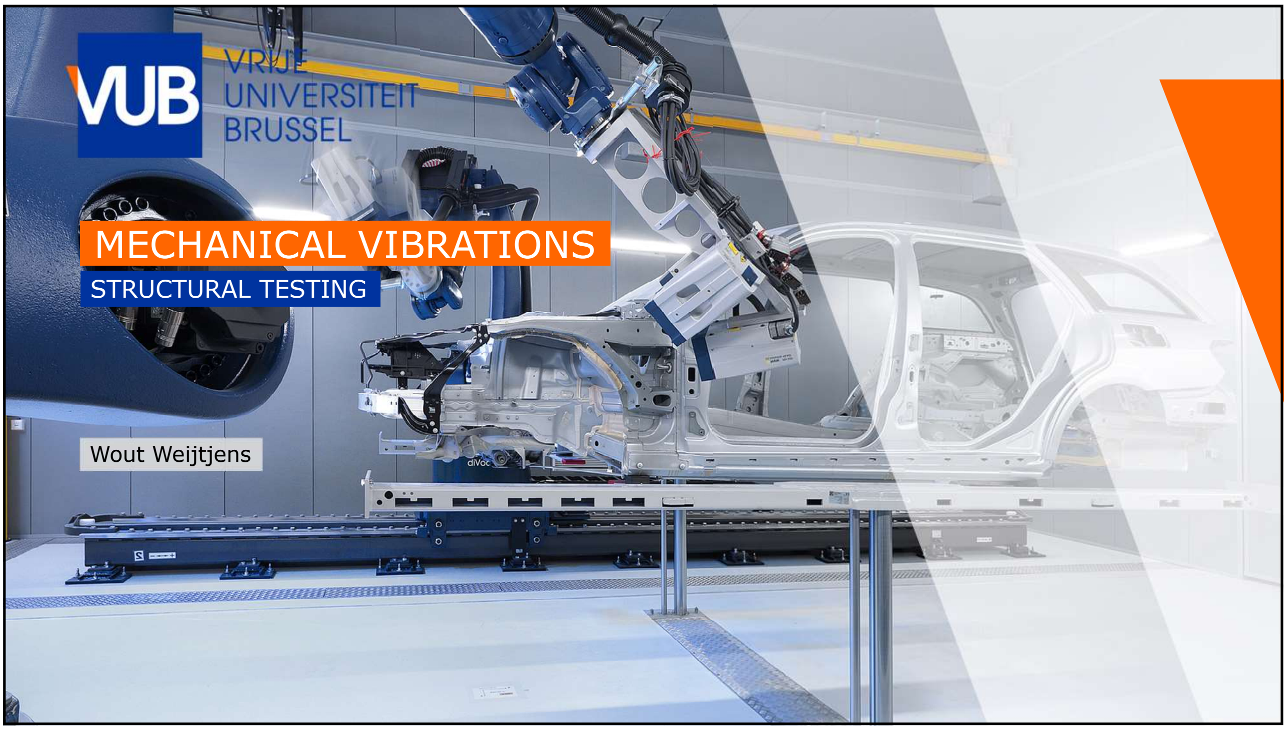
MULTISINE

Example using constant amplitude A_k random phase φ_k

F= 4 F= 20 F= 128



Note Zoomed x-scale top figure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