Modal Shakers and Accessories

that makes Modal Testing more accurate and
easier to setup

Host : Robert Trépanier, eng.

Please mute your telephone microphone during the presentation if you do not have to ask questions. This will keep the background noise down and help a lot during the presentation.

The attached modal excitation solution

Complete Program!

- Competitively priced
- Full range (5) of dedicated modal exciters
- Full program of stingers
- Two robust exciter stands
- Complete range of modal impact hammers

Superior Performance!

- Proven, **durable** design
- Proven **highest force-to-weight** ratio
- Faster and more **productive** test
- Improve **reliability** and **consistency** of mobility measurements
- **Safe** and **easy** operation with maximum **protection** of equipment, test structure and test engineers

One-Stop-Shop

Aiming to provide our customers with the industry's best and most complete tools for modal testing

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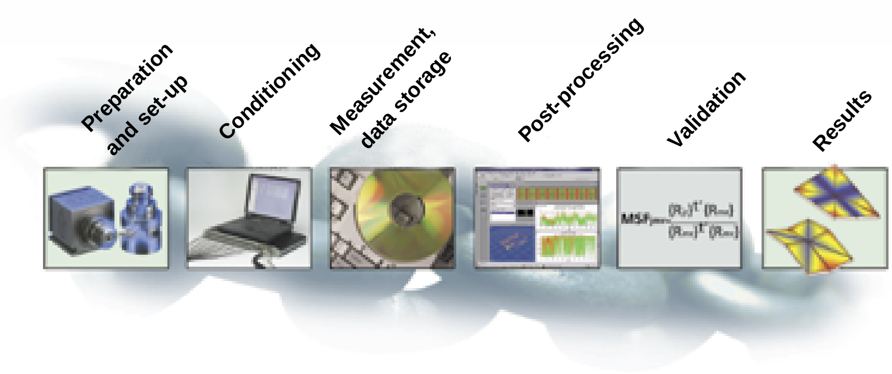
Role of the transducer in the measurement chain



No chain is stronger than it's weakest link!

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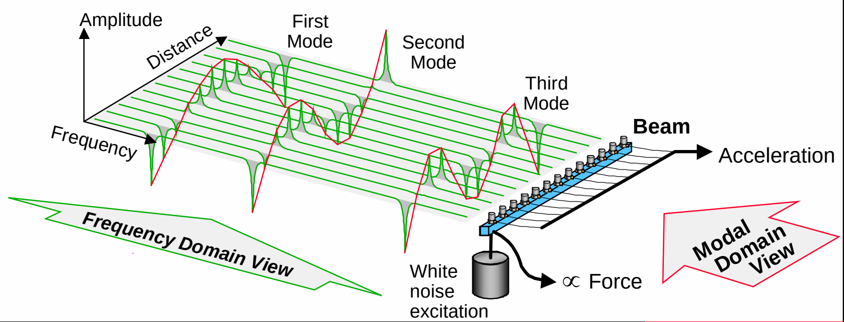
In theory modal testing is straight forward …..

Shaker method:

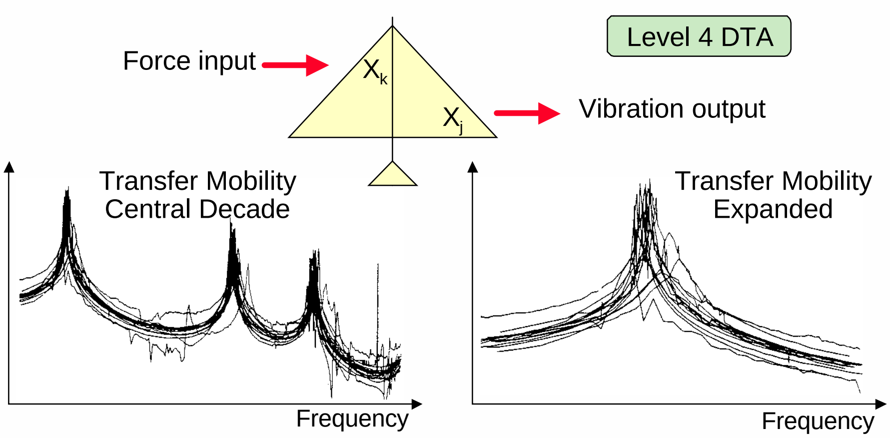
- *Excitation* of the structure at *one point* by shaker with force transducer
- *Response* measured at *a number of points*

- FRF's between excitation point and measurement points calculated
- Modes of structure identified



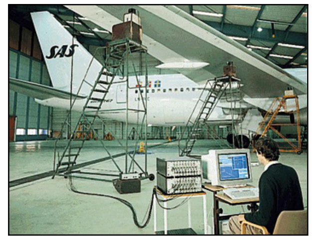
…but in practice, accuracy is difficult to achieve

A state-of-the Art Assessment of Mobility Measurement Techniques
Repeatability results for a Round Robin Test (30 - 3000 Hz) 1981

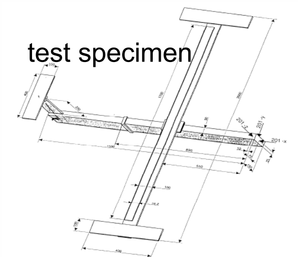


GARTEUR "Round Robin" Test: Level 4 DTA

- Under the auspices of Group for Aeronautical Research and Technology in Europe (GARTEUR): Twelve experienced GVT units from all of Europe performed modal test of the same test specimen (ref. NLR TP 97086U, 1996)
- Results in terms of **repeatability**
  - Damping ratio: ~ 30%
  - Modal frequencies: ~ 4%
- Results in terms of generalized mass **repeatability**:
  - Flutter prediction accuracy: ~ 13%



test specimen



Purpose of the new modal exciters

- Higher force measurement, **accuracy** and **precision**
- Faster and more **productive** test
- Improve **reliability** and **consistency** of mobility measurements
- **Safe** and **easy** operation with maximum **protection** of equipment, test structure and test engineers

and…….

maintain or improve legendary quality and longevity of Brüel & Kjær exciters and power amplifiers

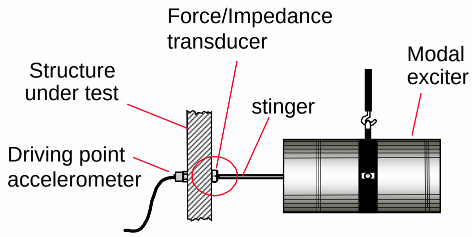
- One stop shopping -

Aiming to provide our customers with the industry's best and most complete tools for modal testing

Achieving **high quality** FRFs: input aspects

- **Minimizing Exciter/Test Structure Interaction**
  - *Solution: Low weight magnesium armature!*
- **Obtaining Valid Force Measurements**
  - *Solution: Stinger with lowest possible bending stiffness!*
- **Distributing and Minimizing Dynamic Force Levels**
  - *Solution: Flexible and versatile set-up!*
- **Exciter ability to "survive" large side loads**
  - *Solution: Rugged construction with 2 x 4 springs!*

- **Choosing Best Exciter Location**
  - *Solution: Low total weight of exciter and trunnion!*
- **Low Frequency Modal Test Performance**
  - *Solution: Highest possible peak-to-peak displacement!*



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Means of implementing excitation

- Standard Methods
  - Attached: Electromagnetic exciter
  - Non-attached: Instrumented impact hammer

- Non-standard Methods
  - Electrohydraulic exciters
  - Eccentric rotating masses
  - Drop hammers
  - Pendulum impactors
  - Suspended cables
  - Rockets
  - Jet engines
  - Acoustic excitation (unscaled mode shapes)

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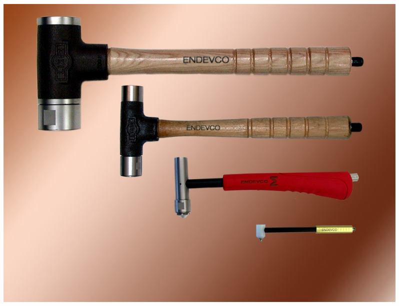
Impact Hammer Excitation



- Conclusion
  - Use for poor man’s modal
  - Best suited for field work
  - Useful for determining shaker and support locations

- Advantages:
  - Speed
  - No fixturing
  - No variable mass loading
  - Portable and highly suitable for field work
  - relatively inexpensive

- Disadvantages
  - High crest factor means possibility of driving structure into non-linear behavior
  - Tip Performance is often overlooked
  - Not good for very large structures
  - Repeatable hammer strikes require ‘calibrated elbow’

Shaker Excitation

- Conclusion
  - Best suited for lab work
  - Good on very light, very large, and difficult objects
  - Tests requiring high degree of repeatability

- Advantages:
  - Repeatable due to electronic control
  - Wide range of excitations
  - Can excite very small thru very large structures
  - More automated test

- Disadvantages
  - More equipment required than hammer
  - Skilled operators necessary to supervise test
  - A lot of setup time required
  - Shaker issues such as: stingers, mounting of shaker, proper shaker selection

Permanent magnet modal exciters

- Type 4824/3624
  - Force rating: **100N** (sine)
  - Frequency range: DC - 5000 Hz
  - Max. rated travel: **25.4 mm (1”)**
  - Armature effective mass: **0.23kg**
  - Weight with trunnion: **21 kg**
  - Power Amplifier Type 2732
  - DC Static Centering Unit optional

4824.pdf

- Type 4825/3625
  - Force rating: **200N** (sine)
  - Frequency range: DC - 5000 Hz
  - Max. rated travel: **25.4 mm (1”)**
  - Armature effective mass: **0.23 kg**
  - Weight with trunnion: **21 kg**
  - Power Amplifier Type 2720
  - DC Static Centering Unit optional

4825_4826.pdf

- Type 4826/3626
  - Force rating: **400N** (sine)
  - Frequency range: DC - 5000 Hz
  - Max. rated travel: **25.4 mm (1”)**
  - Armature effective mass: **0.40 kg**
  - Weight with trunnion: **21 kg**
  - Power Amplifier Type 2721
  - DC Static Centering Unit optional

4825_4826.pdf

Electromagnet modal exciters

- Type 4827/3627
  - Force rating: **650N** (sine)
  - Frequency range: DC - 5000 Hz
  - Max. rated travel: **50.8 mm (2”)**
  - Weight with trunnion: 80 kg
  - Power Amplifier Type 2721
  - DC Static Centering Unit needed
  - Field Power Supply needed
- Type 4828/3628
  - Force rating: **1000N** (sine)
  - Frequency range: DC - 5000 Hz
  - Max. rated travel: **50.8 mm (2”)**
  - Weight with trunnion: 80 kg
  - Power Amplifier Type 2721
  - DC Static Centering Unit needed
  - Field Power Supply needed

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Power amplifiers

- **Type 2732**
  - Drives Type 4824 to full 100N force rating
  - 120 VA output capacity
  - Extensive protective features
  - Voltage and current mode
- **Type 2720**
  - Drives Type 4825 to full 200N force rating
  - 500 VA output capacity
  - Extensive protective features
  - Voltage and current mode
- **Type 2721**
  - Drives Type 4826, 4827 and 4828 to full force ratings
  - 1250 VA output capacity
  - Extensive protective features
  - Voltage and current mode

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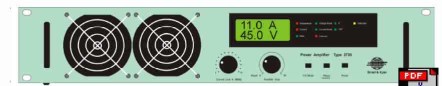

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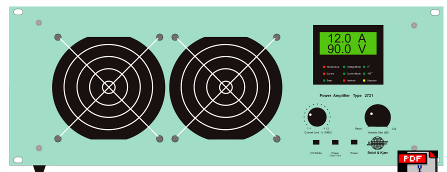

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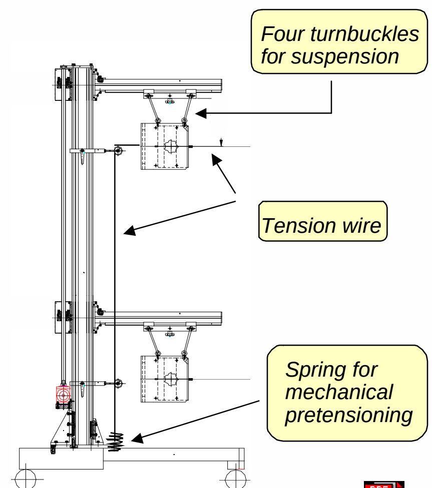
Lateral modal exciter stands

- **Two rugged stands for easy lateral exciter suspension: height 1.4 meters and 2.0 meters**
- **Exciter with trunnion is suspended from arm using four turnbuckles**
- **Inertia masses may be added to trunnion to increase reaction force**
- **Tension wire or push/pull stinger**
  - Spring for mechanical pre-tensioning and turnbuckle for adjustment comes as standard accessory (used only with tension wire stinger)
- **Heavy-duty wheels for maximum mobility and ease of set-up**
  - Wheels can be locked during excitation
  - Base with through holes for ease of permanent installation
- **Exciter is positioned by means of spindle (vertically) and displaced back and forth on arm (horizontally)**



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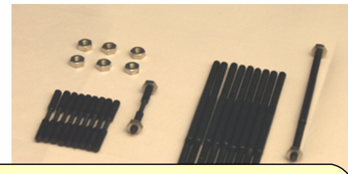
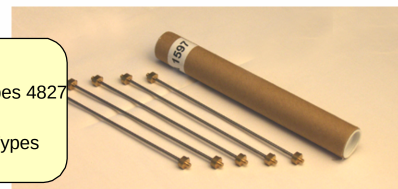
Stingers and adaptors: Push/pull

- Flexible length (500 mm max)
- Large diameter (**UA 1599**), ideal for Types 4827 and 4828
- Medium diameter (**UA 1598**), ideal for Types 4824, 4825 and 4826

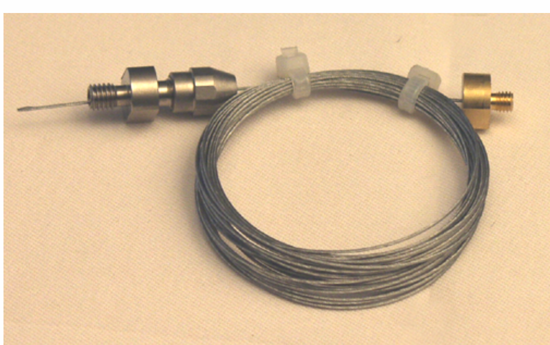


- Fixed length (120 mm)
- Set of 20 nylon stingers (**WZ 0066**), works with Types 4824, 4825, 4826, 4827 and 4828
- Compromise between max. transferable force, weight and bending stiffness. Low weight and good mechanical fuse but low forces can be transferred

- Fixed length (200 mm)
- Large diameter (**UA 1597**), ideal for Types 4827 and 4828
- Medium diameter (**UA 1596**), ideal for Types 4824, 4825 and 4826

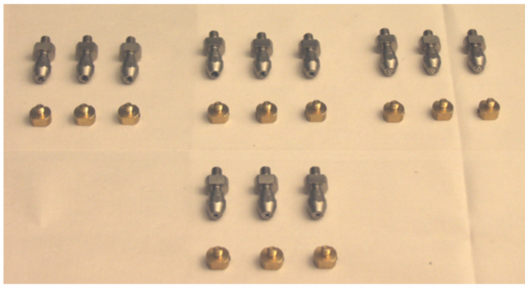


Stingers and adaptors: tension (piano) wire

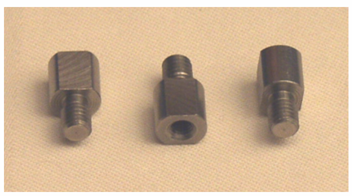


- Type number **UA 1600.** Spool Length 5000 mm
- Best accuracy and precision: Low weight, almost zero bending stiffness!
- Any length possible during test, but the shorter the length, the higher excitation frequency is possible
- Easy alignment during set-up
- Needs pre-tensioning
- Can not transfer as high force as push/pull stingers
- Frequency range 0 Hz to approximately 400 Hz

Stingers and adaptors: thread adaptors



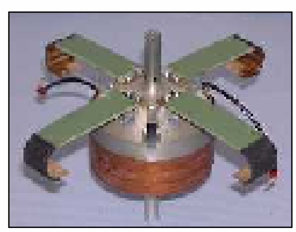
- Four sets of collet chucks and adaptors for four different stinger diameters.
- Each set contains three collet chucks and three adaptors.
- Type numbers: **UA1602**, **UA1603**, **UA1604**, **UA1605**
- Use as spare parts or for attachment of custom made stingers



Types **UA1612** and **UA1614**: Three thread adaptors

Features, advantages and benefits

Attached energy source features required for a successful modal test



- High **force-to-weight** ratio **unique point!**
- High **force-to-price** ratio
- Wide **frequency** ranges
- Smaller types (armature suspended in springs) with full **1" peak-to-peak displacement** for best low frequency performance
- Larger types (armature guided in rolls and suspended with a static DC current from DC Static Centering Unit) with **2" peak-to-peak displacement** for best low frequency performance

Features, advantages and benefits

Attached energy source features required for a successful modal test

- Armature with **high rigidity** and **low mass**
- **Low total weight** of exciter allowing for easy positioning and orientation relative to test object
- Dedicated robust **lateral exciter stands** for easy positioning and orientation.
- All types prepared for attachment and pre-tensioning of **piano wire stinger** technology
- **Hole-through** design on Types 4824, 4825 and 4826 for mechanical pre-tensioning of piano wire stingers
- Complete line of **accessories**, incl. various stingers (push/pull and tension)

Customers, applications and key issues

Less experienced modal people who wish to upgrade their existing test systems (non-dedicated modal laboratories)

Experienced modal people within the aerospace & automotive industry (dedicated modal laboratories)

Customers

Very little modal experience.

broad range of industries

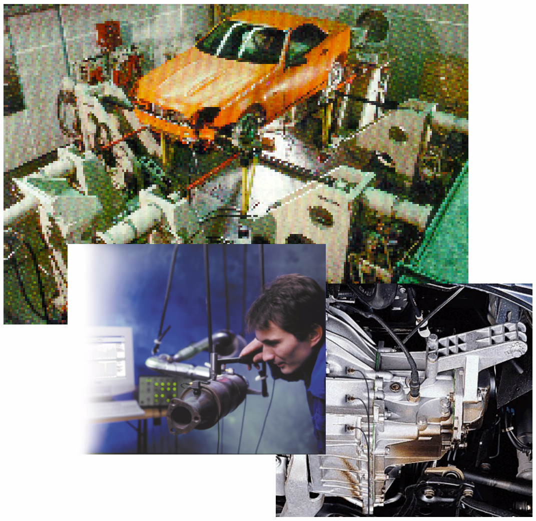
Applications:

- High accuracy and high precision modal test
- Static mass: Structures from 50 kg to 2000 kg (coarse estimate!)
- Dynamic mass: Structures from 0 kg to 200,000 kg (coarse estimate!)

Key issues:

- High force-to-weight ratio
- High force-to-price ratio
- Peak-to-peak displacement
- Long lived operation
- True one stop shopping with all accessories
- Dedicated and purposeful design

Applications: automotive



RDT&E
- Modal testing
- Components design
- Engine/exhaust testing
- NVH analysis

Applications: space and flight testing

Spacecraft development
- Structural testing
- Thermal cycling
- Components testing

Design & verification tests on launch vehicles/rockets
- Structural testing
- Shock testing
- Vibro-acoustic testing

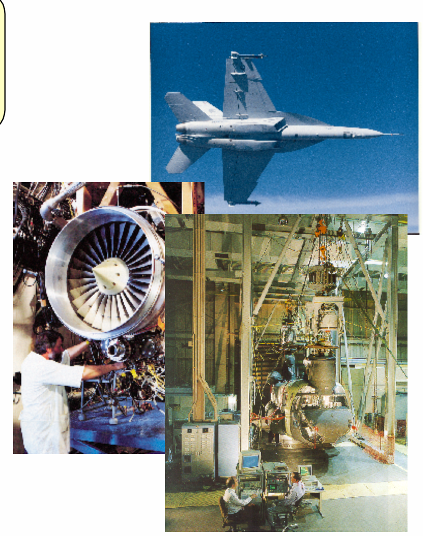
Rocket engines test & development
- Structural testing
- Failure analysis
- Vibration Testing at extreme temperature

Applications: space and flight testing

Aircraft Design & Manufacturing
- Structural analysis
- Landing gear testing
- Vibro-acoustic testing

Helicopter Design & Maintenance
- Structural analysis
- Engine/transmission testing
- NVH testing

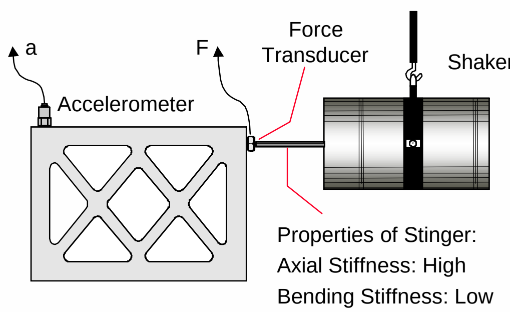
Gas Turbine Design & Testing
- Structural analysis
- Failure analysis
- Engine tuning
- Test cell maintenance
- Repair/Overhaul



Modal test set-up challenges

Accelerometer mounting:
- Stud
- Glue
- Wax
- (Magnet)

Force Transducer and Shaker:
- Stud
- Stinger (Connection Rod)



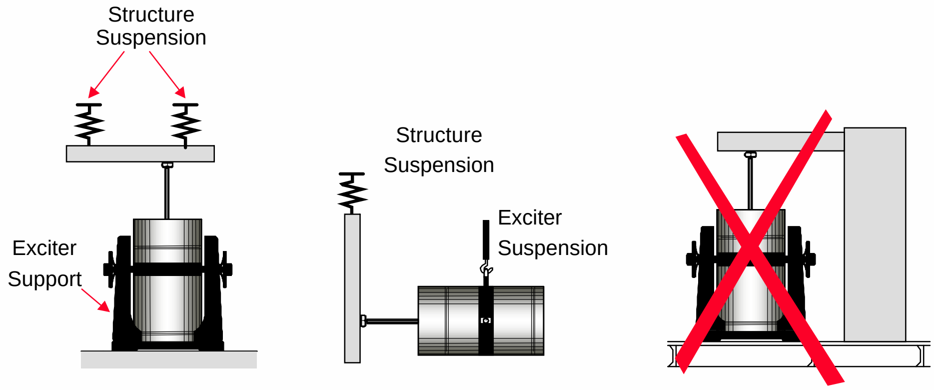
Advantages of Stinger:
- No Moment Excitation
- No Rotational Inertia Loading
- Protection of Shaker
- Protection of Transducer
- Helps positioning of Shaker

Modal test se-up challenges

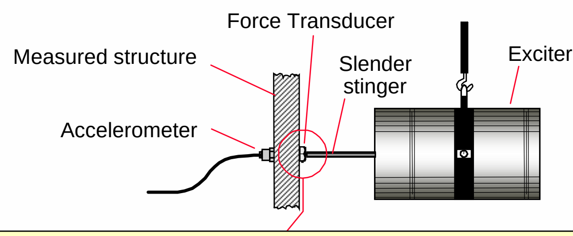
Reaction by external support

Reaction by exciter inertia

Example of an improper arrangement

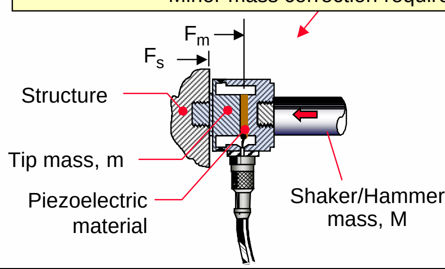


Modal test set-up challenges



Force and acceleration measurements unaffected by stinger compliance, but ...

Minor mass correction required to determine actual excitation



$$F_s = (m + M)\,a$$

$$F_m = M\,a$$

$$\boxed{F_s = F_m \frac{m + M}{M}}$$

Remedy: tests for validity of data

Coherence	$\gamma^2(f) = \frac{\lvert G_{FX}(f)\rvert^2}{G_{FF}(f)\,G_{XX}(f)}$
Linearity	$\left.\begin{array}{l} X_1 = H\cdot F_1 \\ X_2 = H\cdot F_2 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} X_1 + X_2 = H\cdot(F_1 + F_2) \\ a\cdot X_1 = H\cdot(a\cdot F_1) \end{array}\right.$
Reciprocity	$H_{ij}(f) = H_{ji}(f)$

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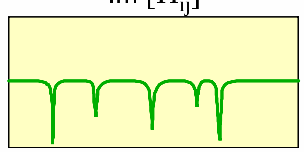
Remedy: check of driving point measurement

- All peaks in

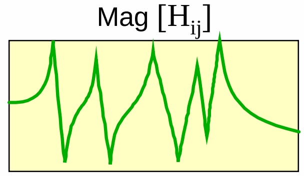
$$\mathrm{Im}\left[\frac{X(f)}{F(f)}\right], \mathrm{Re}\left[\frac{X(f)}{F(f)}\right] \text{ and } \mathrm{Im}\left[\frac{X(f)}{F(f)}\right]$$

Im $[H_{ij}]$



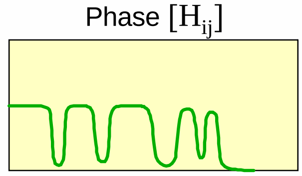
- An anti-resonance in Mag $[H_{ij}]$ must be found between every pair of resonances

Mag $[H_{ij}]$



- Phase fluctuations must be within 180°

Phase $[H_{ij}]$



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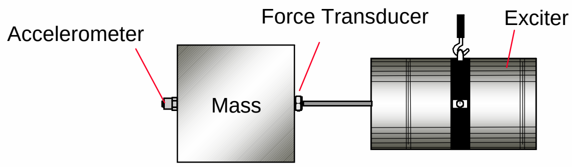
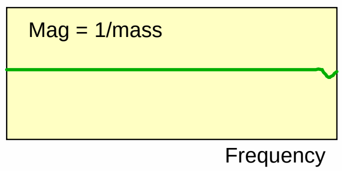
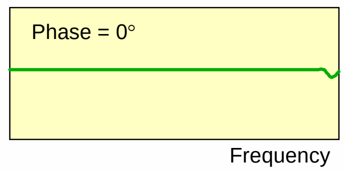
Remedy: Free Mass Calibration

$$A(f) = \frac{a(f)}{F(f)} = \frac{a(f)}{ma(f)} = \frac{1}{m}$$



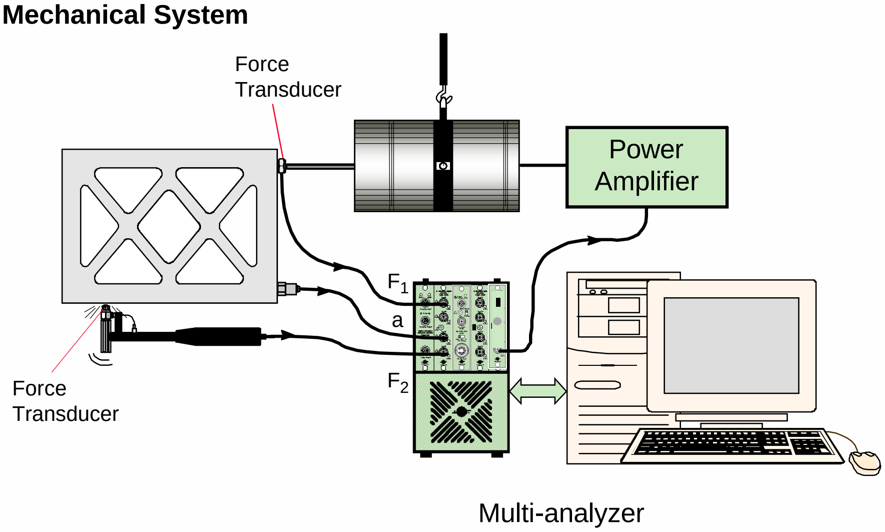
$$\mathrm{Mag}\left|\frac{a(f)}{F(f)}\right| \qquad \angle\frac{a(f)}{F(f)}$$



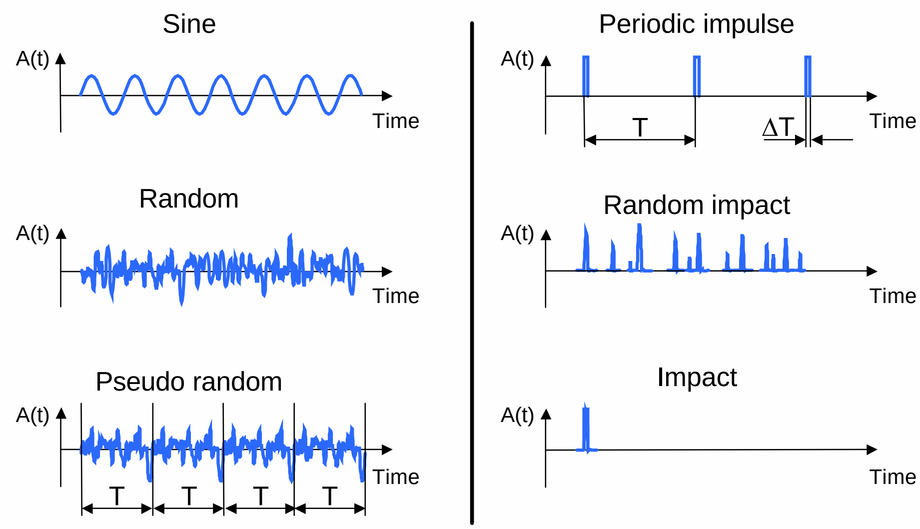


Basic measurement configuration

Mechanical System



Types of excitation signals



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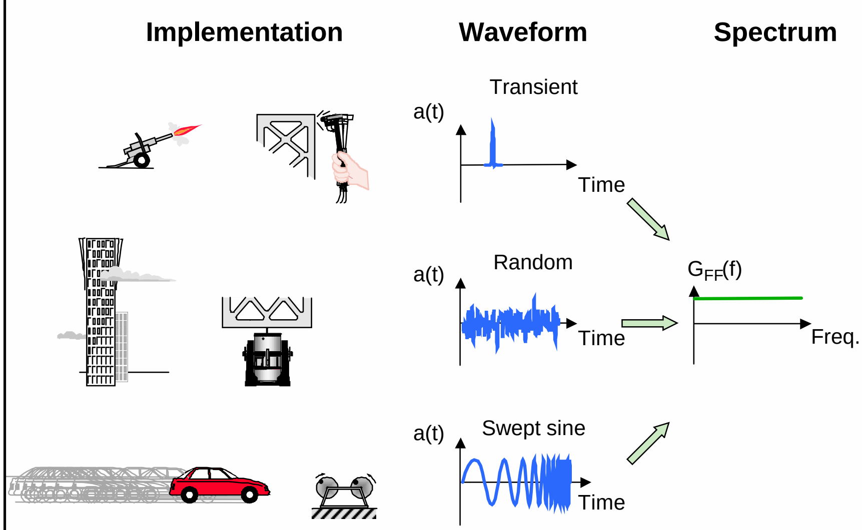
Broadband signals



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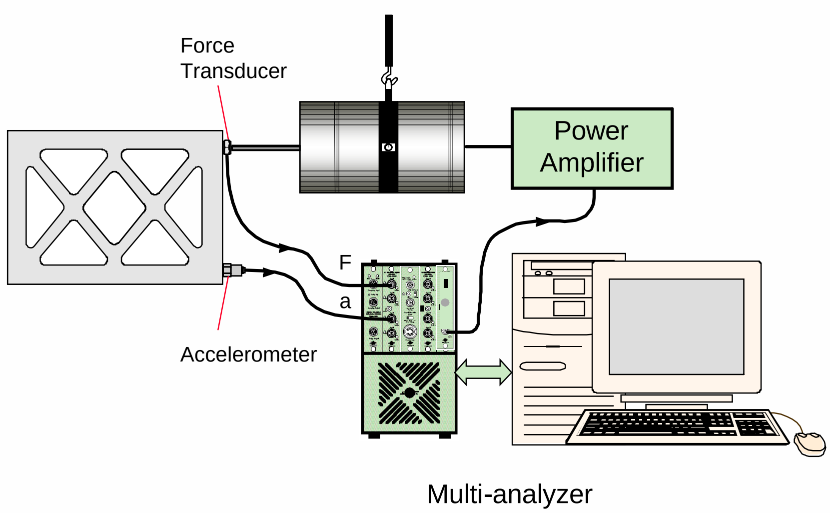
Excitation technique: Important Considerations

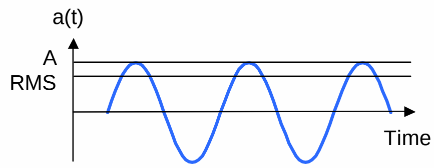
Consideration of:

- Application
- Non-linearities
- Speed of test
- Leakage (analysis)
- Dynamic range
- Crest factor
- Noise at input and/or output
- Equipment available

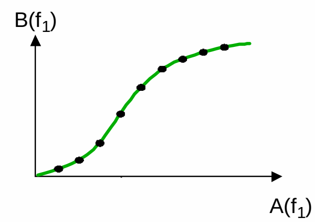
Swept sine technique



Sine excitation



$$\text{Crest factor} = \frac{A}{RMS} = \sqrt{2}$$



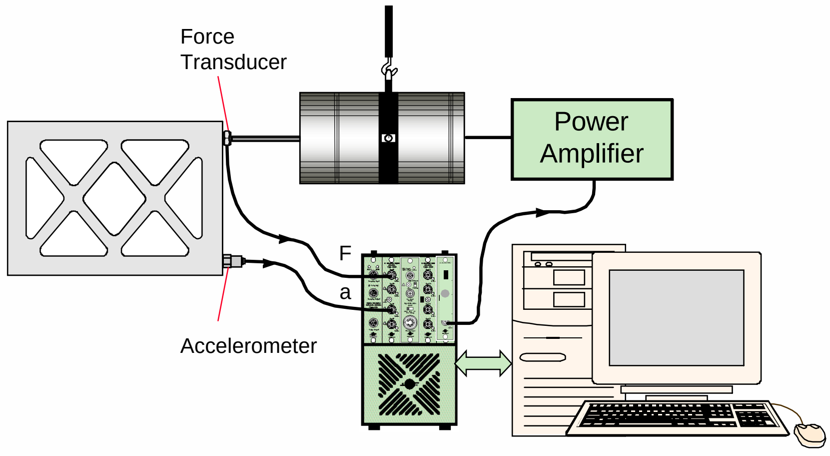
- For study of non-linearities, e.g. harmonic distortion
- For broadband excitation:
  - Sine wave swept slowly through the frequency range of interest
  - Quasi-stationary condition

Swept sine excitation

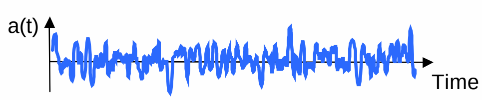
Advantages
- Low Crest Factor
- High Signal/Noise ratio
- Input force well controlled
- Study of non-linearities possible

Disadvantages
- Very slow
- No linear approximation of non-linear system

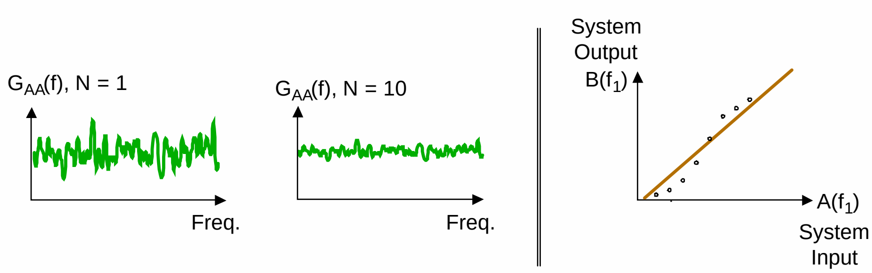
FFT technique



Random excitation

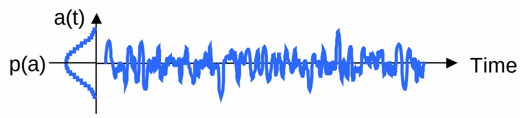


Random variation of amplitude and phase
⇒ Averaging will give optimum linear estimate in case of non-linearities

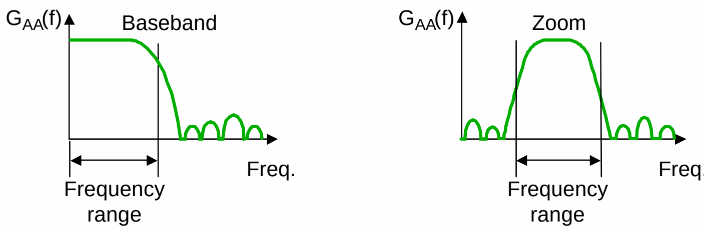


Random excitation

- Random signal:
  - Characterized by power spectral density (G_{AA}) and amplitude probability density (p(a))



- Can be band limited according to frequency range of interest



- Signal not periodic in analysis time ⇒ Leakage in spectral estimates

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Random excitation

Advantages
- Best linear approximation of system
- Zoom
- Fair Crest Factor
- Fair Signal/Noise ratio

Disadvantages
- Leakage
- Averaging needed (slower)

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Burst random

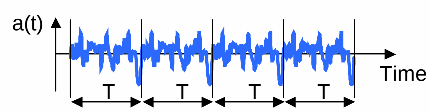
- Characteristics of Burst Random signal :
  - Gives best linear approximation of nonlinear system
  - Works with zoom

Advantages
- Best linear approximation of system
- No leakage (if rectangular time weighting can be used)
- Relatively fast

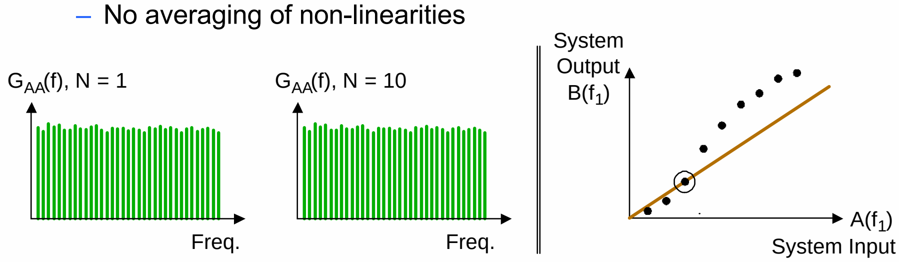
Disadvantages
- Signal/noise and crest factor not optimum
- Special time weighting might be required

Pseudo random excitation

- Pseudo random signal:
  - Block of a random signal repeated every T

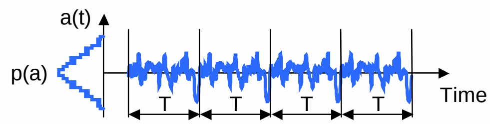


- Time period equal to record length T
  - Line spectrum coinciding with analyzer lines
  - No averaging of non-linearities

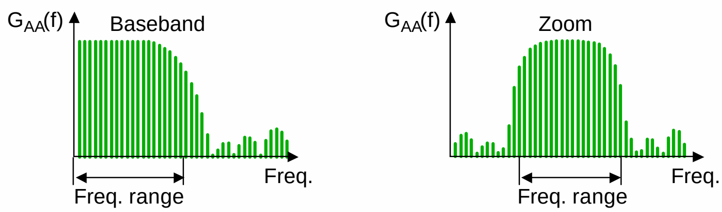


Pseudo random excitation

- Pseudo random signal:
  - Characterized by power/RMS (G_{AA}) and amplitude probability density (p(a))



- Can be band limited according to frequency range of interest



Time period equal to T
$\Rightarrow$ No leakage if Rectangular weighting is used

Pseudo random excitation

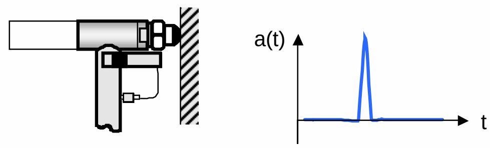
Advantages

- No leakage
- Fast
- Zoom
- Fair crest factor
- Fair Signal/Noise ratio

Disadvantages

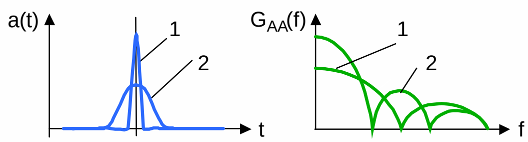
- No linear approximation of non-linear system

Impact excitation



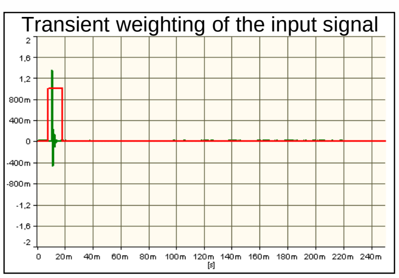
- Magnitude and pulse duration depends on:
  - Weight of hammer
  - Hammer tip (steel, plastic or rubber)
  - Dynamic characteristics of surface
  - Velocity at impact

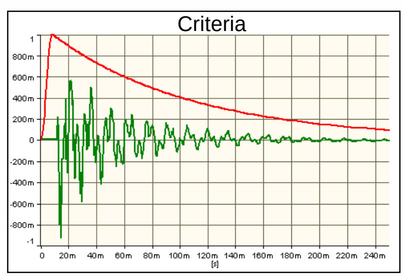
- Frequency bandwidth inversely proportional to the pulse duration

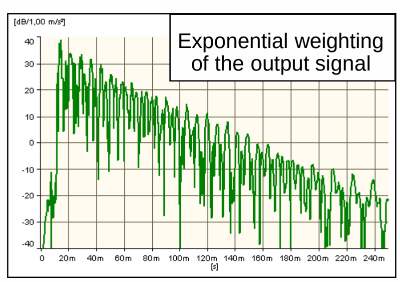


Weighting functions for impact excitation

- How to select shift and length for transient and exponential windows:







- Leakage due to exponential time weighting on response signal is well defined and therefore correction of the measured damping value is often possible

Impact excitation

Advantages

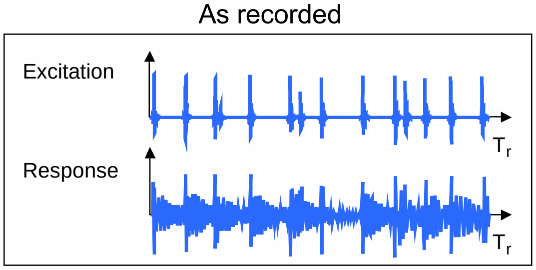
- Easy to use in the field
- No elaborate fixturing
- Fast

Disadvantages

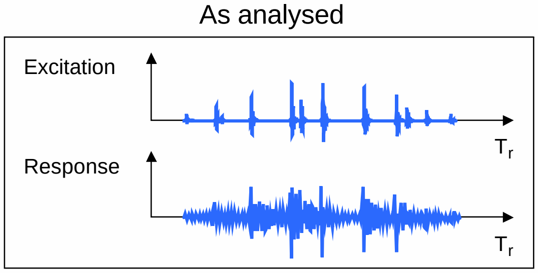
- No linear approximation of non-linear system
- Limited control of excitation bandwidth
- Special weighting functions in order to increase Signal/Noise ratio and/or avoid tranctation errors

Random impact excitation

As recorded



As analysed



- More energy per time record than single impact
- Lower crest factor than single impact
- Useful for long record time i.e.:
  - low frequencies
  - zoom measurements

Random impact excitation

Advantages

- Easy to use in the field
- No elaborate fixturing
- Fast
- Lower crest factor than single impact

Disadvantages

- High crest factor
- Only useful at low frequencies or zoom
- No linear approximation of non-linear system
- Limited control of excitation bandwidth
- Leakage

Guidelines for choice of excitation technique

- For study of non-linearities: → Swept sine excitation
- For slightly non-linear system: → Random excitation
- For perfectly linear system: → Pseudo random excitation
- For fields measurements: → Impact excitation
- For high resolution field measurements: → Random impact excitation

Tips and tricks for best results

- **Verify measurement chain integrity prior to test:**
  - transducer calibration
  - Mass Ratio calibration
- **Verify suitability of input and output transducers:**
  - operating ranges (frequency, dynamic range, *phase* response)
  - mass loading
  - mounting
  - sensitivity to environmental effects
  - stability
- **Verify suitability of test set-up:**
  - transducer positioning and *alignment*
  - pre-test: ratling, boundary conditions, rigid body modes, signal-to-noise ratio, linear approximation, excitation signal, repeated roots, maxwell reciprocity, force measurement, exciter-input transducer-stinger-structure connection

- **Remember:**
  - quality FRF measurements are the foundation of experimental modal analysis!

Stingers: key link for accuracy

- Purpose:
  - To only transmit force in the sensitive direction of the force transducer/impedance head
  - Mechanical fuse - protection of structure and exciter
  - Make structure/exciter alignment easier
- Ideal stinger: *zero bending stiffness* and indefinite axial stiffness and no mass
- Practical designs:
  - Tension wire (characteristics: zero bending stiffness, low mass)
  - Push/pull (characteristics: some bending stiffness, more mass)
- Conclusion: *use tension wire* whenever possible
- Limitation of tension wire:
  - Structure must not move when preloaded!
  - Set-up is more time consuming
  - Pre-load must be applied and verified
  - Limited force (< 200 N sine peak) and frequency (< 400 Hz)

The End!

Any Questions?

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