Analysis:

Philosophy, Technology & Exploitation

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Why, *i*

Sir Isaac Newton

"Those who assume hypotheses as first principles of their speculations … may indeed form an ingenious romance, but a romance it will still be."

Gottfried Wilhelm Leibniz

Roger Coates,

Preface to Sir Isaac Newton's
Principia Mathematica
2nd edition 1713

Why, *ii*

- **The ultimate purpose of any analysis task is to reduce the risk in decision making.**
- A numeric tool to study parameter influence allow fast knowledge buildup
- Drive the mathematical model with tools toward design optimum - faster, higher, better, cheaper, …

Analysis types

Sometimes

- '**Conceptual design**' – rough design to support strategic decisions, e.g. rear/front wheel drive? *You must be very fast as this phase lasts days or a few weeks at the most.*

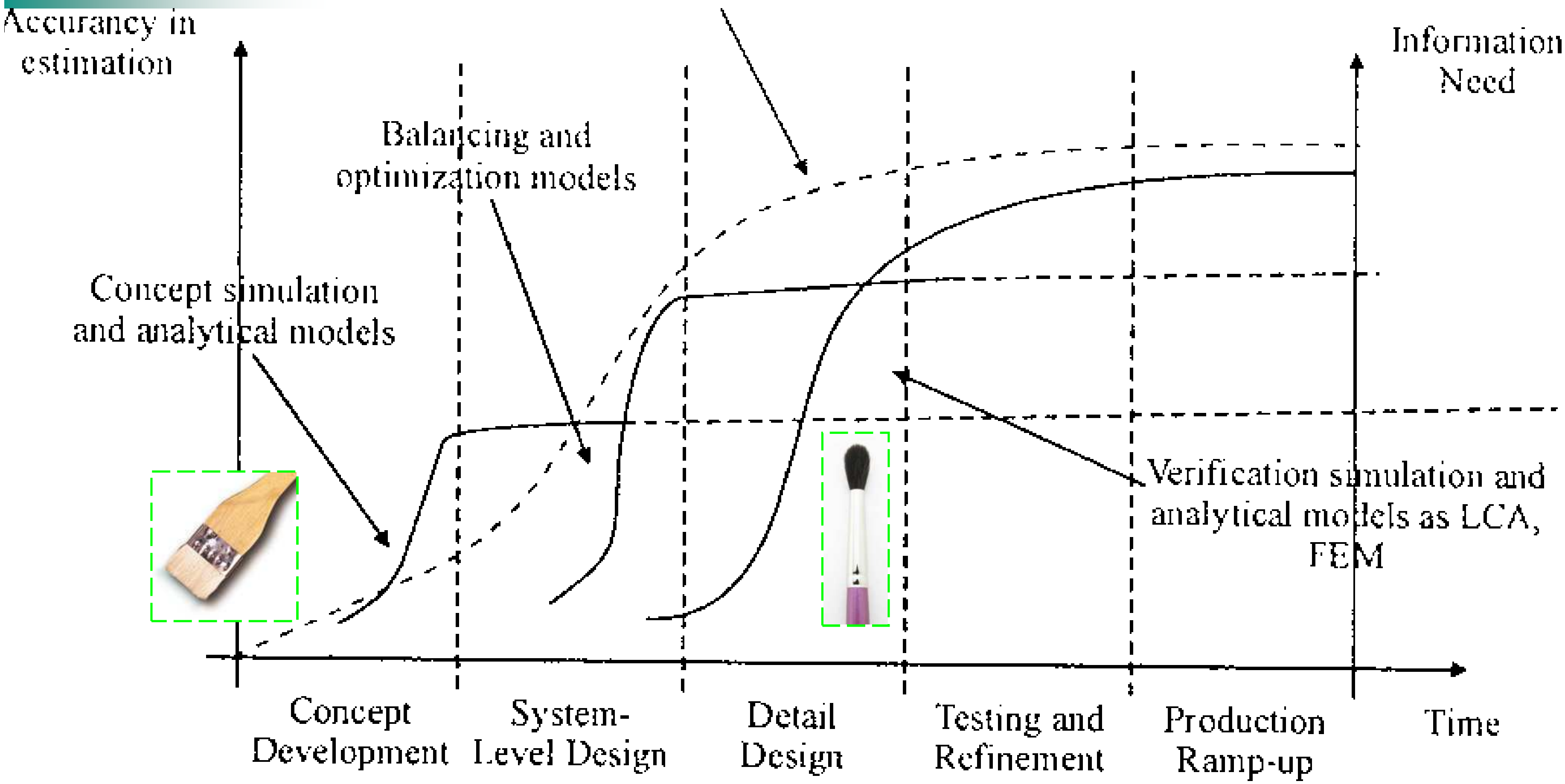
New trend

- '**Design before CAD**' – design toward relevant properties and specifications. Get the rough outline for important subsystems. *Requires a systematic approach & accumulated knowledge wrt definition of goals.*

As-is

- '**Design after CAD**' – check & approve the design & fine tuning. *You are too late for any dramatic changes to the design.*

One or several models?



Lars Almefeldt, **Lic.Report "*Requirements Management in Theory and Practice: From Requirements Formulation to Product Concept*"**

The crux of the matter

A model must capture
the sought after phenomena
for analysis truly to reduce
risk.

Bad FE is worse than no FE

- as it may erroneously replace
better motivated rules-of-thumb
or practical experience

Other considerations

Computer Aided Engineering (CAE) can be exploited only when designed properties are effectively translated into real production.

A single CAE model should be expected only to capture production when manufacturing tolerances do not lead to product variation.

So, how useful is analysis?

For between true science and erroneous doctrines, ignorance is in the middle.

Hobbes

Leviathan

Model assumptions & QA

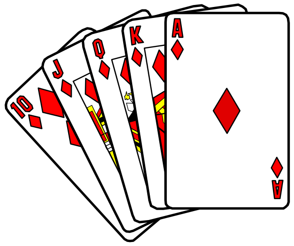
- Any model is based on a set of assumptions about the problem – *these assumptions can be either:* ***correct, wrong,*** *or* ***not validated***.
- **Not validated** model assumptions do not reduce the risk in decision making even when correct.
- Model Quality Assurance (QA) aims at validation or rejection of model assumptions – *in other words, it is a technique to build up a knowledge of what to* ***trust and distrust****.*

Simulation versus reality?

There exists special techniques for model Quality Assurance

- **PreTest planning**
- **EMA/ODS** *(**E**xperimental **M**odal **A**nalysis/**O**perational **D**eflection **S**hape)*
- **Model correlation**
- **Model updating**

A game of chance in the input data deck?



Types of QA: *Test/Test, Test/FE & FE/FE*

Start simple – *rudimentary bookkeeping goes a long way*

- Compare CAD, CAE & manufactured weight and Centre of Gravity

- Compare CAD, CAE & manufactured object material, component part lists etc..

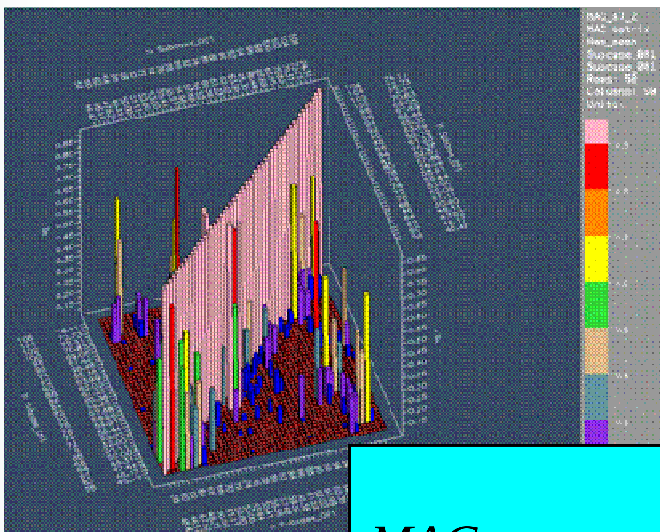
- Compare CAD, CAE & manufactured object main dimensions, …

PreTest Analysis

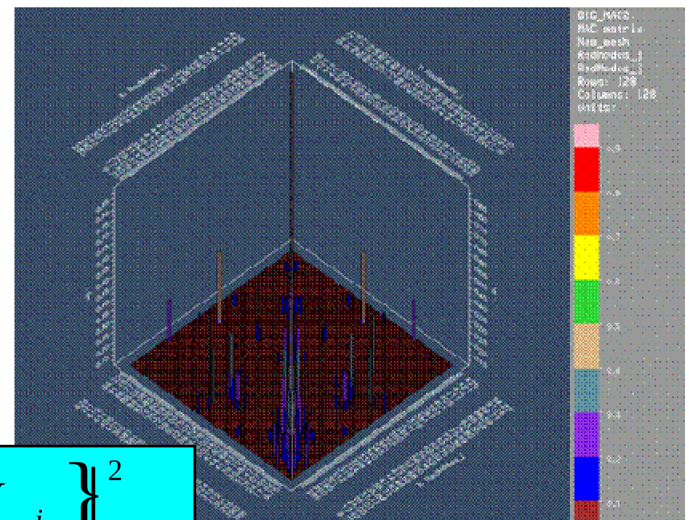
PreTest analysis
to maximize the test
quality and effectiveness.

- Prepare geometry data for the test.
- Suggest excitation positions for the test.
- Find a test set up that allows mode shapes to be distinguished from each other (= low off-diagonal MAC values) with as few points as possible

Poor test set up

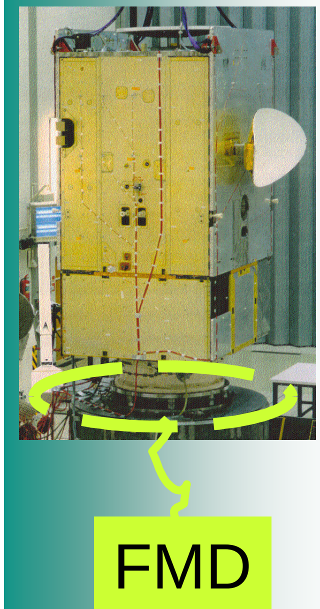


Good test set up



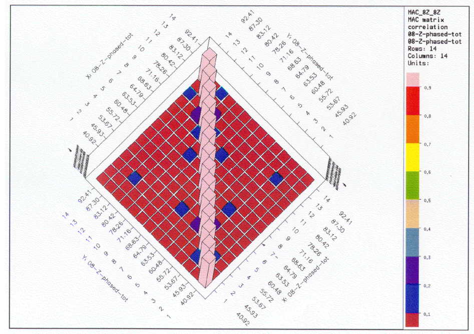
$$MAC_{ij} = \frac{\left|\{V_i\}\cdot\{V_j\}\right|^2}{\left|\{V_i\}\right|^2 \left|\{V_j\}\right|^2}$$

The Olympus satellite

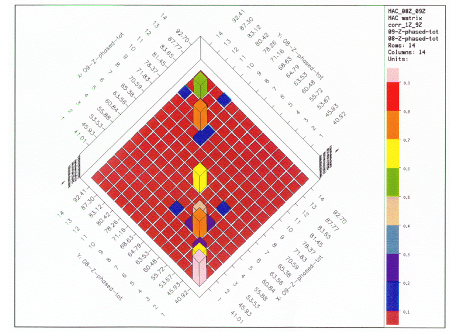


Test/Test correlation
to study repeatability

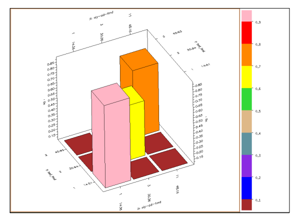
Modes from a single test



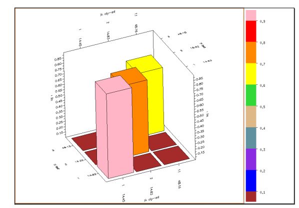
High/Low vibration amplitude



Test/FE correlation to QA
the simulation model

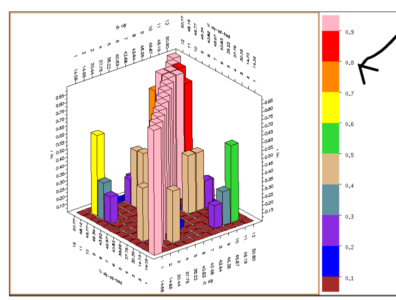


MAC
1-1 0.93
3-3 0.63
4-4 0.75



MAC
1-1 0.93
2-2 0.78
4-4 0.70

FE/FE correlation to study
the effect of the Force
Measurement Device (FMD).



All MAC values on the diagonal are larger than 0.99

FE w FMD [Hz]	FE [Hz]	% difference [-]
14.35	14.45	-0.7
14.72	14.83	-0.7
30.36	30.39	-0.1
48.16	48.16	0.0

Model updating

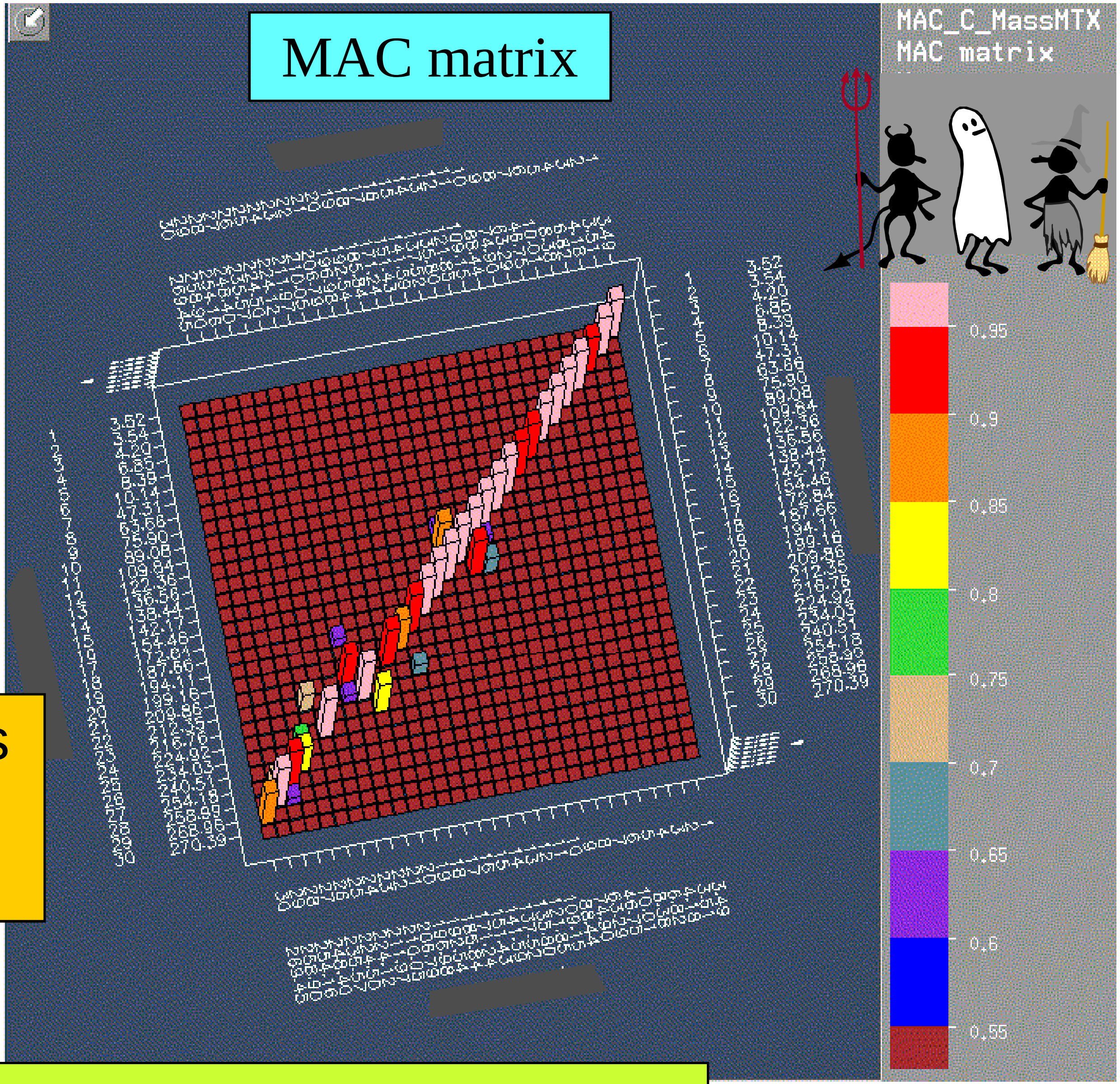
- Adjust unkown/erroneuos parameter values for a model to better replicate test or other results

- A form of optimization

- Expect sensible results only when model assumptions are valid, *i.e. the model must be sound and proper before model updating is motivated.*

State-of-the-art FE software from two major vendors & identical input data.

Identical mode shapes generate MAC values of unity



Our tools have limits

Fundamental assumptions in most dynamic analysis

- The system is linear, time invariant and shows no influence from ‘unknown’ environmental factors.
- Pre-stressing effects are not present.
- Boundary conditions are foreseeable and captured from simple assumptions.
- Dynamic forces are known and foreseeable in magnitude and phase
- Vibration response is small with respect to characteristic dimensions.
- Damping mechanisms are well known with respect to their type, magnitude and distribution.
- Damping is light and evenly distributed across the system.

Dynamic response varies with damping

Conventional pipe | With damping solution

Click on a picture to animate and listen to the difference between the conventional pipe and the damped pipe

The sound you hear is an 3-axial acceleration signal that is amplified though a loadspeaker
the accelerometer is the tiny metal cube near the hammer

Why is damping important?

Force balance:

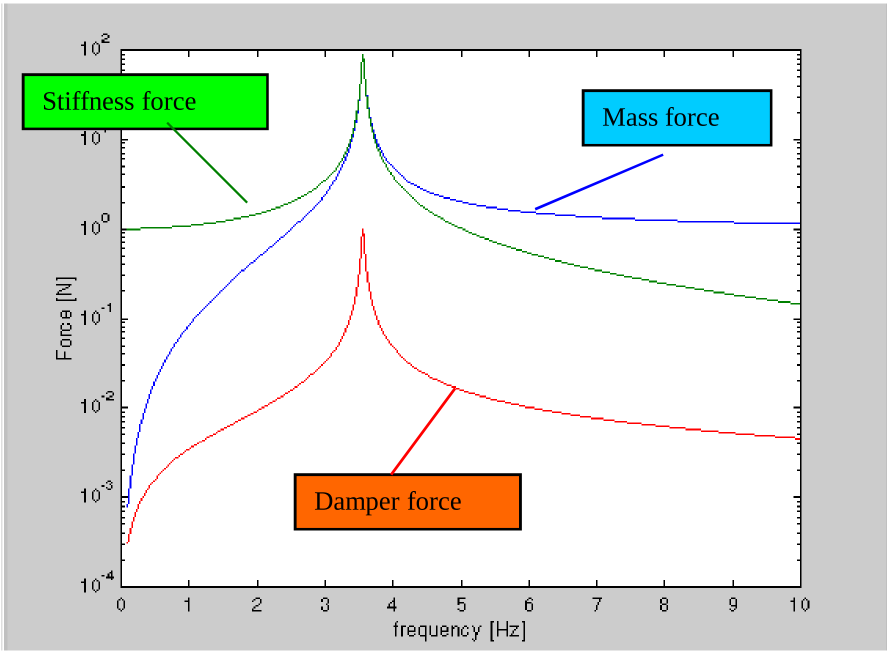
$$\left[-\omega^2 M + i\omega C + K\right]X = F$$

At resonance:

$$-\omega^2 MX + KX = 0$$

Damping controlled!

$$i\omega CX = F$$



Peak response

$$|X| = \frac{|F|}{\omega_0 C}$$

Should it be damping, or the dam-d thing?

knik, Lund

What damping has a system?

- Data from four pipe systems in a large building

% of critical damping

2.93	2.88	1.90	0.53
1.44	1.35	1.96	0.96
2.91	1.31	1.15	1.05
1.95	1.96	1.82	0.61
1.90	1.00	2.22	0.89
0.76	1.18	0.96	1.55
1.89	0.50	0.98	
1.53	1.60	1.97	
1.92	2.56	0.87	
1.60		2.03	
1.19			
1.00			

$\xi = C/C_{critical}$

This yields

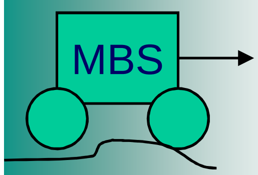
1.53% ± 0.65% (σ)

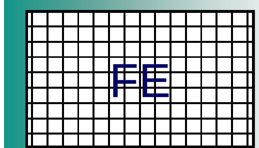
i.e. a variation within
[**0.88%, 2.18%**]

with 67% probability

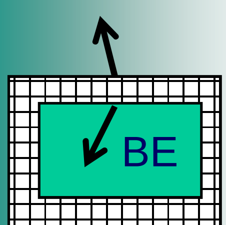
Example: Assuming 1.5% damping for all modes will underestimate response by a factor of (1.5/0.53 =) ~3 and overestimate response by (2.93/1.5 =) ~3, i.e. a factor ± 3 variation.

Common analysis methods





Elements inside of a domain



Elements on domain interface

- **Multi Body System (MBS)**. Analysis of ***mechanisms and dynamics of multiple bodies*** involving contact etc. Dynamic flexibility can be introduced using Craig-Bampton modes.
- **Finite Element** (FE). *Most structural FE software is restricted to analysis of **a bounded domain**. Recently, theory for analysis of open acoustic domains has been added through the use of Infinte-FE. Infinte-FE is limited to certain shapes on the boundary. Open structure domains can be approximated be the use of damped end elements. The domain can be open, closed, or a combination of both. Properties can vary from one element to another in the domain. The FE method can handle non-linear analysis. The FE method tends to execute faster than BE analysis for comparable tasks and is more general than BE. FE is the most general method available today.*
- **Boundary Element** (BE). *A BE method **describes the response within a domain from its boundary**. Thus, the behaviour withing the domain must be uniform. The domain can be infinite, bounded, open, closed, or a combination of all four.*
  The BE method is a poor choice for time domain analysis. BE models can be generated with less user effort than FE models (which matters). BE is limited to linear analysis.

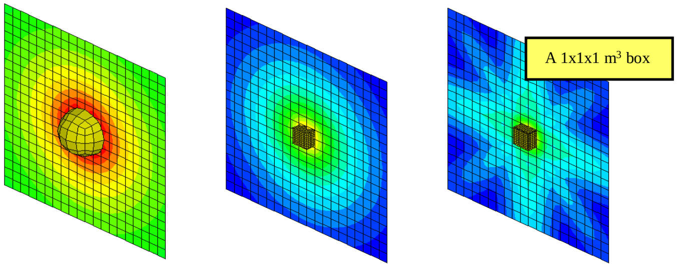
Analysis types, *i*

- **Non-linear with large deflection**, *(FE/MBS)* e.g. with plastic yield like weapons impact analysis.
  - *Very expensive analysis type. The best recourse is to investigate the use of substructuring where linear parts of the model are treated using e.g. component modes. Analysis must be made in the time domain.*
- **Non-linear with small deflection** *(FE/MBS),* e.g. with pretensioning effects that lead to frequency shift
  - *Expensive analysis type. See comment above. Analysis can be made in the time domain and in some cases also in the frequency domain (in case of a point of operation at which the system is linear).*
- **Linear,** '99% of the business'. *(BE/FE/MBS/...)*
  - *Least expensive analysis type. Analysis can be made using direct techniques or modes. Analysis can be made in the frequency domain or in the time domain.*

Analysis types, *ii*

- Uncoupled (*In vacuo*) structural vibration, rigid walled & open space acoustic vibration without objects: *Effects from fluid and gas loading is ignored* *No interaction*

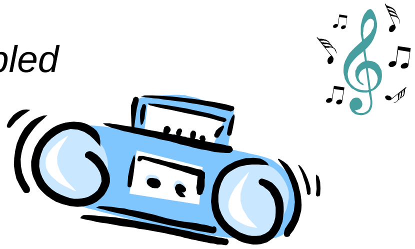
- Sound radiation, scattering & vibration from pressure loading: *Effects from structural/acoustic loading is ignored. Vibration -> sound or vice versa.*
  One way interaction = *weakly coupled.*



A sphere at 75 Hz. A box at 75 Hz. A box at 600 Hz.

- Coupled vibroacoustic response

The influence from fluid/gas loading on the structure is taken into account. Vibration generates sound and sound generates vibration.
Two way interaction = *strongly coupled*



Analysis techniques

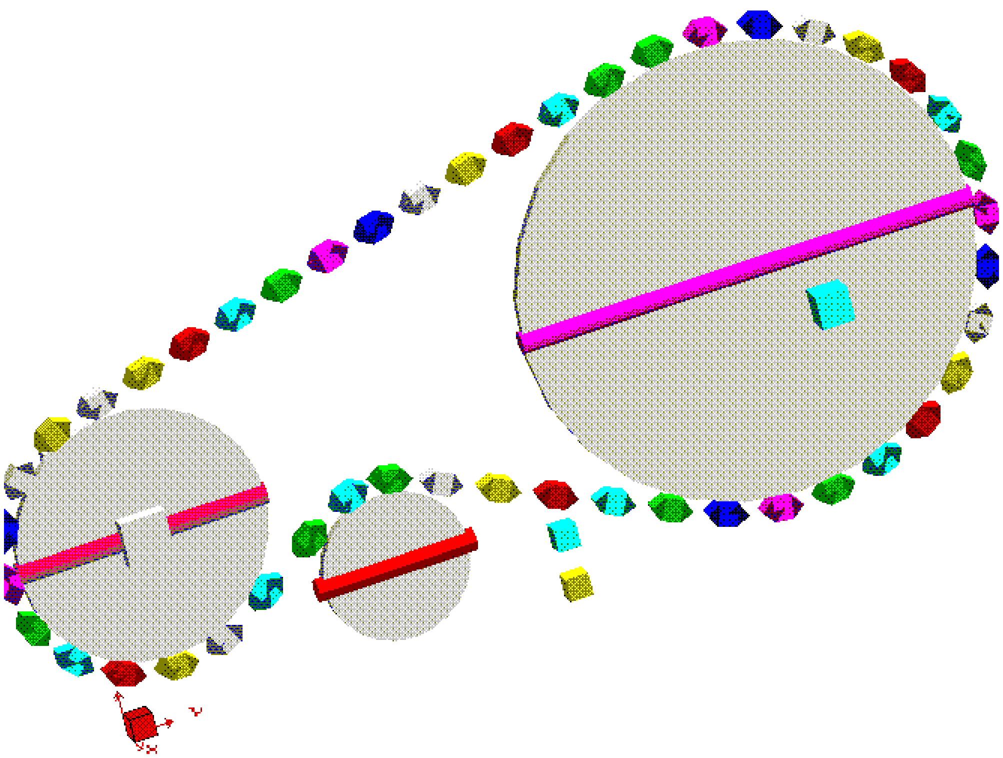
- **Direct** analysis. *The system matrix is set up and solved for at every frequency. This is the most exact and general approach, but also tends to be the* ***slowest****. Analysis of open domains always require a direct analysis irrespective of the method*
- **Modal** analysis. *The model is analysed and its natural modes are identified. This is a model reduction step as the problem is reduced from N degrees of freedom (dof) to M modal dofs. This reduction can create reduction in processing time by orders of magnitude. This reduction is particularly useful whenever the mode information can be re-used sevaral times.*

Multi Body System *(MBS)*:

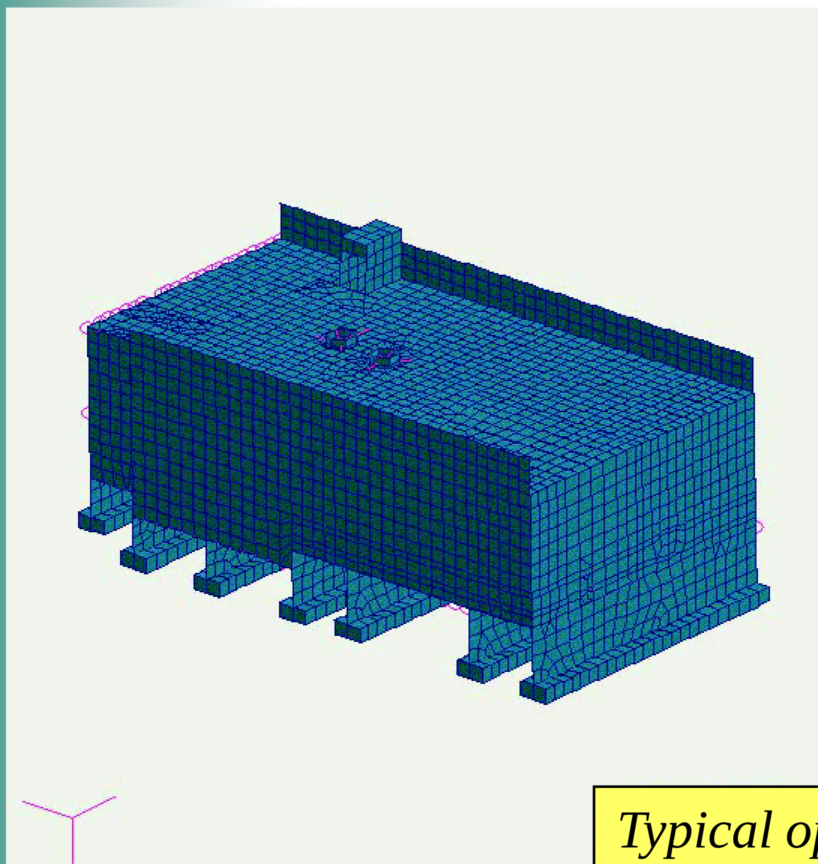
A belt drive system

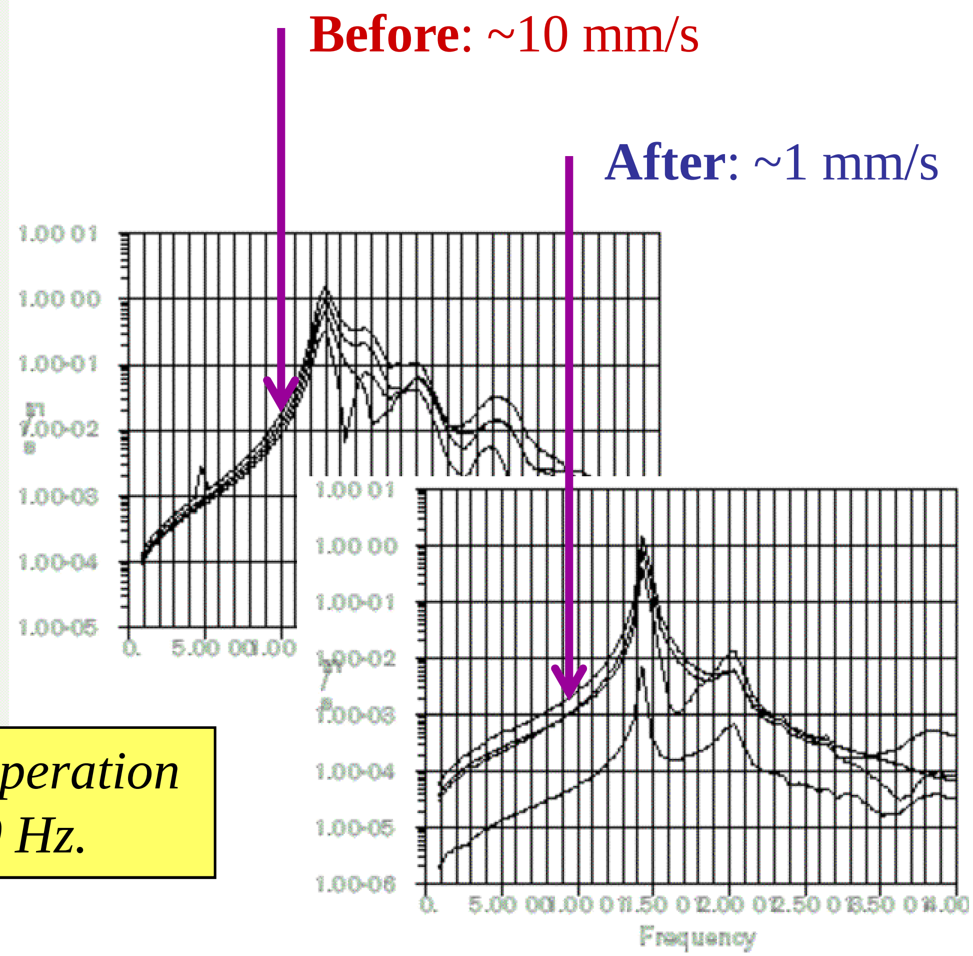
- Quasi-static MBS analysis

Step 1. The pre-tensioner is activated.
Step 2.The system is started.
Step 3. Auxiliary equipment is activated when the system is at maximum speed.



Forced Dynamic vibration:
A mixer operating in a building

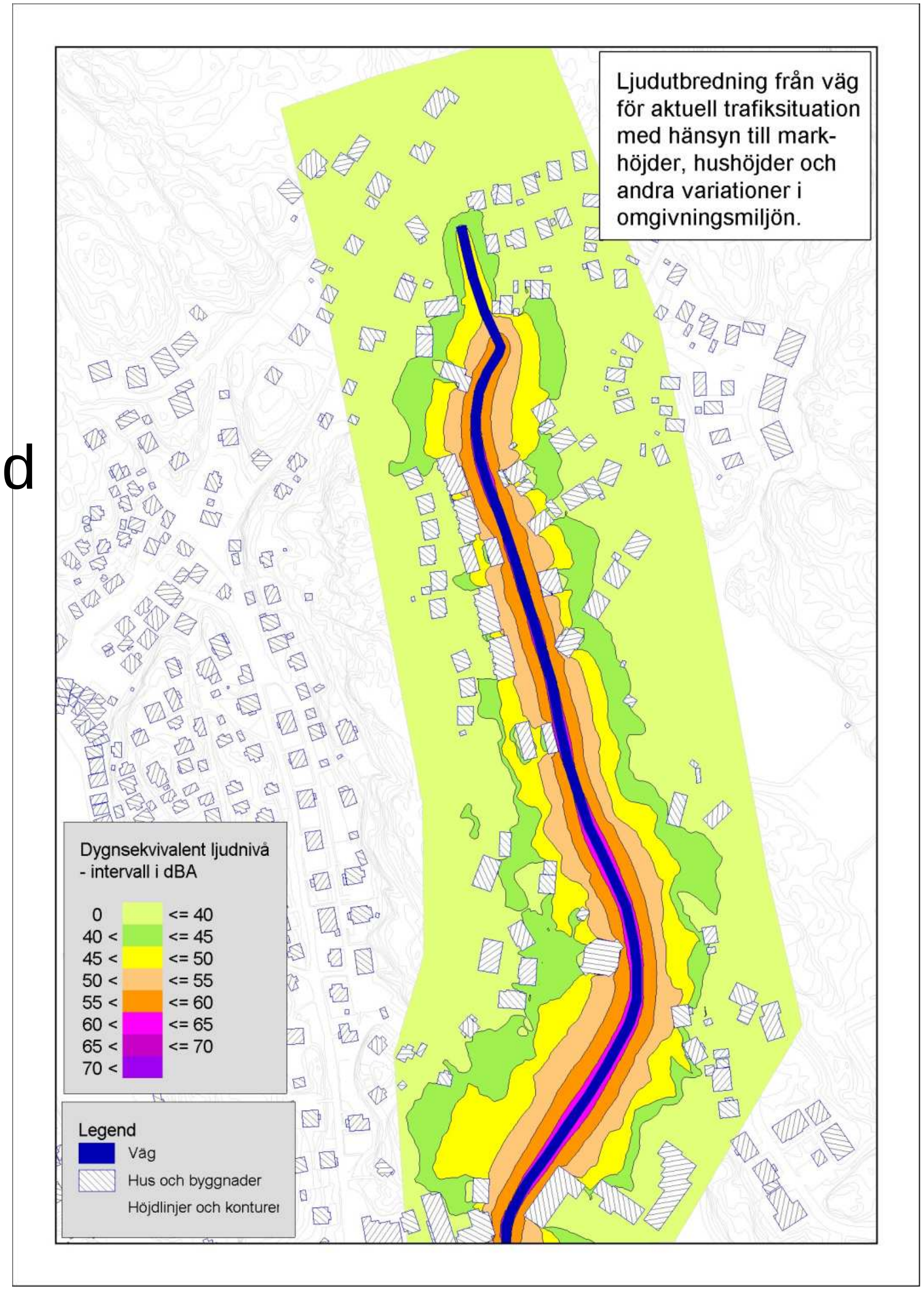




Typical operation at 10 Hz.

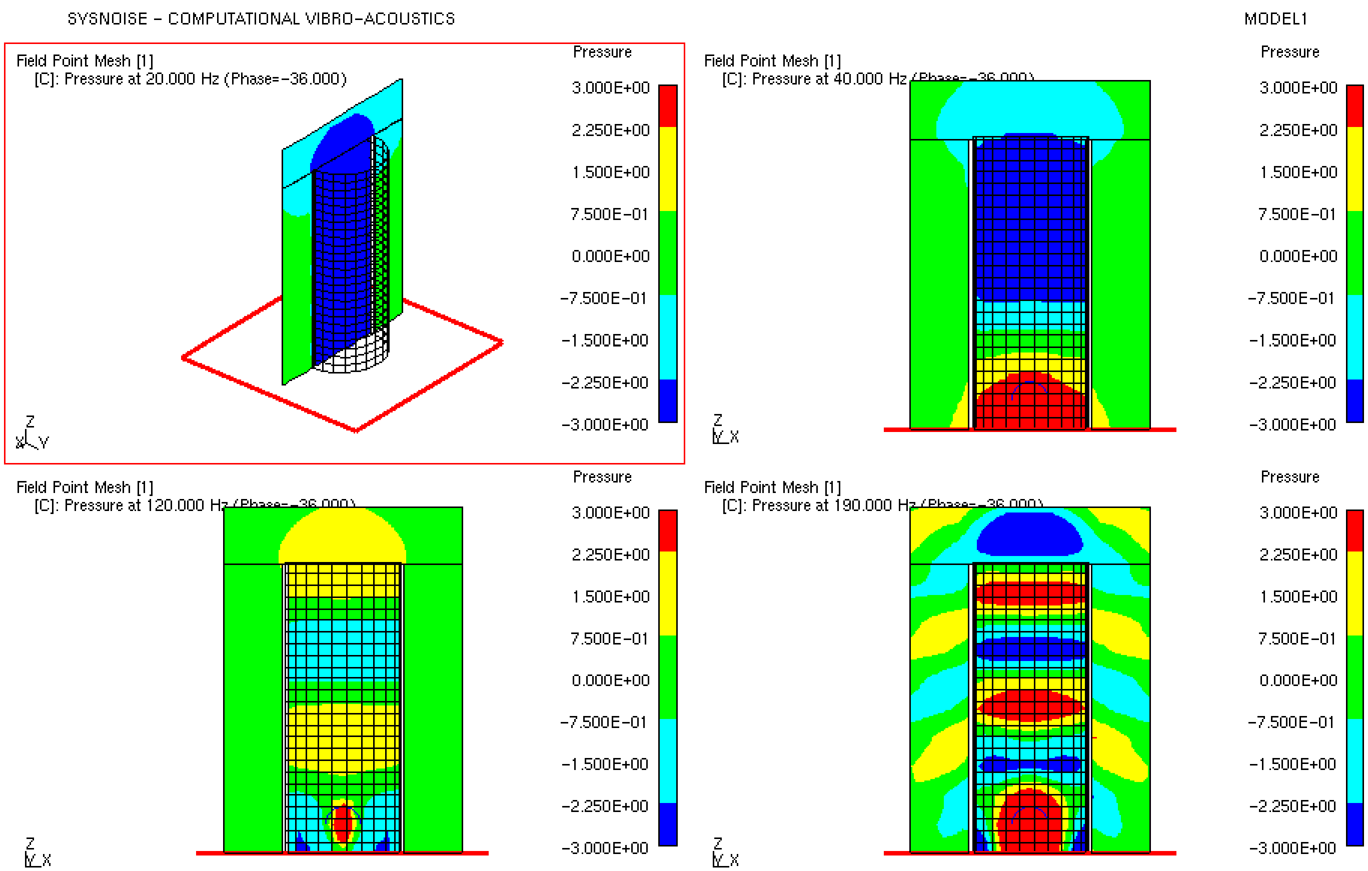
Uncoupled

Sound dispersion analysis using the Scandinavian sound analysis method and the software SoundPlan



Sound radiation from a funnel

The funnel is located on a reflecting plane



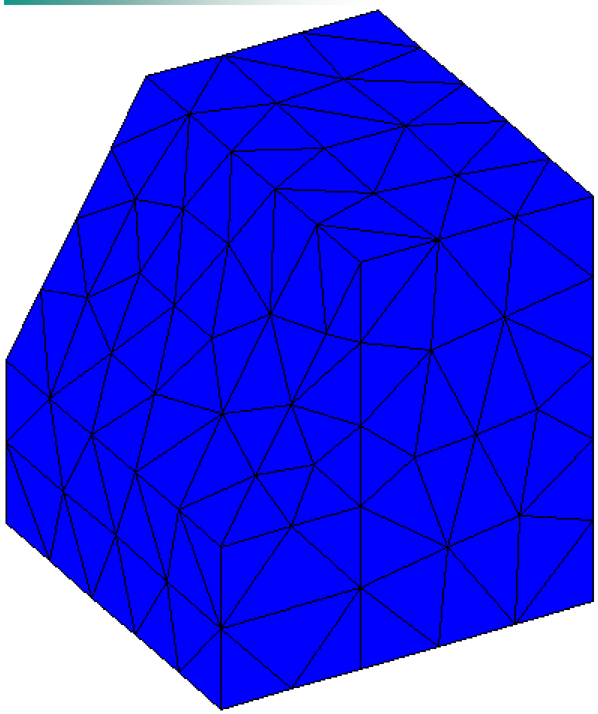
The wave front becomes directive at higher frequency

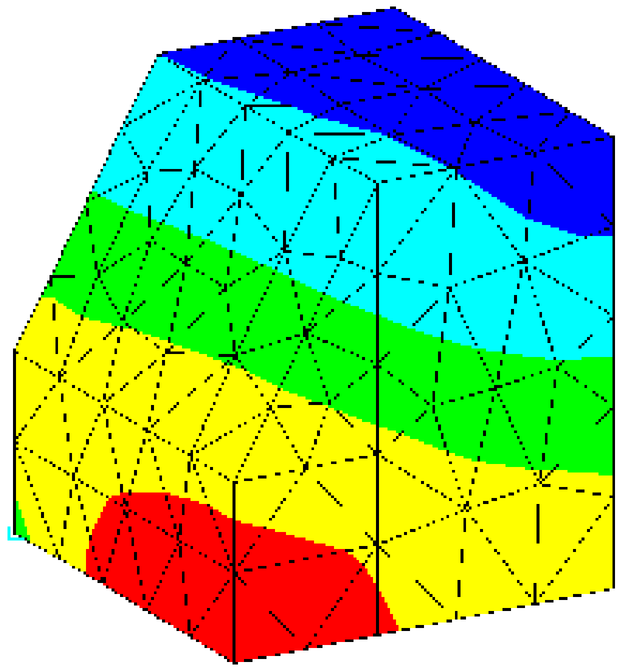
Time domain, mode, & free space analysis

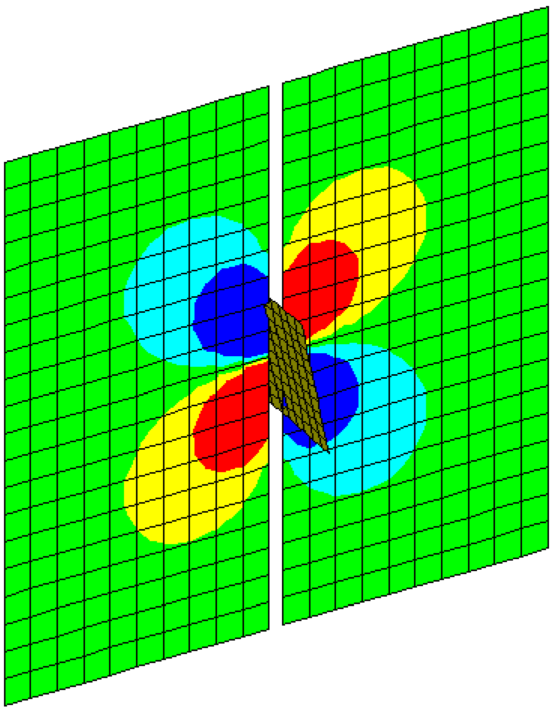
Time domain

Mode analysis

Free space







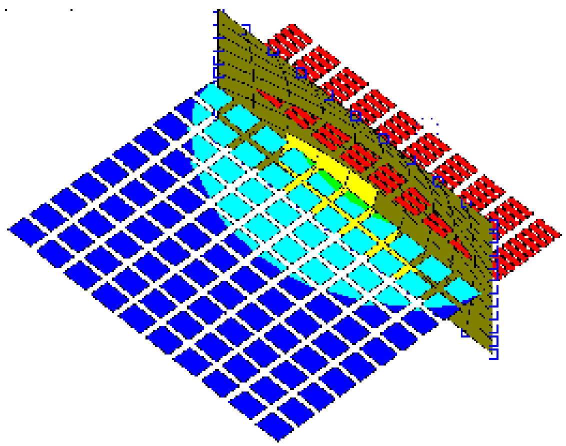
FE. A source is turned on at the LHS lower corner

FE. 1st acoustic mode

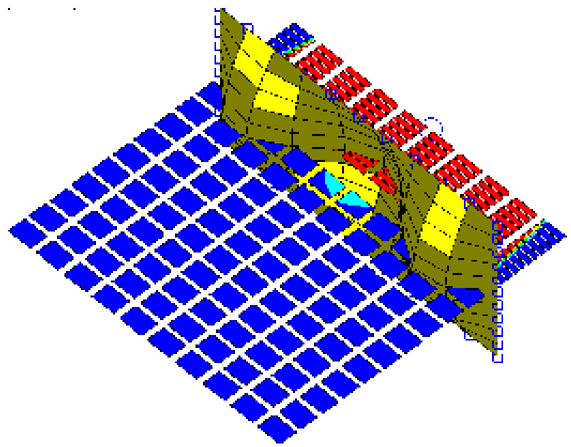
BE sound radiation from rotating plate

Sound transmission of plane wave across flexible plate in baffle

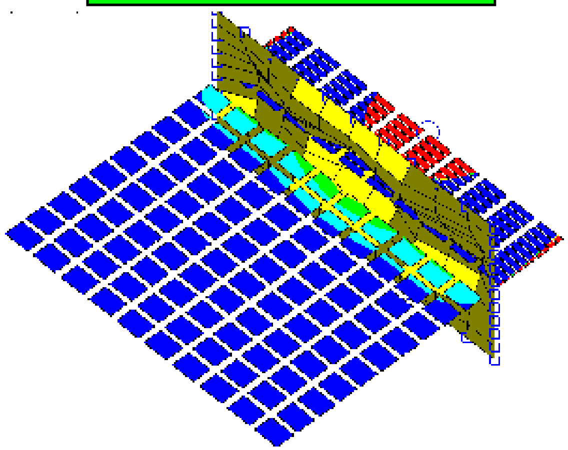
[1,1 type mode]



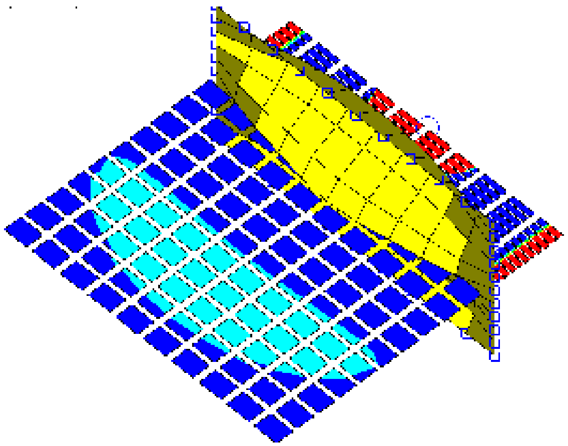
[3,1 type mode]



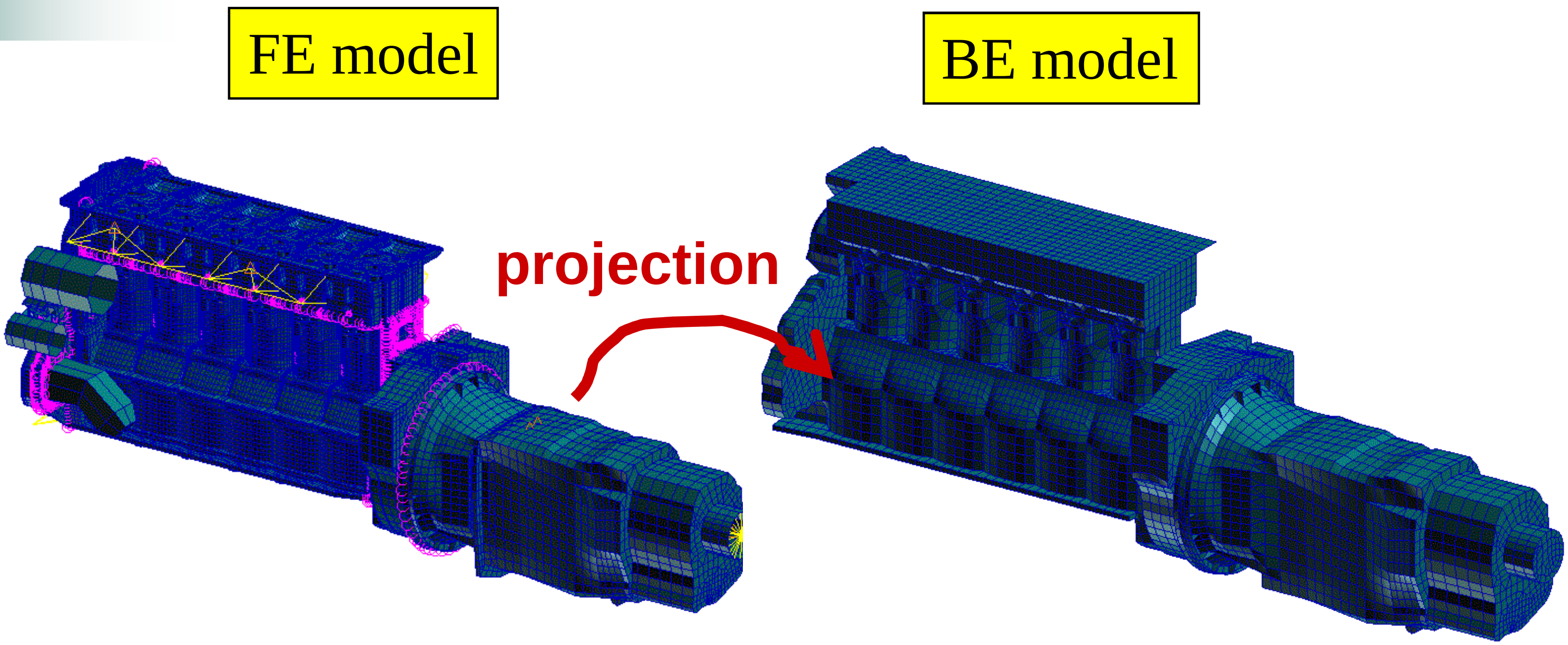
[3,3 type mode]



[1,3 type mode]



Data projection

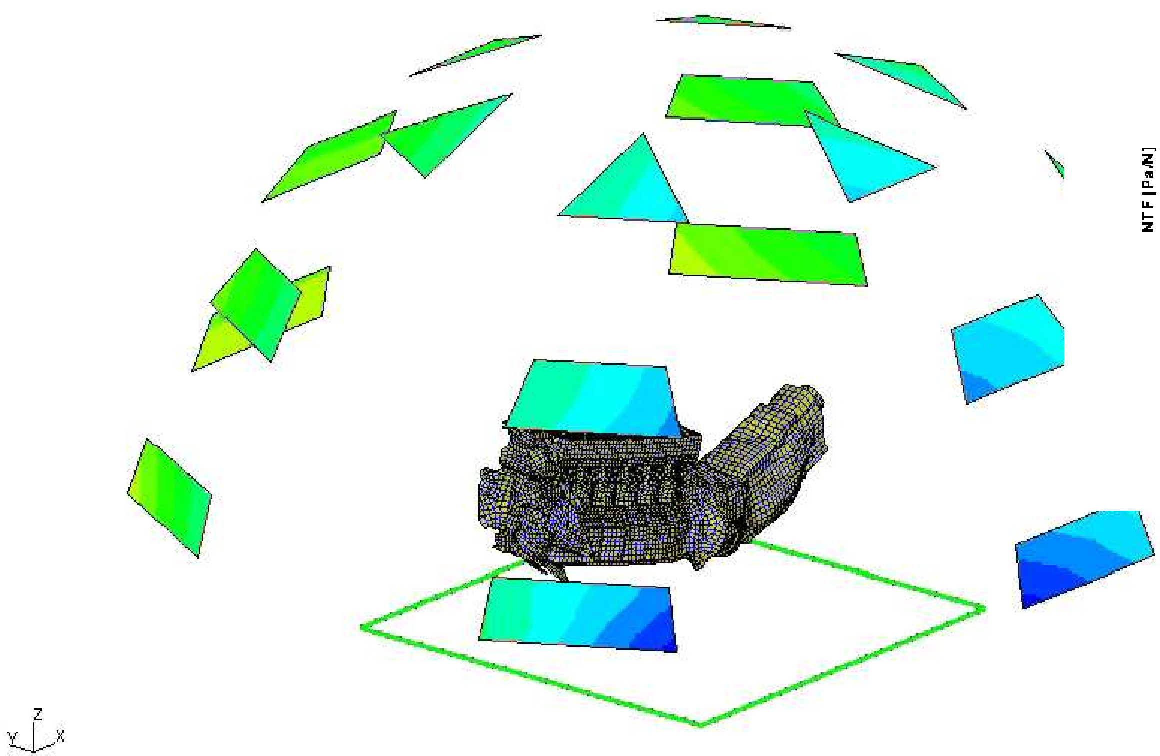


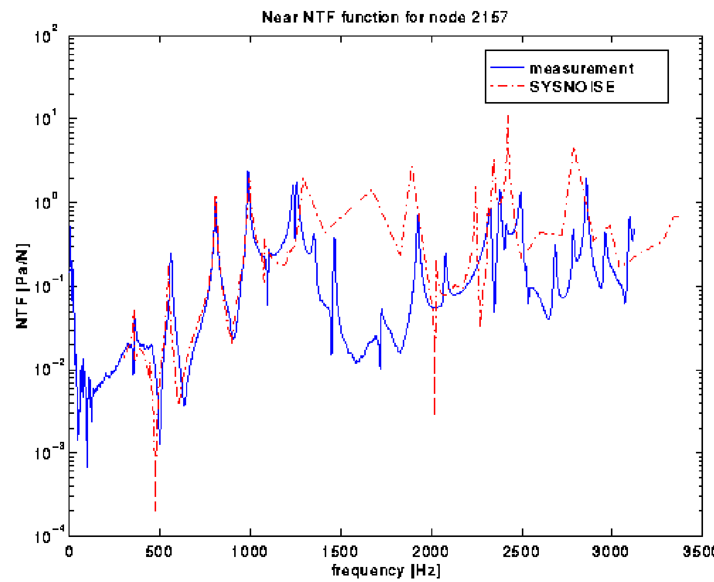
The acoustic model mesh tends to be smaller than the structure mesh to save computational effort.

Vibration data is **projected** from the FE onto the BE mesh.

Example, weakly coupled:

Sound radiation from powertrain





Validation (other product) example. Sound radiation is accurately predicted when structure response is correct.

The loading from air on the structure is ignored for the thick PT structure

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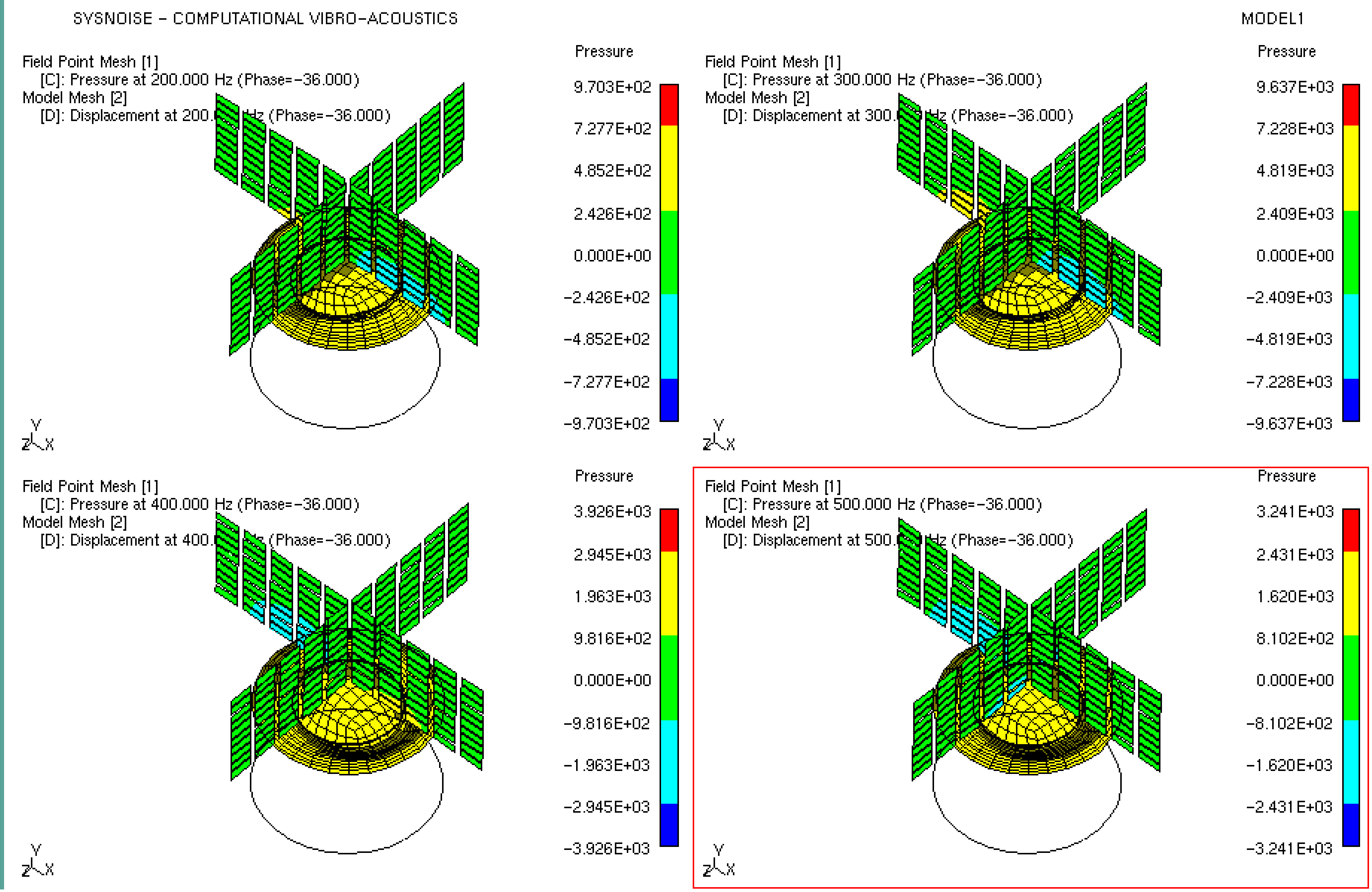
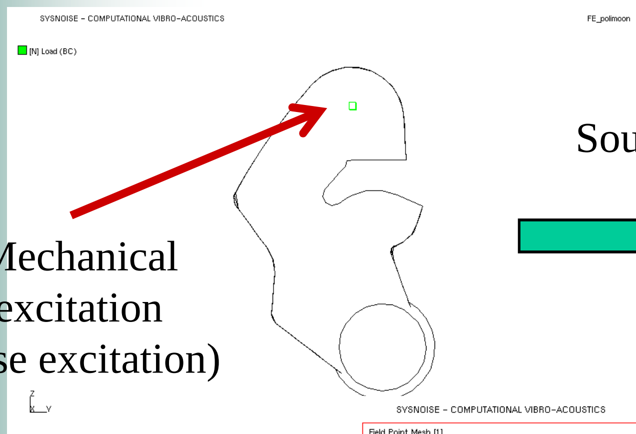
BE fluid/structure analysis of loudspeaker excitation problem

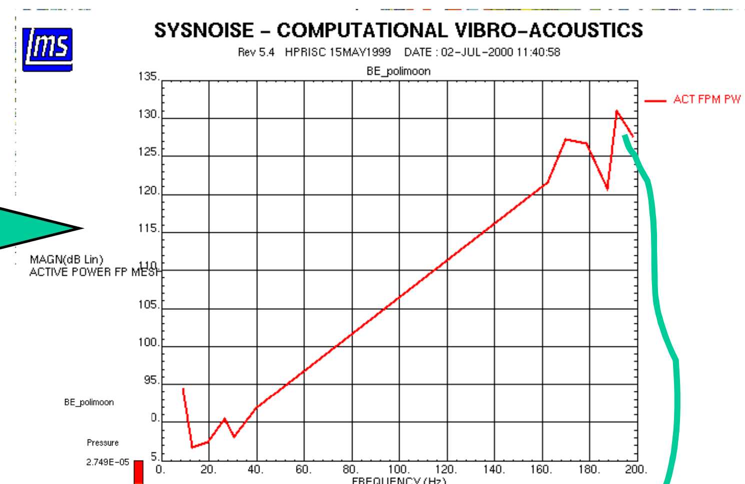


Coupled sound radiation analysis

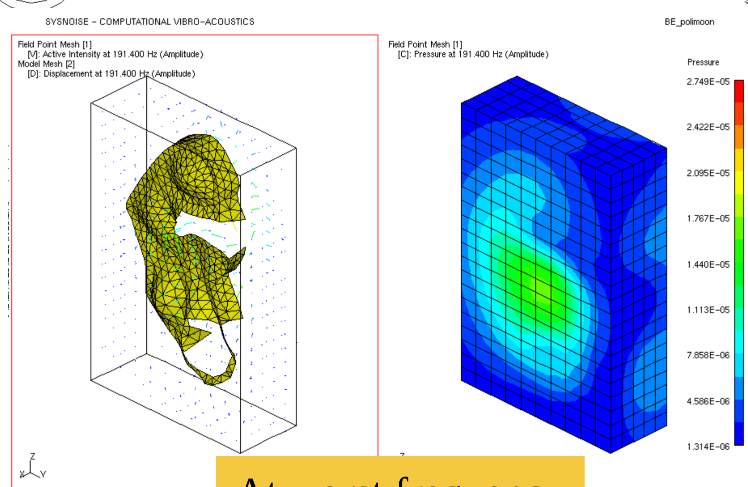


Mechanical
excitation
(base excitation)

Radiated
Sound Power [W]



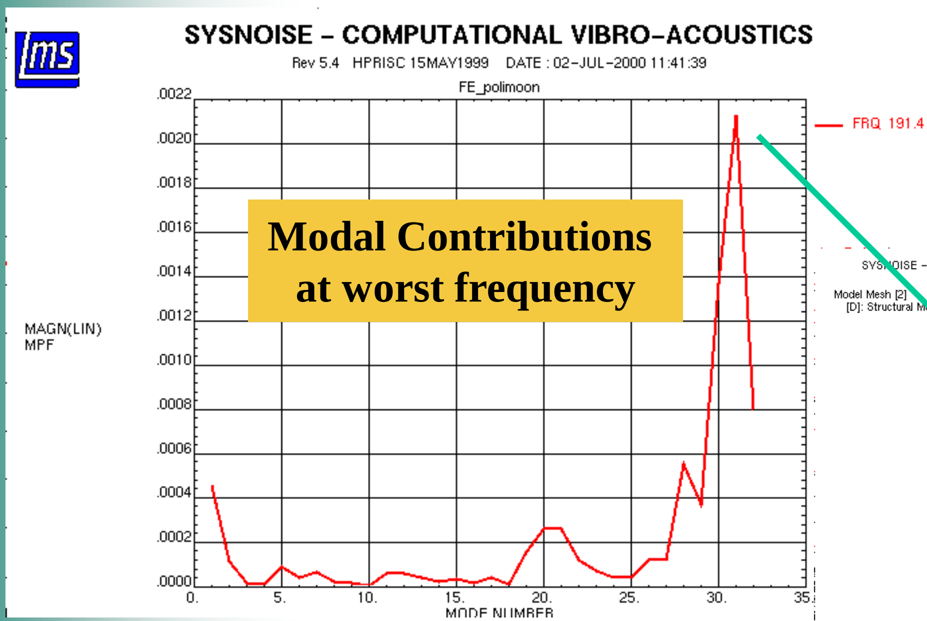
Vibration
&
active sound intensity

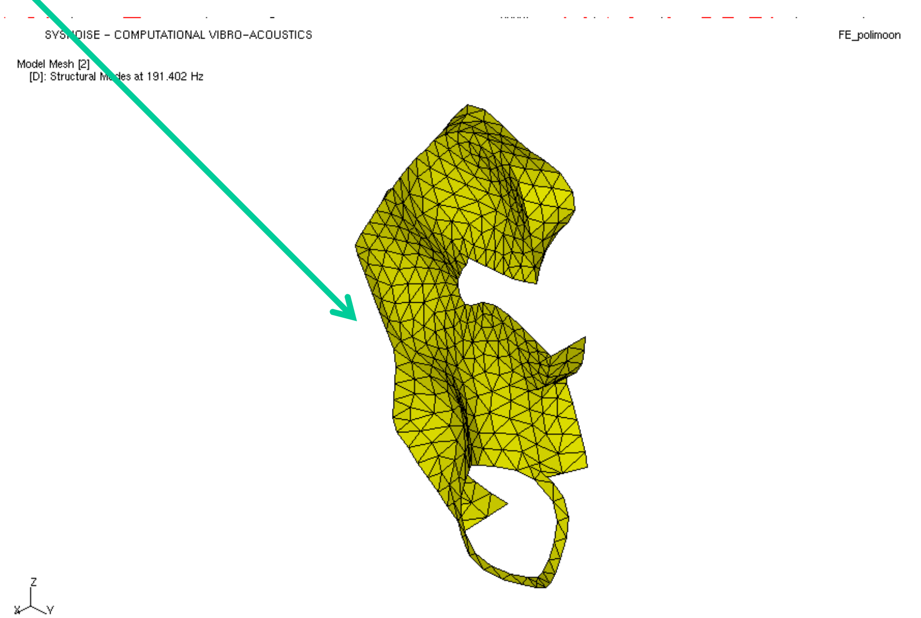


At worst frequency

Sound pressure
near the cover

Problem identification

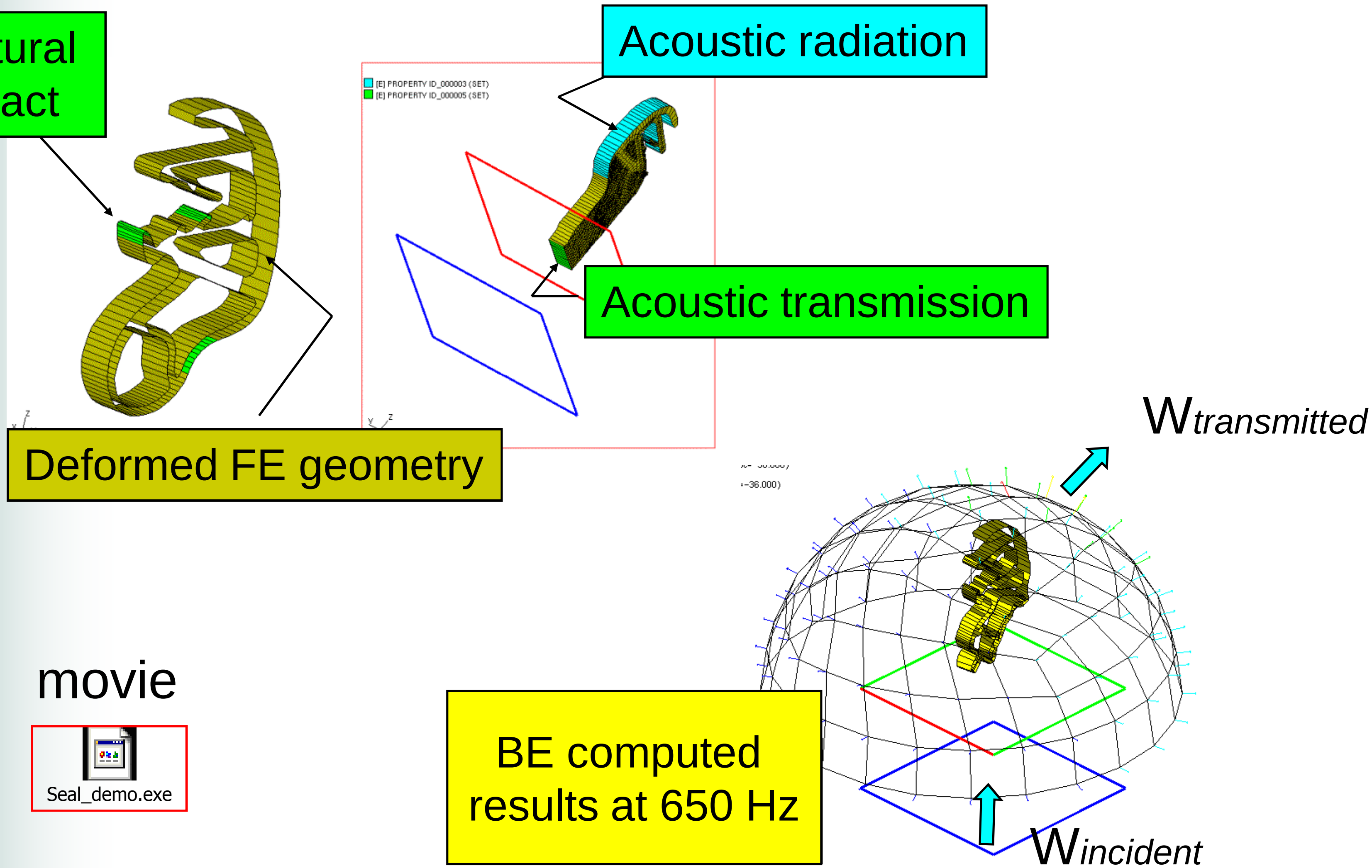




Structure excitation problem mode

Example: fully coupled analysis

– Sound transmission through a rubber seal



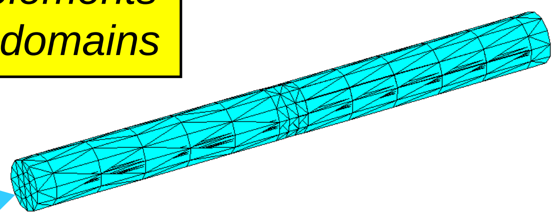
movie

Seal_demo.exe

Example: Infinite FEM – *fully coupled analysis interior/exterior domain*

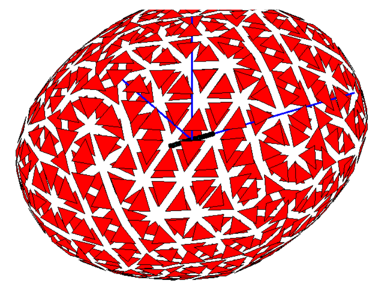
Interior domain

These elements link the domains



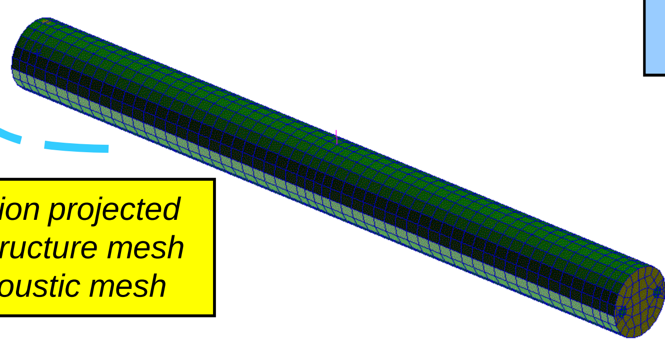
Acoustic domain

Exterior domain



Structure

Structure domain

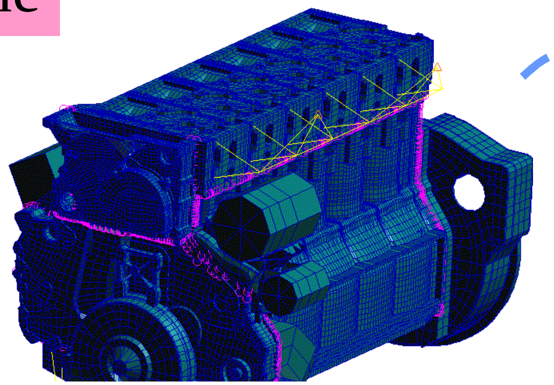


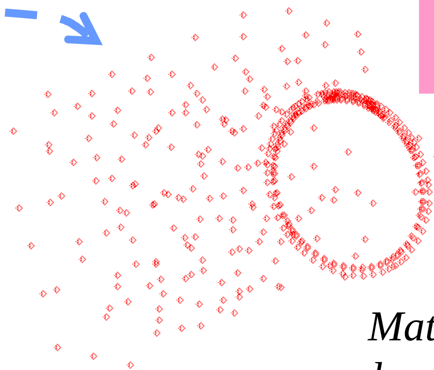
Vibration projected from structure mesh to acoustic mesh

Infinte elements are located on the 'egg' shell to prevent acoustic reflection

Example: Modal substructuring

Engine



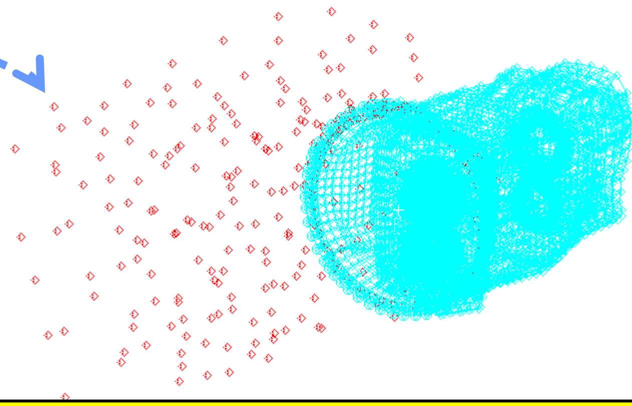


Component mode model

Mathematical model description not shown

‘Engine’ with gearbox

Local modes model



Physical model

Modes up to 1300 Hz	
Engine model: 8926s (CPU)	Full model: 4h6min
CompModes only: 18s (CPU)	SEREP/physical model: 6min34s (est.)
Ratio: *495*	**Ratio**: *38*

- Julius Bendat

Think like a computer
and
- you will soon be replaced by
one

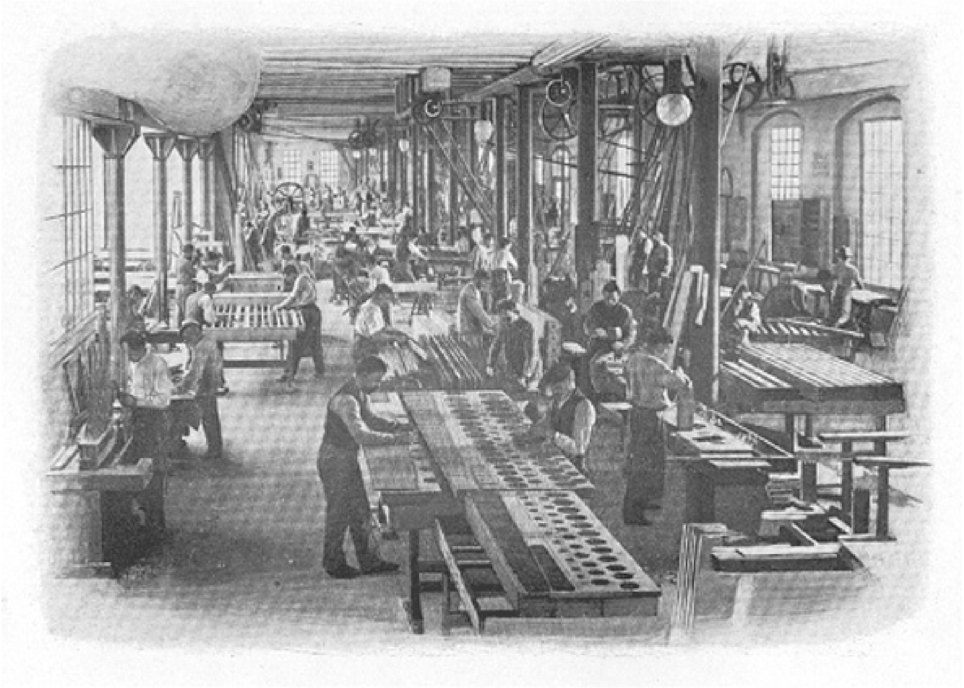
Fun statement – but, is it really true?

Current workstyle:

Close to handicraft, project may not complete if one 'maestro' drops out, results may easily vary from one operator to the next due to unstructured process

To be workstyle:

Combine skills, exploit automation, assemble work tasks into as few tools as possible, move data faster, strive for operator independence on quality for end result



QRING

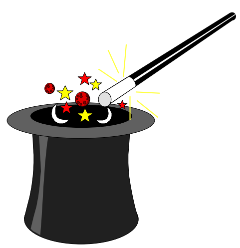
A new way of working

There are four key elements in the work methodology

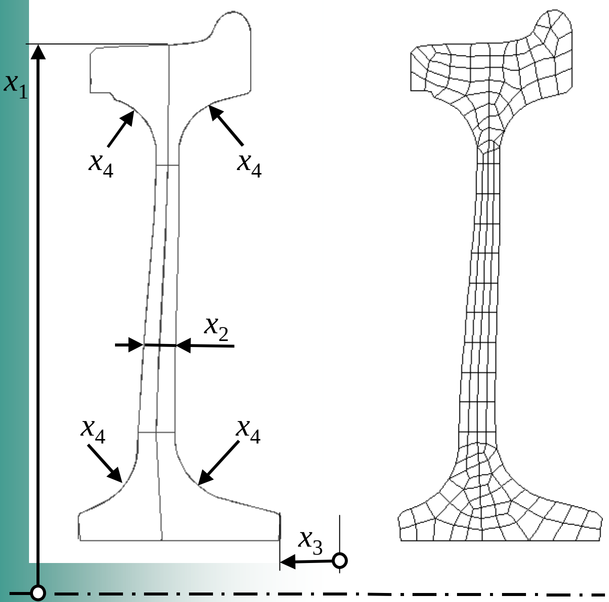
1. **Automate** the workflow. *'work 8 days a week'*
2. Use **Design of Experiments** (DoE) theory to plan work.

   Maximize the analysis power per simulated case.
3. **Optimize**. *Use stepwise refinements, or DoE based design space exploration techniques.*
4. **Multidisciplinary**. *Team up for integrated approaches*.

Combine resources and disseminate knowledge to stay competitive



A low noise wheel, with low track wear (low weight) & maintained fatigue resistance from combination of MSC/PATRAN, MSC/NASTRAN, TWINS and MATLAB & shape optimization (4 design variables) and constrained layer damping CLD (thickness, 1 design variable).



4 / (5) input variables,

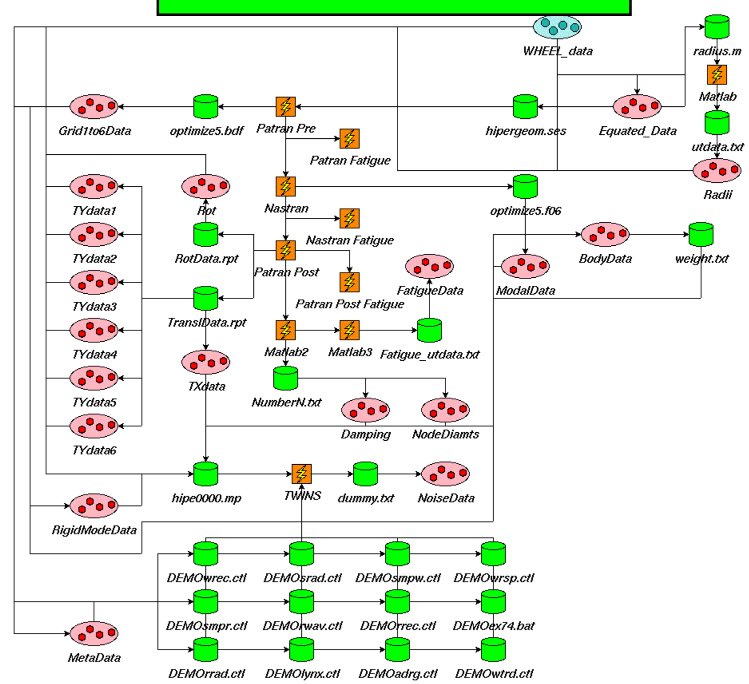
720 intermediate variables

3 outputs

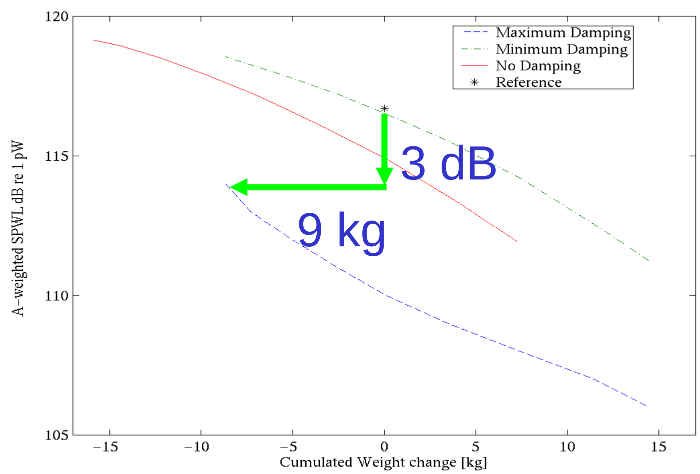
(weight, SPWL, fatigue stress)

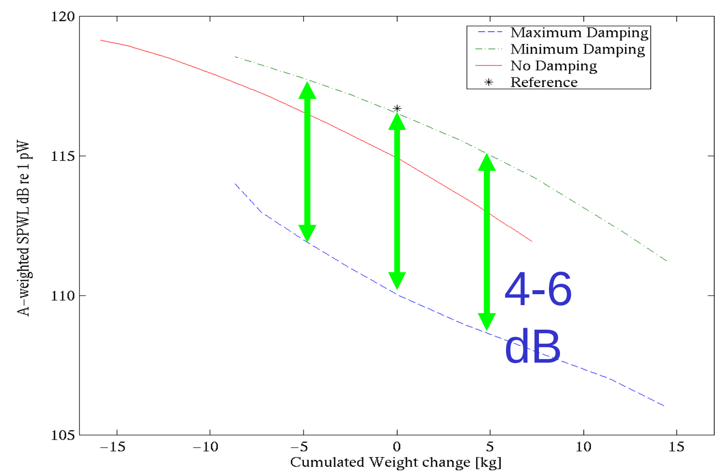
81 designs were executed
and analysed in ~2.5 hours
by **two** experts
(HP C3600 computer and Pentium II PC)

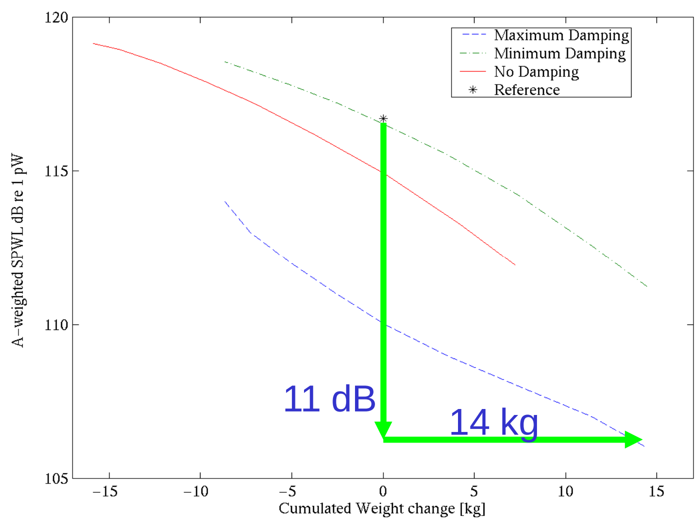
Automated workflow

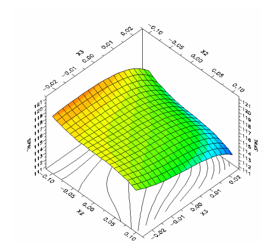


'dB/kg': *Several optima*

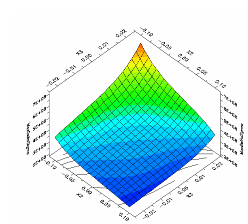




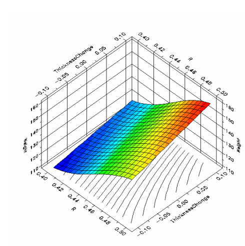




A-weighted sound power



fatigue stress



weight

Response Surface Models (RSMs) where Sound, Fatigue & weight are expressed as functions of wheel dimensions

A reduced risk – *perhaps, not always*

- Optimizer engines will find and exploit any **loopholes** in your thinking.
- So - the result of optimization depends very much on how you pose your question to the system and how you let it operate in the search for the answer.

- **Optimization takes time** – you must make your analysis model fast to be able to exploit the technique.
- Poorly thought out or badly executed optimization, can therefore become a drain of time and resource.

Thank you for taking the time