POLYTECH.MONS

Pyroshock identification using deconvolution methods in the frequency and time domains

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ThalesAlenia Space
A Thales / Finmeccanica Company

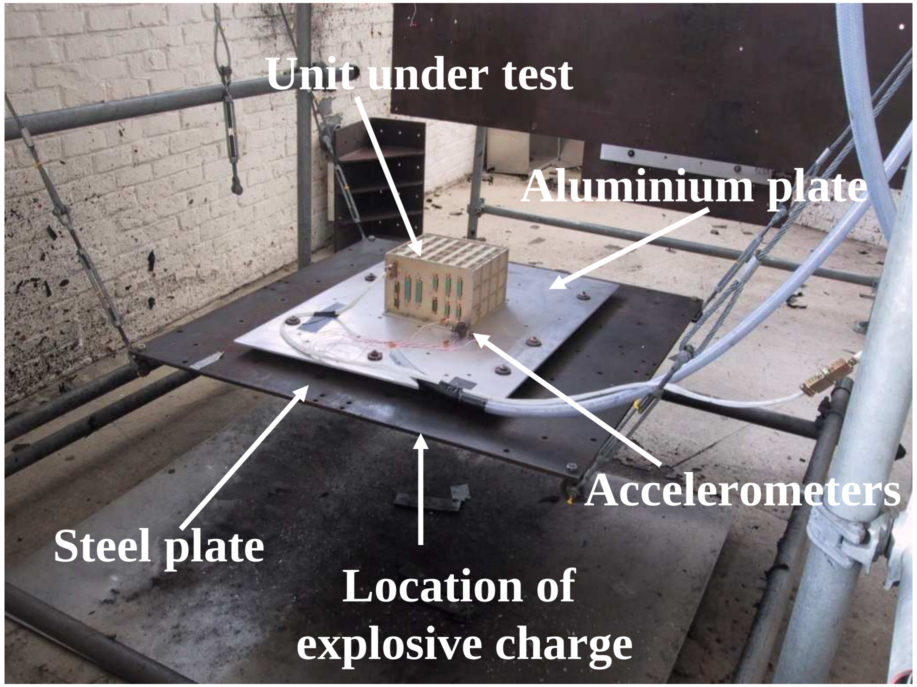
Context of the research

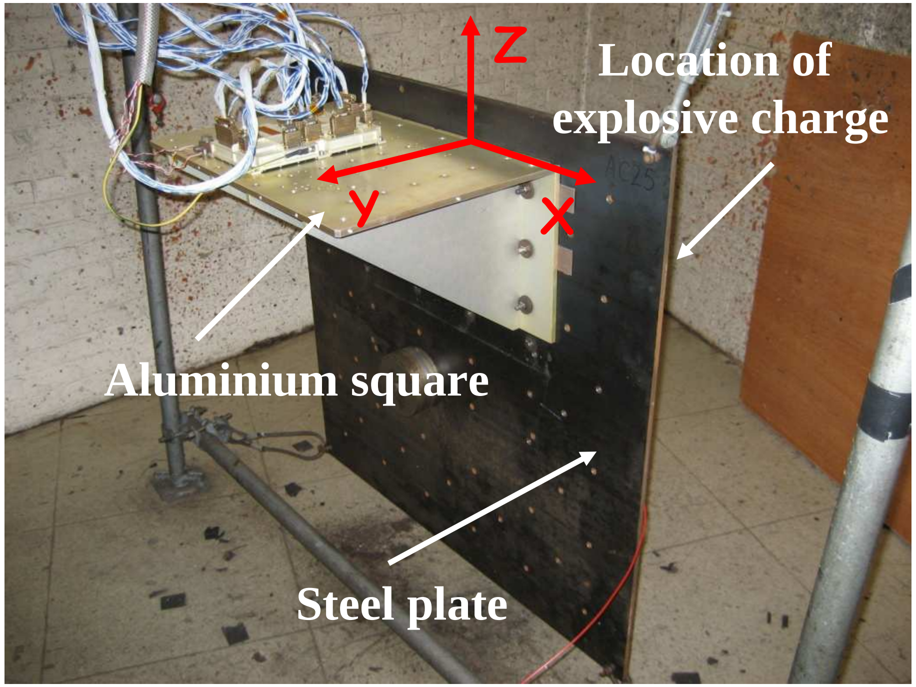
- In space industry, material suppliers must demonstrate that their equipment can stand the onboard vibrations

- Tests based on pyrotechnic excitations are largely used due to
  - the (high) required level;
  - the impulsive nature of the actual excitation

Thales pyroshock test facility

- As an electronic supplier for space vehicles, Thales disposes of a pyroshock test laboratory
- Different configurations exist





How to tune the parameters of the facility (number of plates, material, amount of explosive,…) to meet the specifications ?

Pyroshock model

Purpose of the research**:** develop a pyroshock model of the test facilities used by Thales Alenia Space ETCA (Belgium – Charleroi) in order to help in tuning the parameters so as to meet the SRS specifications

The pyroshock model requires

Dynamic model of the test facility

- Updated Finite Element Model (wrt experimental modal analysis)

Description of the excitation sources

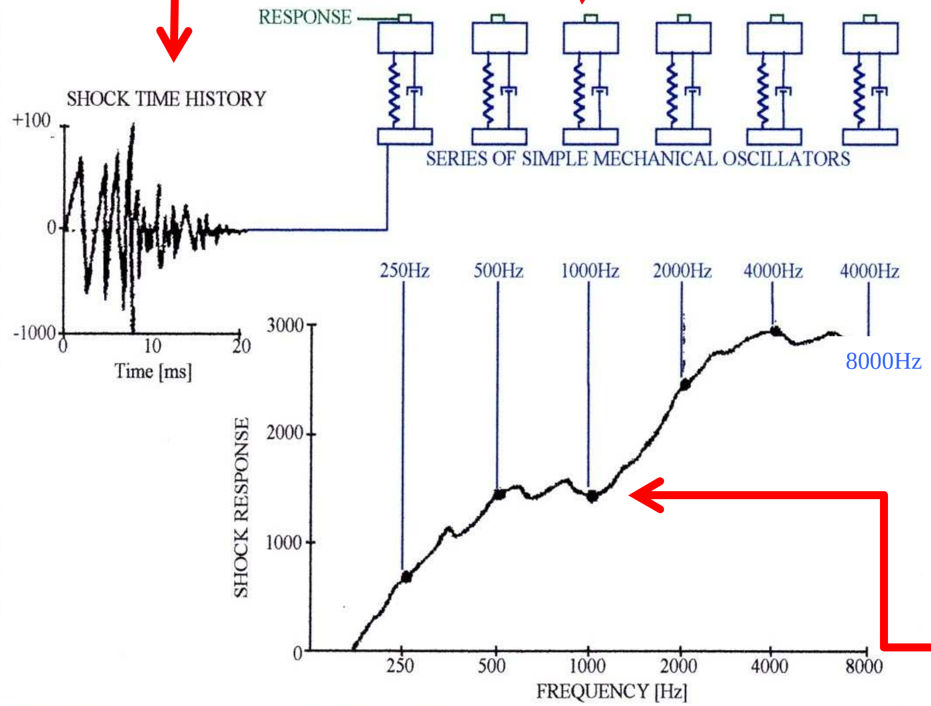
Identification by inverse methods

- Deconvolution Methods
- Equivalent Mechanical Shock (EMS)

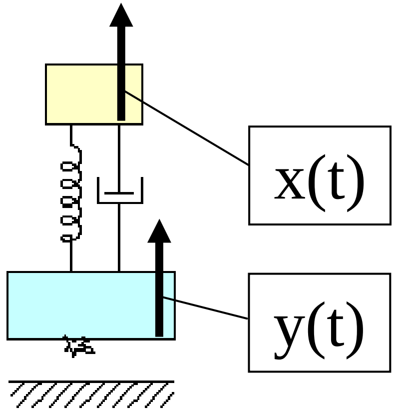
Shock Response Spectrum (SRS)

Data — **Choice of a frequency f** → **Motion equation of the corresponding oscillator**

($\omega_0 = 2\pi f$)



$$\ddot{\delta} + 2\xi\omega_0\,\dot{\delta} + \omega_0^2\,\delta = -\ddot{y}$$



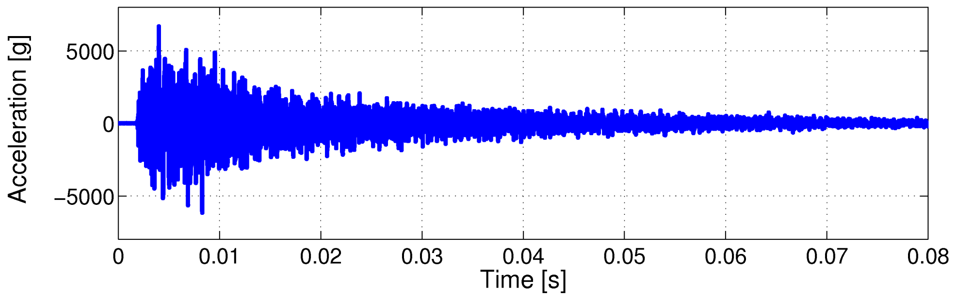
$$\delta(t) = x(t) - y(t)$$

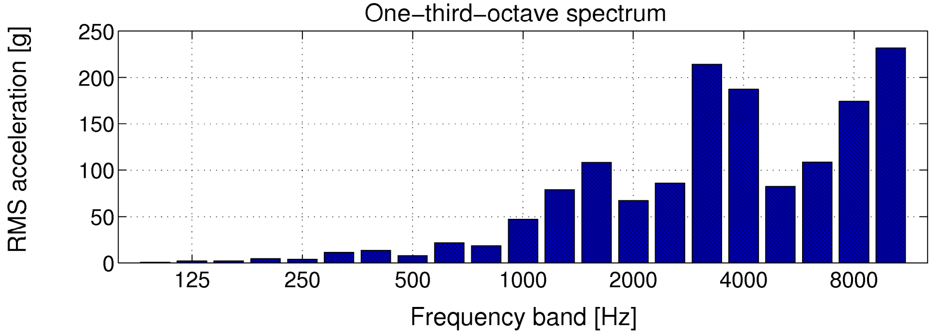
$$SRS(f) = \omega_0^2\,|\delta_{max}|$$

For pyroshock specifications $\xi = 5\%$

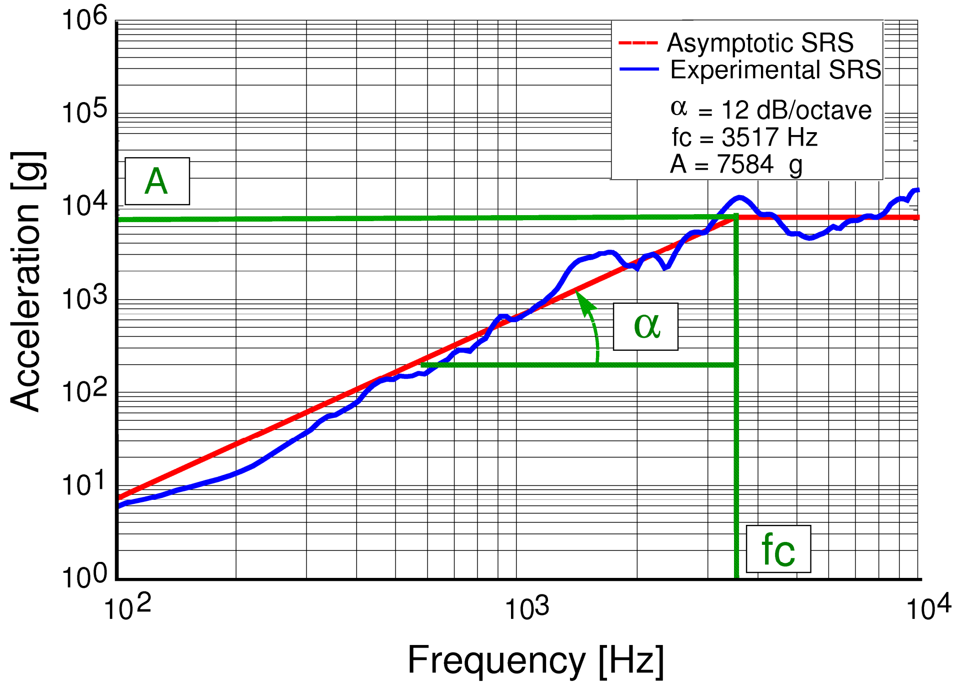
Example of SRS

Time history of the acceleration for a typical pyroshock





The associated SRS

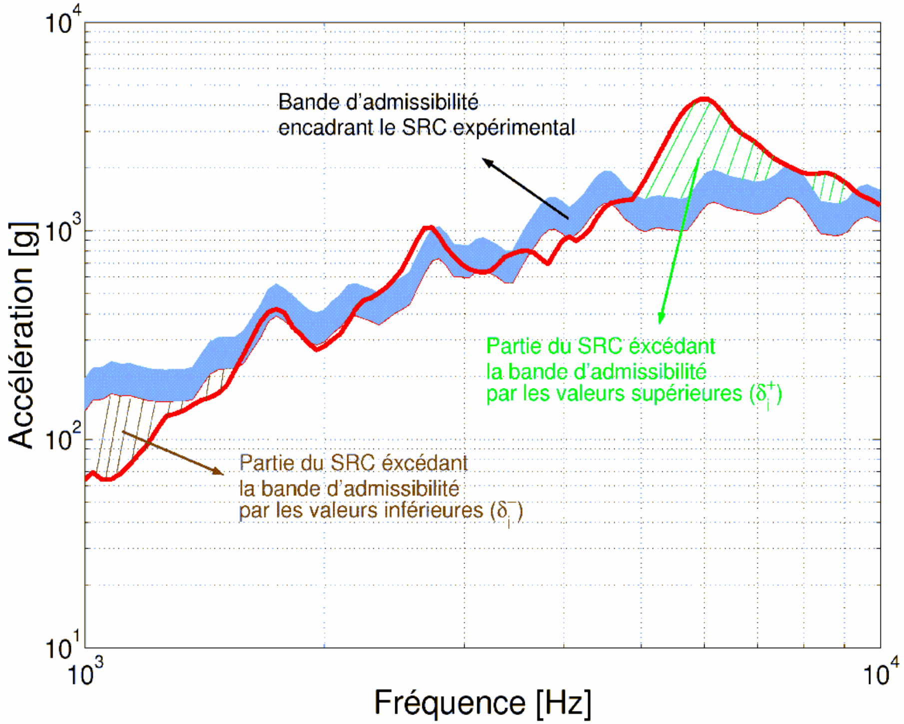


SRS is not FFT !

Statistical indicators to compare SRS

• $\Delta_i(f)$: represents the difference at frequency *f* between experimental and simulated SRS in terms of frequency for node number *i*

$$\Delta_i(f) = \left| SRS_i^{simulated}(f) - SRS_i^{Measured}(f) \right|$$



• $\mu(\Delta_i)$ and $\sigma(\Delta_i)$: correspond to the mean and the standard deviation of the indicator Δ_i(f) along the frequency range [1 – 10 kHz]

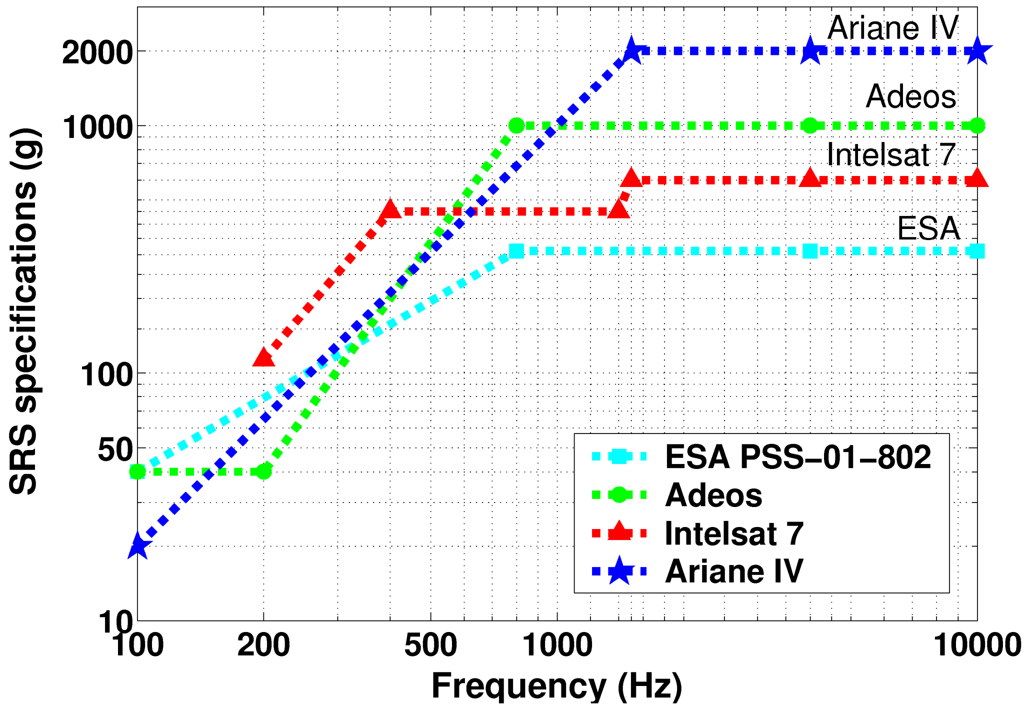
• $\delta_i^{+(-)}$: purcentage of the SRS exceeding the acceptability band by the superior (inferior) value for the node number *i*

• $S_{-1.5dB}$: mean purcentage exceeding the acceptability band considered on the **whole set of measured nodes**

$$S_{-1.5\,\mathrm{dB}} = \frac{1}{N_{\mathrm{SRS}}} \sum_{i=1}^{N_{\mathrm{SRS}}} (\delta_i^+ + \delta_i^-)$$

• μ_G and σ_G : represent to the mean and the standard deviation respectively of the frequency difference between experimental and simulated SRS considered on the **whole set of measured nodes**

Pyroshock specifications

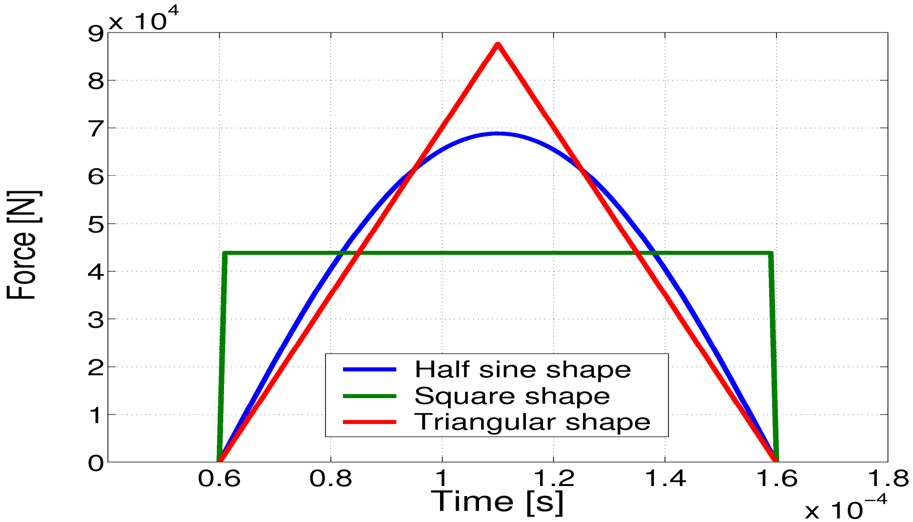


Difference admitted between specified and applied SRS

- ± 6 dB for natural frequencies ≤ 3000 Hz
- +9 dB/-6 dB for natural frequencies > 3000 Hz

Equivalent Mechanical Shock

Definition: EMS corresponds to the mechanical force which has to be applied to the FE model to generate equivalent acceleration fields



Hypotheses:

- Linear model
- localized impact (center of the explosive charge)
- Unidirectional impact

Parameters of the EMS

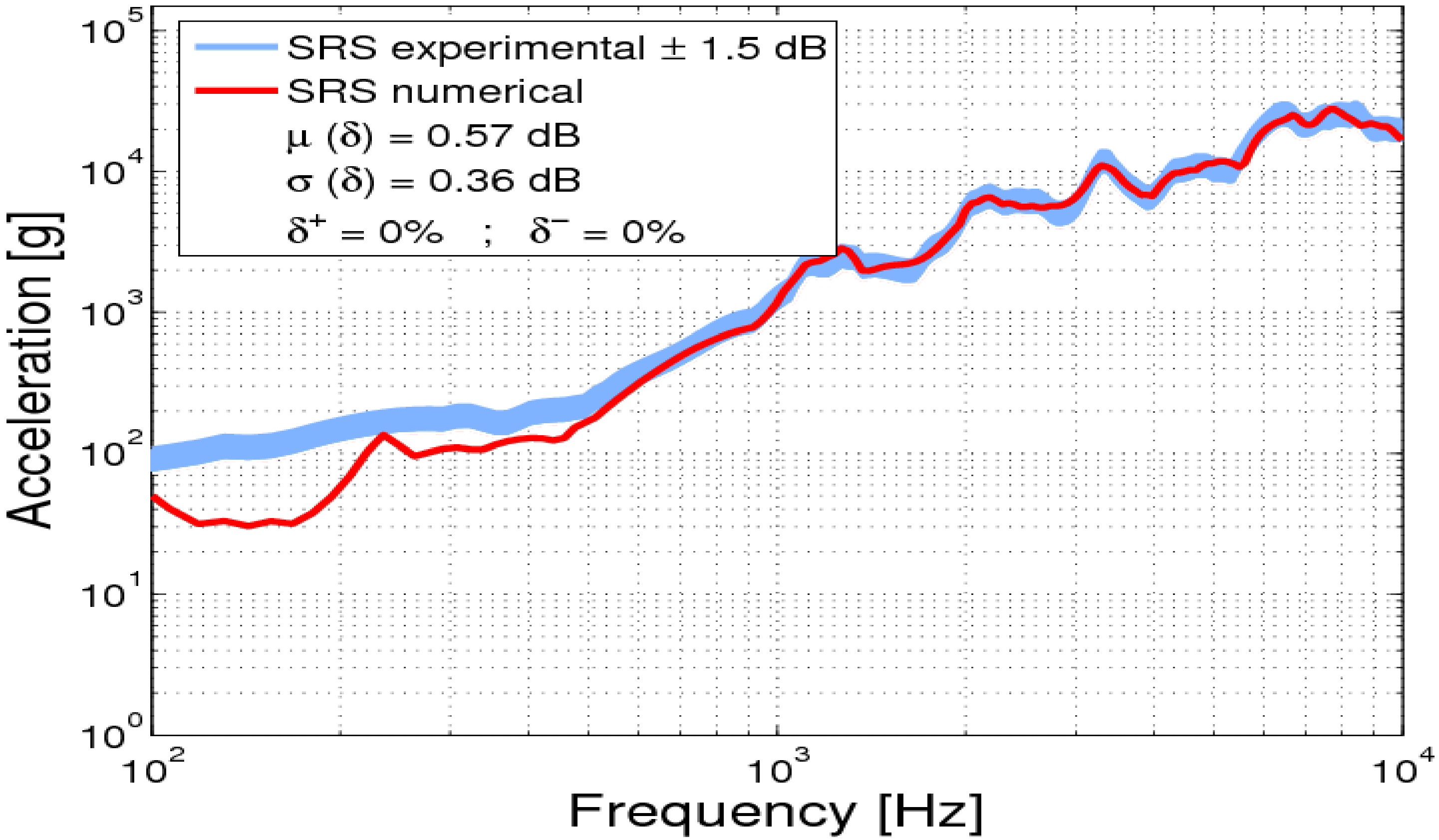
- ❑ The intensity F_{max} of the impact
- ❑ The duration τ of the impact

=> F_{max} and τ are chosen so as to minimize the gap between experimental and simulated SRS

Results of EMS

- Very good match between experimental and simulated SRS
- the shock identified on a structure gives good SRS when applied on another structure

Admissibility Band ± 1.5 dB



Deconvolution - Definition

Direct problem: find response from the force

In a linear system, input force f and response x are linked by

$$x(t) = h(t) \otimes f(t) = \int_{-\infty}^{\infty} f(\tau)\, h(t-\tau)\, d\tau$$

Excitation force (at a given point)

Response

Response for impulse at the same point (characteristic of the structure)

Inverse problem: find force from the response

Principle of the deconvolution: find g(t) (Wiener's filter) so that

$$f(t) = g(t) \otimes x(t) = \int_{-\infty}^{\infty} g(\tau)\, x(t-\tau)\, d\tau$$

Convolution in frequency domain

In frequency domain the relationships become

$$x(t) = h(t) \otimes f(t) \leftrightarrow X(\omega) = H(\omega) \cdot F(\omega)$$

$$f(t) = g(t) \otimes x(t) \leftrightarrow F(\omega) = G(\omega) \cdot X(\omega)$$

And we deduce

$$G(\omega) = H(\omega)^{-1}$$

Unfortunately it is not so simple

- *H* may have zeros at some frequencies (solved if several points);
- Practically, there is a noise *b(t)* on *x(t)*

$$x(t) = h(t) \otimes f(t) + b(t)$$

- *f(t)* (or *H*) results from the model which also involves some imperfections

Frequency domain deconvolution

If the noise *b*(t) is not correlated with the force *f*(t) , the optimal Wiener's filter in the frequency domain is written:

$$G(\omega) = \frac{H^*(\omega)}{\left(|H(\omega)|^2 + \beta(\omega)\right)} \quad \text{with} \quad \beta(\omega) = \frac{S_{ff}}{S_{bb}}$$

The excitation force in the frequency domain is given by

$$F(\omega) = G(\omega)\, X(\omega) = \frac{H^*(\omega)\, X(\omega)}{\left(|H(\omega)|^2 + \beta(\omega)\right)}$$

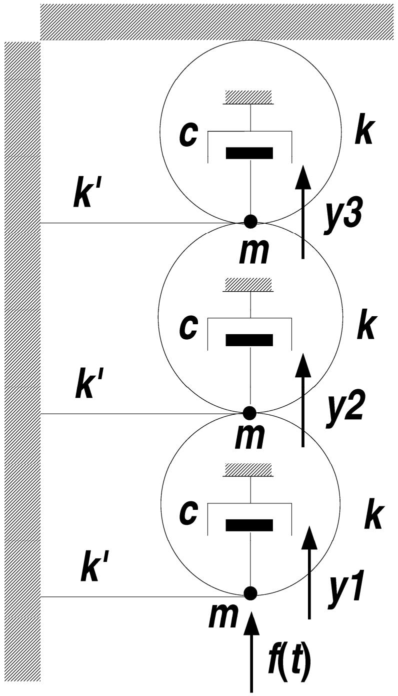
For *n* responses, the force spectrum is given by

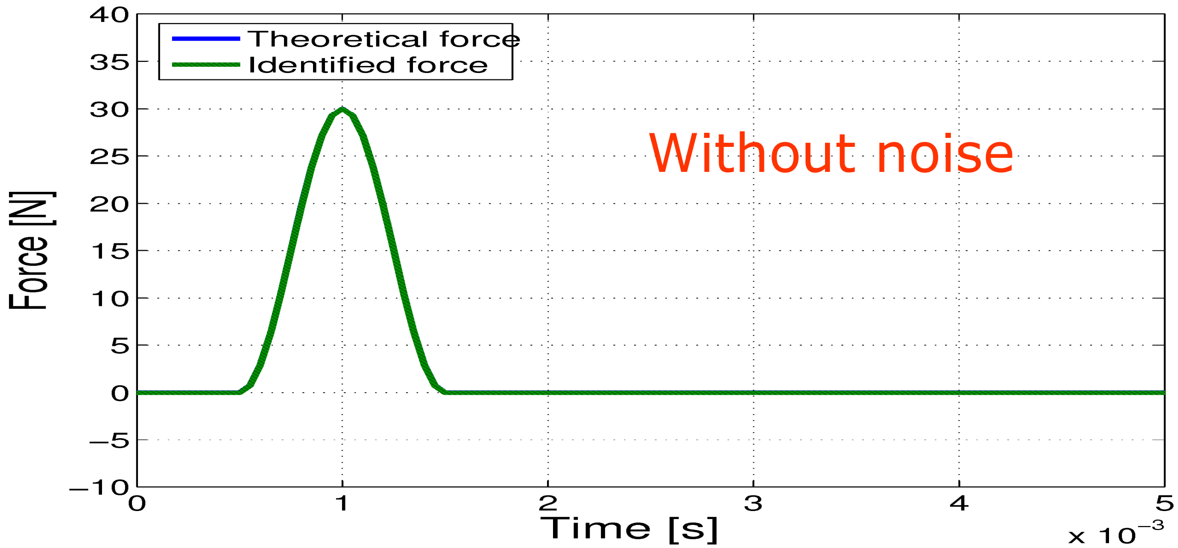
$$\{\mathrm{F}(\omega)\} = \left([\mathrm{H}]^{\mathrm{H}}[\mathrm{H}] + \mathfrak{R}[\mathrm{I}]\right)^{-1} [\mathrm{H}]^{\mathrm{H}} \{\mathrm{X}(\omega)\}$$

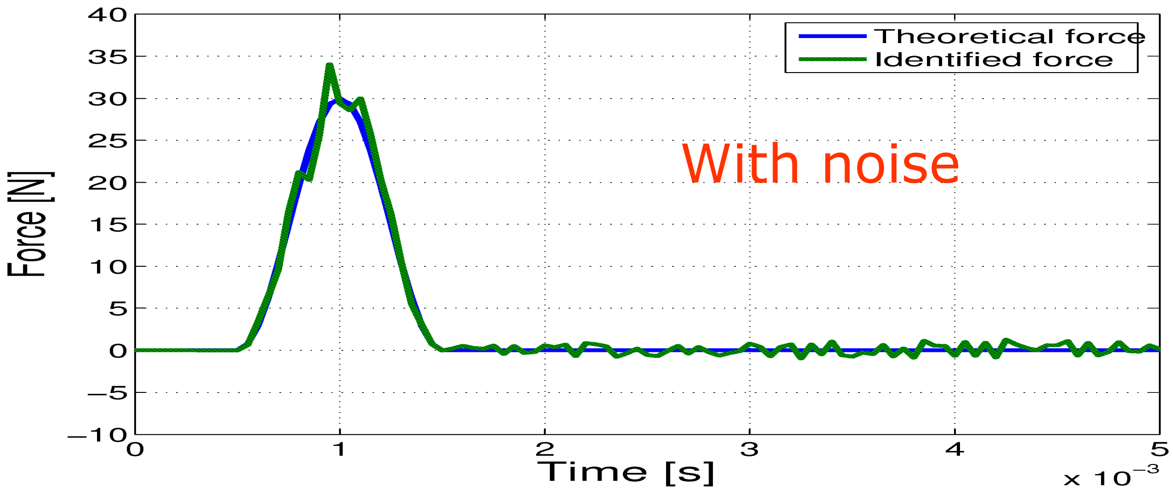
If the regularization term R(ω) is neglected, we come down to the principal coordinates method

A theoretical example

3 DOF system







Time domain deconvolution

Principle: the force profile is evaluated as a sum of weighted wavelets

$$f(t) = \sum_{b=0}^{M-1} \lambda_b \phi_b(t) \quad M < N$$

$N = T/h$

$M = t_m/h$

$h =$ sampling period

The force profile is automatically null after t_m

In our case, we retained the half-sine wavelet

$$\phi_b(t) = \begin{cases} \frac{1}{2}\left(1 - \cos\left(\frac{2\pi}{\tau}(t - b\tau_d)\right)\right) & b\tau_d \leq t \leq b\tau_d + \tau \\ 0 & \text{elsewhere} \end{cases}$$

τ is the duration of the wavelength

τ_d is the time shift between two successive wavelets (τ_d is taken equal to *h* here)

Time domain deconvolution

The amplitudes λ_b are found by solving

$$[\mathbf{G}]\{\lambda\} = \{\mathbf{X}\}$$

with

$$\mathbf{G}_{ij} = \int_0^T \psi_i(t)\psi_j(t)dt \qquad \mathbf{x}_i = \int_0^T \psi_i(t)x(t)dt$$

where $\psi_i(t)$ is the response of the system to wavelet ϕ_i

Rem: ψ_{i+1} is just ψ_i shifted by τ_d , so that the response of the system must be calculated only once.

For *n* responses, the system becomes

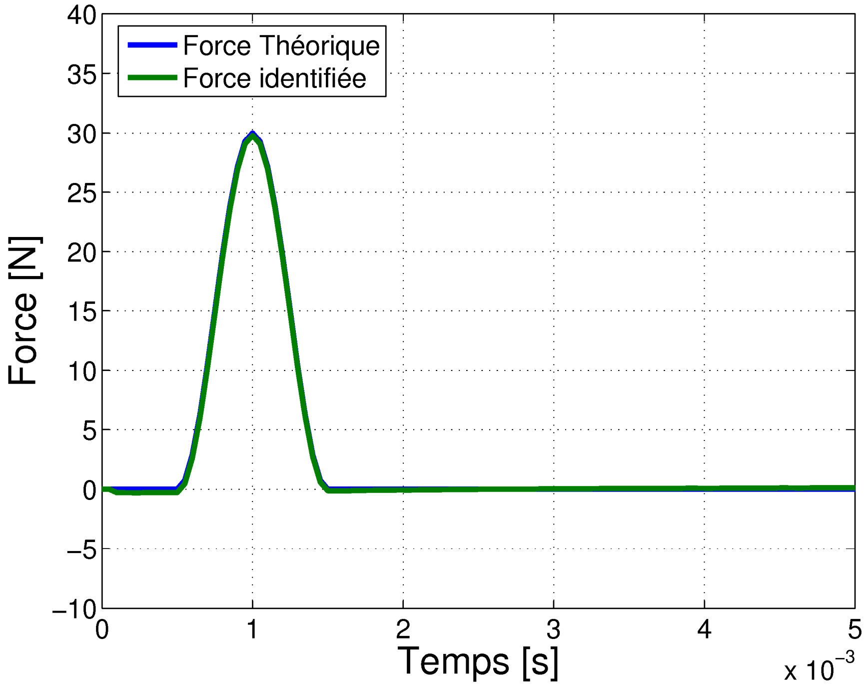
$$\left(\sum_i [\mathbf{G}_i]\right)\{\lambda\} = \sum_i \{\mathbf{X}_i\}$$

Results on a simple system

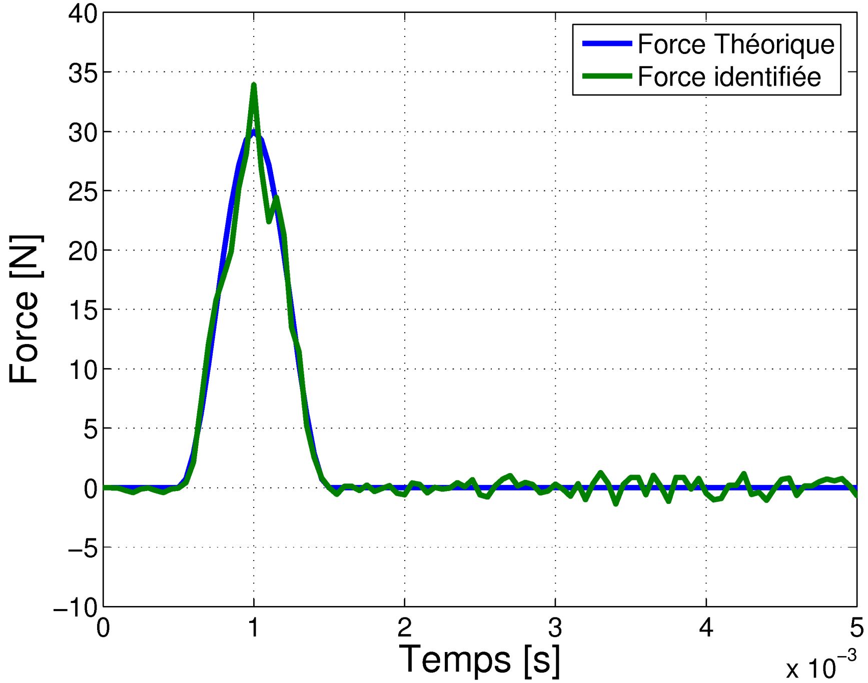
Results are comparable to the Wiener's method

T=1s, h=0.05 ms, M= ?, N= 20000, τ=0.0005 s , τ_d=h

Without noise



With noise

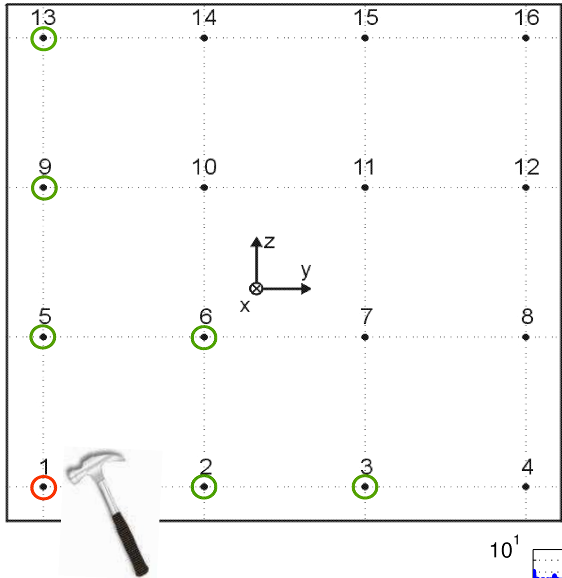


Advantages of the time domain

The advantages of the method are

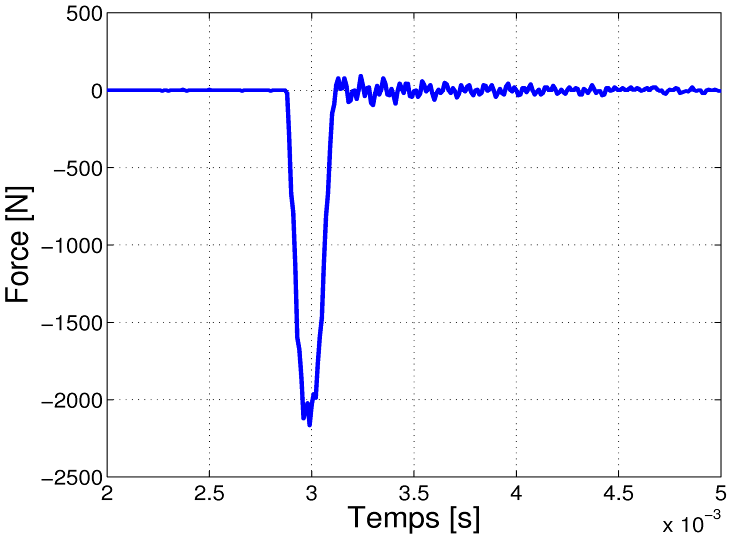
- The possibilty to limit the duration of the force (interesting for impluse loads)
- A better representation of the wave propagation in the structure (reflexions)

Application
Suspended plate and hammer impact



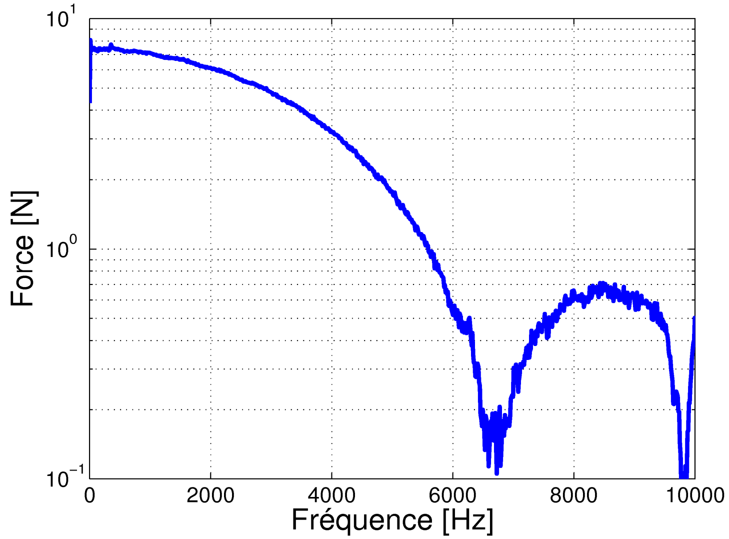
Characteristics of the plate

A	1 m^2
h	15 mm
ρ	7800 kg/m^3
E	207 GPa
ν	0.33



Acquisition parameters

T	$\approx$ 0.08 s
f_s	100000 Hz
N	8191

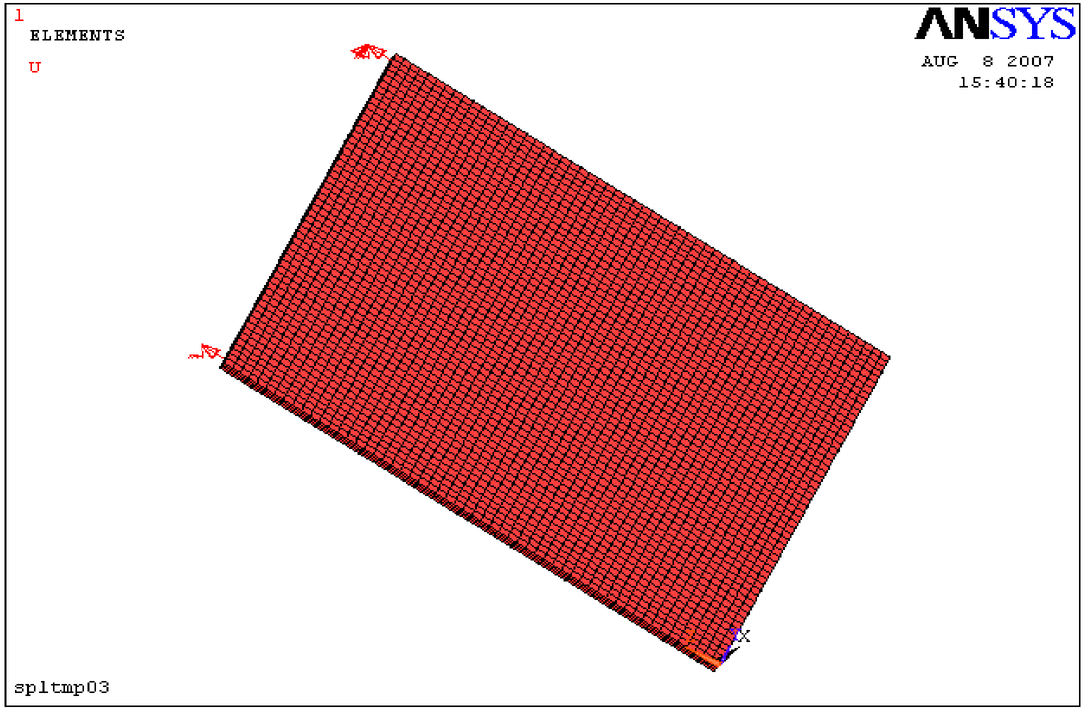


Finite Element Model

FE model built under ANSYS 8.1 software

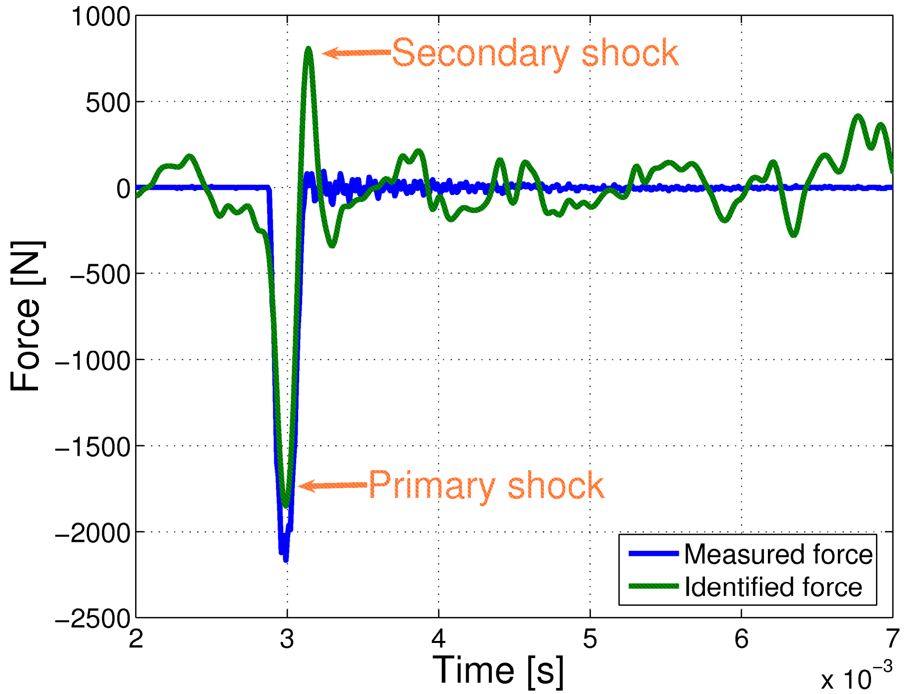
- Modelling of the plate with SOLID45 elements
- Six elements per bending wavelength
- Three elements along the thickness

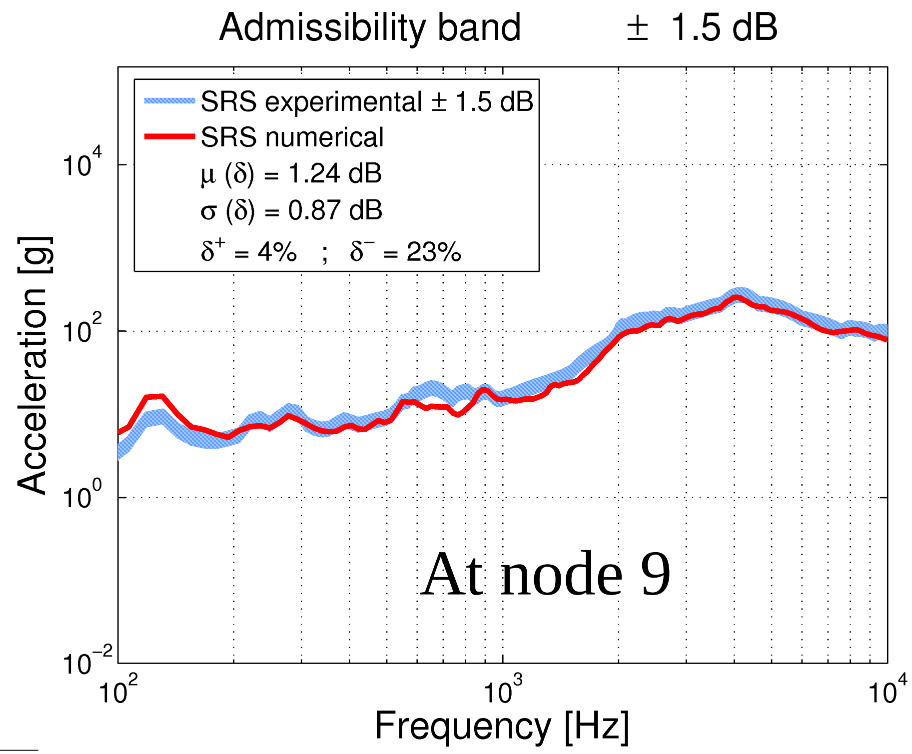
The model compares successfully to the results of an experimental modal analysis up to 1000 Hz



f^E (Hz)	f^S (Hz)	Δ_k (%)	MAC
47	49	3.4	0.98
92	89	3.7	0.85
124	127	2.5	0.69
231	224	2.4	0.88
282	282	0.6	0.98
457	445	2.6	0.83
488	477	2.2	0.77
493	498	1.2	0.84
564	560	0.73	0.98
622	635	2.1	0.80
738	730	1.0	0.64
790	771	2.5	0.85
796	803	0.9	0.73
897	919	2.4	0.68
898	899	0.1	0.66

Results of the Wiener's approach

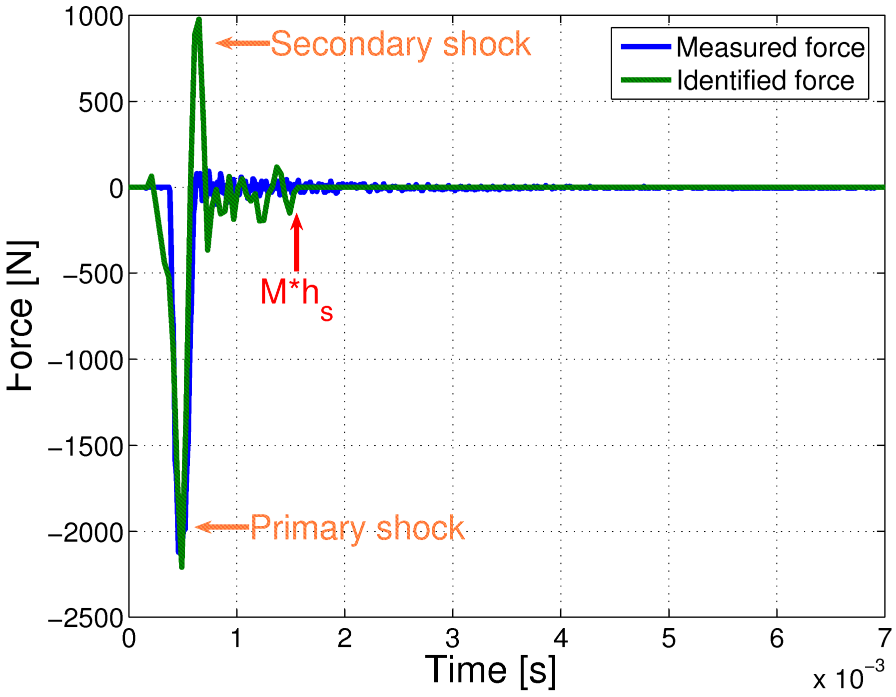


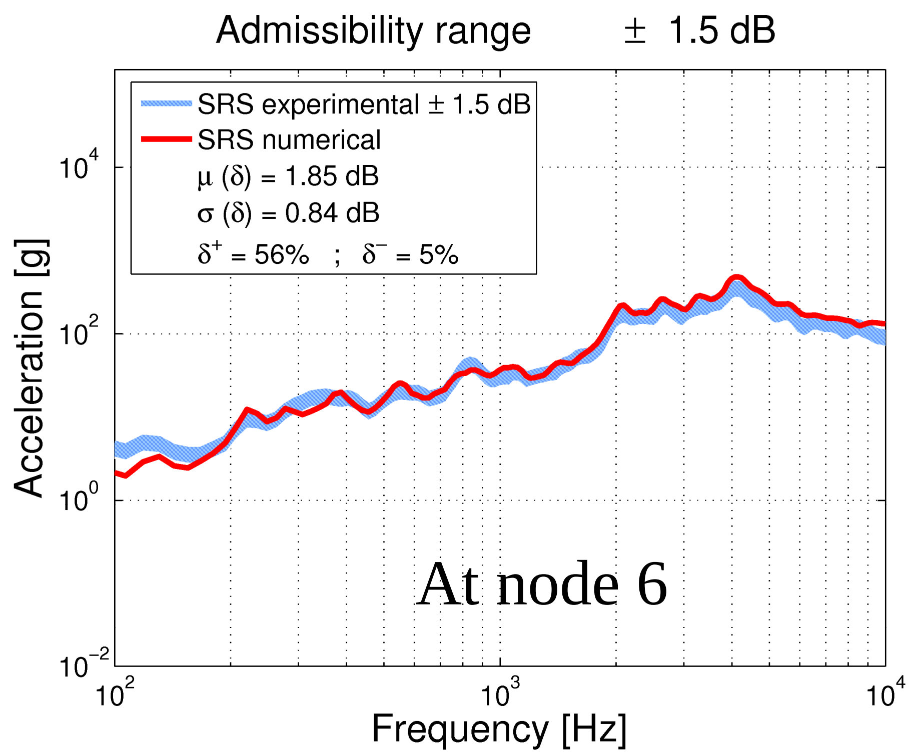


Wiener method ($\Re(\omega) = 0$)				
Nœud	$\mu(\Delta_i)$ (dB)	$\sigma(\Delta_i)$ (dB)	δ_i^+ (%)	δ_i^- (%)
6	1.67	1.03	1	49
2	1.37	0.94	1	31
3	1.36	0.91	3	35
5	1.44	1.17	1	38
9	1.24	0.87	4	23
13	1.81	1.15	3	42
	μ_G (dB)	σ_G (dB)	$S_{-1.5\,\text{dB}}$ (%)	
	1.48	1.01	38	

On average, the simulated SRS is lower than the actual one

Results with the wavelet decomposition





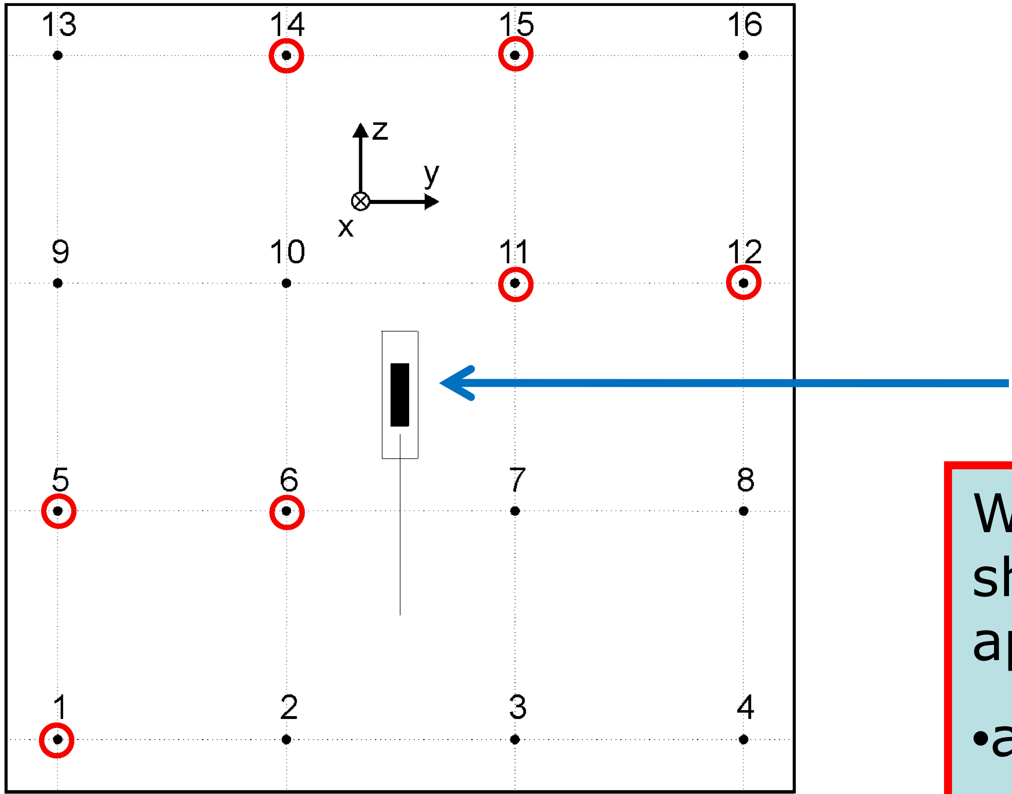
Wavelet decomposition method

Nœud	$\mu(\Delta_i)$ (dB)	$\sigma(\Delta_i)$ (dB)	δ_i^+ (%)	δ_i^- (%)
6	1.85	0.84	56	5
2	1.33	0.69	28	9
3	1.51	0.77	38	6
5	1.25	0.69	14	11
9	1.45	0.84	31	7
13	1.67	1.06	28	13

μ_G (dB)	σ_G (dB)	$S_{-1.5\,dB}$ (%)
1.51	0.81	43

The global level is better represented than for Wiener

Application: suspended plate and pyroshock

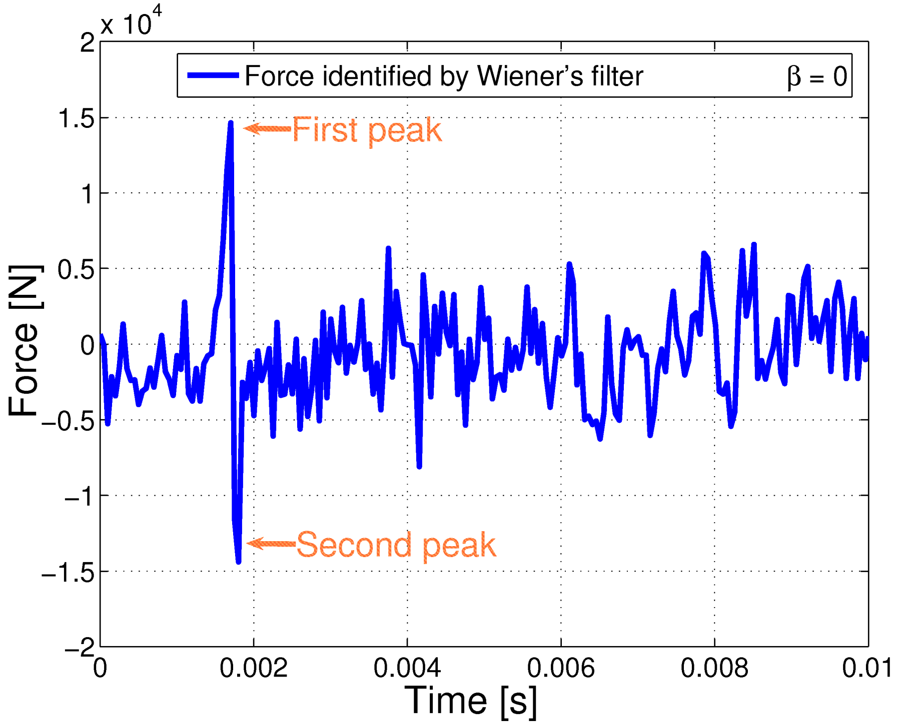


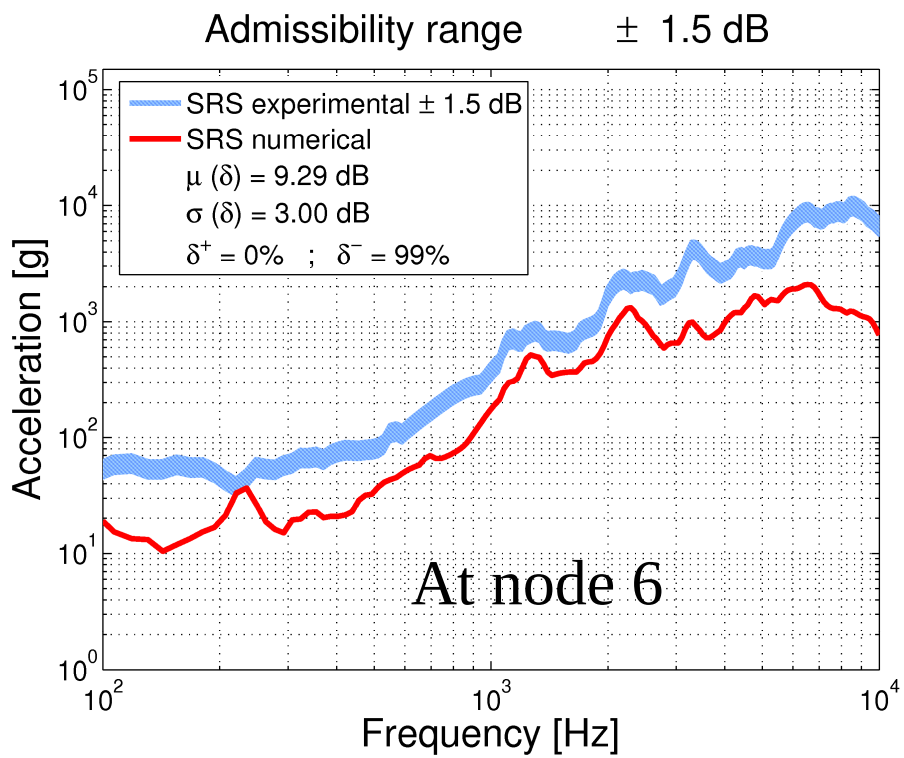
Explosive charge

We try to reproduce the shock by a single force applied

- at the center of the plate
- perpendicularly to the plate

Results with Wiener's filter



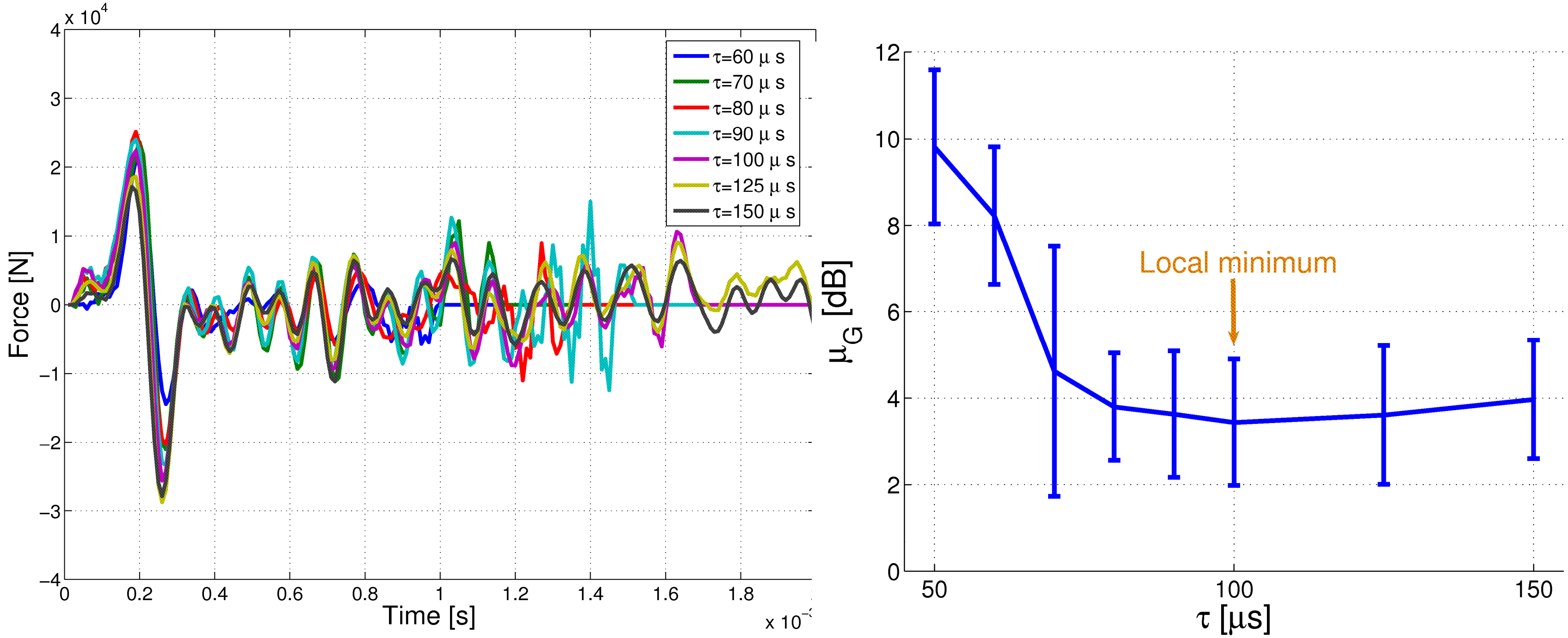


Wiener's method ($\Re(\omega) = 0$)				
Nœud	$\mu(\Delta_i)$ (dB)	$\sigma(\Delta_i)$ (dB)	δ_i^+ (%)	δ_i^- (%)
1	7.55	2.89	0	94
14	8.36	2.60	0	100
11	9.22	2.99	0	100
6	9.29	3.00	0	99
15	9.13	3.13	0	100
12	8.95	3.03	0	100
5	9.48	2.77	0	100
	μ_G (dB)	σ_G (dB)	$S_{-1.5\,\text{dB}}$ (%)	
	8.85	2.91	99	

The global level is seriously underevaluated !

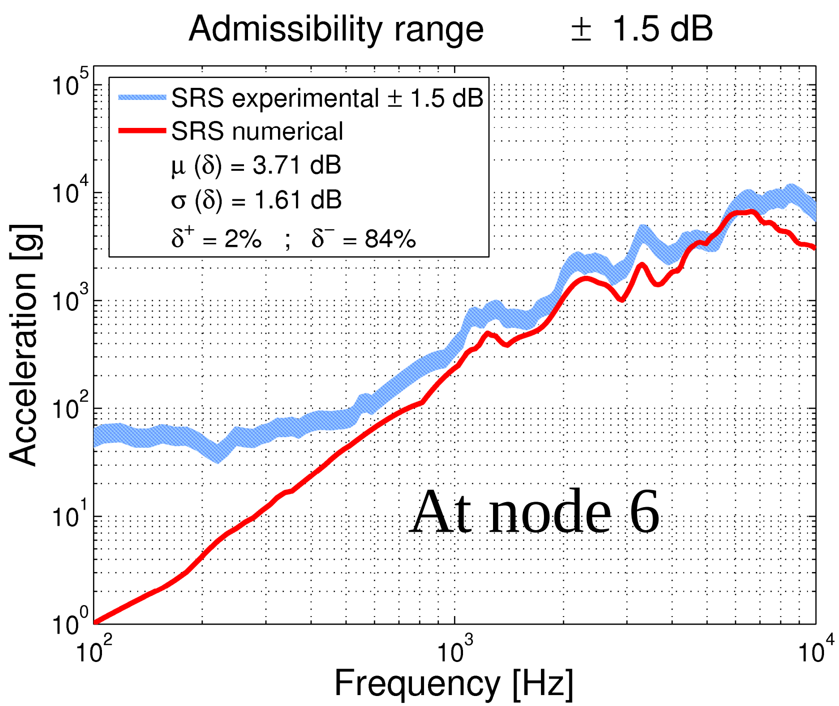
Application of the wavelet deconvolution

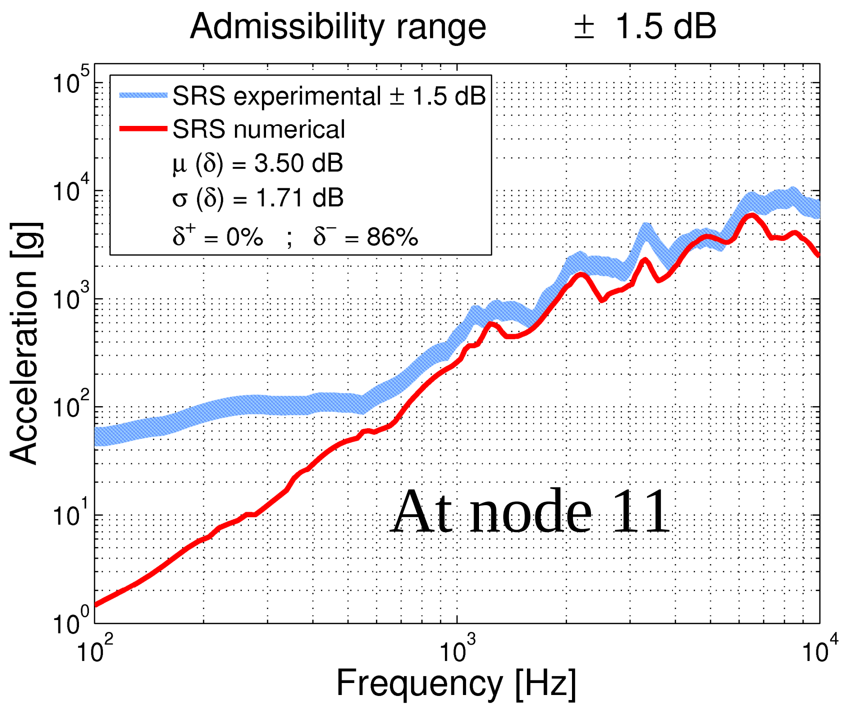
The duration of the wavelet influences the results



The duration of the wavelet shouln't be too short !

SRS obtained from the wavelet deconvolution





The level is too low, especially below 1kHz

Conclusions

- Purpose of the research is to a reliable pyroshock model (structure+excitation) in order to be able to make the test device as close as possible to specifications by simulation

- Two deconvolution methods have been presented in order to identify the pyroshock by an inverse approach
  - the Wiener's method in the frequency domain
  - the wavelet deconvolution method in time domain

- Both methods behave properly for hammer impacts

- Both methods are unable to properly identify the profile of a localized force equivalent to a pyroshock

CONTACTS

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Comparison EMS - wavelet

	Wavelet analysis				EMS		
Length	F_{max} (N)	τ (μs)	$F_{max} * \tau$	2 $F_{max} * \tau$	F_{max} (N)	τ (μs)	$F_{max} * \tau$
0	23947	$\approx$ 100	2.39	4.79	83518	60	5.01
4 cm	29468	$\approx$ 100	2.94	5.89	129830	60	7.79
10 cm	43415	$\approx$ 100	4.34	8.68	203980	60	12.24
20 cm	67250	$\approx$ 100	6.86	13.45	199260	80	15.94