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Division V

GENERATING MOTION FOR SEISMIC QUALIFICATION OF COMPONENTS ON SEMI-RIGID SUPPORTS. APPLICATION TO THE ITER LEAK DETECTION SYSTEM

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INTRODUCTION

The determination and the control of the seismic motion transferred to the mechanical components and their supporting structures represent a major issue for the seismic design of non-structural elements, the anchoring and the seismic qualification of active components. Structures that can not be considered as completely rigid are very commonly used in the industry. This type of support may amplify the input seismic motion imposed by the building structure. It is interesting to use simplified analytical formulae to generate the FRS transferred by these support from the input FRS provided in the building structure.

This paper presents an adaptation of the approach promoted in several (French) working groups within the Association Française du génie Parasismique (AFPS) in charge of drafting guideline for critical industrial facilities and for critical facilities (hospital, school, emergency facilities). The methodology has been applied to a component of the ITER Fusion facility under construction in Cadarache (France).

SIMPLIFIED METHOD TO GENERATE SEISMIC SPECTRA

The approach promoted in several (French) working groups within the Association Française du génie Parasismique (AFPS) in charge of drafting guidelines for critical industrial facilities and for critical facilities (hospital, school, emergency facilities) has been applied and improved. The AFPS guidelines for the supporting structures of critical industrial facilities propose a simplified formula based on the work developed inside the French Association for Earthquake Engineering (AFPS, 2011 and 2013) and the German standard for nuclear facilities (KTA, 2012).
The seismic floor response spectrum is given by the following formula:

$$a_H = S_a\left(T_i, q_p, D_1\right) \times K_T(T_E, D_1, D_2) \quad (1)$$

where:

- $S_a\left(T_i, q_p, D_1\right)$: absolute acceleration at period T_i of the building, for the reduction factor q_p and damping factor D_1 of the building structure;
- q_p: reduction factor taking into account the nonlinear behaviour of the building structure, the support of the equipment and the equipment itself;
- D_1: damping factor for the building structure;
- $K_T(T_E, D_1, D_2)$: amplification factor taking into account the interaction between the building structure and the equipment;
- T_E: period of the equipment;
- D_2: damping factor for the equipment.

The zero period acceleration (ZPA) of the floor response spectrum, with a reduction factor $q_p = 1$, is given by:

$$S_a = \sqrt{\bar{\gamma}^2\left(1 - \sum_{i=1,N}\Gamma_i\varphi_i\right)^2 + \sum_{i=1,N}(\Gamma_i\varphi_i S_a(T_i))^2} \tag{2}$$

- $\bar{\gamma}$: ground acceleration for T = 0;
- S_a : spectral acceleration of the design spectrum at period T_i. If S_a is known for 5% damping (for EC8) and the modal damping is different from 5%, a correction factor (n_1) has to be applied to S_a;
- φ_i: i^{th} mode shape value;
- Γ_i : modal participation factor for mode i;
- N: number of dynamic modes considered;
- The amplification function for a damping value of 5% for the building structure and 5% for the equipment is given by the formulas:

$$K_T = 1 \qquad \text{if: } f_{limit} < f_E \tag{3a}$$

$$K_T = 5n - \left[(5n-1)(log(1.2\frac{f_n}{f_E})/log\frac{1.2f_n}{f_{limit}}\right] \qquad \text{if: } 1.2f_n \le f_E \le f_{limit} \tag{3b}$$

$$K_T = 5n \qquad \text{if: } 0.8f_1 \le f_E \le 1.2f_n \tag{3c}$$

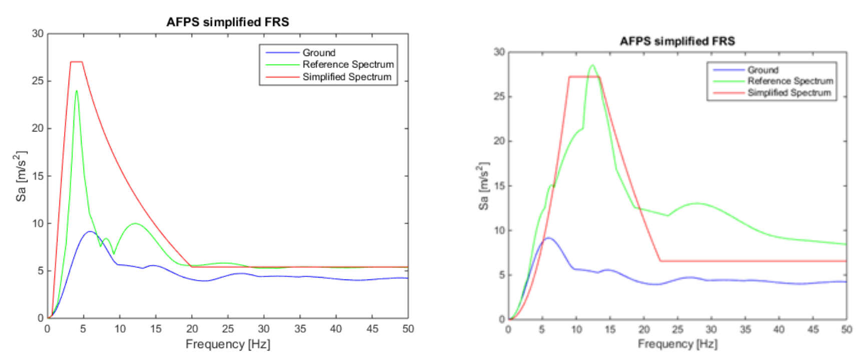
$$K_T = 5n/\left(0.8\frac{f_1}{f_E}\right)^2 \qquad \text{if: } f_E \le f_1 \tag{3d}$$

- f_1 to f_n – main eigenmodes of the building in the considered direction ;
- f_{limit} – limit frequency equal to 16.7 Hz [7] ;

For different values of damping for the building structure and for the equipment:

$$n = n_1 \times n_2 \text{ with } n_1 = \sqrt{\frac{10}{5+D_1}}, \quad n_2 = \sqrt{\frac{5}{D_2}} \tag{4}$$

For 5% damping in the system, in case of resonance between the building structure and the equipment, the amplification factor is equal to $K_T = 5$.
Details of these formula and example of applications are given in Combescure *et al*. (2021).



a: Flexible structure (f_1=4.0Hz, f_2= 10.5Hz) b: Stiff structure (f_1=11.2Hz, f_2=29.4Hz)

Figure 1. Comparison between time-history (green) and the original AFPS simplified method (red) with different input motion (blue)

The approach has been adapted to the case of semi-rigid supports with input FRSs with potential complex shape. The results obtained from the original simplified method have been compared to results of time-history analysis on two simplified models of structure/support with 2 dofs (Figure 1). In the case of a flexible structure (Figure 1a), we can observe that the original formula is envelop of the FRS determined with a time-history analysis. In the case of a stiff structure (Figure 1b), we can observe that the original simplified formula is not enveloping the FRS and the ground response spectrum at low frequency.

The original simplified formula has been modified by taking a weighted average between the ground spectrum and the peak value predicted by the standard simplified formulas.

$$S_a(f, D_1) = \alpha \cdot S_{a,\ ground} + (1-\alpha)\cdot S_a(f_{peak}) \qquad 0 \le f \le f_{peak} \tag{5}$$

The weight α is defined:

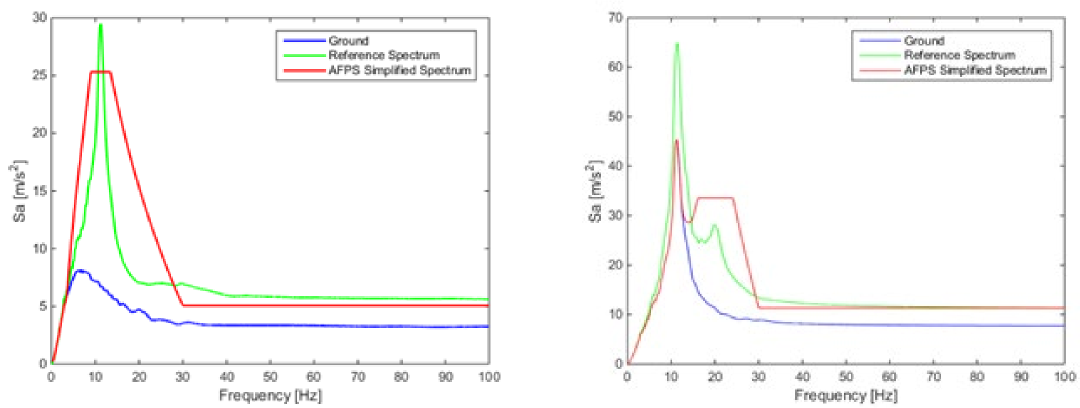
$$\alpha = \begin{cases} 1 & for\ 0 \le f \le k \cdot f_{peak,ground} \\ 1 - \frac{f - k\cdot f_{peak,ground}}{f_{peak} - k\cdot f_{peak,ground}} & for\ f_{peak,ground} \le f \le k \cdot f_{peak} \end{cases} \tag{6}$$

- $S_{a,\ ground}$: elastic response spectrum at the ground level;
- $f_{peak,\ ground}$: frequency at which the ground spectrum assumes its maximum values;
- f_{peak} : frequency at which the maximum value of the structure is predicted by the three previous formulas e.g. $0.8f_1$;
- k: is a factor that represents the fraction of $f_{peak,ground}$ from which the weighted average starts. It depends on the rigidity of the system.

A second modification has been made to better reproduce the response of stiff system. Rigid systems with The amplification factor K_T has been modified to get K_T=1 for extremely rigid systems and intermediate values for not highly rigid ones:

$$\begin{cases} 5 & if\ f_1 < 1.5\boldsymbol{f_c} \\ 1 & if\ f_1 > 3\boldsymbol{f_c} \\ 5 + \frac{1-5}{3\boldsymbol{f_c} - 1.5\boldsymbol{f_c}}(f_1 - 1.5\boldsymbol{f_c}) & if\ 1.5\boldsymbol{f_c} \le f_1 \le 3\boldsymbol{f_c} \end{cases} \tag{7}$$

The modified simplified formula has been applied to the 2 dofs stiff structure submitted to a large band motion representative of a ground motion (Figure 2a) and to a narrow band motion representative of a transferred seismic input (Figure 2b). The results of the simplified formula has been compared with the results of time history analysis (green curves).



a: 2 dofs model excited by a large band motion

b: 2 dofs system excited by a narrow band motion

Figure 2. Comparison between time-history (green) and the improved simplified method (red) with different input motion (blue)

APPLICATION TO THE ITER LEAK DETECTION SYSTEM (LDS)

The methodology has been applied to the ITER Leak Detection System (LDS) that aims to provide the leak detection capabilities for the primary vacuum systems comprising Torus vacuum vessel, Neutral Beam vacuum systems and the Cryostat vacuum system of the ITER machine (Figure 3). The structures, systems and components (SSC) used on the design of the Leak Detection Systems shall meet the requirements under the specified load cases including the seismic action. A part of the systems will be qualified by test or using existing tests. An independent FEA model has been developed with ANSYS using pipe and beam elements with lumped masses for the main components that should be qualified on shaking table (Figure 4). This model has been developed in order to control the work performed by the consortium in charge of the design and the qualification of the system.
The system has been studied performing static analysis, response spectrum analysis and applying the simplified formulae above-mentioned to transfer the seismic FRSs (Kaldas, 2021). The FRS available at the location of the components inside the ITER Tokamak complex has been used as input response spectrum. The FEA model shows 12 natural frequencies below 35 Hz starting from 11.25Hz. They are mainly local eigenmodes. The results of the application of the simplified formulae to generate the FRS together with the values of the main eigenfrequencies (vertical green lines) are given in Figure 5. From these results, we can conclude that the supports are not fully rigid but are amplifying the seismic motion only at high frequencies.

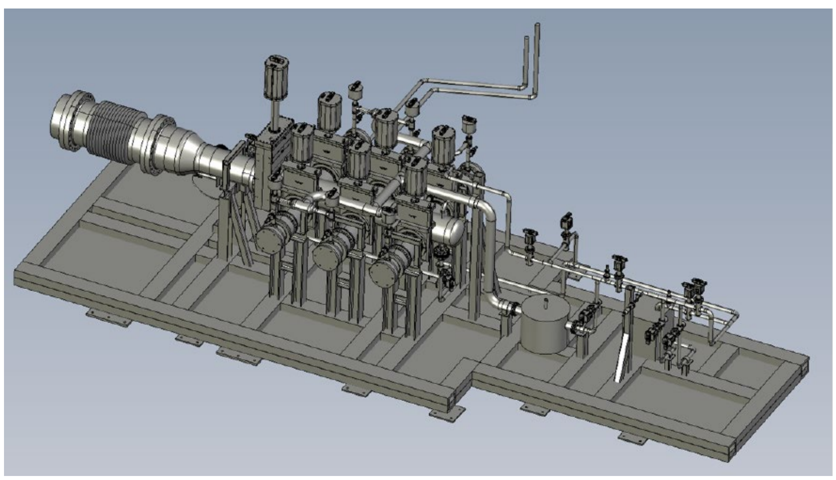
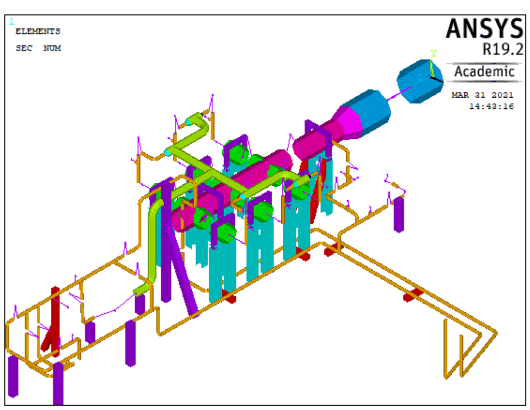


Figure 3. View of one of the system of the ITER Leak Detection System (LDS)



			Outer Diameter / Side length (mm)	Wall thickness (mm)
○	DN500		508.00	9.53
○	DN300		323.85	9.53
○	DN250		273.1	9.27
○	DN100		114.3	6.02
○	DN40		48.3	3.68
I	HEB120		120.0	11.00
□	RECT80		80	8
□	RECT100		100.0	10.00

Figure 4: View of the ANSYS model including supports, pipes and components.

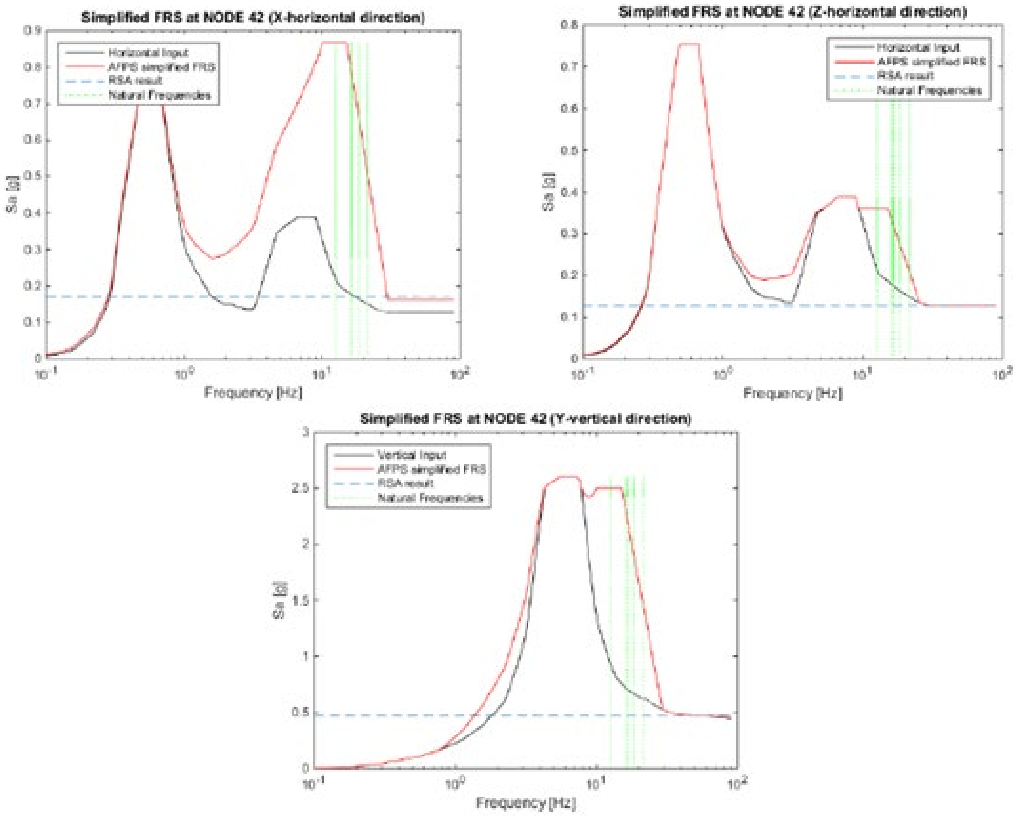


Figure 5. Example of transferred FRS using the simplified method (in red) compared to the input FRS (in black).

DEVELOPMENT OF RRS FOR THE SEISMIC QUALIFICATION OF ACTIVE COMPONENTS

The experimental seismic qualification of Safety Important active Components requires the determination of the RRS (Required Response Spectrum). The propagation of this input data for the qualification should be properly controlled and the information well stored in the qualification database. The seismic FRSs determined with transient calculations, frequency-based direct calculations or simplified method are curves. It is important to characterize the seismic input for the seismic qualification through, if possible, few physical parameters. The idea is to simplify the RRS curves into a set of parameters in order to ease their propagation to the experimental facilities in charge of the seismic qualification. For example, in standards such as RCC-E, the RRS is defined by a limited number of parameters (Figure 6). At low frequency, the RRS is defined by a value of spectral displacement compatible with the limitation of the shaking tables used for the qualification. It is completed by the values of ZPA and the spectral acceleration on the RRS plateau with lower and upper corners frequencies.

In the Tokamak building of ITER facility, the seismic FRSs are given at more than 1000 locations. The potential amplification through the local support should also be considered for the definition of the RRSs. A method has been proposed to identify the main physical parameters of the FRSs and calculate easily envelops (Mugica, 2021). Because of the seismic isolation, the horizontal FRSs have a specific shapes with two peaks and low values of ZPA but high values of spectral displacement. The automatic generation of the simplified RRS is based on the determination of local maximum values of spectral quantities. In addition to the spectral acceleration S_a, spectral velocity S_v and spectral displacement S_d, we have introduced the derivative of the acceleration named as S_c and the integral of the displacement named S_f:

$$Sc = \omega S\text{a} \quad (8a)$$

$$S\text{f} = \omega^{-1} S\text{d} \quad (8b)$$

The local maximum values are determined in two intervals:

- From 0 to 2 Hz: it corresponds to the first peak for the horizontal FRSs and to the non-amplified part of the vertical FRSs;
- From 2Hz to 35 Hz: it corresponds to the second peak for the horizontal FRSs and to the part of the vertical motion amplified by the vertical eigenmodes of the building.

Once the local maximum known, the values of frequency determining the transition between two constant spectral quantities (constant Sa, constant Sv, constant Sd, etc…) can be defined with the following formulae:

$$f_{Sa-Sv} = \frac{S_a}{2\pi S_v} \tag{9a}$$

$$f_{Sv-Sd} = \frac{S_v}{2\pi S_d} \tag{9b}$$

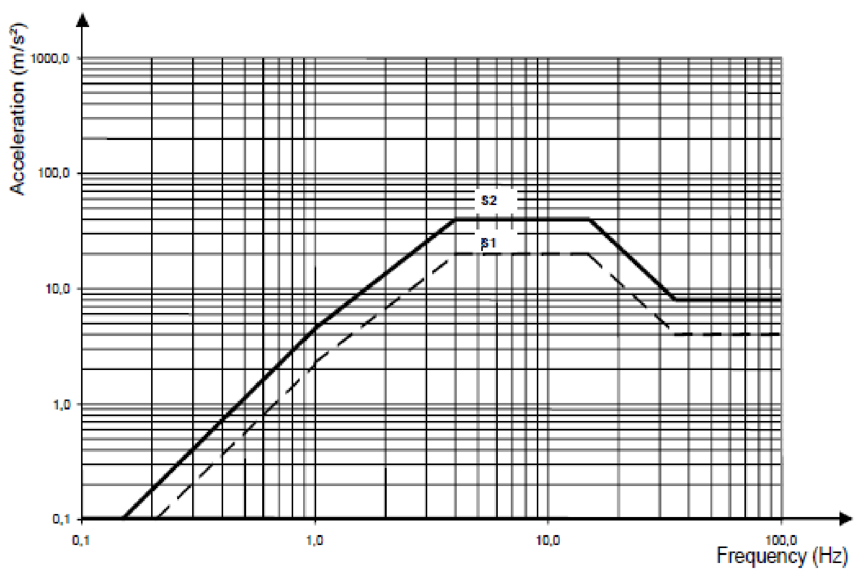
$$f_{Sd-Sf} = \frac{S_d}{2\pi S_f} \tag{9c}$$

$$f_{Sc-Sa} = \frac{S_c}{2\pi S_a} \tag{9d}$$

The RRS plateau (constant spectral acceleration) is defined by the 2 frequencies $f_{Sa\text{-}Sv}$ (lower corner) and $f_{Sc\text{-}Sa}$ (upper corner). In addition, the zero-period-acceleration is the magnitude of the spectral acceleration at which all curves converge regardless of damping. ZPA starts at the so-called cut-off frequency.

For the horizontal RRSs, the valley between the two peaks deserves a special treatment for the determination of the constant acceleration segment that is independent of the damping values similarly to the ZPA.

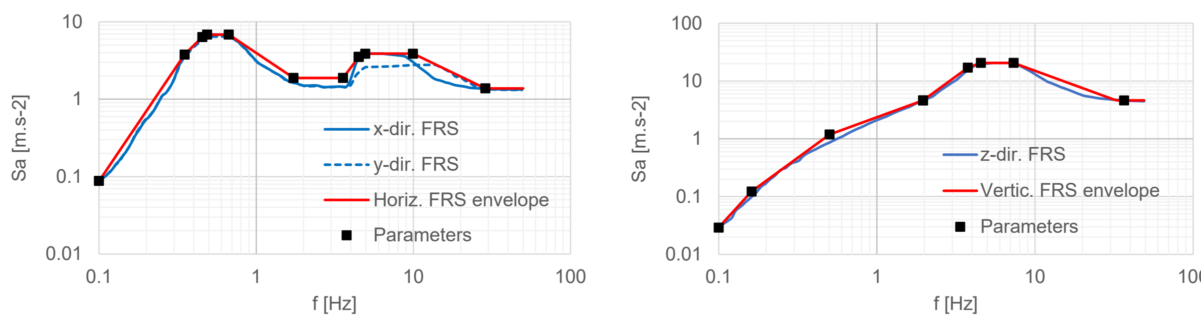
Once all points defined, the RRS is defined piecewise linear (Figure 7).



Singular point/ Seismic level	Below 1 Hz (constant movement)	1 Hz (movement)	4 Hz	15 Hz	35 Hz	Above 35 Hz
S2	0.114 m	0.114 m	40 m/s²	40 m/s²	8 m/s²	8 m/s²
S1	0.057 m	0.057 m	20 m/s²	20 m/s²	4 m/s²	4 m/s²

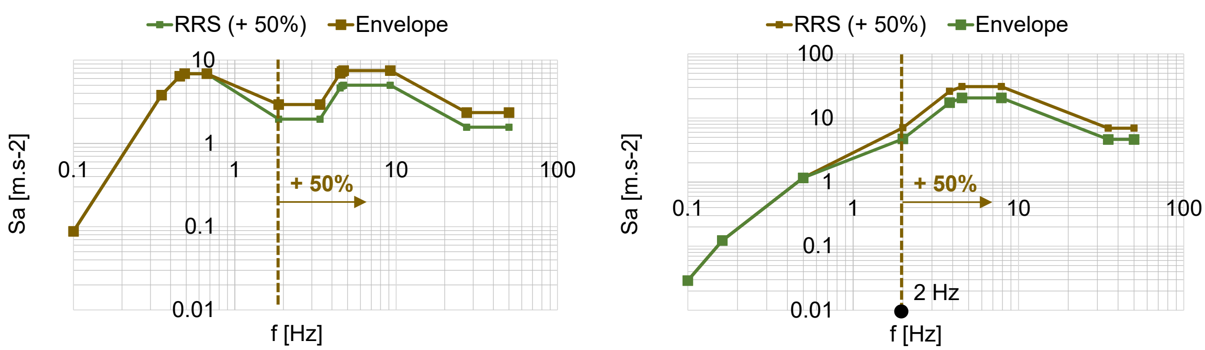
Figure 6. Example of RRS from RCC-E (RCC-E 2019)

Additional margins may be added only on a part of the RRS through an increase of the spectral acceleration or a broadening of the RRS (Figure 8). It is also common that the initial RRS cannot be used due to the capacity of the testing tables. The capacity of the shaking table is given by its maximum values of displacement, velocity and acceleration. When the values of spectral displacement and spectral velocities exceed the maximum permissible for the shaking table in question, the need arises to filter the RRS. Because of the seismic isolation, it is the case of the horizontal RRS in ITER. Table 2 shows an example of such a filtering for a shaking table with maximum values of spectral displacement and pseudo velocity of 0.25 m and 2.5 m/s respectively (shaking table with maximum displacement of 0.10 m and maximum velocity of 1m/s).
Statistics can also be elaborated in order to define a limited number of RRS for qualification.



a: Horizontal RRS b: Vertical RRS

Figure 7. Example of RRSs



a: Horizontal RRS b: Vertical RRS

Figure 8. Example of margin application

CONCLUSION

This paper has presented an adaptation of the AFPS simplified formula to transfer the seismic floor response spectrum. The basis of this formula and the main assumptions have been summarized. An application to several 2 dofs stiff and flexible structures and to a real system have been presented. The approach has been adapted to the case of semi-rigid supports with input FRSs with potential complex shape (with two peaks). The results obtained from the simplified method have been compared to results of time-history analysis on simplified model of structure/support. In the last part, an automatic procedure is proposed to simplify the FRS and obtain the Required Response Spectrum (RRS) for the experimental qualification of components. With the proposed format, the propagation and the storage of the seismic input used for the qualification are easier.

Table 1: Example of horizontal RRS (see Figure 8a).

Id.	f [Hz]	S_c [m.s^{-3}]	S_a [m.s^{-2}]	S_v [m.s^{-1}]	S_d [m]	S_f [m.s]
#1	0.10	5.54E-2	8.82E-2	1.40E-1	2.23E-1	3.55E-1
#2	0.351	8.38	3.80	1.73	7.83E-1	3.55E-1
#3	0.455	1.83E+1	6.41	2.24	7.83E-1	2.74E-1
#4	0.488	2.11E+1	6.87	2.24	7.31E-1	2.38E-1
#5	0.671	2.90E+1	6.87	1.63	3.87E-1	9.19E-2
#6	1.87	3.44E+1	2.93	2.50E-1	2.13E-2	1.81E-3
#7	3.37	6.21E+1	2.93	1.39E-1	6.55E-3	3.09E-4
#8	4.49	1.97E+2	6.97	2.47E-1	8.73E-3	3.09E-4
#9	4.61	2.13E+2	7.33	2.53E-1	8.73E-3	3.01E-4
#10	4.72	2.23E+2	7.50	2.53E-1	8.53E-3	2.88E-4
#11	9.19	4.33E+2	7.50	1.30E-1	2.25E-3	3.90E-5
#12	27.3	4.04E+2	2.35	1.37E-2	7.97E-5	4.64E-7
#13	50.0	7.38E+2	2.35	7.48E-3	2.38E-5	7.58E-8

Table 2: Example of filtered RRS.

Filtered RRS				
Id.	f [Hz]	S_a [m.s^{-2}]	S_v [m.s^{-1}]	S_d [m]
#1	0.100	9.87E-2	1.57E-1	2.50E-1
#2	0.796	6.25	1.25	2.50E-1
#3	4.72	7.50	2.53E-1	8.53E-3
#4	9.19	7.50	1.30E-1	2.25E-3
#5	27.3	2.35	1.37E-2	7.97E-5
#6	50.0	2.35	7.48E-3	2.38E-5

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