Response Spectrum Transformation for Seismic Qualification Testing

Nouredine Bourahla, Farid Bouriche and Yacine Benghalia

***Abstract*—**Seismic qualification testing for equipments to be mounted on upper storeys of buildings is very demanding in terms of floor spectra. The latter is characterized by high accelerations amplitudes within a narrow frequency band. This article presents a method which permits to cover specified required response spectra beyond the shaking table capability by amplifying the acceleration amplitudes at an appropriate frequency range using a physical intermediate mounted on the platform of the shaker.

***Keywords*—**floor spectra, response spectrum, seismic qualification testing, shaking table

I. Introduction

THE early 1970s saw the first inclusion for nonstructural provisions other than walls, parapets, and chimneys. The provisions have grown to include a wide variety of nonstructural components and building systems since the mid-1970s, but the seismic codes have yet to recognize the need for qualification of owner-supplied equipment that is not fixed to the building. The codes have also yet to come to grips with systems qualification and continued performance for facilities.

Qualification involves the acceptance of components and systems for use in a seismic environment and compliance with code requirements. There are numerous methods by which seismic qualification can be realized. Each method has a narrow window of applications for effective seismic qualification [1,2]. The method based on dynamic testing using shaking table is one of the most reliable methods.

In general, the dynamic excitations for seismic qualification tests of equipments are defined in terms of response spectra or modulated sinusoidal waves, specified according to the environmental conditions: seismo-geologic context or the type of the building and the height of the floor [3]. Obviously the seismic qualification tests of equipments cannot be carried out if the required response spectrum (R.R.S) is not covered by the performance curve of the shaking table. The R.R.S. are dominated by low frequencies and sometimes may go beyond the system capacity. In order to overcome this problem, a procedure for spectra transformation is developed to amplify the acceleration at the base of the specimen at low frequencies to cover the required response spectra.

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The procedure is based on introducing a physical interface between the shaking table and the specimen. The interface is a support capable to carry the equipment and transmit the vibrations from the shaking table to the specimen. The design and the limitation of this method are presented below..

II. Procedure for Spectrum Transformation

To perform the qualification tests for equipments, the required response spectrum RRS needs to be determined on the basis of the environmental conditions of the equipment site. In case that the RRS is not totally covered by the performance curve of the shaking table, therefore a physical amplifier support may be used as described hereafter. It should be noted however that this method is first developed for rigid specimen. The spectrum transformation procedure as shown on Fig. 1 can be carried out in three steps:

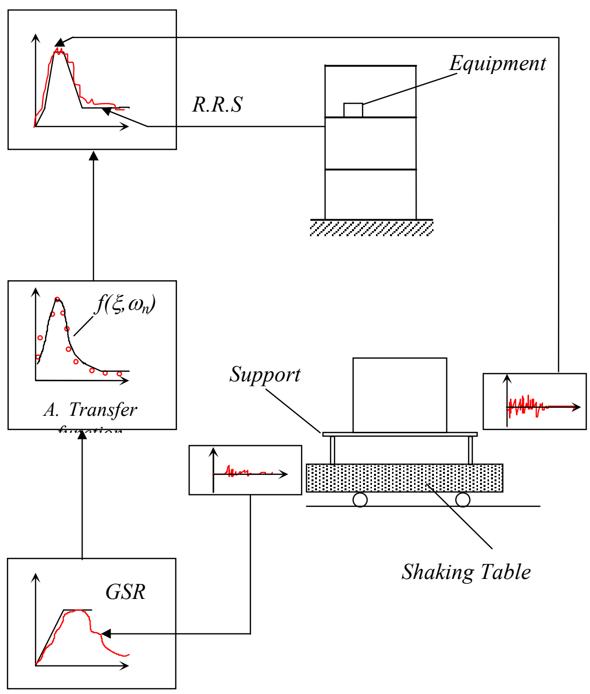

Fig. 1 Illustration of the procedure of the spectrum transformation

- Generate an acceleration time history which can be reproduced on the shaking table GRS which has a response spectrum limited by the intersection of the RRS and the performance curve of the shaking table.
- Identify the pulsation ω_n and the damping ratio ξ of the transfer function of the single degree system (support+specimen) by curve fitting the amplitude ratios RRS/GRS. The geometric and material properties of the support can be then derived by considering the resistance and the overturning moment criteria
- Compute the transferred acceleration time history and its response spectrum. The latter should be very close to the test response spectrum (TRS).

To illustrate the use of this technique, the performance curve of the small shaking table (1m x 1m) of the Civil engineering department at the University of Chlef (Algeria) is used to define the GRS to be transformed into an RRS.

A. Generation of the Acceleration Time History (GRS)

A spectrum compatible acceleration time history is generated using an iterative algorithm based on the statistic relationship between the response spectrum and the power spectral density [4,5]. The spectrum is derived from the performance curve of a mono-axial shaking table [6]. Fig. 2 shows the generated acceleration time history and both the computed and target response spectrum GRS.

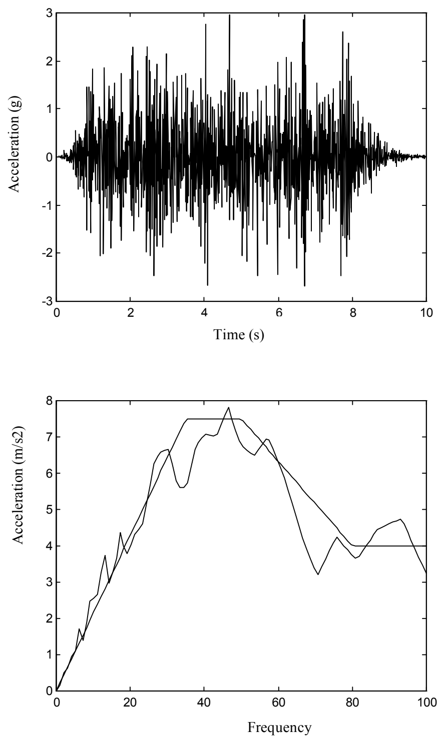

Fig. 2 Generated acceleration time history and the GRS

B. Interpolation of the Support Parameters ω_n and ξ

The specimen is supposed to be rigid body having a mass M and considered as an additional mass to the support which is supposed to be a one degree system characterized by a stiffness k, a mass m+M (m is the mass of the support) and a damping ratio ξ.

The pulsation of the system is $\omega_n = \sqrt{\frac{k}{M+m}}$

The parameters ω_n and ξ of the support which are required for the spectrum transformation are determined by curve fitting the frequency amplitude ratios RRS/GRS (Fig.3), using the transfer function of a single degree of freedom (SDOF) [2]:

$$\frac{X_1}{X_2} = \frac{\sqrt{1+\left(\frac{2\xi\omega}{\omega_n}\right)^2}}{\sqrt{\left(1-(\frac{\omega}{\omega_n})^2\right)^2+\left(\frac{2\xi\omega}{\omega_n}\right)^2}} \quad (1)$$

Where :

X_1 : Frequency amplitudes of the accelerations on the support.

X_2 : Frequency amplitudes of the accelerations on the shaking table.

The parameters ω_n and ξ are determined from the best curve fit of the amplitude ratios RRS/GRS represented in Fig. 3.

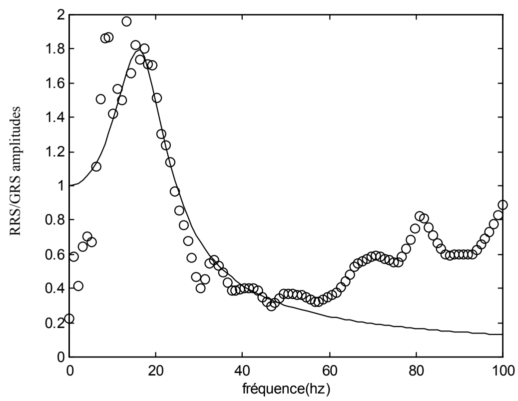

Fig. 3 Curve fitting of the amplitude ratios RRS/GRS

C. Determination of the Geometric and Material Properties of the Support

The support is designed to be mounted on the platform of the mono-axial shaking table of 1m x 1m with a grid of 37 M8 holes distant of 20cm.

The support is composed of a platform supported by n steel columns. The number of columns *n*, the diameter *D* of the cross section, the height *h* of the columns and the grade of the steel will be determined using the expression of the system pulsation and should fulfill the resistance and the overturning moment criteria.

- System pulsation

Considering the rigidity of n fixed ended columns:

$$k = \frac{12nEI}{h^3} \tag{2}$$

and the geometric characteristics of the column cross section :

$$I = \frac{\pi D^4}{64} \tag{3}$$

The pulsation of a SDOF:

$$\omega_n = \sqrt{\frac{k}{m+M}}$$

$$\omega_n = \sqrt{\frac{3n\pi ED^4}{16(m+M)h^3}} \tag{4}$$

- Resistance criteria

The resistance condition for a combined axial force and flexural moment is :

$$\frac{M_f}{W} + \frac{N}{A} \leq [\sigma] \tag{5}$$

for a circular cross section:

$$W = \frac{\pi D^3}{32}$$

For the particular case of this type of testing, the stress due to the axial load is negligible compared to the stress provoked by the flexural moment. The expression of the above condition becomes:

$$\frac{32M_f}{\pi D^3} \leq [\sigma] \tag{6}$$

The moment at the base and the top of fixed ended columns in terms of the shear force in the frequency domain is given by:

$$M_f = \frac{T \times h}{2} \tag{7}$$

The total shear force at the base of the support considering the maximum frequency amplitude of a single degree of freedom is given by:

$$T(\omega) = \frac{(m+M)\ddot{X}_2(\omega)}{\sqrt{\left(\left(1-(\frac{\omega}{\omega_n})^2\right)^2 - (\frac{\omega}{\omega_n})^2\right)^2 + \left(\frac{2\xi\omega}{\omega_n}\right)^2}} \tag{8}$$

By substituting (7) and (8) into (6), the resistance condition becomes:

$$\sigma(\omega) = \frac{16(m+M)\ddot{X}_2(\omega)}{\pi D^3 \sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(\frac{2\xi\omega}{\omega_n}\right)^2}} h \leq [\sigma] \tag{7}$$

- Overturning moment condition

The expression of the condition of the overturning moment in the frequency domaine can written as :

$$M_{OT}(\omega) = T(\omega) \times h \leq OTM \tag{8}$$

$$M_{OT}(\omega) = \frac{(m+M)\ddot{X}_2(\omega)}{\sqrt{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(\frac{2\xi\omega}{\omega_n}\right)^2}} h \leq OTM \tag{9}$$

The over-turning moment limit OTM is a characteristic of the shaking table.

For a specimen mass limit of 500kg (capacity of the shaking table), a standard diameter of 8mm (holes on the shaking table platform) and a maximum number of columns (37 elements) an investigation is carried out by trial and error to explore the feasibility and flexibility of the method for different steel grades.

It has been found that a wide range of frequencies can be achieved within the above physical limits. The performance of the transformation technique is examined for two types of floor response spectrum.

III. Evaluation of the Spectrum Transformation Procedure

The efficiency of the transformation technique is examined in terms of the form of the RRS, the frequency range and the amplification ratio.

A. The Form of the Required Response Spectrum RRS

Two forms of RRS are considered; the first is a narrow band and the second is a large band for an S.M.S level of 5% damping ratio [7]. The parameters of the support are first determined by curve fitting and both the RRS and the TRS are presented on the same figure.

Fig. 4 shows that the procedure is capable to the cover even the response spectrum with large band. Away from the peak, it is noticed that the amplitudes of the TRS are very reduced by the transfer function.

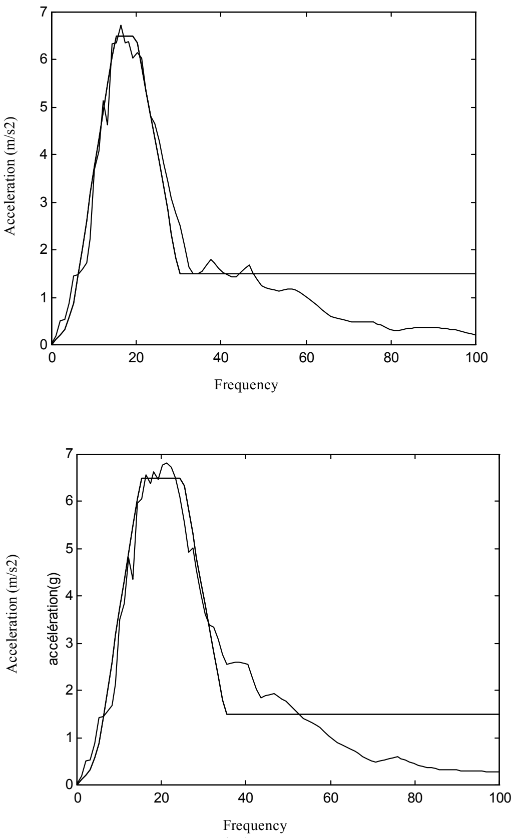

Fig. 4 Spectrum transformation of large and narrow band

B. Maximum Amplification Ratio RRS/GRS

Two RRS of different intensities are considered; an SMS (Security Earthquake) and an SNA (Admissible earthquake) levels with 5% damping ratio [6].

The obtained results using the same procedure shows that the high level RRS is difficult to cover. It is noticed that when the ratio is more than twice, the band around the peak becomes narrow (fig.5)

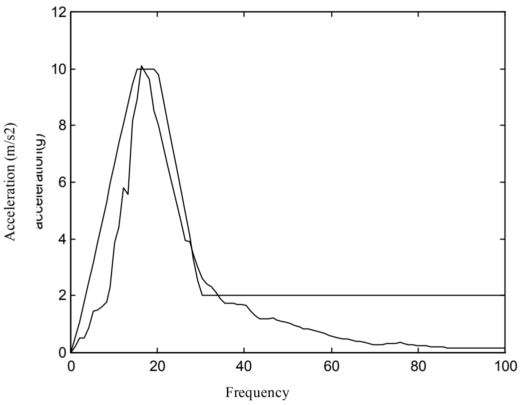

Fig. 5 Spectrum transformation of high amplification ratios RRS/GRS

C. Frequency Range

Using different frequency ranges for the peak of the RRS, it is noticed that the transformation procedure becomes less efficient for low frequency ranges (Fig. 6).

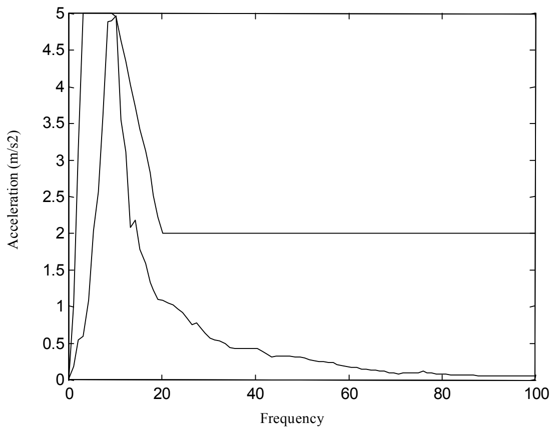

Fig. 6 Spectrum transformation at low frequency range

IV. Conclusion

The seismic qualification testing using shaking table is one of the most reliable methods to prevent damage of equipments in strategic buildings. The performance limits of the shaking table are the major difficulties in performing this type of testing. A simple technique is presented to overcome some of the physical limits of the shaking table. The method is based on supporting the specimen on an interface capable to amplify and transmit safely the vibrations from the shaking table platform to the base of the specimen. The procedure to determine the geometric and material properties of the support are detailed together with examples showing the potential of the spectrum transformation for a mono axial shaking table.

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