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Reduction Factor for Human Loads in Dancing Halls

Facteur de réduction pour les charges humaines dans les salles de danse

Ein Reduktionsfaktor für menschenerzeugte Lasten in Tanzsälen

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SUMMARY
In this paper a reduction factor for dynamic loads in dancing halls is proposed. This factor relates the computed spectral values of the structural response, considering on the one hand the actual partially-correlated loads and on the other hand deterministic, fully correlated design loads. The reduction obtained is compared with the results from measurements included in the bibliography.

RESUME
L'article propose un facteur de réduction des charges dynamiques dans les salles de danse. Ce facteur est déduit de la relation entre les valeurs spectrales de la réponse structurale, calculée pour la valeur estimée de la corrélation partielle des charges et pour la valeur unitaire de cette corrélation. La réduction ainsi calculée est comparée avec des valeurs mesurées, mentionnées dans la bibliographie.

ZUSAMMENFASSUNG
In diesem Aufsatz wird ein Reduktionsfaktor für die in Tanzsälen erzeugten dynamischen Lasten vorgeschlagen. Dieser Faktor gibt das Verhältnis zwischen den Spektralwerten der Bauwerksantwort wider, die einerseits mit den wirklichen, teilweise korrelierten Lasten und andererseits mit den deterministischen, vollkorrelierten Lasten gerechnet werden. Der Reduktionsfaktor wird anschliessend mit Messungsergebnissen aus der Literatur verglichen.

1. INTRODUCTION

Excessive vibrations of dancing halls and other structures due to dynamic loads imposed by assemblies have been noted in recent years. These vibrations were annoying to the users and, in some cases, calculations have even shown an unacceptable loss of structural safety.

The increase in the number of structures needing repair leaded to the development of different load models. These models, derived on a deterministic basis, do not take into account the correlation between the individuals which leads to an unrealistic linear increase of the dynamic load with the number of participants.

To investigate this assumption a more general, stochastic model was developed and measurements were carried out on a dance hall to evaluate the model parameters. Based on this model a reduction factor for the structural response computed by a deterministic load model can be derived.

2. STOCHASTIC LOAD MODEL

The proposed model aims to represent the physical phenomena and must, therefore, take into account the principal characteristics of this type of loads:

- They are almost periodic, characterized by narrow peaks in the frequency domain, and can be decomposed into several harmonics of the basic frequency, usually up to three, each of them owing a different degree of randomness.
- Assembly loads are made up from individual point loads, all of the same type and correlated with each other. Considering that we are interested, in the practice in a determined frequency to check the case of resonance only the correlation between individuals at the same harmonic should be investigated.

The loads are modeled as a random field of time and space. Under the assumption of homogeneity, it is described by its complex valued cross spectrum, $C(\xi, f)$, computed between any two points at a distance ξ on the load field. The coefficient $\rho_f(\xi)$, defined as follows,

$$\rho_f(\xi) = \frac{C(\xi, f)}{C(0, f)} = \frac{C(\xi, f)}{S(f)} \tag{1}$$

can be seen as a spatial correlation coefficient [6], whose square module is the coherency function and whose imaginary and real parts define a phase angle,

$$\begin{cases} |\rho_f(\xi)|^2 = \Re^2[\rho_f(\xi)] + \Im^2[\rho_f(\xi)] \\ \phi_f(\xi) = -\arctan \frac{\Im[\rho_f(\xi)]}{\Re[\rho_f(\xi)]} \end{cases} \tag{2}$$

Because only the harmonics of the load function are of interest the spatial correlation coefficient has to be computed only for these harmonics.

2.1 Time correlation

Load histories are measured from individuals at rhythmic movements (jumping, dancing, etc.) and filtered with a bandpass filter to obtain separate time functions for each harmonic. The correlation function for a harmonic is of the form:

$$R_n(\tau) = a_n(\tau)\cos(2n\pi f_0\tau) \tag{3}$$

where nf_0 and $a_n(\tau)$ represent, respectively, the n^{th} harmonic[1] and the envelope of the correlation function.

Based on the observation of measurements, the following model is suggested for the envelope:

$$a_n(\tau) = \begin{cases} \sigma_n^2[\eta_{d,n} + (1-\eta_{d,n})\frac{\Gamma_n-\tau}{\Gamma_n}] & \text{for } 0 \leq \mid\tau\mid \leq \Gamma_n \\ \sigma_n^2\eta_{d,n} & \text{for } \mid\tau\mid > \Gamma_n \end{cases} \tag{4}$$

According to (4), the correlation consists of a deterministic part, $\sigma_n^2\eta_{d,n}$, that is own to the rhythmic stimulus of the music, and a stochastic part given by the time-dependent fluctuation of the load amplitude and period. This random portion has a correlation length of Γ_n.

2.2 Space correlation

The space correlation coefficient defined in (1) is modelled by mutually independent functions for its module and for its phase angle:

$$\begin{aligned} \mid\rho_n(\xi)\mid &= k_{d,n} + (1-k_{d,n})e^{-k_{a,n}\xi} \\ \phi_n(\xi) &= \lim_{c\to\infty}\Phi_n(1-e^{-c\xi}) \end{aligned} \tag{5}$$

The function for the module allows the existence of a deterministic part, k_d, in accordance with the time correlation model. The phase angle is assumed to be independent of the distance ξ between individuals.

2.3 Model parameters

The identification of the parameters from the response acceleration measurements with duration length of 20 and 40 seconds on a structure during one dancing event have shown [1,2] that the coefficient k_d can be made equal to η_d. This means that the mean value arising from an increasing number of persons can indeed be estimated by building the mean on the time axis. According to this the load field can be considered isotropic.

The values of the parameter k_a were, in general, very high. Therefore the exponential decrease in the first equation of (5) can be approximated with the step function showed in fig.1, where ξ_1 is assumed to be the smallest distance between any two persons.

For the phase angle, values between 10 and 30 degrees were found. Due to its variance the identification of this parameter was more difficult than the one of the coherency.

3. LOAD REDUCTION

3.1 Reduction factor

Based on the load model presented, a structure independent reduction factor for the structural response can be derived.

The structural response, computed on a deterministic basis, which implies a full correlated load field, is then multiplied by the reduction factor, in order to take into account a realistic space correlation.

[1] Indeed, the harmonic frequency is identified with the middle frequency of the spectral peak

To derive such a factor some assumptions have to be made, which are fullfilled under most practical conditions:

1. The random load field is considered homogeneous
2. The simplification in fig.1 may be applied with $\xi_1 \cdot \mu = 2$, where μ is the density of the uniformly distributed persons, and $M = \xi \cdot \mu$ the number of persons.
3. All the load points on the structure have the same transfer function to the output point, i.e., structure dependent influences on the reduction factor are neglected[2].

The power spectral value of the response displacement at point y at the n^{th} harmonic is computed as follows:

$$S_{yy}(nf_0) = [H(nf_0)]\, S_{pp}(nf_0)\rho_n\, [H^*(nf_0)]^T \tag{6}$$

which can be simplified to:

$$S_{yy} = |H_y|^2\, S_{pp} M \left[1 + \frac{M-1}{M}(\rho_n + \rho_n^*)\right] \tag{7}$$

where the frequency was dropped out for simplicity.

In these equations the vector of the transfer functions $[H(nf_0)]$ contains M elements all of them having the same value, H_y. The power spectrum of the loads is given by the product of the spectral values at the harmonic frequency $S_{pp}(nf_0)$ multiplied by the correlation coefficient ρ_n. If the correlation coefficient follows the step function of fig.1, the model parameters according to (5) are:

$$\left\{ \begin{array}{rcl} |\rho_n|^2 & = & k_{d,n}^2 \\ -\arctan \frac{\Im[\rho_n]}{\Re[\rho_n]} & = & \Phi_n \end{array} \right. \tag{8}$$

From (7) and (8), taking into account that the reduction factor is defined as a relation between the spectral value S_{yy} for the actual correlation and the one for a full correlated load field

$$K_\rho^2(f) = \frac{S_{yy}(f)}{S_{yy}(f)\mid_{k_d=1.0,\Phi=0.0}}, \tag{9}$$

the following expression can be derived for the load reduction factor:

$$K_{\rho,n}^2 = \frac{1}{M} + \frac{(M-1)}{M} k_{d,n} \cos\Phi_n. \tag{10}$$

For increasing M this factor tends asymptotically to the following limit:

$$\lim_{M\to\infty} K_{\rho,n}^2 = k_{d,n} \cos\Phi_n \tag{11}$$

[2]This is a common but not always a conservative assumption for load reduction factors

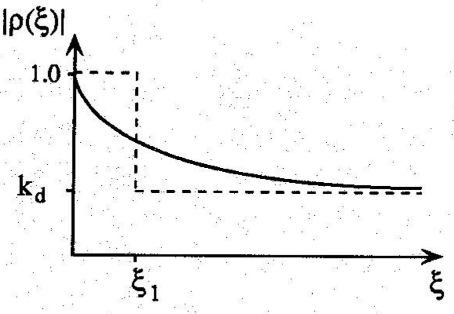

Figure 1: Correlation coefficient approximated with a step function

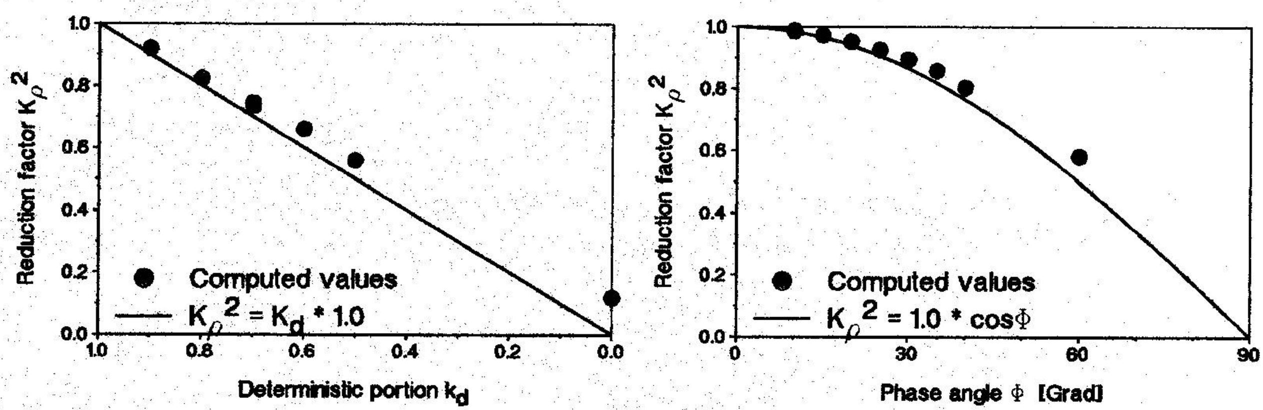

Figure 2: Comparison of the reduction factor with the computed values by means of the power spectral method.

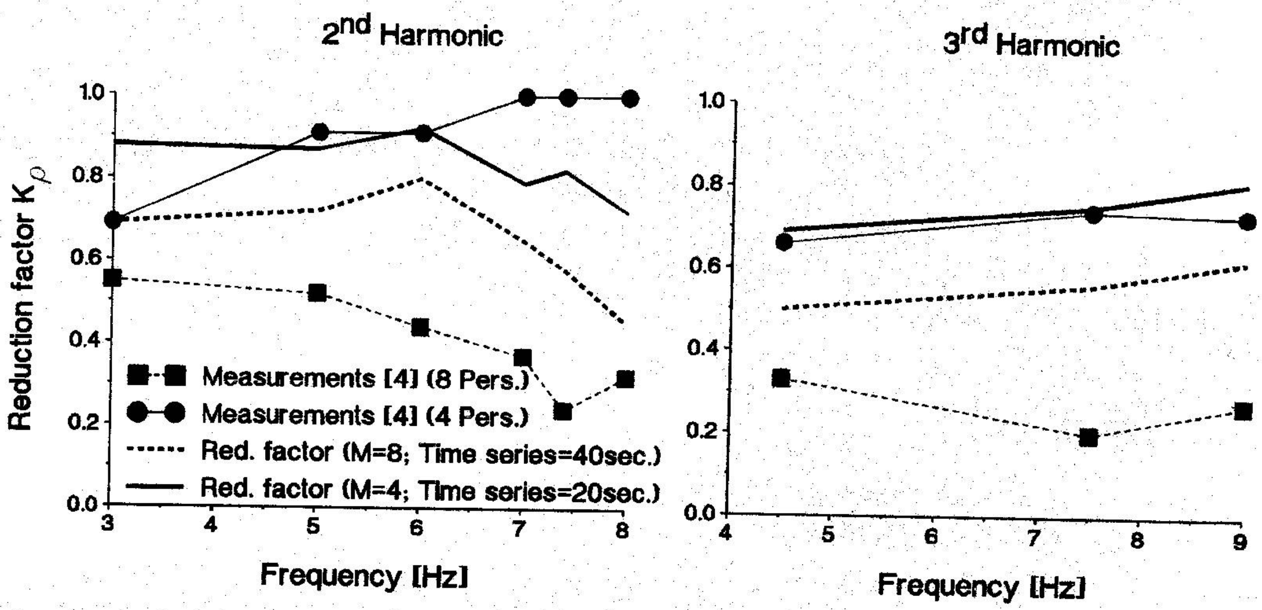

Figure 3: Comparison of the reduction factor with measurements from [4]

Equation (11) is compared with the results from the stochastic method (6) applied to a dancing hall, described in [1], for $M = 90$ and using the load model of (8). Fig.2-a and 2-b show the variation of the reduction factor as a function of $k_{d,n}$ and Φ_n respectively.

Both plots show a good agreement of eq.(11) with the computed values. However, caution should be taken when using this factor since the reduction may not lie on the safe side, as shown in the figures. The differences between computed values and eq.(11) increase when the load field becomes fully uncorrelated.

3.2 Comparison with measurements

The reduction given by (11) and the results of measurements from [4] are compared in fig.3, for the second and third harmonics of the vertical load arising from rhythmical jumping. The parameters for the reduction factor were computed from measurements made in [2] where the durations of the time series were 20 and 40 seconds respectively for the computation of the parameters for groups of 4 and 8 persons. The phase angle was assumed to be zero, a rather conservative assumption, since no reliable value was found from the measurements.

From this figure it can be concluded that, for groups of 4 persons any reduction may be unsafe, whereas for groups of 8 persons the reduction factor remains always on the safety side. The same can also be said for the first harmonic. This phenomen can be explained either by the ability of synchronisation of small groups or by the statistical bias because of small samples.

4. CONCLUSIONS

Starting from a stochastic model, a simple way was found to take into account a possible reduction of the structural response computed on a deterministic basis.

The main advantage of this analysis is that the load field can be considered isotropic and, therefore, the parameter k_d of the spatial correlation can be estimated from the load time series measured on individuals.

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