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Numerical modelling of dynamic stress of core barrel excited by coolant flow

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ABSTRACT: In this paper the theoretical method of vibration response of structures to random exciting forces due to a fluid flow is applied to explore the influence of coolant flow parameters on dynamic deformation of a core barrel. A physical model of the PWR core barrel is used to demonstrate by numerical experiments the mentioned influence. The mean flow velocity vector of the coolant flow is the basic for the hydrodynamic excitation expressed by a coherence function of the fluctuating surface pressure of the coolant flow both in axial and circumferential directions, stated as the dependence on the values of the correlation lengths. The results of the coursés of the generalized spectral loadings and of the ms amplitudes of stress distributions are shown at the dependence on the coolant flow parameters.

1 INTRODUCTION

Vibrations, and consequently, their deformations induced by fluid flow, are sometimes considered to be a secondary parameter in design, but only until a failure has occurred. Failures resulting from the vibrations of fluidodynamic origin have not been avoided in nuclear reactors (Blevins 1979, Corr 1970), though extraordinary attention has been given to their safe operation. The problem under discussion has an interdisciplinary character and lies on the interface of several scientific fields.

This paper applies the method of the numerical solution of vibration random structure response to explore, by numerical experiments, the influence of fluid flow characteristics on dynamic deformations and the behaviour of a core barrel surrounded by a fluid flow. The magnitudes and the distributions of the stochastic stresses are studied in relation to the dependence on the values of the mean flow velocity and pressure wave correlation length.

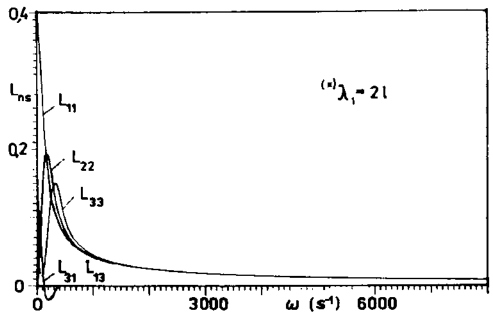

Fig. 1. Axial spectral loadings at parameter $^{(x)}\lambda$.

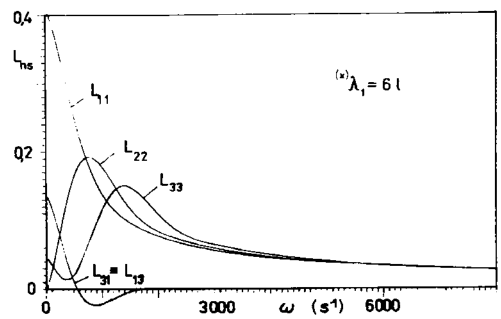

Fig. 2. Axial spectral loadings at parameter $^{(x)}\lambda$.

2 THEORETICAL BACKGROUND

The core barrel under consideration is replaced by a r-degree-of-freedom system. The ith element of a core barrel is regarded as a continuum. The frequency modal properties of the system including a core barrel with surroundings are known. To simplify the problem, we assume: (1) there is not coupling between individual modes of vibrations, (2) no coupling between the flow excitation and core barrel response is introduced, (3) the flow random excitation, expressed in terms of the fluctuating pressure $p(t)$ of the fluid where it is in contact with the core barrel is stationary and ergodic.

Using modal analysis and Fourier transform to solve the equations of motion, we obtain an expression for the vector $s_y(\Omega)$ of dimension r of the power spectral density (psd) of the core barrel displacements. In matrix symbolical form we have (Kuzelka 1985):

$$s_y(\Omega) = \tilde{W}\ |{}^{D}H(\Omega)|\ \ |l(\Omega)|\ , \tag{1}$$

where $\tilde{W}$ is the matrix of dimension $(r \times r^2)$ of modal vectors with elements $w_\alpha^{(i)} w_\beta^{(i)}$ of the associated conservative system; ${}^{D}H(\Omega)$ is the diagonal matrix of dimension $(r^2 \times r^2)$ of generalized spectral compliances with elements H_α, H_β^* (the asterisk indicates a complexly conjugated function); $l(\Omega)$ is the vector of dimension r^2 of generalized spectral loadings given by:

$$\tilde{l}(\Omega) = {}^{T}\tilde{\tilde{W}}\ \hat{p}(\Omega)\ , \tag{2}$$

where $\tilde{\tilde{W}}$ is the matrix of dimension $(r^2 \times r^2)$ of modal vectors with elements $w_\alpha^{(i)} w_\beta^{(k)}$; $\hat{p}(\Omega)$ is the vector of dimension r^2 the elements of which can be expressed by the following expression:

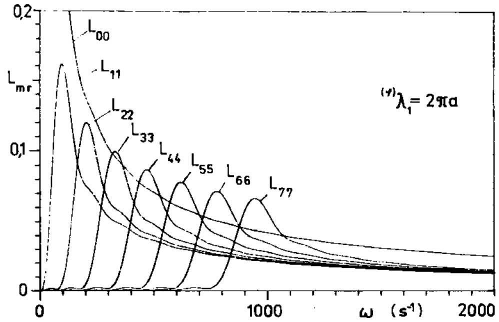

Fig. 3. Hoop spectral loadings at parameter $^{(\varphi)}\lambda$.

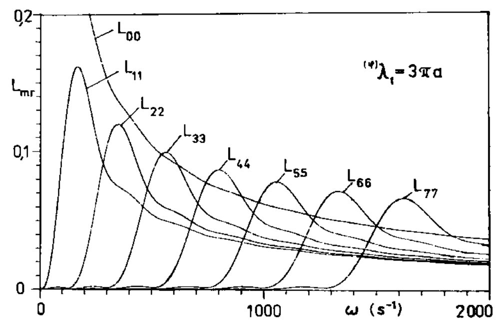

Fig. 4. Hoop spectral loadings at parameter $^{(\varphi)}\lambda$.

$$\hat{p}_{ik}(\Omega) = \lim_{T \to \infty} \frac{1}{T} \int_{-T}^{T} \int_{-T}^{T} \int_{S_i} \int_{S_k} p_i(t_1) p_k(t_2) \times \exp(\Omega(t_1 - t_2))\, dt_1\, dt_2\, di\, dk \,, \tag{3}$$

where T is half of the realization time of the random process and S_i, S_k, is the contact surface of the ith and kth elements respectively, of the core barrel. An analytical expression can be gained for $\tilde{I}(\Omega)$. Then, the generalized spectral loadings, $L_{\alpha\beta}(\Omega)$, related to a unit surface are done:

$$L_{\alpha\beta}(\Omega) = \frac{1}{S^2} \int_{S} \int_{S} w_\alpha(A_1) w_\beta(A_2) \times G_{p1p2}(A_1, A_2, \Omega)\, dA_1\, dA_2 \,, \tag{4}$$

where A_1 and A_2 are sites on the contact surface S of the core barrel; $w_\alpha(A_1)$ and $w_\beta(A_2)$ are the coefficients of the distribution of displacement amplitudes of the α and β modes, respectively, of vibration at A_1 and A_2, respectively; $G_{p1p2}((A_1, A_2, \Omega)$ is the coherence function of the pressure field of the fluid flow at the sites A_1, A_2. Equation (4) represents one of the possible forms of the so-called acceptance integral first introduced by Powell (1958). If the function of the fluctuating contact surface pressure is a separable function then, consequently, the functions of the generalized spectral loadings are also separable functions. So, we have spectral loadings in the axial and in the circumferential directions, and a total generalized spectral loading. To express the coherence function of a homogeneous turbulent flow a Bessel function of the first kind of zero order, dependent on fluid flow parameters, was used in the computations.

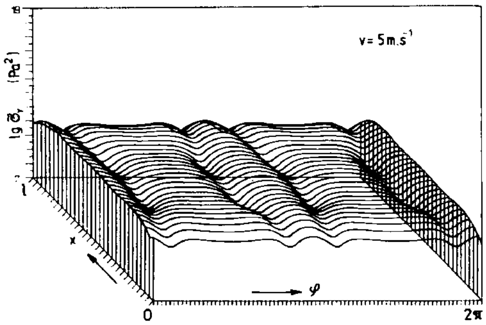

Fig. 5. Distribution of ms axial stress amplitudes at parameter v.

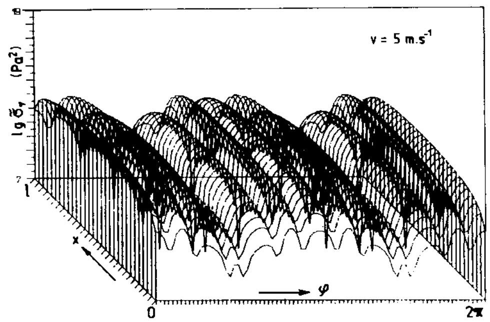

Fig. 6. Distribution of ms hoop stress amplitudes at parameter v.

The vector of the amplitude of the root mean square (rms) displacements y of dimension r can be obtained from the psd of the displacements trough integration over all the angular frequencies Ω,

$$\bar{y} = \left(\frac{1}{2\pi} \int_{0}^{\infty} s_y(\Omega)\, d\Omega \right)^{1/2} . \qquad (5)$$

The distribution of this vector is used for the approximate estimations of the vectors of ms stress amplitudes in the axial, $\tilde{\sigma}_x$, and hoop, $\tilde{\sigma}_\varphi$, directions:

$$\tilde{\sigma}_x = \left(K_x \frac{d^2 \bar{y}}{dx^2} \right)^2 , \qquad \tilde{\sigma}_\varphi = \left(K \frac{d^2 \bar{y}}{dx^2} \right)^2 , \qquad (6)$$

where K_x , K_φ are constants given by the dimensions and material properties of the core barrel.

3 RESULTS OF NUMERICAL MODELLING

To study the dynamic deformations in a core barrel due to various changes of the exciting fluid flow parameters, the ODEZ 4 code was developed. For the proper computations, a physical model of the PWR core barrel of dimension: t/a =0.046, a/l =0.231 was used (a - middle surface radius, t - thickness, l - length). The model was considered to be supported at both ends continuously and replaced by the system of 2400 degrees of freedom. The frequency spectrum of the model was fixed in both air and water. The values of natural frequencies and of generalized damping ratios were considered for 24 selected vibration modes including the influence of liquid and of limited surroundings (Kuzelka & Neuman 1983).

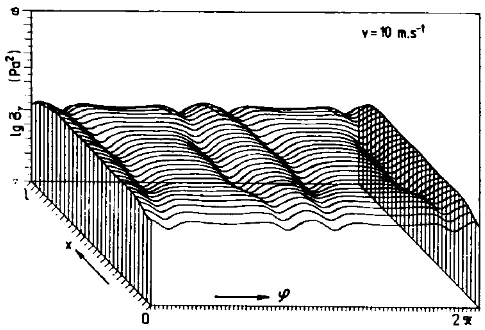

Fig. 7. Distribution of ms axial stress amplitudes at parameter v.

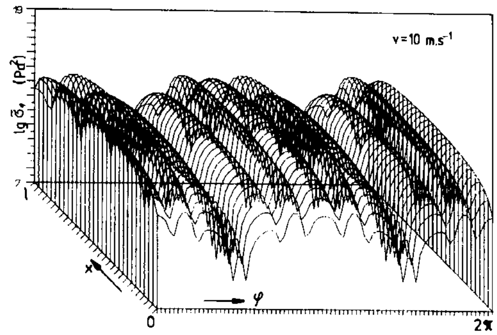

Fig. 8. Distribution of ms hoop stress amplitudes at parameter v.

Generalized spectral dimensionless loadings were computed for the various pressure wave correlation lengths λ. Some results of computations are plotted in figs. 1 to 4. The courses of axial generalized spectral loadings for some joined and cross factors at two different correlation lengths are shown in figs. 1 and 2, while figs. 3 and 4 present the courses of the circumferential spectral loadings. Comparing the plotted cross loading with the joined one (fig. 1) it is obvious that the cross terms are smaller and become very quickly damped with increasing frequencies. As for correlation length, we can see that the spectral loading values are rising and their maxima shift to regions of higher exciting frequencies, with its growth.

The graphical expression of the results of computations of the ms stresses at two different mean flow velocities are presented in figs. 5 to 8. It can be seen that the amplitudes of ms stresses are significantly dependent on the flow parameter changes.

4 CONCLUSIONS

From the obtained results and their analysis certain conclusions can be drawn, such as:

1. The pressure wave correlation length and the mean flow velocity of the coolant significantly affect the magnitudes of the dynamic deformations of the core barrel.
2. The distributions of the ms hoop stress amplitudes are non harmonic with a number of waves around the circumference.
3. The distributions of the ms axial stress amplitudes are non harmonic, too, with only several waves around the circumference.
4. The maximum values of the ms axial stress amplitudes are lower by more than one order in comparison with the hoop ones.
5. The values of maxima of generalized spectral loadings in the axial and in the circumferential directions are independent of the coolant parameters. With growing pressure wave correlation lengths, however, they shift into the region of higher exciting frequencies.

6. The distributions of the ms stress amplitudes are symmetrical to the axial plane, resp. to the plane dividing the axis of the core barrel in half.

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