STATISTICS OF ICE-STRUCTURE INTERACTION

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ABSTRACT

The spectral analysis of the time histories of ice crushing against structures reveals the quantitative relation between ice velocity, structural stiffness and contact area. The dominant ice crushing frequency shifts to the right along frequency axis with increasing velocity and structural stiffness, the peak amplitude decreases and spectral background rises. The variance of ice force depends on structural stiffness and is almost independent on ice velocity. Using the experimental or computed ice force spectra the structural response of various offshore structures can be predicted in different ice environments. The spatial correlation of the ice crushing against wide structures are studied numerically. The characteristic correlation dimension is introduced. It is shown that crushing of the slowly moving ice is spatially uncorrelated and excites the rigid body modes of the structure. When increasing velocity moves the dominant ice force peak close to the structural natural frequency the ice crushing becomes spatially correlated and locks in on this frequency.

INTRODUCTION

In earlier studies of ice-structure interaction it was found that the magnitude and frequency of ice force were related to the ice velocity, thickness and size of crushing fragments. It was observed that ice crushing pressure decreased when a critical rate of indentation was exceeded. At higher rates of indentation the ice crushing pressure increased slightly with the rate of indentation (Kärnä et al, 1993). The existence of a dominant or characteristic ice crushing frequency was noticed by many researchers during laboratory and field measurements. Määttänen (1975) associated this frequency lated. The notion of spatial correlation is introduced below.

SPATIAL CORRELATION OF ICE CRUSHING

The random process is stationary in space if it is invariant to the translation in this space. That is, when for its cross correlation function, the following expression holds

$$R(r_1,r_2,\tau) \equiv R(r_1-r_2,\tau) \ . \qquad (2)$$

Here r_1 and r_2 are two arbitrary points in space. By introducing a characteristic length λ associated with a spatial cross-correlation function, the spatial stationarity of excitation can be related to a mechanical system of consideration. If the length λ is small relative to the dimensions of a mechanical system, the excitation can be approximated as stationary.

By analogy with a turbulent fluid flow, the cross spectral density function of the ice crushing process can be approximated by the following expression (Gibert 1986)

$$G(r_1,r_2,f) = G_p(f)\prod_{k=1,2,3} e^{-\frac{|r_1-r_2|}{\lambda_k}n_k + \frac{(r_1-r_2)n_k 2\pi i f}{v_k}} \ . \qquad (3)$$

where n_k is the unit vector in the k-direction, λ_k is characteristic length in k-direction, v_k is velocity of characteristic translation in the k-direction, $G_p(f)$ is power density function derived from the measurement data. As seen from (3) the product term of the cross spectrum represents a spatial correlation function. It is assumed further that the ice crushing process is going on along the width of the structure simultaneously. This means that the transverse translation of disturbance occurs instantly and expression (3) simplifies to the following

$$G(r_1,r_2,f) = G_p(f)\prod_{k=1,2,3} e^{-\frac{|r_1-r_2|}{\lambda_k}n_k} \ . \qquad (4)$$

If correlation length λ is small relative to the dimension of the structure (wave length), the excitation is stationary in space, otherwise the excitation is stationary only in time. The experimental studies of certain spatially random processes (pressure fluctuation in pipework with singularities) (Gibert 1976) show that the spatial coherence function decreases exponentially with $|r_1-r_2|/\lambda$, where characteristic length λ is an inherited property of the mechanical system (λ is a pipe diameter for turbulent flow). The analogy between the two processes (similarity of power density spectra) suggests that there may be a characteristic length associated with the geometry of an ice-structure system (ice thickness or size of ice breaking fragments or a certain structural dimension) which makes the random process stationary in space. The small value of λ means that the signals coming from two nearby points are non-correlated. In contrast, the large λ means that two signals at distant points within the system are correlated. The response of various structures as a function of λ is studied on the basis of mode superposition analysis (Kajaste-Rudnitski and Gibert 1987).

On the basis of the available information about such kind of structure (Bruce and Harrington, 1982), the approximate FE model of the offshore caisson platform is made. The bottom of the platform is not attached by any means to the sand berm. The caisson is prevented from slipping along the foundation berm by its own gravity. No friction forces are applied to the bottom of the model.

The spectral analysis procedure used for this research permits creating the user subroutine to define the load spatial correlation according to (4).

The frequency analysis of the structure shows that the first 15 natural modes at frequencies from 1.11 to 1.85 Hz represent the global distortion of the caisson as a whole frame. The higher modes from 5.6 Hz have a local appearance and represent distortion of the vertical bulkheads inside the inner and outer caisson shells while the shells themselves remain undisturbed. From 5.6 Hz on, the inner caisson walls become more and more distorted and transfer vibrations to the sand core. So, after the excitation frequency rises above 5.6 Hz, the sandfill core begins to vibrate with the inner wall of the caisson. Returning to relation (1), note that ice crushing against slender and narrow structures is a random process in the time domain defined by its autocorrelation function, and deterministic or perfectly correlated in space (within the contact area). Accordingly, in the frequency domain it is defined by its power spectral density function. Suppose that along the contact line (or band) of the wide structure there exist a number of small lengths (or patches) within which the ice crushing is spatially correlated and relation (3.2) is valid. Evidently, between the ice forces generated within diffrent patches, a certain correlation exists. Since there is no experimental or any other quantitative information about this spatial correlation, assume that it is defined by cross spectral density function (4). *G(f)* in (4) represents the ice force spectrum available experimentally or numerically. Depending on correlation length λ, ice crushing may be fully correlated along the whole contact line or poorly correlated when, within each patch, ice breaks at a certain particular frequency according to (1). For full spatial correlation, *K* in (1) is the stiffness of the whole structure at ice level in ice movement direction whereas *K* is a local stiffness when spatial correlation is poor. The structural response will vary from no reaction at all when excitation is uncorrelated, to a spatially deterministic one when excitation is fully correlated. It is essential, therefore, to establish the kind of structural dimension which represents or is related to the correlation length. For fully correlated excitation, the longitudinal acceptance tends to its maximum when $\lambda/L \geq 1$ Actually, *L* is a contact line. So, formally $0 \leq \lambda \leq L$.

Suppose that ice crushing against a caisson is spatially fully correlated. Consider the situation when slowly moving ice sheet crushes with a dominant frequency far below the first natural frequency, for example 0.3 Hz (Sodhi 1988). One of the ice tank force spectra is chosen to be modified as *G(f)* term in (4). Its frequency coordinates and amplitudes are corrected as was done previously for slender structures. The stiffness correction from tank 60 kN/mm to caisson 103 MN/mm is not made.

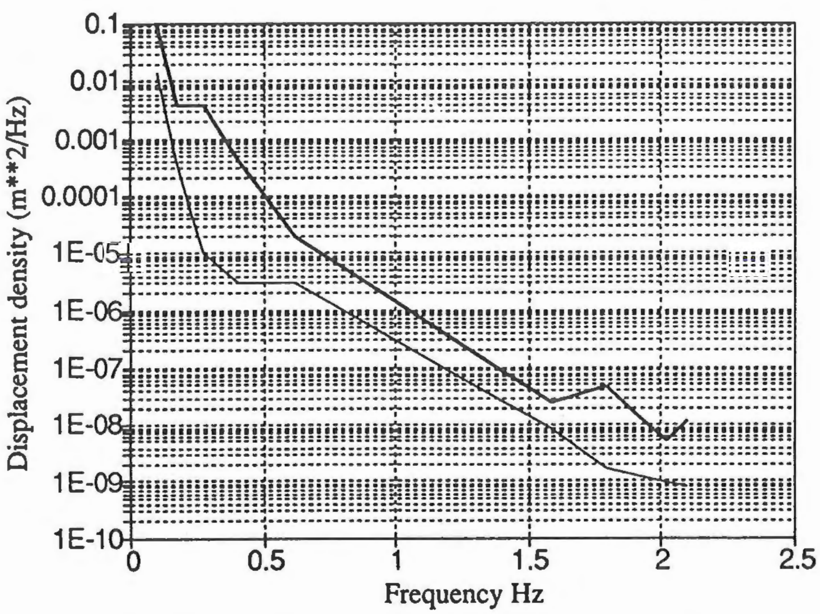

Fig. 10. Spectral displacement response to modified spatially correlated (thick line) and poorly correlated (thin line) spectral load.

The response spectrum, Fig. 10, represents the exponentially decreasing line with slight elevation at ice crushing frequency and at structural third and fifteenth natural frequencies. The appearance of this spectrum is similar to the spectral density of pressure fluctuation in turbulent flow. The spatially correlated and uncorrelated input produces almost the same response. This means that spatially correlated input at this low frequency does not excite the structure at its natural frequencies. Therefore, the assumption about full spatial correlation of ice crushing is wrong in this case; the ice crushing force is poorly correlated in space. The characteristic length λ is small. It is seen from Fig. 10 that the narrow-banded low frequency ice force excites the structural rigid body modes. At a frequency of 0.3 Hz, they are the rocking movements of the caisson. These movements could be clearly seen in the animated picture of the structural response. The original shape of the caisson remains undeformed. When the ice velocity increases, the ice crushing frequency approaches one of the structural resonance frequencies. The corresponding global mode is excited. Thus, when an ice sheet moves straight against the caisson side at a velocity of 28 mm/s the fourth natural mode may be excited at frequency 1.65 Hz.

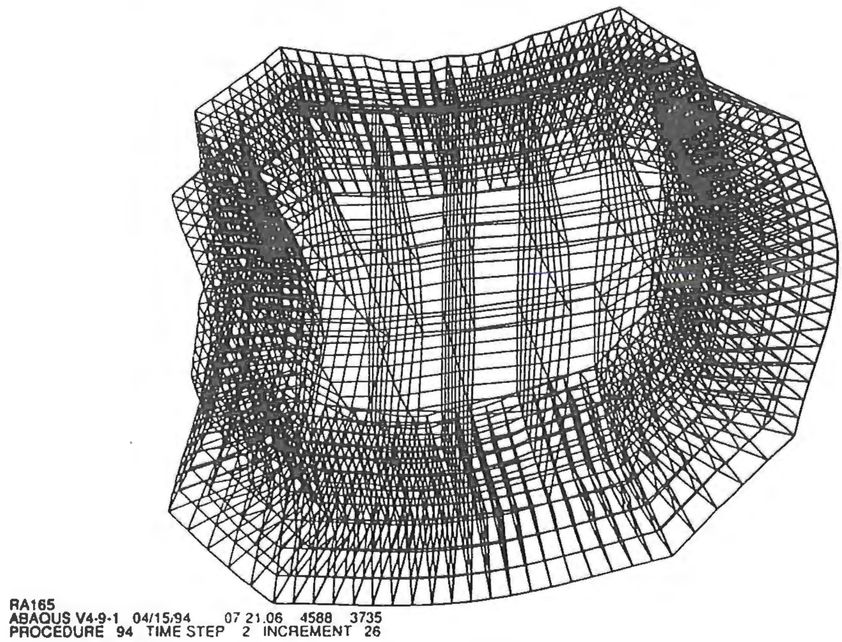

Fig. 11. The deformed shape for the modified spectral excitation. Dominant frequency is 1.65 Hz.

The deformed shape of the caisson due to this excitation is shown in Fig. 11. The spectral displacement response to the correlated and poorly correlated input at the middle of the caisson side is shown in Fig 12.

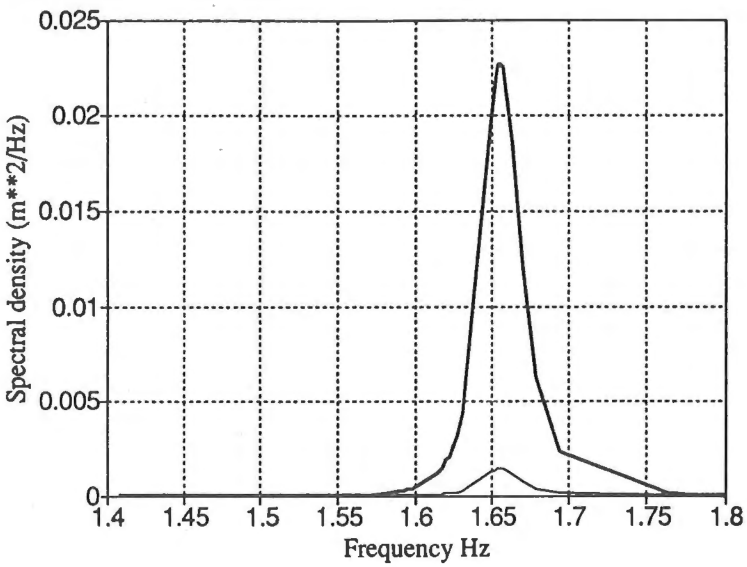

Fig. 12. Spectral displacement response to the correlated (thick line) and poorly correlated (thin line) excitation at frequency 1.65 Hz in the middle of the caisson side.

The entire caisson side is distorted allowing deep penetration of the ice sheet edge. The ice crushing process becomes spatially correlated, ice crushes simultaneously along the whole side. The characteristic length is large. Similar phase-locked ice crushing was observed by Jefferies and Wright (1988). The structural response is a narrow-banded, almost periodic process (Fig. 12). The displacement distribution along the loading line shows the bending of the entire caisson side with maximum deflection at the middle point. Comparing these two ice crushing events (Fig. 11 and Fig. 12), it is seen that λ is rather a structural property (but not structural dimension) and clearly depends on the structural modal shapes, specifically on the modal deflection in the ice movement direction. It is not constant as in the turbulent flow process (pipe diameter) but changes from mode to mode and is a function of ice penetration δ, $\lambda = \lambda(\delta)$. Appearance of this function may be established experimentally by measuring or computing the coherence between output signals at different locations along a deformed contact line. This is a subject of future studies. If ice crushes at a frequency close to that of global natural mode allowing deep penetration of the ice edge, the crushing is spatially correlated. Otherwise, ice crushing is poorly correlated in space. Evidently, the dominating frequency prediction (1) for ice-large structure interaction is meaningful when ice crushing is spatially correlated since in this case, K means the global structural stiffness in the ice movement direction. For poorly correlated excitation, the relation (1) may be used locally and its significance for the whole structure is nil. Ice crushes at different frequencies along the contact line depending on local stiffness. So function $\lambda(\delta)$, when found, will define the range of application of (1) for large offshore structures.

CONCLUSION

The quantitative relation (1), linearly binding the ice-structure interactive parameters, can be derived from the field or laboratory measurements and then used to predict the structural behaviour. The tank tests and field observations confirm its existance. More experimental data are needed to verify its validity for extrapolation purposes. If proved being valid, the relations (1) and (4) may be very useful in the ice-structure interaction research and offshore structure design since in this case there is no need in elaborate material and interaction models.

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