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CROSS-FLOW INDUCED VIBRATIONS OF TUBE BANKS: HYDRODYNAMIC FORCES AND MATHEMATICAL MODELS

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CROSSFLOW-INDUCED VIBRATIONS OF TUBE BANKS: HYDRODYNAMIC FORCES AND MATHEMATICAL MODELS

Shoei-sheng Chen*

The potential for flow-induced vibration of tube banks is well known (3,4). Numerous investigations have been made to obtain a better understanding of tube vibration phenomena in heat exchangers, particularly in high temperature, high performance heat exchangers used in nuclear reactor systems. Based on different excitation mechanisms, different mathematical models have been developed (2). However, in those models, a single excitation mechanism is considered, and in most cases, a single tube is taken as a model for tube banks. The objective of this paper is to present a method of analysis for the hydrodynamic forces acting on tube banks and a mathematical model for multiple tubes and multiple excitation mechanisms incorporating tube/fluid coupling.

The hydrodynamic forces acting on tube banks are analyzed using the two dimensional potential flow theory. Consider a group of k tubes vibrating in a crossflow. Let the displacements of tube i in the two orthogonal directions be u_i and u_{i+k} respectively. The corresponding two components of the hydrodynamic force acting on tube i are H_i and H_{i+k} respectively. These components are given by

$$H_m = \rho\pi \sum_{n=1}^{2k} \left(\frac{R_m + R_n}{2}\right)^2 \left(\alpha_{mn} \frac{\partial^2 u_n}{\partial t^2} + \beta_{mn} \frac{\partial u_n}{\partial t} + \gamma_{mn} u_n\right) + q_m \qquad (1)$$

$$m,n = 1,2,3,\ldots 2k$$

where t = time, ρ = fluid density, R_m = tube radius, q_m = steady fluid force, and α_{mn}, β_{mn}, and γ_{mn} are coefficients for inertia forces, hydrodynamic damping, and fluidelastic forces. The hydrodynamic forces can be calculated for a group of tubes arranged in any pattern and the tubes may have different diameters. Numerical results for these force coefficients will be presented.

Once the hydrodynamic forces are known, the equations of motion for tube banks are derived to include the effects of various excitations. These equations can then be analyzed in a straightforward manner. Free vibration, forced vibration, and stability can be studied based on the same equations. The results obtained from the model include: (1) natural frequencies and mode shapes of coupled tube/fluid vibration; (2) responses of each tube to various types of excitations; (3) critical flow velocities at which large tube oscillations occur. For example, consider a group of identical tubes. The critical flow

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velocity V_{cr} is given by

$$\frac{V_{cr}}{f_c d} = k\left[\frac{m_c(2\pi\zeta_c)}{\rho d^2}\right]^{1/2} \qquad (2)$$

where d = tube diameter, ρ = fluid density, k = constant, m_c = sum of tube mass and effective added mass, f_c = natural frequency of coupled modes, and ζ_c = modal damping ratio of coupled modes (1). Therefore, the critical flow velocity of a tube bank depends on many parameters: tube diameter, tube rigidity, tube arrangement, fluid density, tube and hydrodynamic damping, etc.

A series of experiments on vibration of tube banks subjected to crossflow is also being conducted at Argonne National Laboratory. The objectives are to verify the theory and to obtain the information for hydrodynamic forces and detailed tube motions. The tests for inertia forces have been completed; the results show that the theory and experiment are in good agreement. The general experimental approach as well as preliminary experimental data will be discussed.

Based on the results of this study, several general conclusions can be drawn.

(1) Large tube oscillations may be associated with fluidelastic instability, vortex shedding, or other mechanisms. These mechanisms interact with one another; in each flow-velocity range, there may be a dominant mechanism. Therefore, a single excitation mechanism cannot be used to correlate all laboratory and field data.

(2) A tube bank subject to fluid flows will respond as an integrated system rather than as a collection of many individual tubes. This is attributed to fluid-coupling effect. All fluid-coupling effects should be included in the model to obtain the proper description of the orbital path of tube motion.

(3) The natural frequencies of coupled modes increase slightly with flow velocity, while the damping ratios of some modes decrease. When the flow velocity reaches a certain value, the damping of a certain mode becomes zero and the tubes lose stability by flutter. Depending on system parameters, flutter flow velocity may be lower or higher than the "lock-in" flow velocity associated with vortex shedding.

(4) Detuning the tubes has a beneficial effect on flutter flow velocity.

(5) The flutter flow velocity increases with system damping. However, in certain cases, flutter flow velocity may decrease slightly, or remain nearly constant, with increasing damping because of change of instability modes.

(6) One of the most critical instability modes of tube-rows is associated with the mode that involves predominantly an up- and downstream movement of the central tube with transverse movement of the

wing tubes such that the central tube moves downstream through a narrow gap and upstream through a wide gap.

(7) As the number of tubes in a tube bank increases, the flutter flow velocity, in general, decreases. Therefore, using a single-tube approximation may not be conservative.

(8) In the flow-velocity range in which vortex shedding is dominant, although the excitation is in the lift direction, the tube will have a relatively large displacement in the flow direction because of fluidelastic coupling. On the other hand, in the flow-velocity range in which fluidelastic instability is dominant, the motion may be initiated by other excitation mechanisms, but it is the fluidelastic coupling that produces large-amplitude oscillations.

The model has demonstrated that, once the fluid-force coefficients are known, it is capable of predicting the details of tube-fluid interactions, including instabilities and responses to various types of excitations. With this model, improved design criteria can be established to eliminate detrimental flow-induced vibrations in tube banks.

REFERENCES

1. Chen, S. S., "Vibration of Nuclear Fuel Bundles," Nuclear Engineering and Design, Vol. 35, 1975, pp. 399-422.

2. Chen, S. S., "Flow-Induced Vibrations of Circular Cylindrical Structures," To appear in Shock and Vibration Digest.

3. Nelms, H. A., and Segaser, C. L., "Survey of Nuclear Reactor System Primary Circuit Heat Exchangers," ORNL-4399, April 1969.

4. "Flow-Induced Vibration in Heat Exchangers," The Winter Annual Meeting of ASME, Dec. 1, 1970.