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FLOW-INDUCED VIBRATION AND INSTABILITY OF SOME NUCLEAR-REACTOR-SYSTEM COMPONENTS

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SUMMARY

The high-velocity coolant flowing through a reactor system component is a source of energy that can induce component vibration and instability. In fact, many reactor components have suffered from excessive vibration and/or dynamic instability. The potential for detrimental flow-induced vibration makes it necessary that design engineers give detailed considerations to the flow-induced vibration problems.

Flow-induced-vibration studies have been performed in many countries. Significant progress has been made in understanding the different phenomena and development of design guidelines to avoid damaging vibration. The purpose of this paper is to present an overview of the recent progress in several selected areas, to discuss some new results and to identify future research needs. Specifically, the following areas will be presented: examples of flow-induced-vibration problems in reactor components; excitation mechanisms and component response characteristics; instability mechanisms and stability criteria; design considerations; and future research needs.

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1. Introduction

The high velocity coolant flowing through a reactor component is a source of energy that can induce component vibration and instability. In fact, many reactor components have suffered from excessive vibration and/or instability. The potential for detrimental flow induced vibration makes it necessary that design engineers give detailed considerations to the flow-induced vibration problems.

There are numerous possible vibration and instability problems in nuclear plant and internal components. These problems have been discussed extensively in various conferences, such as the past SMiRT conferences, Keswick conferences, Karlsruhe conferences, and different ASME meetings. It is not possible to review all these problems in this brief review. Instead, this paper will examine recent development of several selected areas. Specifically, it will deal with the vibration and stability of circular cylindrical structures subjected to internal or external flow.

2. A Typical Example of Vibrational Problems in Reactor Components

Past failures caused by flow induced vibrations have been documented in some detail; for example, Refs. 1 and 2 analyze a series of typical problems. Most recently, the event of the leakage of a steam generator which occurred after only 3000 effective full power hours of operation has attracted much attention [3,4]. The leakage is caused by the so-called "shake and break" phenomenon. Dozens of the steam generator tubes at Ringhals 3 reactor in Sweden were found to have worn down to only 10% of their original thickness. The leakage signaled the beginning of a troublesome period for a series of other reactor plants. The clear source of the problem is flow induced vibration. When a plant is operating at the top end of its capacity, the flow sets up vibrations in the tubes. As the tubes rub against the baffle plates, they rapidly wear away. Because of this problem, the manufacturer, utilities and regulatory agencies have worked together in an attempt to find a solution. In the mean time, some reactor plants have to be operated at reduced power levels. This example shows that flow induced vibration can lead to economic, maintenance, safety, and operational problems. Therefore, reactor designers can no longer consider the flow-induced vibration problem as being the secondary design parameter.

3. Characterization of Flow Induced Vibration

The vibration of a structure in fluid flow involves very complicated phenomena. The characterization and mathematical modeling of these phenomena remain a difficult task. It is still not possible to solve all these problems using the fundamental principles in fluid and structural mechanics. Therefore, different simplified models are developed to describe the observed phenomena.

Let structural displacements be defined as column vector q; $\dot{q}$ and $\ddot{q}$ are the structural velocity and acceleration, respectively. The dynamic structure/flow interaction can be described by the following matrix equation:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{Q\}$$
$$[M_s + M_f]\{\ddot{q}\} + [C_s + C_f]\{\dot{q}\} + [K_s + K_f]\{q\} = \{Q\} \quad (1)$$

where M is mass matrix including structural mass M_s and fluid added mass M_f; C is damping matrix including structural damping C_s and fluid damping C_f; and K is stiffness matrix including structural stiffness K_s and fluid stiffness K_f; and Q is the excitation forces. In general, M, C and K are functions of q, $\dot{q}$ and $\ddot{q}$; therefore, a complete solution is rather difficult to obtain. Fortunately, in many practical situations, the linearized equation can be used to obtain the necessary information.

In general, C and K are not symmetric. Therefore, the structure may be subjected to different types of vibration and instability:

• Divergence: Static instability may be caused by the displacement-dependent fluid force, such as buckling of a tube conveying fluid.

• Dynamic Instability: Oscillatory instability may be caused by the displacement-dependent fluid force as well as velocity-dependent fluid force, such as the instability of tube arrays in crossflow.

• Response to Fluid Excitation Forces: Both static structural displacement and oscillatory displacement may be caused by various flow excitation forces, such as the deformation caused by fluid centrifugal force in a tube conveying fluid and fuel rod oscillations caused by the turbulence flow.

• Acoustoelastic Response: Flow field, structure, and acoustic medium may interact with one another, such as the synchronization of vortex shedding, tube vibration and acoustic resonance in a heat exchanger tube bank.

Although different structural components in different flow fields may respond in many different ways, the response characteristics can generally be classified according to the characteristics of the parameters [M], [C], [K] and {Q} given in eq. (1).

4. Recent Progress in Selected Subject Areas

4.1 Instability of Tube Arrays Subject to Crossflow

The progress up to 1979 can be found in a review on this subject [5]. Since then, significant progress has been made in different aspects.

4.1.1 Mathematical Models

The analytical development of this subject has been very exciting. Tanaka and his colleagues, in a series of papers, publish the fluid-force data measured for tubes oscillating in flow [6-8]. Based on the measured fluid forces, the critical flow velocity can be calculated and correlates experimental data well. Chen [9,10] develops further his model using the fluid-force data measured by Tanaka. Two distinct mechanisms are distinguished based on eq. (1): fluid-damping-controlled instability and fluidelastic-stiffness-controlled instability. Based on this model, the inconsistency among experimental data obtained by different investigators as well as different phenomena reported in literature can be resolved reasonably well.

Whiston and Thomas [11] and Price and Paidoussis [12] reexamine the quasi-static models. These models are useful for fluidelastic-stiffness-controlled instability but probably are not applicable for fluid-damping-controlled instability.

Lever and Weaver [13] develop an analytical model based on a series of approximations and an empirical coefficient. The measurements needed to quantify the mathematical model are reduced significantly. The approach is novel and promising. However, further development and assessment of the model remain to be made.

4.1.2 Experimental Studies

Experiments are conducted by various investigators in the following four major areas: determining the stability constants [14-17]; verifying the mathematical models [8,18]; investigating the detailed flow field around tube arrays [19]; and testing more realistic heat exchangers [20,21]. These studies have provided many additional data to establish the stability boundaries. Certainly, more carefully designed tests are still needed to quantify the required coefficients.

4.1.3 Stability Criteria

Various stability criteria have been proposed based on the analytical results and experimental data. Most of these criteria can be grouped into two classes:

- The critical flow velocity U/fD (U = flow velocity, f = tube natural frequency and D = tube diameter) is a function of the mass damping parameter,

$$\frac{U}{fD} = \alpha_1 \left(\frac{2\pi m \zeta}{\rho D^2}\right)^{\alpha_2}. \tag{2}$$

where m = tube mass per unit length, ζ = damping ratio, and ρ = fluid density.

- The critical flow velocity is a function of mass ratio $m/\rho D^2$ and damping $(2\pi\zeta)$,

$$\frac{U}{fD} = \beta_1 \left(\frac{m}{\rho D}\right)^{\beta_2} (2\pi\zeta)^{\beta_3}. \tag{3}$$

The constants α_1, α_2, β_1, β_2 and β_3 are summarized by Chen [22].

Among different investigators working in this field, there is no agreement in using a particular equation. Based on the mathematical model [9], Chen and Jendrzejczyk [23] have demonstrated that eq. (2) is applicable for high mass-damping parameter region with $\alpha_2 = 0.5$ and eq. (3) is applicable for low mass-damping parameter region.

4.1.4 Design Considerations and Research Needs

Although the detailed interaction process of tube motion and fluid flow remains unknown, there are several design guides [22,24,25] which can be applied in design and evaluation of such systems to avoid detrimental instability.

To improve the stability criteria, we have to develop analytical methods to compute various fluid-force coefficients. This is one of the problems that is certain to be pursued in the field of computational fluid dynamics. In addition to the prediction techniques, understanding the basic fluid dynamics for flow across a vibrating tube array is very important. The interaction process of tube array and crossflow is certain to receive more attention in the future. Furthermore, the instability associated with the different modes of a continuous, loosely supported, tube called "tube-support-plate-inactive modes," has to be assessed with respect to tube damage. The interaction of tube with baffle-plate support during instability of a tube-support-plate-inactive mode is an important area to be pursued.

4.2 Response of Cylinder Arrays to Flow Excitations

The three major excitation sources are turbulent buffeting, vortex shedding and acoustoelastic vibration. The random pressure fluctuations exist practically for all flow velocity ranges. Numerous studies have been made on turbulence-induced vibration [26]. If the turbulence spectrum and spatial correlations in a cylinder array are known, and if the cylinder oscillations do not affect the flow field, cylinder responses can be calculated based on eq. (1). However, the information on the level of turbulence, its spectral distribution and scale is not known in general.

The characterization of vortex shedding across a single cylinder and synchronization of a single cylinder with vortex shedding are fairly well understood [26,27], although analytical solution of the detailed interaction process remains difficult [28]. The problem of two cylinders in crossflow also has been discussed in some detail [29]. However, this is not the case for cylinder arrays. For example, the basic question of the existence of vortex shedding in cylinder arrays remains not satisfactorily answered.

Strouhal numbers associated with vortex shedding for in-line and staggered tube arrays have been collected from different sources [30]. However, there are many parameters which can affect the periodicity of vortex shedding such as cylinder arrangement, cylinder pitch, upstream turbulence and vibration amplitude. One of the difficulties is to separate the vortex excitation from other flow excitations.

In a flowing fluid, structural motions are coupled with flow field. A structure that undergoes a displacement can exert feedback control on acoustic field. In general, the phenomenon is rather complicated. For example, in a heat exchanger tube bank subject to crossflow, acoustic waves perpendicular to both tube axis and the flow direction can be generated. If the vortex shedding frequency is close to an acoustic frequency, the flow field and acoustic field are coupled and reinforced with each other. The worst case occurs when the acoustic frequency, vortex shedding frequency, and tube natural frequency are the same. Under such conditions, serious tube oscillations could occur.

Efforts are being made to separate the effects of these three dominant excitaltons [19,31-35]. These studies are direacted to the following objectives: (1) measuring the time average and fluctuating pressure around cylinders and on the surface of cylinders; (2) determining the span-wise correlation of fluid field; (3) investigating the effect of upstream turbulence; (4) measuring the fluid excitation force in two-phase flow, and (5) developing techniques to suppress acoustoelastic vibration. The progress in this area is not as drastic as in the instability problem.

At present, techniques are available to estimate the response of cylinder arrays to turbulence [32,36]. However, the correlation of cylinder response to damage attributed to turbulence remains a difficult task. Vortex-induced resonance appears to be insignificant except in the first and last rows or that when it synchronizes with acoustic frequencies. The state of the art in this problem area is still far from complete. Characterization of flow excitations in cylinder array is a challenging subject in fluid mechanics.

4.3 Tubes Conveying Fluid

The dynamics of tube conveying fluid has been the subject of numerous investigations [26]. This is because of the intrinsically interesting characteristics as well as its practical significance. Instability usually occurs at high flow velocities, which are not frequently encountered in practice; therefore, instabilities are more of academic interest. However, subcritical vibrations always exist no matter what flow velocity ranges.

Instability at high flow velocities continues to receive attention [37-46]. In contrast to past studies, emphasis has been placed on different nonlinear theories. The results from nonlinear theories have shed some light on the inadequacy of the linear theory. For example, it has been believed that a tube fixed at both ends can become flutter [41]. The nonlinear theory has demonstrated that sustained flutter motions are impossible; this tends to agree with the available experimental observations.

Nonlinear theories of tubes conveying fluid will continue to receive attention. In addition, certain aspects of the linear theory and experiments will be pursued. Those are attributed to the fact that this is one of the most practical models of nonconservative systems.

In the area of subcritical vibration, no significant progress has been made. However, this is much more important for many system components such as piping systems in nuclear plants. Characterization of these systems due to different flow excitations will receive more attention in the future [42].

4.4 Circular Cylinders Subject to Axial Flow

In contrast to internal flow, most external flow studies are focused on subcritical flow ranges. Although investigations have been made to study the stability behavior at high flow velocities [43], subcritical vibrations are far more important. In particular, various investigations are motivated by the need to design nuclear fuel bundles free from detrimental vibrations.

Recent studies on the subcritical vibration include characterization of turbulent pressure fluctuations [44-46], development of analytical model [47,48], test on fuel rod vibration and response of other system components [49-51]. Wall-pressure fluctuations within the turbulent boundary layer on the surface of cylinders have been measured for a cylinder in annular flow and seven-rod array. At this point in time, there are no sufficient data to characterize systematically the turbulent pressure field in a cylinder array. Much more work is needed; however, those measurements are not easily made.

Several studies are published to improve the analytical model. For example, the hydrodynamic damping is determined for a fuel rod model in still fluid and in flowing fluid; semi-empirical formula for predicting the hydrodynamic damping in rod bundles is given. In addition, additional analytical models to predict the cylinder response have been proposed.

Test of fuel rod model remains one of the indispensable ways to verify the fuel rod response to turbulent flow excitations. Prediction is difficult to make to account for the effects of the different parameters such as temperature, grid spring force and irradiation. Fortunately, the cylinder displacements are normally very low in practical situations.

4.5 Other Problem Areas

There are other subject areas which have received more attention:

- Leakage flow [52]: Flow passing through the annulus geometries can cause structural instability; this is called leakage flow mechanism. This problem has been identified in some reactor components, such as fuel stringer, upper internal structure hung above the reactor core, flow control device, slip-fit joint and baffle-plate leakage flow.

- Surveillance of Flow Induced Vibration [53]: The concern prevailing in nuclear industry is to increase the power plant operating availability. One concept to improve power plant availability includes automated surveillance and diagnostics. Studies are being made to develop techniques such that flow induced vibration can be detected before it causes damage.

• Flow Induced Vibration and Damage: It is fairly easy to identify that flow induced vibration is one of the main causes of the damage in many situations. However, it is rather difficult to develop a thorough understanding of the relation between vibration and damage in general. Effort will have to be made to establish the proces of damage caused by vibration and to answer the question how much vibration is too much.

5. Closing Remarks

• Significant progress has been made in the last few years in the study of stability of tube arrays. The controversy among different investigators and inconsistency among different test data now can be resolved reasonably well. Future studies are expected to be placed on the computation of fluid forces, understanding of flow field, and calculation of effective flow velocity in practical heat transfer equipment.

• Responses of cylinders to turbulence pressure fluctuation, acoustic excitation, and vortex shedding are receiving continuing attention. Much more clear separation of different excitation sources will have to be made to settle the remaining issues.

• The stability of cylinders subject to axial flow will be studied because of its intrinsically interesting characteristics. However, more emphasis will be focused on the nonlinear theories and experiments.

• Subcritical vibration of cylinder arrays in axial flow remains difficult to predict accurately because of the lack of information on flow excitations. Assessment of new fuel-bundle design remains to rely on model tests.

• Instability attributed to leakage flow, relation between vibration and damage, and vibration surveillance are some subject areas which will receive more attention.

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