FLOW-INDUCED VIBRATIONS OF CIRCULAR
CYLINDRICAL STRUCTURES

by

Shoei-sheng Chen

Components Technology Division

Base Technology

June 1977

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ABSTRACT

This report reviews the problems of flow-induced vibrations of circular cylindrical structures. Firstly, the general method of analysis and classification of structural responses are presented. Then, the presentation is broken up along the lines with stationary fluid, parallel flow, and cross flow. Finally, design considerations and future research needs are pointed out. Extensive references are included.

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NOMENCLATURE

C_m	Added mass coefficient
$[C]$	Damping matrix
D	Cylinder diameter
f	Vortex shedding frequency
h	Shell thickness
$[K]$	Stiffness matrix
m	Cylinder mass per length
M	Effective mass(= tube mass + effective added mass) per unit length
$[M]$	Mass matrix
m_f	Displaced mass of fluid by cylinder
n	Exponent in Eq. (5)
q	Generalized coordinate
Q	Generalized force
R	Shell radius
Re	Reynolds number
V	Flow velocity
V_r	Reduced flow velocity
γ	Self-added mass
ζ	Damping ratio
μ	Eigen value of added mass matrix
ρ	Fluid density
Ω	Cylinder natural frequency in vacuo
Ω_c	Natural frequency of coupled mode
Ω_s	Natural frequency of a single cylinder in an infinite fluid
Ω_u	Natural frequency of uncoupled mode

I. INTRODUCTION

Flow-induced vibration of circular cylinders has been known to man since ancient times; the vibration of a wire at its natural frequency in response to vortex shedding was known in Ancient Greece as Aeolian tones. But systematic studies of the problem were not made until a century ago by Strouhal who established the relationship between vortex shedding frequency and flow velocity for a given cylinder diameter [1]. The early research in this area was summarized by Goldstein [2].

Since the old Tacoma Narrow Bridge fell in 1940, flow-induced vibration has attracted the attention of many researchers. Furthermore, the trends in modern structures, which have become lighter, more slender due to the use of high-strength materials, and the development of advanced nuclear power reactors have increased the importance of flow-induced vibration problems in civil and mechanical structures. Because of the concern of the potential for detrimental vibration in many practical system components such as suspension bridges, tall buildings, chimney stacks, heat-exchanger tubes, ocean piles, transmission lines, and reactor system components, extensive studies have been made in the last decade. There are available several reviews which deal with general flow-induced vibrations and contain material relevant to circular cylindrical structures [3-13].

The objective of this report is to review the state-of-the-art and indicate the areas where fruitful work may be done to improve the state-of-the-art for flow-induced vibrations of circular cylindrical structures. The discussion begins with the classification of structural responses; excitation mechanisms and general method of solution are pointed out. Then the discussion is broken up along the lines with stationary fluid, parallel flow, and cross flow. Finally various methods for suppressing detrimental flow-induced vibrations are considered and research needs are pointed out. No attempt

is made to include all publications but it is believed that most of the important ones are included.

II. GENERAL CONSIDERATIONS

As we know, flow-induced vibrations are rather complex and diverse phenomena. In order to understand the general characteristics of structural responses in fluid environment, one must identify the basic excitation mechanisms. The following contains a list of potential excitations: vortex shedding [14,15]; fluidelastic mechanism [16,17]; turbulent buffeting [18,19]; jet switching [20]; acoustic noises [21-23]; flow pulsations [24, 25]; turbulent boundary layer pressure fluctuations [26,27]; and others. Under different situations, different excitation sources may be the dominant excitation mechanism. Sometimes it is rather difficult to identify which is the dominant one, and sometimes, two or several excitation mechanisms may interact with one another.

The cylindrical structural system upon which fluid excitations act, and by which motions are executed, will depart from its equilibrium position; the new configuration of the system may be represented by the generalized coordinate $\{q\}$. In general, the equations of motion may be reduced to [28,29]

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{Q\} \quad , \quad (1)$$

where M is a mass matrix including added mass effect, C is a damping matrix including fluid dynamic damping, K is a stiffness matrix including fluidelastic effect, and Q is a generalized force including fluid excitation forces. Note that M , C , K , and Q may be dependent of q and these matrices are not necessarily symmetric. The interdependences which rule

fluidelastic behavior of a cylindrical structural system can be represented by Fig. 1.

Based on Eq. 1, general response characteristics of a system can be analyzed. A circular cylindrical structural system immersed in a fluid stream may vibrate for different causes; the behavior can be classified as follows:

Static Behavior

1. Static Deformation: Static displacements may be induced by steady fluid forces such as drag force [30], fluid centrifugal force [31], and static fluid pressure [32].

2. Static Instability: Buckling of cylindrical tubes has been observed experimentally [33]. It is the same phenomenon as an Euler column subject to an axial compression.

Dynamic Behavior

1. Forced Vibration: In subcritical flow velocity ranges, the structure is subjected to flow excitations. If the excitation force is periodic, such as vortex shedding, large oscillations associated with resonance can occur [34]. On the other hand, if the excitation is due to random pressure fluctuations, only small amplitude oscillations may be induced [8,26].

2. Self-Excited Vibration: Large amplitude vibrations are frequently observed in heat exchanger tube banks [16]. It also occurs in pipes conveying high velocity fluid [8,17].

3. Parametric Resonance: Pulsating or two-phase flows can induce parametric and combination resonances [24,25].

Note that static deformation, static instability, force vibration, and self-excited vibration follow each of the four individual loops shown in Fig. 1, while parametric resonance involves both loops 3 and 4. In many

Fig. 1. Fluidelastic Responses of Circular Cylindrical Structures

practical problems, they do not follow a single loop; for example, in the lock-in region of vortex-induced vibration of a single cylinder, it involves both loops 3 and 4, while in the other flow velocity ranges it follows loop 3 only.

III. VIBRATIONS IN STATIONARY FLUID

When a structural element which is submerged in a fluid vibrates, the surrounding fluid must be displaced to accommodate the motions. This effect is usually accounted for using the added mass concept which was originated in the last century. Ideally, the added mass should be calculated from the three-dimensional Navier-Stokes equations. Obviously, this is difficult even in simple cases. In many practical cases involving small-amplitude oscillation, added mass can be computed from the potential flow theory; a summary of the potential flow results for circular cylindrical structures were compiled recently by Chen and Chung [35], which provided formulas, graphs, and computer program. It should be recognized that the potential flow theory has its limitations. Several experimental results for a single cylinder have demonstrated in certain period parameter ranges the potential flow solution may be in serious error [36-38]. However, in most vibration problems, one is more interested in the threshold of large oscillations, or steady-state, small-amplitude oscillations; in these cases, the potential flow theory is applicable.

When the fluid is viscous, the fluid force can be divided into two components; one is in phase with the acceleration (added mass effect) and the other is opposing to the movement (damping effect) [39-41]. In practical situations, the effect of fluid viscosity on added mass is small except in a confined region. However, fluid viscosity contributes

significantly to system damping; in particular, in a confined region, the damping associated fluid viscosity can be very large. So long as the vibration amplitude is small, the linear viscous flow theory will give sufficiently accurate results [39]. As the vibration amplitude becomes large, the nonlinear effects of flow field will be important. In fact, it has been shown that the added mass and damping depend on vibration amplitude [41,42].

The effect of fluid compressibility on structural motion is somewhat similar to fluid viscosity. Due to fluid compressibility, the added mass for a single cylinder in an infinite fluid will depend on wave length and the radiation damping may be significant [43]. In addition to its effect on structural modes, due to fluid-structure coupling, there exist acousto-elastic modes in which structural motion and fluid motions are strongly coupled [44,45]. If the vibration of a structure is of main concern, the fluid can be considered incompressible.

Because of the concern of flow-induced vibration in nuclear reactor vessels, thermal shields, and core barrels, vibrations of circular cylindrical shells containing fluid have been investigated in detail in recent years [44-51]. Contrary to tubes or rods vibrating in a liquid that the added mass is usually small, the added mass for shells can be very large. For example, a cylindrical shell containing fluid, the added mass is equal to $\rho R C_M / h$ where ρ = fluid density, h = shell thickness, R = shell radius, and C_M = added mass factor. The added mass factor depends on the axial and circumferential wave numbers and is in the range from 0.1 and 1.0 in most practical situations [45]. There is another difference between shells and tubes. For slender tubes vibrating in lower modes, the added mass is not dependent of vibrational modes, whereas the added mass for cylindrical shell is strongly a function of shell mode shapes.

Another area in which significant progress has been made is coupled vibrations of multiple structural elements. In a group of cylinders, because of fluid coupling effect, the motion of any cylinder will excite the others and all cylinders will respond as a group rather than as an individual one. This behavior has not been well recognized, although the dynamic response of a group of cylinders submerged in a liquid has been of great interest to many engineers. Many studies have been made; those include two parallel cylinders [52-54], two cylinders located concentrically and separated by a fluid [40,47,49,51,55-57], a row of cylinders [16,20,29,58-60], and a group of cylinders [28,61-69]. When a group of cylinders vibrates in a liquid, there is a definite phase relationship among the cylinders; these types of motions are called coupled vibration. On the other hand, if only one of the cylinders is oscillating while all others are stationary, it is called uncoupled vibration. The general dynamic characteristics of coupled vibration are different from that of a single cylinder. To illustrate the difference, consider a group of identical cylinders with natural frequency in vacuo Ω , and mass per unit length m . The natural frequencies for three different cases are as follows:

- (1) single cylinder in infinite fluid:

$$\Omega_s = \frac{\Omega}{\left(1 + \frac{m_f}{m}\right)^{1/2}} \quad (2)$$

- (2) uncoupled vibration of multiple cylinders:

$$\Omega_u = \frac{\Omega}{\left(1 + \frac{\gamma}{m}\right)^{1/2}} \quad (3)$$

- (3) coupled vibration of multiple cylinders:

$$\Omega_c = \frac{\Omega}{\left(1 + \frac{\mu}{m}\right)^{1/2}} \quad (4)$$

where m_f = displaced mass of fluid; γ = added mass of the cylinders; and μ = eigenvalue of added mass matrix [28]. These relationships have been confirmed experimentally [69]. The results of these studies show that in a group of cylinders there are infinite number of frequency bands corresponding to the infinite number of natural frequencies in the case of a solitary cylinder [67]. In each frequency band, there are $2k$ natural frequencies for a group of k cylinders; those frequencies are distributed near the frequency of the corresponding single cylinder. Within each frequency band, the steady state response of multiple cylinders are significantly different from that of a single cylinder. In the past, uncoupled modes have been used in calculating cylinder response. Now it is clear that coupled modes should be employed for cylinder bundles.

IV. PARALLEL-FLOW-INDUCED VIBRATION

In reference to the orientation of fluid flow with respect to the axis of structures, it is convenient to classify flow-induced-vibration problems as parallel and cross flows. Parallel-flow problems can further be divided into internal and external flows according to the position of fluid with respect to structure. In this section, vibration and stability of cylinders conveying fluid [17,24,25,27,31-33,70-129] and cylinders subject to external parallel flow [26,28,130-184] are considered.

Earlier studies of parallel-flow problems dealt with internal flow. Interest in the subject was largely because of its applications in many practical systems such as oil pipelines, fuel lines, and other piping systems and its intrinsic characteristics. The problems which have been studied included cantilevered pipes [76,77,79,83,90], articulated pipes [17,88,115], pipes with pinned or fixed end conditions [33,71,81], elastically supported pipes [93,104], and cylindrical shells [27,122-129].

The fluid flows discussed included steady flow, pulsating flow [24,112-118], and two-phase flow [119-121]. One of the most fascinating problems is fluid-conveying pipes fixed at the upstream end and free at the downstream end. This is a classical example of nonconservative system; therefore, numerous studies have been made. It has been shown that the pipe loses stability by flutter. In the subcritical flow velocity ranges, flow-induced oscillation of a cantilevered pipe is usually small because of large damping value associated with the Coriolis force. If the downstream end is fixed or pinned, the system has been called conservative system [103], gyroscopic conservative system, or nonconservative system [101]. In this case, as the flow velocity reaches a certain value, the pipe becomes unstable by buckling and in the subcritical flow velocity range, the Coriolis force does not contribute to damping. It has also been shown that the flutter-type instability is possible for pipes with support at the downstream end, although those flow velocities are higher than the buckling flow velocity. A complete analysis of a pipe clamped at the upstream end and elastically supported at the downstream end was analyzed recently [104]. It was shown that the pipe may lose its stability by buckling, flutter, or both, depending on the magnitudes of the displacement as well as rotational springs at the end. It should be pointed out that those studies are based on the linear theory. Once a pipe becomes unstable, the linear theory is not applicable any more. Therefore it is difficult to see the significance of the higher critical flow velocities other than the lowest one.

Relatively little attention has been directed to curved pipes; only two papers were found to be published in the last three years. Hill and Davis [100] examined the effect of initial forces on the vibration and stability of clamped pipes using the finite-element technique. They show

that neglecting initial forces results in out-of-plane buckling, while including these forces prevents buckling within the elastic limit. Doll and Mote [111] also considered the curved pipes using the finite element method. However, their results show that for pipes with small curvature, the analytical results based on the inextensional theory agree better with experimental data than the variable curvature theory.

Parametric and combination resonances in pipes conveying fluid are possible for periodic flow rate [24,112-118] and two-phase flow [119-121]. Analytical investigations have been made for articulated pipes, simply-supported pipes, and cantilevered pipes. Paidoussis [24] has conducted an experiment demonstrating the existence of both parametric and combination resonances with a harmonically perturbed flow velocity; they are found to occur over specific ranges of pulsation amplitudes and frequencies, and of flow rates. Two-phase-flow-induced instability also has been noted by Hara [119,120]. In general, it requires a relatively large perturbation to induce instability and with large value of flow velocity. This is probably not likely to occur in practical system components.

When a pipe is relatively short compared with pipe diameter, the potential flow theory rather than slug flow has been used to study instability problem [122-129]. It has been shown that flutter is possible for all types of end conditions. However, in the case of pinned or clamped end conditions, buckling always precedes the onset of fluttering-type instability. This is similar to the results using beam theory with slug flow. Fluttering-type instability of shells has been observed experimentally, but buckling-type instability has not been verified [125].

No significant progress has been made in the area of vibration induced by external parallel flow. However, it continues to receive attention

because of the concern of nuclear fuel rod wear due to vibration in the design of advanced reactors. The main thrust of the analytical/experimental work has been toward the development of prediction method of fuel rod response under operating conditions. For a single cylinder vibration in an ideal flow condition, several semi-empirical corrections are available to predict rod amplitude: Paidoussis' empirical correction [141], Chen's parametric model [150,151], Reavis' correction [142], and Chen-Wambsganss' method [26,155]. While these expressions are useful in design to predict rod response within order of magnitude, current state of the art is such that an accurate prediction of vibration amplitude is difficult without experimental information.

One of the improvements on the mathematical modeling of fuel bundle vibration is the fluidelastic coupling developed by Chen [28]. In all previous models, a single cylinder is taken as the model for rod bundles. Obviously, this is not appropriate, in particular, when the cylinders are closely packed such as a nuclear fuel assembly. The analytical and experimental results show that the general characteristics of fuel bundle are significantly different from that of a single rod. In the future, fluid-elastic coupling effect will have to be included in the development of mathematical model.

V. CROSS-FLOW-INDUCED VIBRATION

Our understanding of various types of fluid excitations of cylinders in cross flow is still not sufficiently complete to predict all the vibration problems at the design stage and to identify the precise mechanism causing system failure because of so-called cross-flow-induced vibration. However, past experiences and results of basic research enable us to know some of the most important mechanisms. The following discussion will cover each mechanism and related analytical/experimental results.

Vortex Excited Oscillation

Vortex-induced vibration of cylinders has long attracted the attention of many investigators from both academic and practical points of view. A concise history of the study is found in the reviews by Marris [3] and Berger and Wille [185]. The vortex shedding can excite cylinder vibration in the lift direction when its frequency approaches the natural frequency of the cylinder. The vortex shedding behind a stationary cylinder may be described by the Strouhal number, fD/V (D = cylinder diameter, V = flow velocity, and f = vortex shedding frequency), which is equal to 0.2 for a single cylinder in the Reynolds number range $10^3 < Re < 2 \times 10^5$. A flexible cylinder, however, can modify the vortex shedding process; i.e., vortex shedding tends to synchronize with the cylinder oscillation [34,186-194]. Experiments have shown that the lock-in region occurs for $V_r (=V/fD)$ near 5. The behavior outside the lock-in region is characterized by random vibration. In order to predict the amplitude of cylinder oscillation as a function of flow parameters, various models have been proposed. Basically there are two types of models: self-excited oscillation model and forced vibration model. In these models, the entire influence of the flow is

regarded as an integral force effect. The interaction between the fluid and the oscillation is taken into account by making the force dependent on the amplitude of vibration.

1. Self-excited Oscillation Model: Based on their experimental observations, Bishop and Hassan [195] first pointed out the nature of the self-excited vortex shedding and suggested that the fluid behavior might be modeled by a simple nonlinear oscillator. The idea has been pursued by Hartlen and Currie [34] who devise a model in which the lift coefficient satisfies a Van der Pol type equation. The model has successfully predicted the experimental characteristics of an elastically mounted cylinder, and the lift force on an externally driven cylinder. Because of the success of this rudimentary mathematical model, refinements of the model have been made by Skop and Griffin [191], Iwan and Blevins [192], and Landal [193]. Funakawa [187] and Nakamura [188] also treat vortex excitation of cylinders in a uniform flow as a self-excited oscillation; they use Birkhoff's oscillator model for the added fluid region behind the cylinder as a fluid subsystem and show that flutter is possible in a limited range of flow velocity including the value at which the vortex shedding frequency for the cylinder coincides with the cylinder natural frequency. Other self-excited models are those by Halle [190] and Di Silvio [194]. Halle proposes an oscillator model in which the fluid behavior is described by a second mechanical oscillator coupled to the cylinder by an equivalent viscous damping force proportional to the relative velocity of the fluid oscillator to the cylinder. Di Silvio [194] uses the concept of a variable vortex-wake width, dependent on cylinder amplitude and vortex-origin time to develop a self-excited model; this model is able to reproduce a certain narrowing of the wake and agrees with the experiments well. These approaches are similar in that the selection of model parameters is based on experimental

observations or assumptions. It appears that the nonlinear model first proposed by Hartlen and Currie [34] shows considerable promise and has been adopted extensively. On the other hand, the one discussed by Di Silvio [194] explains the physical meaning of the wake width in controlling both the frequency and the amplitude of the alternative driving force.

2. Forced Vibration Model: The vortex force is taken as the excitation; the amplitude of the oscillatory fluid force is expressed in terms of a force coefficient and the dynamic pressure. Then the problem is solved as a forced vibration problem of a single degree of freedom [196-199]. The finite correlation length and random nature of the fluid force on a cylinder has been considered in some detail [199]. Therefore, the problem has been treated either as a deterministic problem or analyzed using random vibration theory.

In addition to the transverse oscillation in the lift direction, in dense fluid, drag force can also induce cylinder oscillations in the streamwise direction. Vibrations of cylinders in the flow direction have been observed for single cylinders [200,201] and multiple cylinders [202, 203]. In light fluid, if cylinders are given a relatively large motion in the flow direction, cylinder oscillations in the flow direction can also synchronize with vortex shedding; this has been demonstrated by Griffin and Ramberg [204] for a single tube in wind tunnel.

Vortex shedding becomes more complicated for flow across cylinder arrays. The Strouhal number is no longer a constant but varies with the arrangement and spacing of the cylinders. Extensive studies have been made to measure the Strouhal number by Chen [14] and others; a summary of the experimental results is compiled by Fitz-Hugh [15]. Based on the vortex shedding theory, if one knows the Strouhal number, the flow velocity

at which resonance occurs can be predicted. However, there is little detailed information on the velocity range over which "lock-in" occurs, orbital paths of the cylinder motions, and amplitude of cylinder displacements. One of the main assumptions in this theory is the existence of vortex shedding within cylinder arrays; this appears to be questionable.

Fluidelastic Instability

Connors is the first investigator recognizing the fluidelastic mechanism of cylinder arrays subjected to cross flow [16]. The instability belongs to the classical flutter phenomenon which has been extensively studied in aerospace industry. The essential parameters associated with this mechanism are system damping and fluidelastic forces. When the flow velocity is increased to a certain value, the work done on the cylinder system by fluidelastic forces will be larger than dissipation by damping; therefore, large-amplitude oscillations will occur. Based on the experimentally observed cylinder oscillations and measured fluidelastic coefficients, Connors developed a simple instability criterion for cross-flow-induced instability of cylinder-rows by analyzing the motion of a single cylinder in a cylinder row; the threshold flow velocity is given as follows:

$$\frac{V}{fD} = k \left(\frac{2\pi M\zeta}{\rho D} \right)^n \quad (5)$$

where M = total mass including cylinder mass and added mass, ρ = fluid density, f = cylinder natural frequency, D = cylinder diameter, ζ = modal damping ratio, V = flow velocity, and $n = 0.5$ given in Connors' paper [16]. After the Connors' investigation of fluidelastic instability in wind-tunnel tests, several other authors also investigated the instability experimentally using different cylinder arrangements to find the constant k [205-210]. Some of the experimental data are assembled by Shin and Wambsganss [10]. The constant k depends on many parameters, such as cylinder arrangement,

cylinder/fluid mass ratio, structural and fluid dynamic damping, fluid-elastic coupling, and individual cylinder natural frequencies; the detail is not known. In addition to the experimental approach, mathematical models are also developed to correlate the experimental data. Blevins [211, 212] proposes a mathematical model with fluidelastic coupling for cylinder-rows consisting of identical cylinders; based on an assumed mode, critical flow velocity can be calculated. Most recently, Chen [29,213] has developed a model including fluid inertia coupling, fluid dynamic damping, fluidelastic force, and other excitations. The model can be used to predict the response of cylinder arrays subject to multiple excitations and the analytical results are found to be in agreement with the existing experimental results.

Turbulence Excitation

Turbulent buffeting or inflow turbulence can induce cylinder vibration. In cylinder arrays, separation of boundary layers occurs on a massive scale and turbulence levels can be pretty high. In addition, turbulent pressure fluctuations and other flow noises are also existing in a flow loop; the magnitudes of those noises are most likely system dependent. In general, fluid forces associated with turbulence are random; often the greatest power is associated with eddies whose size is related in a simple way to the cylinder spacing and/or cylinder diameter. When cylinders are subjected to those random excitations, the cylinders will respond primarily at the natural frequencies of the system. Numerous papers have been written on the subject [e.g., 14,18,19,198]. Owen [18] has made one of the most complete theoretical approaches to this problem. He disregards any theory of a superposed regular pattern of excitations.

Theoretically, if one knows turbulence spectrum and spatial correlation in a cylinder array, and assumes that structural oscillations do not

affect the fluid pressure field, it is possible to calculate cylinder responses [67]. However, very little has been done in literature for cylinder arrays. For example, there is little information on the level of turbulence within a cylinder array, its spectral distribution and scale. A systematic study on the turbulence in a cylinder array is needed before one can predict the response of cylinder array to turbulence.

Acoustic Excitation

Acoustic excitation can cause cylinder vibration normal to the flow direction and cylinder axis. For example, in a rectangular flow duct, the transverse acoustic oscillation of the lowest frequency has a wave length equal to twice the duct width. If the natural frequency of vortex shedding is close to an acoustic natural frequency, the flow field and acoustic field couple and reinforce each other; thus, large oscillations of the fluid will occur. The worst case is that when acoustic natural frequency, vortex shedding frequency, and cylinder natural frequency are the same [21-23,214]. There are two prediction methods for potential acoustically induced vibration problems. The first method is the frequency matching of acoustical natural frequency and vortex shedding frequency. Barrington [215] suggests that when the vortex shedding frequency is within 20% of the acoustic frequency, the acoustic vibration problem is probable. The second approach is to impose an additional requirement. For example, Grotz and Arnold [22] state that the ratio of wavelength of noise generated to the width of the free passage for the wave has to be less than 120 for generation of coupled acoustic-fluid dynamic oscillations in in-line cylinder arrays.

Acoustically excited oscillations are important for large heat exchanger with gas flow. In a liquid flow, acoustic natural frequencies are in general higher than the vortex frequency; thus, it will not be a problem for liquid flow. Nevertheless, studies also have been made to

assess the significance of acoustically induced vibration in nuclear reactor core [216]. The main concern is the effect of vibration resulting from the pump on the various structural components in the reactor.

Several other excitation mechanisms also have been considered; those include, among others, jet switching [20], structural borne noises, and flow pulsations. In some cases, those excitations may be important. However, it is believed that, in most cases, the four mechanisms discussed are the most important ones.

VI. DESIGN CONSIDERATIONS

From a practical point of view, what a designer needs is a simple procedure which can be used to ensure that the design life of a structure will not be affected by flow-induced vibration or a simple method that can be adopted to fix vibration problems occurring in a unit already in operation. Because of the complexity of the problem, there is no simple solution available to solve "all" vibration problems. But methods do exist that can be applied to different situations to alleviate flow-induced vibrations. Basically, the methods used to eliminate detrimental vibration can be divided into three classes: (1) Modifying Structural System--The structural system itself may be modified such that it will be less susceptible to vibration. (2) Modifying Flow Field--Fluid excitation forces are eliminated or their characteristics are modified. (3) Modifying Fluid Field and Structural System--Both fluid forces and structural properties are modified simultaneously to reduce the vibration to a tolerable level.

For a known excitation mechanism such as vortex-induced vibration of a single cylinder, one can follow the first method of changing the support parameters, stiffness, or damping in such a way that vibration will not be detrimental; e.g., damper has been successfully applied to alleviate

wind-induced oscillations [217]. In some cases, this cannot be done due to other restrictions. Then the second method can be adopted to avoid the regular shedding of vortices. A thin splitter plate [218,219] can be used for a fixed flow direction, while helical strakes [220] and surface modification [221] provide effective solution for the case when the flow direction may change. Naturally, one may also use the third method to reduce vibration amplitude.

In cylinder arrays, acoustically induced vibration can be suppressed with different methods. De-resonating baffles placed along the flow stream between cylinders are reported by Baird [222] and Cohan and Dean [223] for a single-mode acoustic resonance. Grotz and Arnold [22] have tested the idea of fitting diagonal baffles to avoid the possibility of resonance with higher acoustic modes. For closely-spaced cylinder arrays, removing certain cylinders will change the acoustic natural frequencies and reduce cylinder-fluid coupling. Walker and Reising [21] found that the best position for cylinder removal was longitudinally in the center of the cylinder array and in the transverse direction at the position which could be the pressure nodes of the acoustic standing wave. Zdravkovich and Nuttall [224] also studied the effect of various cylinder omissions and found that the acoustic resonance can be eliminated by unequal longitudinal pitches in two successive rows.

For cylinder-array vibrations caused by other excitation sources other methods can be used. Zdravkovich [225] found that the axial-rod shroud is effective in suppressing vibrations of the tandem cylinder arrangement. In the fluttering problem of cylinder arrays, usually the cylinders at the inlet region are most vulnerable to instability. Mirza and Gorman [226] suggest to arrange a set of rigid "prison-bar" type cylinders at the bundle

entrance or to provide additional support at the inlet region. Detuning of the cylinders are also found to be effective by Southworth and Zdravkovich [209] and Chen [29]. Funakawa [227] reported the use of sprocket chains inserted between the cylinders and vertically tensioned by weights to solve the problem of a steam raising unit. Eilers and Small [228] applied an elliptical bundle inserted in cylinder array to alleviate vibration problem in a reboiler. While all these methods belong to the method of modifying structural system, Brown [229] used a perforated grid to reduce the low frequency energy of the turbulence and successfully fixed his problem.

VII. FUTURE RESEARCH NEEDS

One of the major difficulties in solving flow-induced vibration problems is the characterization of fluid forces. The properties of near and far field flow noises, which exist in the absence of cylinder motion, have to be known before one can predict the cylinder response. This will require extensive experimental programs to obtain the necessary information. The important information is: What are the characteristics of flow noises in a cylinder array? How do they vary with Reynolds number, cylinder position, and other parameters? What is the effect of upstream turbulence and nonuniform incident flow? Most actual flows are neither transverse nor parallel to cylinders. How good is the independence principle of resolving the flow velocity into transverse and parallel components? Does vortex shedding exist within cylinder array? How does it vary with system parameters? Some efforts have been made by various investigators [e.g., 27,143,230,231] to obtain this information, but much more studies are needed.

In addition to flow noises, there are other motion dependent forces, such as fluid inertia force, fluid damping force, and fluidelastic force.

These forces play an important role on structural responses. For a simple case such as a single cylinder subject to a uniform cross flow, one knows pretty well about these forces if the motion is small. However, if the cylinder executes relatively large oscillations, these forces are not well understood. Even more complicated are the forces in a cylinder array. A systematic experimental/analytical study [28,69] has been made to obtain fluid inertia coupling, but there is no experimental data for fluid damping and fluidelastic force available for cylinder arrays.

Analytical methods of prediction are available but they need improvement. Let us consider two typical models: (1) Parallel-Induced Vibration--All existing models are obtained based on a single cylinder consideration. It is doubtful they can be applied to cylinder arrays. The coupling effect is significant in cylinder bundle. Other methods of analysis have to be developed; normal mode approach of using a single mode is not valid any more. (2) Fluidelastic Instability of Cylinder Arrays--Connors' model is frequently used. However, the validity of the model, Eq. 5, remains to be proved. For example, f , M , and ζ are based on those of a single cylinder in stationary fluid. In a cylinder array, f , M , and ζ are found to be those of coupled modes [29]. Further studies are needed to know the dependence of critical flow velocity on cylinder geometry, damping parameter, cylinder detuning, etc. Improvements are also needed for other models.

As far as mathematical models are concerned, one must bear in mind that they can provide practically useful information about the cylinder responses, but can't provide any information about the process in the fluid flow. If one can develop a model, primarily based on the structure of fluid flow, whether based on Navier-Stokes equations or other approximate equations to develop fluid force distribution, this will certainly

enhance our understanding of the basic characteristics of cylinder/fluid interactions. The first problem in this area to be resolved is again a single cylinder subject to a uniform cross flow. Even for this simple problem, no model based on the basic fluid dynamics is available.

In a flow-induced vibration problem, there are methods to bring about a solution to the problem. But it is better to prevent the problem rather than to fix it after it occurs. By increasing the structural stiffness and damping, and reducing flow velocity, it is generally possible to avoid detrimental flow-induced vibration problems. However, designing with large margin of safety factors results in increased cost and decreased performance. Furthermore, the method to reduce vibration frequently requires a compromise to satisfy other requirements. For example, increasing structural stiffness is beneficial from vibrational point of view, but it may increase thermal stress problem. Therefore, there is a need to optimize structural design with respect to the cost and performance without compromising safety. Unfortunately the current state-of-the-art design procedures [e.g., 11,232-234] leave much to be desired; this again points out that an in-depth understanding of the excitation sources and their characteristics, and characterization of system response is definitely needed. Solving flow-induced vibration today, to put it in a more pessimistic way, is still a blend of science and a little art. It uses the powerful tools of a modern technology whenever possible, and the good judgment in those areas which science is unable to explain fully. Until such a time as all the significant design parameters can be fully identified and quantified, the engineer charged with the design must rely on existing information, sound judgment, and model and preoperational tests to avoid detrimental vibrations.

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