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DYNAMIC RESPONSE OF SLENDER RODS IN COAXIAL FLUID FLOW WITH SINUSOIDAL AND RANDOM SUPPORT EXCITATION

by

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A DISSERTATION

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TITLE

DYNAMIC RESPONSE OF SLENDER RODS IN COAXIAL FLUID FLOW

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BY

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NOMENCLATURE

A = cross sectional area of cylinder, ft^2

a_1^2 = EI/m, ft^4/sec^2

C = damping coefficient, lb_f sec/ft^2

C_L = $.5m_fU^2/(2\pi\Omega *(D+\lambda))$ = damping coefficient due to lift force

C_{nd}= $.5C_nm_fU/D$ = damping coefficient due to normal force

C_o = damping coefficient at zero flow velocity, lb_f sec/ft^2

C_n = friction drag coefficient

C_t' = form drag coefficient

C_t = friction drag coefficient

D = diameter of cylinder, ft

E = modulus of Elasticity, lb_f/ft^2

f = exciting frequency, cps

f_s = $F(Re)$ U/D = Strouhal frequency, cps

$H(\omega)$ = frequency response function

I = $\pi/4\{Ro^4-Ri^4\}$= area moment of cylinder about the principle axis, ft^4

L = cylinder length, ft

m_f = ρ_fA = virtual mass per unit length, slug/ft

m_p = $\rho_p\pi\{Ro^2-Ri^2\}$= pipe mass per unit length, slug/ft

m = m_f+m_p = total mass per unit length, slug/ft

Ri = inside cylinder radius , ft

Ro = outside cylinder radius , ft

Re = UD/ν = Reynolds number based on free stream velocity and tube diameter

U = flow velocity, ft/sec

x = axial distance from the origin, ft

y = lateral deflection of neutral axis at position x, ft

Greek Letters

ρ_f = fluid density, slug/ft^3

ρ_p = cylinder wall material density, slug/ft^3

λ = double amplitude of base excitation, ft

α_1 = $C/m\omega_o = CL^2/(EIm)^{.5}$ = equivalent viscous damping parameter

α_o = $C_o/m\omega_o$ = damping parameter at zero flow velocity

ω = dimensionless frequency of oscillation

ω_o = undamped natural frequency, rad/sec

Ω = exciting frequency, rad/sec

ν = kinematic viscosity of fluid, ft^2/sec

ε^* = strain, ft/ft

ρ^* = radial distance from the neutral axis to the measured strain, ft

Φ_{FF} = power spectral density of excitation, g^2/cps

Φ_{yy} = power spectral density of response, g^2/cps, $(\mu in/in)^2$/cps

Constants

a, b, c, d, e, f, g as in Eq. 10

A_i; i = 1, 2, ---, n as in Eqs. 18 through 25

C_i; i = 1, 2, 3, 4 as in Eqs. 28, 29, 30 and 41

INTRODUCTION

Flow induced and structural born vibration problems occur in many fields of engineering. In the past considerable attention has been given to the study of cylinder motion in cross flow. Very recently, the attention is focused on the flow induced vibrations of slender cylinders in axial fluid flow. In practice the dynamical behaviour is of considerable importance for oscillations of above ground oil pipe lines and the flexible cylindrical fuel elements immersed in nuclear reactor coolant channels. There is very little information available on structural born vibrations of pipes carrying fluid, or immersed in flowing fluid, but there is considerable amount of documentation on flow induced vibrations of pipes. The physics of the problem is closely related to the swimming of slender fish [15]. Flexural vibrations of cylinders surrounded by flowing fluid have direct application to problems experienced in nuclear reactor core design and in drilling of oil wells; and the vibration of a pipe containing flowing fluid has direct application to problems experienced in oil pipe lines and in fuel lines of high performance aircraft and missiles. Paidoussis [13] formulated a differential equation to describe the lateral motions of a pipe surrounded by fluid flowing parallel to the axis of the pipe. Because of the similarity between the differential equation for a pipe carrying fluid, presented by Nagulaswaran [11], and the equation presented by Paidoussis [13], it was felt that the general theory describing the transverse vibrations of a pipe surrounded by fluid flowing parallel to the axis of the pipe is the same as that of the pipe filled with flowing fluid. The studies on the stability of pipes

indicate that in the case of flow induced vibrations the differential equations presented by [11] and [13] produce the same results. However, in many researcher's mind there still exist the doubt about the validity of the differential equation for structural born vibrations[18]. It is the intent here to investigate the applicability of the differential equation for base excited systems and to show the effect of different terms on the response of the cylinders in axial fluid flow.

Knudson and Smith [9] were the first to report on the dynamic response of slender cylinders in axial fluid flow under sinusoidal base excitation. They used the simple Bernoulli-Euler beam equation with an equivalent viscous damping coefficient and obtained an exact solution to the boundary value problem. The drawback in their solution is that the damping coefficient was not defined in terms of the damping mechanisms. A detailed analysis of the damping coefficient used by Knudson and Smith [9] is presented in this thesis.

Wambsganss and Boers [17] were the first to study the flow induced vibrations of cylinders in axial fluid flow as a problem in random vibration. They employed a modal analysis method to obtain a solution to the second order differential equation. In this thesis the response of a cylinder, in axial fluid flow, under random base excitation is presented. The solution to the fourth order equation was obtained using Fourier analysis.

Benjamin [1] considered the effect of fluid flow on the motion of a pipe fixed at one end and free at the other. The pipe was assumed to be divided into a series of articulated rigid zones. He was the first worker to observe that the motion of a pipe is independent of fluid friction. Subsequent experiments [2] showed substantial

agreement with the theory for a system with two degrees of freedom.

Gregory and Paidoussis studied theoretically [7] and experimentally [8] the oscillations of a cantilevered pipe having one fixed and one free end. They presented a mathematical argument supporting Benjamin's earlier observation that fluid friction does not enter the problem.

Namat-Nasser, Prasad, and Herrman [12] studied a cantilevered continuous pipe conveying fluid at constant velocity and demonstrated that the Galerkin method, using a two-term approximation, may lead to erroneous results.

In a recent paper Naguleswaran and Williams [11] developed an exact solution for the natural frequency, axial distribution of phase and modal envelops of pinned-pinned, fixed-fixed, and pinned-fixed pipes carrying fluid. The effectsof internal pressure and axial applied tension were considered. They compared their results with those of Galerkin, Rayeigh-Ritz, and Fourier series solutions to the same problem. The authors showed that the two-term Galerkin and Rayleigh-Ritz solutions provide good estimate of frequency and phase. Their experimental results are in agreement with theoretical results at low flow rates, but reveal the difficulty of predicting the critical flow velocity associated with buckling.

Vibration analysis of pipe surrounded by flowing fluid may be divided into the consideration of stability and response problems. In a stability analysis the problem is to determine whether conditions exist that cause structural response to diverge and, if so, to find these conditions (stability limits) in terms of the system parameters. In response analysis ,the problem is to predict the actual motion of

the structure. The stability analysis is generally simple and often supplies sufficient information to consider the vibration problem solved. If the actual motion of the structure is desired, the response problem must be solved. This requires knowledge of the damping mechanism and associated damping laws. Mechanical vibrations are classically analyzed as if occuring in a vacuum; this is most often a reasonable assumption when the fluid environment is a gas. However, when the fluid medium is a liquid, the effect of fluid becomes significant and what might be termed a fluid-elastic analysis is required. The fluid-elastic analysis necessitates drawing from the field of fluid dynamics as well as from fields related to the theory of elasticity and mechanical vibrations. The additional discipline of stochastic processes may be required to account for the randomness of the exciting force.

Paidoussis [13] studied the vibration of flexible cylinders induced by axial flow. Using the differential equation of motion derived from a force balance in the lateral direction, he first solved the simpler stability problem. His approach was to assume motions of the cylinder of the form $Y(\xi)\exp(i\omega t)$, where ω is a dimensionless frequency. With this form for the response, the system will be stable if the imaginary component of ω, $I(\omega)$, is positive and unstable if $I(\omega) < 0$. The complex frequency for finite values of the flow velocity was determined by analytical and numerical methods. Stability in the three lowest modes was considered for a particular case. For sufficiently high values of flow velocity, the system becomes unstable in all three modes. The first mode instability is of the buckling type $[R(\omega) = 0]$, and second and third-mode instabilities are oscillatory $[R(\omega) \neq 0]$.

Wambsganss and Boers [17] studied theoretically and experimentally the parallel flow induced vibrations of a cylindrical rod. The problem was treated as a problem in random vibration. They concluded that the flow induced vibration of a cylindrical rod is a force-excited, narrow band, stationary random process; RMS rod displacement is, in general, approximately proportional to the mean axial flow velocity raised to a power; the exponent varies from 1.25 to 2.5; and system damping increases with increasing flow velocity. They encountered structural born vibrations of high amplitudes in their experimental work.

There is another source of vibration that can significantly affect the response of the cylinders in fluid flow. This source is structural borne vibration which can be transmitted in many ways. The most common would be support excitation which can come from various sources such as pump vibration, valving, earth tremors. etc.

Bishop and Hassan [3] determined fluctuating lift and drag forces on a cantilevered circular cylinder oscillating in a fluid flowing perpendicular to the axis of the cylinder. They observed that the lift and drag forces act on the cylinder with frequency f_s (Strouhal frequency) and $2f_s$, respectively, provided the driving frequency f is appreciably different from f_s. There also acts on the cylinder the inertia force due to the acceleration of fluid mass with the impressed frequency f. When the forcing frequency, f, of the cylinder approaches the Strouhal frequency f_s, the two sets of forces become synchronized. Within the range of synchronization, the lift and drag forces suffer changes in phase and amplitude as the imposed frequency is varied. The amplitude of the cylinder increases in a manner comparable with

the response of a simple oscillator under the influence of an applied harmonic force.

Tobes and Ramamurthy [16] determined the lift force on a circular cylinder oscillating in a fluid flowing perpendicular to the axis of the cylinder. The results obtained show a direct proof of the fluid-elastic nature of the fluid dynamic forces acting on the cylinder. It was inferred that the wake structure behaves like a non-linear mechanical dynamic system.

In a recent paper Knudson and Smith [10] presented the dynamic response of slender cylinders in axial fluid flow with time varying boundary conditions. They considered clamped-free and clamped-pinned tubes (upstream end clamped) at various flow velocities. For each flow velocity the response was determined as a function of support excitation level. They arrived at the following conclusions:

a) The resonant response varies linearly with the support excitation level. In the case of clamped-free tubes, the slope of the linear function depends upon the flow velocity. However, in the case of clamped-pinned tubes, the straight line slope is essentially independent of flow velocity.

b) The general response characteristics can be described in terms of a viscous damping parameter. In the case of a clamped-free tube, the parallel flow acts as a strong damping mechanism which is characterized by a significant increase in the damping parameter as the flow velocity increases. However, in the case of a clamped-pinned tube, the damping parameter is essentially independent of flow velocity.

Eringen [6] considered the response of beams and plates to random

loads. The mean square value of the bending stress in a Bernoulli-Euler beam with external viscous damping was found to be infinite and the mean square value of the displacement was found to be finite.

Samuels and Eringen [14] considered the dynamic response of a simply supported Timoshenko beam to a purely random Gaussian process. A generalized Fourier analysis is applied to the damped Timoshenko beam equation to calculate the mean-square value of displacement and bending stress. A comparison with the calculations based on classical beam theory reveal that the displacement correlation of both beams were in excellent agreement. Moreover, the mean square of the bending stress, contrary to the results of the classical beam theory [6], was found to be convergent.

Bogdanoff and Goldberg [4] calculated the mean-square displacement and stress in a simply supported Bernoulli-Euler beam with distributed external viscous damping for several types of random excitations. Contrary to the conclusions presented in [6] and [14], the mean square stress was found to be finite except for a single concentrated force at the center of the beam and for a force completly random in space.

OBJECTIVES

To the author's knowledge there have been no reports on the dynamic response of slender tubes, in axial fluid flow with support excitation, using the differential equation presented by Paidoussis [13]. In view of this and the fact that questions have been raised as to the validity of the equation for base excited systems, the writer believes that a solution to the differential equation, with time varying boundary conditions, is pertinent to vibration studies of long slender tubes in axial fluid flow. Also, to the author's knowledge no research results