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TECHNICAL MEMORANDUM

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ANNOTATED BIBLIOGRAPHY ON FLOW INDUCED VIBRATIONS

by

T. M. Mulcahy and S. S. Chen

Components Technology Division

ARGONNE
NATIONAL
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BASE TECHNOLOGY

January 1974

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PREFACE

As part of the overall ANL Flow-induced Vibration Program, sponsored by the AEC Reactor Research and Development Division this collection of references and annotations on flow-induced vibrations was compiled as part of the process of determining available information which could be useful in the prediction of the flow-induced vibrations of the internal components of reactors. Particular emphasis was given to surveying analytical prediction methods and results, experimental data and methods, as well as scale modeling practices, procedures, and results.

The Table of Contents serves the dual purpose of locating specific categories of references and outlining the scope of the survey. Because the existence and character of flow-induced vibrations is highly dependent on the geometry and location of the vibrating body in the flow, the categorical breakdown of references is primarily on the basis of configuration. References were obtained by scanning the appropriate open English language literature available in the United States. The bibliography references much of the literature scanned, but inclusion of all of the vast literature available would be quite impossible. However, attempts were made to include review, survey, and comprehensive articles which cite the references deleted from this bibliography. In particular, few references are given which appeared before 1960.

A limit to the "current" status of this bibliography is the built-in obsolescence created by a rapidly expanding literature. As an example, a large number of papers[1] just became available which could not be included. A limit to the breadth of the bibliography is that the large foreign literature was not reviewed. A few foreign references, which have been collected by ANL staff, are included.

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[1] International Symposium on Vibration Problems in Industry, sponsored by The United Kingdom Atomic Energy Authority and National Physical Laboratory of England, Keswick, England, 1973.

Special findings on the state of the art in predicting flow-induced vibrations are self-evident in the annotations. In general terms, much research and development remains before analysis, scale model testing, or bench top testing will replace prototype testing for purposes of reactor internal component design and design confirmation. Analysis probably is most effective in the prediction of the free vibrations of components including the added mass effect of fluids. However, simulation of boundary conditions designed to allow for thermal expansion present difficulties. Usually, some experimental data is required to confirm boundary condition assumptions. With knowledge of the free vibration response, the flow velocity field, and damping; analysis also may be used to estimate and/or avoid significant response of instabilities of isolated components due to parallel flow and cross flow vortex shedding. Also, structural resonance due to pump and other system frequencies can be avoided, if the latter are known a priori. Information on damping, flow velocities, and pump and system frequencies usually require scale model and prototype reactor testing. The normal difficulties of estimating structural damping are increased by the presence of the dense fluids employed in many reactors. Good damping information is a prerequisite for meaningful prediction of forced vibrations.

Progress is being made in the quantitative bench top analysis and simulation of the fluid excited response and instabilities of simple components in uniform cross and parallel flow. However, the theories advanced rely heavily upon experimentation for their characterization, and considerable variation can be observed between different test systems. In any case, transfer of bench top analysis and/or experimental information to the quantitative prediction of reactor component response will require a better understanding of how reactor members of similar geometry are effected by conditions not simulated in bench top studies, such as: the effects of adjacent bodies, nonuniform flow, combined parallel and cross flow, flow turbulence, and structural and fluid borne noise. Most of these topics have just begun to be investigated in the aerospace and building construction industries, where much less difficult conditions to simulate often exist.

Flow-induced vibrations measurements in on-line reactors are desirable because of limited predictive capability. However, nuclear testing is often difficult because of the hostile environment and expense. Limited amounts of information are being gathered. Most vibration information is gained during non-nuclear reactor operation, prototypic component testing, and/or scale model testing. All of these nonprototypic tests require verification of the simulation methods employed before the associated data can be considered valid for prediction purposes. Many modeling approaches have been employed and are being developed, but extensive comparisons to prototype measurements and successful reactor operation must occur before any of the methods become widely accepted.

ACKNOWLEDGMENTS

The authors wish to thank B. L. Boers and H. Halle for their aid in locating and reviewing articles, J. Stephens and V. Stainback for a yeoman's job of typing, and M. R. Sims for his helpful editing suggestions.

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I. GENERAL REFERENCES

A. Flow-Induced Vibrations Review Articles

1. M. W. Wambsganss, *Vibration of Reactor Core Components*, Reactor and Fuel-Processing Technology 10, 208-219 (1967)

Some case histories of problems which have occurred in the nuclear reactor industry which are probably caused by flow-induced vibrations are reviewed. The then existing knowledge as related to reactor geometries of the vibrations of circular cylinders in cross flow, circular cylinders in parallel flow, and parallel flat plate channel flow is reviewed and selected references given. Methods of representing damping, analyzing structural vibrations, and scale model testing are briefly discussed. A good starting point for flow-induced vibration literature related to reactors.

2. J. P. Den Hartog, *Self-Excited Vibrations*, Mechanical Vibrations, 4th ed. (McGraw Hill, 1956), Chapt. 7, pp. 282-329.

A self-contained description of many self-excited vibrations in various fields, using both analytical and intuitive approaches, is presented. Discussion of galloping, vortex excited vibrations, and flutter is included. A good starting point for an individual with a mechanical vibrations background who desires an understanding of flow-induced vibrations.

3. S. R. Heller, *Hydroelasticity*, Advances in Hydrosciences, (Academic Press, 1964), p. 94.

The field of hydroelasticity is defined. Similarities and differences with aeroelasticity are listed. The free surfaces and mass ratio are said to constitute the main differences. The Reynolds number range is expected to be the same in both fields for subsonic transports and surface vessels. Two hydroelastic phenomena: static instability divergence and dynamic instability flutter, are analyzed in detail. Analytical results are compared to data and a brief review of the literature is made. The inability of existing aeroelastic flutter theories to give conservative bounds, except when damping is neglected, on hydroelastic flutter speeds at low mass ratios is explicitly illustrated. Cavitation effects are included also. Vortex shedding excitation at the trailing edges of plates, propeller vanes, and rudders are presented, as are other sources of hydroelastic vibration. In general the extensive article is a good tutorial presentation, especially for hydroelastic divergence and flutter.

4. H. N. Abramson, *Hydroelasticity - Some Problems and Some Solutions*, Fluid-Solid Interaction (American Society of Mechanical Engineers, 1967), p. 187.

   Interaction of elastic structures and dense fluids are discussed, with emphasis placed on the claimed differences between air and water effects: relative mass of fluid, free surface, and cavitation effects. Examples discussed are the hydrofoil boat, flow inside a pipe, plates in water including mode shapes and frequencies, vortex shedding, flutter, plates or tubes in narrow passages, and structure impact on free surfaces. Each example is discussed in some detail, with in depth discussion of hydrofoil vibrations. In particular, flutter theory comparable to that successfully used in aeroelasticity has not proved accurate. Scaling is mentioned but not discussed in depth.

5. Gerrit H. Toebes, *Flow-Induced Structural Vibrations*, J. Eng. Mech., Proc. ASCE 91(EM6), 39 (1965)

   Most observed effects of flow-induced forces on the motion of structures are classified both schematically and analytically. The various types of structural instabilities (divergence, flutter) and nonlinear response (galloping, fluid elastic reasonance, buffeting, etc.) are related clearly to the appropriate symbolic operators in the equations of motion and structural shape. Known and unknown information necessary for analytical solutions are indicated. An example is given to illustrate the ability to analyze linear stability problems. The wide range of nonlinear fluid elastic interactions which are not amenable to analytical solution because of lack of characterization are discussed. A reading of this paper places one at a clear advantage when delving into the details of a vast literature which often lacks perspective.

6. Eduard Naudascher, *From Flow Instability to Flow-Induced Excitation*, J. of Hydraulics Division, Proc. ASCE 91(MY4), 15 (1967)

   Shear-flow instability gives rise to a process of energy transfer from the primary flow to flow fluctuations during which disturbances of a certain type and given frequency obtain a maximum rate of initial amplification. The subsequent trend toward increased randomness and transition to turbulent flow is opposed in the presence of control (i.e., enforced amplification) and replaced by a tendency toward periodic flow oscillations accompanied by periodically alternating forces on the flow boundaries.

   An attempt has been made to classify this control in terms of a few basic mechanisms: extraneous control through periodic disturbances, self-control involving fluid-reasonant feedback, and self-control involving fluid-elastic feedback. Numerous examples of seemingly unrelated periodic flow phenomena can be interpreted as brought about by one or more of these mechanisms. (From author's conclusions.)

7. Peter Sachs, *Wind Forces in Engineering,* (Pergamon Press, 1972)

Current methods of analyzing and predicting the response of structures to wind loads are covered in detail. Step by step procedures are outlined, with examples, for specific structures: bridges, buildings, masts and towers, etc. The pertinent static and dynamic wind parameters necessary for both static and dynamic structural analysis and model testing, methods of measurement, and available data are discussed.

Drag force coefficients for most Reynolds numbers and isolated structural shapes are presented. Good correlation was found between model and prototype drag force coefficient data, but discrepancies were common for local pressure distributions. Interference effects between adjacent bodies are discussed briefly.

Wind tunnel configurations; force, pressure, and velocity measurement systems; and blunt body data corrections to account for tunnel presence (e.g., blockage) are discussed. Simulation rules for various types of models (e.g., rigid, rigid with elastic mounts) are given. Strouhal number similarity is considered mandatory for vibrating bodies. Reynolds number and flow turbulence need to be simulated or accounted for by data correction.

Methods are outlined for predicting dynamic structural response to vortex shedding in the subcritical, transition, and supercritical Reynolds number range;and to galloping, flutter, buffeting, and free stream turbulence. Each method requires considerable empirical data unique to each flow and structural shape including information on flow velocities, flow turbulence, flow-induced forces, and structural damping.

8. E. A. Newland, *Flow-Induced Vibrations of Reactor Core Components - A Bibliography,* AAEC LIB/BIB No. 363, Australian Atomic Energy Commission, Lucas Heights (August 1972)

A chronological bibliography compiled by scanning the Engineering Index 1960 - April 1972, the INIS Atom Index 1970 - 1972, and the Nuclear Science Abstracts 1948 - August 1972.

9. C. Scruton and E. W. E. Rogers, *Steady and Unsteady Wind Loading of Buildings and Structures,* Phil. Trans. Roy. Soc. London, Series A, <u>269</u>, 353-383 (1971)

Characterization of the dynamic wind velocity variations is given including random measures. The limited information on the effects of aspect ratio, free stream turbulence, and high (prototypical) Reynolds number on drag and associated pressure distributions is discussed. Much further theoretical and experimental work is thought necessary in relating the large amount of information on random wind velocity fluctuations to associated forces. New understanding gained since a previous survey paper (see Ref. 10) on vortex and galloping excitation of bluff bodies is presented. Evidence is given of marked changes in response due to vortex shedding when Reynolds numbers are changed from subcritical to supercritical values and when strakes or shrouds are attached to the cylinders.

10. C. Scruton, *Wind-Excited Oscillations of Structures*, Proc. Inst. of Civil Engineers 27, 673-702 (1964)

    Excitation due to vortex shedding, galloping, buffeting, and proximity to other bodies is reviewed. Also, damping of typical structures is included because it is of fundamental importance in controlling flow-induced vibrations. Obtaining full scale data to confirm the validity of model tests performed at distorted Reynolds numbers is considered important future research. The model testing methods and test parameters outlined in this paper are often used and referenced by others.

11. G. V. Parkinson, *Wind-Induced Instability of Structures*, Phil. Trans. Roy. Soc. London, Series A, 269, 395-409 (1971)

    Wind-induced instabilities mechanisms are reviewed in general, with more discussion given to vortex-induced transverse bending oscillations and transverse galloping oscillations. Article provides a good introduction toward understanding the phenomena. For both vortex and galloping excitation, additional research at higher Reynolds numbers in the transcritical and supercritical ranges is deemed necessary.

12. G. Koopman, *Wind Induced Vibrations of Skewed Circular Cylinders*, AD 717 739 (1970)

    A general discussion of the various techniques used to measure the oscillating lift coefficients of wind-induced vibrations of circular cylinders is presented. The discussion is summarized with a brief outline of the various categories of research efforts being conducted on fluid-induced vibrations. Each category is referenced to an appropriate group of papers which exist in the literature. A simple method for determining the oscillating lift coefficient for the wind-induced vibration of a circular cylinder is developed and applied to a typical problem where the longitudinal axis of the cylinder is skewed relative to the direction of the oncoming flow. (Author's abstract)

    Cylinders skewed beyond $\sim$ 15° to the flow were reported to exhibit random oscillation with magnitudes two orders of magnitude less than the periodic oscillations observed for non-skewed cylinders.

13. Nuclear Safety Information Center, Oak Ridge National Laboratory, P. O. Box Y, Oak Ridge, Tennessee, 37830 (615/483-8611, ext. 7253)

    The NSIC reviews the literature and recent developments in any safety related aspects of reactor design, licensing, construction, and operation, as well as fissionable-material handling, shipment, storage, and effects on the environment. Abstracts are kept on computer file and searches can be performed which provide listings under standardized key words or combinations of key words. These listings were found to contain much information on responses to licensing questions. The current procedures (which are not held proprietary) employed by manufacturers to design and test reactors for flow-induced vibrations could be obtained from the responses to the licensing questions. Also, much of the journal literature on flow-induced vibrations was found to be filed on the computer.

14. A. W. Marris, *A Review on Vortex Streets, Periodic Wakes, and Induced Vibration Phenomena,* J. Basic Engr. Trans. ASME, Series D, 86, 185- (June 1964)

A survey is presented of recent experimental and theoretical researches on the problem of periodic wakes behind a cylinder in a stream. A synopsis is given of the present knowledge on the mechanics of wake formation and of the associated hydrodynamic forces for the full Reynolds number range from the first appearance of a stationary vortex pair behind the cylinder up to transition of the boundary layer on the cylinder.

Experimental data are viewed in the light of the theoretical results of Birkhoff, which, it appears, may replace the classical theory based on the first order stability of a potential flow street of vortex filaments.

The paper closes with a discussion of the problem of the induced vibration of a spring mounted cylinder in a stream. (Author's abstract)

15. G. V. Parkinson, *Mathematical Models of Flow-Induced Vibrations of Bluff Bodies,* IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

Several forms of flow-induced vibration of bodies are discussed briefly, and two, vortex-induced vibration and galloping of long bluff cylinders, are selected for detailed consideration. The importance of the size and shape of the cross-section afterbody and of the details of vortex formation are emphasized. Several semi-empirical mathematical models of the body oscillation dynamics are examined for both forms of oscillation. Some approaches to improved models compatible with the known characteristics of the separated flows and of the nonlinear oscillations are considered. (Author's summary)

16. S. Goldstein, *Modern Developments in Fluid Dynamics,* Vols. I and II (New York: Dover Publications, 1965) (first pub. in 1938)

This classic book offers a wealth of information on the flow around rigid, stationary objects. Many experimental investigations into flow-induced vibrations of bodies build on the information provided in the texts.

17. M. V. Morkovin, *Flow Around a Circular Cylinder - A Kaleidoscope of Challenging Fluid Phenomena,* Sym. of Fully Separated Flows, ASME, 102-118 (1964)

See Ref. 21, Sec. IIA1-7.

B. Structural Damping

1. E. E. Ungar, *The Status of Engineering Knowledge Concerning the Damping of Built-Up Structures*, J. of Sound and Vibration 26(1), 141-154 (1973)

   The importance of the effects of structural joints on the damping of built-up structures is pointed out, and the energy dissipation mechanisms associated with squeezing, rocking, and shearing motions are discussed for simple joints that are dry, lubricated, or provided with viscoelastic inserts. The damping mechanisms and behaviors of built-up beams and of skin-stringer structures are discussed as far as they are currently understood, and available damping estimation methods are summarized. Difficulties in defining and measuring the damping of skin-stringer structures are indicated, and it is pointed out that particularly the high-frequency damping of built-up beams and the low-frequency damping of skin-stringer configurations require further investigation. (Author's abstract)

   Some examples selected from the literature are given. Damping due to fluids away from joints is not discussed. There are 35 references given in the review article.

2. N. Granick and J. E. Stern, *Material Damping of Aluminum By Resonance-Dwell Technique*, Shock and Vibration Bulletin 34(5) (1965)

   Material damping has been considered as stress amplitude dependent in intermediate and high stress levels. In this same stress range, contributions to material damping from frequency dependent inelastic mechanisms have been considered negligible. These conditions are at variance with the findings of this investigation for the material tested. The relation between material damping, stress amplitude and frequency was experimentally examined for aluminum 2024-T4. The test method used was a resonant-dwell technique with "identical" double cantilever reeds. Tests were run in air (760 mm, 70°F) and in vacuum (0.2 mm, 70°F) at stress amplitudes up to 20,000 psi and at frequencies from 15 to 1500 cps. Results showed that damping as measured in air was largely aerodynamic drag and was displacement amplitude and frequency dependent, and damping as measured in vacuum was wholly material damping, independent of stress amplitudes up to 20,000 psi and dependent on frequency. Good correlation with the Zener theory of thermal relaxations was found (see Ref. 3). (Authors' abstract)

   Air damping was found to be as much as 10 times greater than material damping.

3. S. H. Crandall, *On Scaling Laws for Material Damping*, NASA Tech. Note NASA TN D-1467 (Dec 1962)

Similarity analyses are made to provide scaling laws which indicate the effects of amplitude, frequency, and material properties on the resonant damping experienced by structural elements when the damping is due to internal material properties. Two nonlinear damping "laws" are considered. The first concerns frequency-independent hysteresis damping, in which the material damping coefficient g satisfies a relation of the form

$$g = \left(\frac{S}{S_o}\right)^n \qquad \text{(i)}$$

where S is the stress amplitude, and S_o and n are material constants. The second damping law concerns nonlinear damping for which

$$g = \left(\frac{S}{S_o}\right)^n \frac{\omega\tau}{1 + \omega^2\tau^2} \qquad \text{(ii)}$$

with the relaxation time τ being an additional material constant. Correlations provided by the scaling laws were performed on data from a large number of tests with steel, brass, and aluminum cantilever beams (reeds). The steel and brass data were correlated reasonably well on the basis of (i) while the aluminum data were better correlated on the basis of (ii). (Author's summary)

Others have found these scaling relations valid (see Ref. 2).

4. B. Lazan, *Damping of Materials and Members in Structural Mechanics* (Pergamon Press, 1968)

A comprehensive treatment of damping nomenclature, mechanisms, material representations, methods of determining damping for different structural members and materials, and relations between different damping measurements is given. Also, most of the existing damping information for engineering materials are tabulated with references through 1968. The general statement is made that η (energy density dissipated/strain energy density) peaks as a function of frequency and temperature at values less than 0.01 for low stress levels, and generally η is an order of magnitude smaller. The book is the starting point for the characterization of the material damping of vibrating structures.

5. R. Plunkett, *Transient Response of Real Dissipative Structures,* Isolation and Damping, Shock and Vibration Bulletin 42(4) (January 1972)

Almost all the information we have on damping has been gained from measurements on structures vibrating at a single frequency at constant or almost constant amplitude. In calculating system response to transient, random or fluctuating excitation, it is customary to use spectral decomposition, modal analysis or some other procedure involving linear superposition. In most cases of transient excitation, this will give conservative results since most real damping increases non-linearly with amplitude; this may result in a greatly overdesigned structure and prejudice the designer against the use of frangible stress relief devices. In a few cases involving coulomb friction where the damping decreases (due to no relative joint motion because of motion in two mode shapes rather than one for which damping is usually measured) with increasing amplitude, it may lead to underdesign or instability. (Author's abstract)

6. B. R. Hanks and D. G. Stephens, *Mechanisms and Scaling of Damping in a Practical Structural Joint,* Shock and Vibration Bulletin 36(4) (1967)

An investigation was conducted to determine the effect of geometric scale on the damping in a practical beam-joint assembly. A cantilever configuration was utilized wherein the beam was bolted between two angle brackets at the support. Four geometrically similar assemblies, covering a scale range of approximately 20 to 1, were tested. Free decay of the fundamental mode was measured over a range of joint clamping pressures and beam tip amplitudes. Also, damping changes resulting from the addition of liquid lubricants and viscoelastic films to the joint interfaces were investigated. Data indicate that an increase in model size results in a decrease in damping attributed to the structural joint. Furthermore, joint damping is shown to be slightly dependent on vibration amplitude and to vary as an inverse function of joint clamping pressure. Joint damping may be substantially increased by the addition of liquid lubricants or viscoelastic films at the joint interfaces. (Author's abstract)

Calculated material damping and measured joint damping were found to be negligible.

C. Fluid Damping and Added Mass

1. W. E. Baker, W. E. Woolam, and D. Young, *Air and Internal Damping of Thin Cantilever Beams*, Int. J. Mech. Sci. 9, 743-766 (1967)

   Both internal and external damping forces (explicit expressions are given) are introduced into equations for free transverse vibration of very thin rectangular beams in air, and solutions to these equations are obtained by energy methods and digital computer. Predicted decrements of free vibration decay are then compared with experiments on cantilevers run in normal atmosphere and at reduced pressures, and with similar experiments by previous investigators. In this manner, the analytical techniques are verified, and considerable physical insight into the damping process is gained. (from Authors' summary)

   Fluid (air) damping proportional to velocity, but not viscosity (Reynolds No.), and dynamic pressure is found at low and high amplitudes, respectively.

2. R. J. Fritz, *The Effect of Liquids on the Dynamic Motion of Immersed Solids*, Paper No. 71-VIBR-100, Proc. 3rd ASME Vibrations Conf., Toronto, Canada, September 8-10, 1971.

   Potential solutions for a rigid cylinder in motion within a rigid stationary tube are employed, as an example, to derive the added (hydrodynamic mass) masses of the cylinders for the case where both cylinders are in motion. A table is given listing some existing added mass information for single body motion in the presence of another stationary body. A general method is proposed for calculating the added mass for several bodies in motion. Guidelines are given to establish when the assumption of potential flow is valid. Experimental data is given to support the concentric cylinder solutions for added mass.

3. H. Gauzy, *Inertia and Damping Measurement*, Manual on Aeroelasticity, Chapt. 3, Vol. IV, North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development (1968)

   The determination of linear viscous and more general structural damping coefficients by frequency sweep, energy dissipation at resonance, and transient decay methods is discussed in detail. The determination of generalized masses by the displacement of natural frequencies and energy dissipation methods is discussed equally well.

4. D. G. Stephens and M. A. Scavullo, *Effects of Pressure Environment on Damping of Vibrating Structures*, Shock and Vibration Bulletin 34(5) (1965)

An investigation was conducted to determine the mechanism of the air damping exhibited by rigid bodies of different shapes oscillating in a pressure environment. Circular and rectangular panels, as well as a sphere and cylinder, were attached to cantilever springs and the free decay of an induced oscillation was measured at pressure levels from atmospheric to 4×10^{-2} torr. Data are presented to show the effect of pressure, vibratory amplitude, shape, and surface area on the air damping of the models. Results indicate that the magnitude of the air damping may greatly exceed the structural damping of the system. The air damping associated with the panels is directly proportional to the pressure and amplitude which is indicative of dissipative loads proportional to the dynamic pressure. Furthermore, the panel damping was found to be independent of shape and a nonlinear function of the surface area. The sphere and cylinder exhibit viscous damping characteristics which are in good agreement with available theory. (Authors' abstract)

Amplitudes of vibration usually exceeded 0.1 inches at a frequency of 3.8 cps.

5. R. King, *The Hydrodynamic Damping of Natural Vibrations of a Cantilevered Cylinder*, The British Hydromechanics Research Association, Report No. RR1122 (January 1972)

The viscous damping of circular cylinders vibrating in varying depths of still water has been investigated using four different elastic cantilevers and a rigid cylindrical pendulum. The energy dissipated per cycle was obtained by integrating Stokes' element damping function over the immersed length. Damping was inferred from measurements of the amplitude decay of transient motion when the cylinder was released from an initial free end displacement of up to one diameter. In all cases the damped motion was found to be independent of amplitude, thus confirming viscous damping. It was assumed that the non-correlation of Reynolds number along the cylinder was chiefly responsible for the observed damping effects. This non-correlation either completely suppressed the establishment of turbulent flow; or it ensured that, over a representative time, the turbulent content of flow was small compared with the viscous contribution.

Frequencies were varied by altering the water level, attaching concentrated masses and springs to the cantilever free end and by adjusting the pendulum spring rate.

Theoretically predicted values of logarithmic decrement were in close agreement with experimental results. (Author's summary)

6. R. King, *The 'Added Mass' of Cylinders*, The British Hydromechanics Research Association, Report No. TN1100 (April 1971)

   The 'added mass' of cantilevered elastic circular cylinders is experimentally and theoretically investigated, using two 1-in.-diameter hollow cantilevers of differing materials and lengths. Both cylinders were vibrated freely in quiescent water at the fundamental frequencies, and subsequently excited by vortex shedding in flowing water to vibrate in the free modes recorded in quiescent water. For cantilever free vibrations it is shown that the 'added mass' function may be represented by a uniformly distributed loading equivalent to the mass/unit length of fluid displaced by the cylinder outer surface. It is further shown that the flow-direction vibrations excited by vortex shedding in flowing water coincided in period with the natural frequencies recorded in quiescent water. This demonstrates that the 'added mass' is unaffected by streaming flow and vortex shedding. The mode shapes and frequencies were varied by adjusting the water depth and by attaching concentrated masses and springs to the cantilever free end. Over the range of experimental variables used, the 'added mass' function was seen to be independent of frequency, amplitude and modal shape. Computed frequencies of transverse vibrations of cantilevers vibrating in varying depths of water agreed closely with observed experimental values. (from Author's summary)

7. N. Granick and J. E. Stern, *Material Damping of Aluminum by Resonance-Dwell Technique*, Shock and Vibration Bulletin 34(5) (1965)

   See Ref. 2, Sec. IB-1.

8. F. T. Mavis, *Virtual Mass of Plates and Discs in Water*, J. Hydr. Proc. ASCE 96, 1947-1951 (1970)

   A simple experimental method for accurately determining the virtual (added) mass of rigid plates and discs is demonstrated.

9. A. T. Jones, *Vibration of Beams Immersed in a Liquid*, Exp. Mech. 10, 84-88 (1970)

   Experimental and analytical analysis of a vibrating beam (50" x 1" x ¼") immersed in a fluid and carrying concentrated mass and concentrated rotatory inertia was performed. It was found that mode shapes are not influenced by either the density or viscosity of the fluid, and that natural frequencies can be corrected to within 10-percent accuracy by adding an apparent mass. To adequately approximate frequency response, modal damping must be added. In this way, the linear theory gives an adequate description of the beam. (Author's abstract)

   Based on assumed damping, low frequency modes exhibit viscous damping; whereas at higher frequency modes, damping is independent of viscosity. Amplitudes related to damping are not quantitatively discussed.

10. W. Blake, *On the Damping of Transverse Motion of Free-Free Beams in Dense, Stagnant Fluids*, Shock and Vibration Bulletin 42(4), 41-55 (1972)

The damping of free-free (thin rectangular) beams vibrating in dense, still fluids has been found to be dominated by viscous damping at low frequencies and radiation damping at high frequencies (above 1 KHZ). Loss factors were found to depend as

$$\eta = 4.4 \frac{\rho_o}{\rho_p h} \frac{\nu}{\omega}$$

at low frequencies: ρ_o and ρ_p are the densities of the fluid and beam, respectively, ν the fluid kinematic viscosity (centistokes), h the beam thickness (inches), and ω the frequency of vibration (rad/sec). η was found independent of the length and width of the beams and the sharpness of the edges.

11. C. C. Shih and H. J. Buchanan, *The Drag on Oscillating Flat Plates in Liquids at Low Reynolds Nos.*, J. Fluid Mech 48, 229-239 (1971)

Drag forces on rigid flat plates oscillating perpendicular to the plane of the plate in a still fluid at low Reynolds numbers (1-1057) showed significant Reynolds number dependence below a value of 250. Strouhal or frequency parameter dependence was significant throughout the Reynolds number range. This extends the work of (Ref. 12) to a lower Reynolds number range.

12. G. H. Keulegan and L. H. Carpenter, *Forces on Cylinders and Plates in an Oscillating Fluid*, J. Res. Nat. Bur. Standards 60, 423-440 (1958)

The inertia and drag coefficients of cylinders and plates in simple sinusoidal currents are measured and related to a Reynolds number and a Strouhal number. For the plates, there is strong dependence on the Strouhal number and weak dependence on the Reynolds number.

13. J. R. Peoples, *Natural Frequencies and Damping of Full Scale Hydrofoils by "Pluck Test" Methods*, Shock and Vibr. Bull. 43, 39-46 (1972)

Pluck testing to determine several low natural frequencies was successfully used on a complex prototype hydrofoil and strut system. The frequency spectrums of selectively mounted accelerometers were analyzed for natural frequencies. Log decrements were then determined from the recorded signal after filtering all information except that in approximately a 10% bandwidth about a specific natural frequency.

14. I. G. Currie, R. T. Hartlen, and W. W. Martin, *The Response of Circular Cylinders to Vortex Shedding*, IUTAM/IAHR Symp. on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

An interesting derivation of aerodynamic damping is given which had to be included to fit analytical model to data.

Also see Ref. 10, Sec. IIA2-5.

15. E. Kiss, *Analysis of the Fundamental Vibration Frequency of a Radial Vane Internal Steam Separator Structure*, Proc. Conf. Flow-Induced Vib. in Reactor System Components, ANL-7685 (1970), pp. 335-343.

See Ref. 17, Sec. IVA-6.

16. J. R. Driscoll, *Forces on Cylinders Oscillating in Water*, Masters Thesis, Naval Post-Graduate School, AD-758516 (Dec 1972)

The total force acting on a rigid cylinder oscillating harmonically in still fluid was found by experiment to be describable as the sum of two components, drag and inertia, for which associated coefficients of added mass c_m and drag c_D were experimentally determined. c_m was found to be a strong function of relatively large displacement/diameter ratios (range of 0.5-2.5), but independent of a Reynolds number based upon maximum cylinder velocity (range of $1 - 8 \times 10^{-4}$). c_d was found to be a strong function of both relative displacement and Reynolds number.

D. Characterization of Damped Structures

1. Glenn F. Brammeier, *A Study of Amplitude Frequency Plots with Nonlinear Damping*, Shock and Vibration Bulletin, 40(5), 261 (1969)

On the basis that Saturn V dynamic test vehicle data was shown to be extremely sensitive to excitation force levels during yaw testing, a curve fitting technique was developed which included several forms of nonlinear damping. The purpose was to show how to obtain a form of nonlinear damping which better describes the structural system response. Several techniques are discussed for determining which data assumptions best fit a particular set of experimental data.

2. S. H. Crandall, *The Role of Damping in Vibration Theory*, J. Sound Vib. 11, 3-18 (1970)

Important structural and acoustic damping mechanisms are discussed and an indication of how the damping depends on amplitude and frequency of cyclic motion is given. The idealized models of damping which are commonly employed in theoretical analyses (steady state, random, and stability analysis) are described and some limitations are noted. The damping of a beam due to the surrounding air is one of the examples discussed. Modeling lightly damped systems by an equivalent (by Matkhin loss factors) ideal dashpot is argued as being adequate when the frequency at which damping is important is known in advance. However, when the frequency at which damping is important depends upon damping (e.g., instability of dynamic systems) then more faithful models of damping are required.

3. R. R. Reed, *Analysis of Structural Response with Different Forms of Damping*, NASA Technical Note TN D-3861 (July 1967)

Five different analytical representations of the damping force are investigated to provide a basis for deciding what type may exist in a given structural system. These representations of the damping force are incorporated along with a nonlinear spring force in a single-degree-of-freedom representation of the structural response.

The dependence of energy losses per cycle on amplitude and frequency for sustained and transient response is shown. Spring plus damping force as a function of displacement yields hysteresis loops of different shapes for different damping forces. Also, by selecting reasonable numerical values, transient displacement versus time curves and hysteresis loops are obtained by numerical integration on a digital computer. Considerable differences in the response envelopes are observed using the same numerical coefficients in each case. (from author's summary)

4. M. W. Wambsganss, Jr., B. L. Boers, and G. S. Rosenberg, *Method for Identifying and Evaluating Linear Damping Models in Beam Vibrations*, Shock and Vibration Bulletin 36(4), 65 (1967)

The study was motivated by the desire to model mathematically the dynamic response of a beam-type element in which significant energy dissipation could be attributed to the contact of the component with adjacent similar components. The three damping mechanisms considered are viscous, stress, and load damping.

A theoretical analysis is carried out based on the usual assumptions in (Euler) beam theory and the further assumption of the damping being small enough that the natural frequencies and mode shapes are unaffected. The analysis leads to a sensitive method, compatible with results obtained from tests on a vibration exciter, for identifying the effective damping mechanisms. The method is illustrated by application to the modeling of the response of a cluster of cantilevered beams clamped together at the base. This model is being employed in the preliminary analysis of the interaction effects of vibrating fuel rods in a nuclear reactor core. Damping models are identified and curves of damping coefficients as a function of cluster size are presented. (from authors' summary)

II. CROSSFLOW-INDUCED VIBRATIONS OF SIMPLE STRUCTURES

A. Single Circular Cylinders in Uniform Flow

1. *Rigid, Stationary*

1. Y. N. Chen, *Fluctuating Lift Forces of the Karman Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 1: The Vortex Street Geometry of the Single Circular Cylinder*, J. Engr. Industry, Trans. ASME Series B 94(2), 623 (May 1972)

The geometry of the vortex street for single circular cylinders will be calculated from the measured values given by numerous investigators about the steady pressure drag coefficient and the Strouhal number, whereby the Kronauer minimum drag criterion comes into use. The calculated results will be compared with the experimentally determined ones. A good agreement can be achieved between both. The Bearman-Strouhal number $S_B = fh/U_s$ will also be computed as a function of the Reynolds number. Furthermore a new wake number $C = fh^2/\Gamma$ will be introduced. It will be shown that this new number is universally much better than the Bearman one. It remains constant at 0.165 for an ideal flow over the whole Reynolds number range up to the highest value of 10^7 ever measured hitherto. (Author's abstract)

Most data on longitudinal and lateral vortex spacing, vortex convection velocity, base pressure, separation point location, and steady drag as a function of Reynolds number are included.

2. Y. N. Chen, *Fluctuating Lift Forces of the Karman Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 2: Lift Forces of Single Cylinders*, J. Engr. Industry, Trans. ASME Series B 94(2), 623 (May 1972)

The fluctuating lift force of the Karman vortex on a single circular cylinder will be investigated theoretically for an ideal inviscid vortex street with rectilinear vortices. In this investigation the model introduced by von Karman will be used. As a result, the relationship between the fluctuating lift coefficient C_L and the characteristic dimensions of the vortex street can be derived. This leads to establishing the equation between the fluctuating lift coefficient C_L and the steady pressure drag coefficient C_D. Since the curve of the theoretical lift coefficient practically envelops the spreading field of the experimentally determined points, the theory can be considered to be adequate to give the right order of magnitude for the lift of the Karman vortex. It will further be shown, that the spread of the measured values is in connection with the correlation length of the vortex along the cylinder axis. (Author's abstract)

Existing fluctuating lift force and span wise correlation length data are reviewed and references given.

3. Y. N. Chen, *The Relationship Between the von Karman Vortex Street and the Steady Drag of a Single Circular Cylinder,* Flow-Induced Vibration in Heat Exchangers (ASME, 1970), p. 85.

   The cross-flow literature for a rigid-stationary cylinder dealing with the relationship between the steady drag coefficient, base pressure coefficient, boundary layer separation point, laminar to turbulent transition point, vortex formation, and Reynolds number is critically reviewed. Pertinent references are given. The overview presented of the many investigations dealing with specialized topics listed above is intended to reveal characteristics useful in solving vibration problems of single cylinders and tube bundles.

4. C. Graham, *A Survey of Correlation Length Measurements of the Vortex Shedding Process Behind a Circular Cylinder,* AD 650849 (MIT) (October 30, 1966)

   A survey has been prepared to describe in one paper the work that has been done to measure correlation lengths of the vortex shedding along the axis of a rigid-stationary circular cylinder. A brief description of vortex shedding behind a cylinder is first presented. The results of ten investigations are then studied to determine what quantities should be measured and where to measure them to obtain realistic correlation lengths. A smooth curve of correlation length versus Reynolds number up to 10^6 is included. Larger correlation lengths are projected to occur for cylinders which vibrate at approximately the vortex shedding frequency.

5. Y. C. Fung, *Fluctuating Lift and Drag Acting on a Cylinder in a Flow at Super Critical Reynolds numbers,* J. Aerospace Sciences <u>27</u>, p. 801 (1960)

   Experimental results on the fluctuating lift and drag coefficients (RMS and peak values) in air crossflow with Reynolds numbers (0.3 - 1.4) x 10^6 (supercritical flow) are presented for a fairly smooth, rigid, stationary cylinder. Limited data for prescribed lift direction motion are also given. The forces were measured with strain gauge transducers at the supports. The response was found to be random at these high Reynolds numbers with none of the sharp peaks in the power spectrum previously observed at subcritical Reynolds numbers. The spectrum for different Reynolds numbers did not vary significantly for the limited motion studies of the cylinder. No drastic changes were found in the power spectrum.

6. P. W. Bearman, *On Vortex Shedding From a Circular Cylinder in the Critical Reynolds Number Régime,* J. Fluid Mech. <u>37</u>(3), 577-585 (1969)

   The (air) flow around a circular cylinder has been examined over the Reynolds number range 10^5 to 7.5 x 10^5, Reynolds number being based on cylinder diameter. Narrow-band vortex shedding has been observed up to a Reynolds number of 5.5 x 10^5, i.e., well into the critical régime. At this Reynolds number the Strouhal number reached the unusually high value of 0.46. Spectra of the velocity fluctuations measured in the wake are presented for several values of Reynolds number. (Author's abstract)

The effect of using highly polished surfaces to extend narrow band vortex shedding to higher than previously observed Reynolds numbers is clearly demonstrated; however, slight perturbations in the flow upstream of the separation point are noted to result in a breakdown of the laminar separation bubbles and into a broad band of vortex shedding frequencies.

7. A. Roshko, *Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number*, J. Fluid Mechanics 10(3), 345-356 (May 1961)

Drag coefficient on a large, fairly rough (sand-blasted finish) circular cylinder in wind at Reynolds numbers from 10^6 to 10^7 was measured. Wall interference corrections were made. The drag coefficient was observed to increase from its low supercritical value to 0.7 at $Re = 3.5 \times 10^6$ and then become constant. Values of the pressure coefficient around the cylinder were found to be different, but bounded above and below by pressure values previously obtained for subcritical and immediately supercritical Reynolds numbers, respectively. Also, for $Re > 3.5 \times 10^6$, definite vortex shedding was observed to occur with a Strouhal number 0.27. The history of wake development was also outlined. A splitter plate was found to suppress periodic vortex shedding and produce a small decrease in drag and pressure coefficients but not as markedly as the changes which occur at subcritical Reynolds numbers.

8. G. W. Jones, Jr., *Unsteady Lift Forces Generated by Vortex Shedding About a Large, Stationary, and Oscillating Cylinder at High Reynolds Numbers*, ASME Paper No. 68-FE-36.

The lift forces, steady drag, and base pressure were measured in air at Reynolds numbers from 0.36 to 18.7 million for both a rigid stationary and laterally oscillated cylinder. Solid-blockage interference was considered negligible. Data on the steady drag coefficient, C_d, and vortex shedding frequency Strouhal number, s, were similar to previous investigations with new data ($C_d = 0.54$ and $s = 0.3$) at the highest Reynolds numbers ($8 - 17 \times 10^6$). The frequency content of the unsteady lift force on the stationary cylinder is classified as wide-band random, narrow-band random, and quasi-periodic for Reynolds number ranges of $(1.4 - 3.5) \times 10^6$, $(5.5 - 6.0) \times 10^6$, and greater than 6.0×10^6, respectively. The scatter which exists in the lift data in the Reynolds number range up to 6.0×10^6 is attributed to surface asymmetrics (roughness, surface particles, etc.)

Oscillation of the cylinder at or near the vortex shedding frequency resulted in lift forces several times larger, depending upon motion amplitude, than for the stationary cylinder. Oscillation at frequencies far removed from the vortex shedding frequency produced no noticeable effects. The unsteady lift was found to provide a negative damping effect for cylinder oscillations below the vortex shedding frequency and a positive damping effect for those above the vortex shedding frequency.

9. E. Achenbach, *Distribution of Local Pressure and Skin Friction Around a Circular Cylinder in Cross-Flow Up to Re = 5 x 10^6*, J. Fluid Mechanics 34(4), 625-639 (1968)

In a large range of Reynolds numbers, 6 x 10^4 < Re < 5 x 10^6, the (air) flow around single cylinders with smooth surfaces has been investigated. Local pressure and skin friction distribution around the cylinder were measured (with rotatable probe ports in the cylinder wall). The total drag, the pressure drag, and the friction drag were calculated. By means of the skin friction distribution, the position of the separation points, separation bubbles or transition points can be localized. These data allow one to define three states of the flow: the subcritical flow, where the boundary layer separates laminarly; the critical flow, in which a separation bubble, followed by a turbulent reattachment, occurs; and the supercritical flow, where an immediate transition from the laminar to the turbulent boundary layer is observed at a critical distance from the stagnation point. According to the total drag coefficient, the values found in this paper connect the subcritical region represented by the measurements of Wieselsberger (1923) and Fage & Warsap (1930) with the supercritical range in which Roshko (1961) carried out his experiments. (from Author's abstract)

10. J. S. Humphreys, *On a Circular Cylinder in a Steady Wind at Transition Reynolds Numbers*, J. Fluid Mechanics 9(4), 603 (1960)

An experimental investigation is made of lift and drag forces associated with subsonic flow of air around a polished, rigid, stationary cantilever circular cylinder at Re = 4 x 10^4 to 5 x 10^5. End conditions proved to be of unexpected importance for lower Re. Observed changes in spanwise direction, three dimensional effects, are thought to be of importance in indicating the critical Reynolds number for which the attached boundary layer changes from laminar to turbulent flow.

11. W. E. Simon, *The Unsteady Surface Pressure Around Circular Cylinders in Two-Dimensional Flow*, Wind Loads on Buildings and Structures, Nat. Sur. Stand. Building Science Series 30, 87-91 (1970)

The unsteady surface pressure around (rigid-stationary) circular cylinders in two-dimensional (air) flow has been measured in the subcritical, supercritical, and transcritical flow regions. A representation of the crosspower spectral density has been developed which is a reasonable representation of the data and which applies to all three regions. The most important result is the essential similarity of the subcritical and transcritical regions. (Author's abstract)

12. S. K. Jordan, *Oscillatory Drag, Lift, and Torque on a Circular Cylinder in a Uniform Flow,* The Physics of Fluids 15(3), 371-376 (1972)

Numerical solutions of the equations governing time-dependent, viscous, incompressible, fluid flow past a circle are presented and believed valid, on the basis of available experimental data, in the Reynolds number range (40-400). The time and Reynolds number history of the drag, lift, torque, pressure distributions, boundary layer separation point, and the flow pattern of the Kármán vortex street are illustrated. References are given to past laminar flow solutions.

13. G. V. Parkinson and T. Jandali, *A Wake Source Model for Bluff Body Potential Flow,* J. Fluid Mechanics 40(3), 577-594 (1970)

A theory is presented for two-dimensional incompressible potential flow external to a symmetrical bluff body and its wake. (The experimentally determined values of the separation point location and base pressure coefficient are required a priori.) The flow inside the separation streamlines is ignored and base pressure is assumed constant at the separation value. Features of the theoretical model include a finite wake width, a pressure distribution on the separation streamlines decreasing asymptotically towards the free stream value at infinity and a simple analytic expression for the pressure distribution on the body. Comparisons of the theory with experimental data and with other theories are presented for the normal plate, the circular cylinder, the 90° wedge, and the elliptical cylinder. Although simpler to apply than the other theories, the present theory produces at least as good agreement with the experimental data. (from Author's abstract)

The paper references other approximate theories intended to predict some of the important features of the complex flow around bluff bodies.

14. Y. Chen, *Wake Swing and Vortex Shedding in a Cross Flow Past a Single Circular Cylinder,* IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

The real Karman vortex street will be simulated by an ideal, semi-infinitely long rectilinear vortex street. By means of this model the lift force exerted by the vortex on the cylinder and the length of the vortex formation zone can be determined (experimental values of the Strouhal number and drag coefficient are required a priori). These theoretical results correspond reasonably well to the experimental value. By consideration between the moment of the inertia force and that of the mass inertia of the corresponding vortex field with its rotating angular displacement, a wake number fh^2/Γ can be derived, which should remain constant in spite of the variation of the Reynolds number. The theory is confirmed by the experimental results according to which fh^2/Γ is equal to a value of 0.165 for an ideal flow up to a Reynolds number of 10^7. (from Author's summary)

15. R. E. D. Bishop and A. Y. Hassan, *The Lift and Drag Forces on a Circular Cylinder in a Flow Fluid*, Proc. Royal Soc. London, Series A 277, 32 (1964)

Apparatus is described in detail for measuring directly fluctuating lift and drag forces and steady mean drag force on a circular cylinder in water. Suppression of three-dimensional effects, free-surface effects, blockage effect, and sensitivity and accuracy of measurement are discussed. Results are given for stationary cylinder for Re range from 3600 to 11000.

16. A. D. K. Laird, *Eddy Formation Behind Circular Cylinders*, J. Hydraulic Division, Proc. ASCE, 763 (June 1971)

Emphasis is placed on describing how and why eddies form in the wake of rigidly supported smooth cylinders in crossflow of incompressible fluid via modelling the behavior of the shear layers. Potential flow theory is used. A combination of vorticity in shear layers emanating from boundary layers and instability of these layers is considered the principal cause of eddy formation. Shear layers calculated with a simple model are readily disintegrated by flow disturbances and periodic wakes produced. The potential flow theory modelling presented is stated to give useful qualitative predictions of flow about bluff cylinders. Possible modelling refinements to obtain quantitative predictions are suggested.

17. D. W. Sallet, *On the Spacing of Karman Vortices*, J. Appl. Mechanics, Trans. ASME 36, 370-372 (1969)

Equations for the absolute dimensions of the Karman vortex street are developed in terms of the coefficient of drag and the Strouhal number of the vortex shedding bluff body. The body is assumed to be of large slenderness ratio and of uniform cross section. The predicted vortex spacings are compared with the experimental results of other investigators for circular cylinders, flat plates, and a wedge. (Author's abstract)

18. J. H. Gerrard, *An Experimental Investigation of the Oscillating Lift and Drag of a Circular Cylinder Shedding Turbulent Vortices*, J. Fluid Mechanics 11, 244-256 (1961)

The oscillating lift and drag on circular cylinders are determined from measurements of the fluctuating (air) pressure on the cylinder surface in the range of Reynolds number from 4×10^3 to just above 10^5.

The magnitude of the r.m.s. lift coefficient has a maximum of about 0.8 at a Reynolds number of 7×10^4 and falls to about 0.01 at a Reynolds number of 4×10^3. The fluctuating component of the drag was determined for Reynolds numbers greater than 2×10^4 and was found to be an order of magnitude smaller than the lift. (Author's abstract)

19. J. H. Gerrard, *A Disturbance-Sensitive Reynolds Number Range of the Flow Past a Circular Cylinder*, J. Fluid Mechanics 22(1), 187-196 (1965)

The change by an order of magnitude of the oscillating properties of the (air) flow past a circular cylinder in the Reynolds number range 2×10^3 to 5×10^4 is demonstrated experimentally. It is shown that in this range these properties are highly susceptible to small disturbances of the frequency of the transition waves which precede turbulence in the shear layers just downstream of the cylinder. It is suggested that this susceptibility is responsible for the different lift coefficient values measured by various workers. (from Author's abstract)

20. R. T. Keefe, *An Investigation of the Fluctuating Forces Acting on a Stationary Circular Cylinder in a Subsonic Stream and of the Associated Sound Field*, Institute of Aerophysics, University of Toronto Report No. 76 (1961)

An experimental investigation is made of the fluctuating life and drag forces acting on a stationary circular cylinder over airflow Reynolds number of 5000 to 100,000. Clear evidence is given of the significant changes which can occur in lift force response when openings in the wind tunnel walls near the end of the cylinder are sealed. Closely spaced discs also are found to increase the lift coefficient on the test section between them. Conjecture is made that the discs increase the two-dimensionality of the flow (correlate vortex shedding). In light of these tests, one can understand the large scatter which appears in the lift coefficient data.

21. M. V. Morkovin, *Flow Around A Circular Cylinder - A Kaleidoscope of Challenging Fluid Phenomena*, Sym. on Fully Separated Flows, ASME, 102-118 (1964)

Recent experimental and theoretical studies related to the flow around circular cylinders across an extended Reynolds number range are reviewed and interpreted. The features of generation of attached and free vorticity layers and their dynamics are emphasized. Attention is also focused on the multiple instabilities of the overall flow field and of various subfields. Present knowledge on their transition to turbulence is summarized. As Reynolds number increases, the resulting unsteady, three-dimensional, interacting, vortical patterns appear to be the key to some of the perplexing experimental observations. (Author's abstract)

This extensive review complements that of Goldstein (see Ref. 16, Sec. IA-5) through 1963

22. D. W. Sallet, *On the Prediction of Flutter Forces*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

The prediction of the fluctuating lift forces which occur on (stationary) cylindrical bodies in cross flow is discussed. Equations are developed which permit the estimation of the maximum lift coefficient for a bluff cylindrical body exposed to uniform approach flow. By combining the results of a potential flow analysis with experimentally found values for the Strouhal number and the coefficient of drag, the lift coefficient can be expressed as a function of the Reynolds number. It is found that the lift forces are inversely proportional to the frequency of vortex shedding, after certain simplifying assumptions are introduced. (Author's abstract)

23. A. Naumann and H. Quadflieg, *Vortex Generation on Cylindrical Buildings and Its Simulation in Wind Tunnels,* IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

A general criterion for the existence of alternating vortex shedding in the wake of (stationary) circular cylinders is presented; in order to avoid the periodic vortex formation the conception of a 3-dimensional disturbance has been made such as a non-straight-lined flow separation, steplike or tapering change of the cross section, free ends of cylinders, etc. For the study of the flow behavior past cylindrical bodies at transcritical Reynolds numbers a simulation method is proposed which uses turbulence as well as separation wires on cylinders in the sub- and supercritical Reynolds number range. The comparison of some flow data gained by this simulation method with those known from experiments in the true transcritical range shows an encouraging consistency of measuring values. (Author's summary)

24. C. J. Apelt, G. S. West, and Albin A. Szewczyk, *The Effects of Wake Splitter Plates on the Flow Past a Circular Cylinder in the Range* $10^4<R<5\times10^4$, J. Fluid Mech. 61(part 1), 187-198 (1973)

Experiments were carried out using (rigid, stationary) models having $L/D \leq 2$, and the resulting pressure distributions and vortex shedding characteristics are presented. It is concluded that splitter planes reduce the drag markedly by stabilizing the separation points and produce a wake narrower than that for a plain cylinder, raise the base pressure by as much as 50%, and affect the Strouhal number to a lesser degree. (from Authors' abstract)

25. J. P. Batham, *Pressure Distributions on Circular Cylinders at Critical Reynolds Numbers,* J. Fluid Mech. 57(part 2), 209-228 (1973)

Measurements have been made of the mean and fluctuating pressure distributions of long circular cylinders, having smooth and rough surfaces, at Reynolds numbers of 1.11×10^5 and 2.35×10^5 in both uniform and turbulent streams. The presence of free-stream turbulence at these Reynolds numbers was found to suppress coherent vortex shedding on the smooth cylinder and give rise to a complex pressure field in which the mean pressure distribution was almost independent of Reynolds number over the small range of Reynolds numbers tested. The pressure distributions on the rough cylinder were found to be completely different in uniform and turbulent streams; the presence of turbulence gave rise to an increase in the level of vortex shedding energy, and produced mean pressure distributions similar to those obtained on smooth cylinders at Reynolds numbers of the order of 10^7. (Author's abstract)

26. T. Okamoto and M. Yagita, *The Experimental Investigation on the Flow Past a Circular Cylinder of Finite Length Placed Normal to the Plane Surface in a Uniform Stream*, Bull. JSME 16, 805-814 (1973)

It is found that the separation point of the circular (rigid, stationary) cylinder removes forward with a decreasing ratio l/d (length/diameter) except in the neighborhood of the free end of the cylinder, and the local drag coefficient changes greatly when l/d varies from 6 to 7 because a vortex street does not exist at $l/d \leq 6$. The vortices shedding frequency decreases as the free end of the cylinder is approached and it depends on both l/d and Reynolds number (10^3 - 10^4). (from Authors' abstract)

2. *Rigid, Spring-Damper Mounted*

1. N. Ferguson and G. V. Parkinson, *Surface and Wake Flow Phenomenon of the Vortex-Excited Oscillation of a Circular Cylinder*, J. Engr. for Indus., Trans ASME 89(4), 831-838 (1967)

Fluctuating air pressure measurements were made on the surface and in the wake of a rigid, spring-damper mounted circular cylinder in vortex-excited lift (only motion allowed) oscillation at subcritical Reynolds numbers, (1.5 - 4.1) x 10^3. Large amplitude oscillations and pressure fluctuations at the structural natural frequency were found to occur over a range of flow velocities for which vortex shedding also occurred at the structural natural frequency (lock-in). For flow velocities below lock-in values, both the pressure and displacement signals showed a beat modulation due to contributions at both the structural and vortex shedding frequency. The lock-in range ended suddenly with vortex shedding returning to that governed by a Strouhal number of 0.2. During lock-in the phase shift between lift force and displacement was found very sensitive to flow rate. (More than a 90° phase shift occurred during lock-in.) Comparison to forced oscillation data of Hassan/Bishop and stationary cylinder data was considered good.

2. V. C. Mei and I. G. Currie, *Flow Separation on a Vibrating Circular Cylinder*, The Physics of Fluids 12(11), 2248-2254 (1969)

The location of the boundary-layer separation point on a circular cylinder has been investigated experimentally for a stationary cylinder and for a cylinder which is performing vortex-excited oscillations. The results for the stationary cylinder are in close agreement with published data. For the vibrating cylinder, the range of angular displacement of the separation point was found to depend upon the vibration amplitude and frequency, and the peak displacement occurred at a different frequency from that which gave the peak cylinder amplitude. As the frequency of the wake motion increases beyond that which gives that maximum range in the location of the separation point, the range of the motion of the separation point decreases. For given cylinder and wake frequencies, the higher the cylinder amplitude, the greater the motion of the wake. (from Author's summary)

Test specimen is rigid and cantilevered from base which allowed rotations and supplied variable damping for vibration studies for a Reynolds number of 1.67 x 10^4 in air.

3. R. Blevins, *Vortex Induced Vibration of a Circular Cylindrical Structure*, ASME Paper No. 72-WA/FE-39 (1972)

A model is developed for the vortex force on a rigid-spring damper mounted cylinder vibrating transverse to the flow at the structural natural frequency and peak amplitude due to vortex shedding in subcritical Reynolds number flow. The vortex force is assumed to act harmonically at the cylinder natural frequency in phase with the cylinder velocity. Selected existing air and water data on maximum reasonant amplitude, as a function of damping, and a damped linear oscillator model are used to obtain an analytical representation for the resonant force which increase in magnitude with vibration amplitude. The increase of force magnitude is justified on the basis of other experimental data (IIA3,1) which indicates that span-wise correlation of vortex shedding increases with vibration amplitude from a near zero value for a stationary cylinder. The model is successfully employed to predict the resonant amplitude for a rigid cantilevered cylinder pivoted at the base for which experimental data is available. The model is suggested to be useful for general deformable beams.

In reference (8) Umemura, Yamaguchi, and Shiraki made similar attempts to obtain analytical expression for resonant forces on the basis of other experimental data but were unsuccessful because of poor correlation of the data.

4. M. Funakawa, *The Vibration of a Cylinder Caused by Wake Force in a Flow*, Bulletin of JSME 12(53), 1003 (1969)

To clarify the exciting mechanism and correlation between exciting force and ratio of vibration amplitude to cylinder diameter, three experiments have been conducted for Re = 2.65×10^4 and 1.43×10^3:

1) Wind tunnel test on an elastically supported cylinder.

2) Two-dimensional model basin (water) test on a cylinder oscillated with a crank mechanism.

3) Wind tunnel test on a cylinder oscillated with a crank mechanism.

Variation of the separation point and pressure fluctuations with vibration and flow velocity are discussed. It is concluded that exciting mechanism is a self-induced vibration. Theoretical analysis to explain test results is also presented.

5. D. W. Sallet, *On the Self Excited Vibrations of a Circular Cylinder in Uniform Flow*, Shock and Vibration Bulletin 40(3) (1969)

This report discusses the influence of densities and change in flow regime upon the flutter motions, and describes experimental results of (water) tests at high Reynolds numbers ($0.4 - 2.7 \times 10^5$) in which the average densities of the (rigid-elastically mounted) cylinder and the fluid differ only slightly. It was found that the cylinders do not exhibit a unique response amplitude and frequency for a given fluid approach velocity but will undergo flutter motions over large amplitude and frequency ranges. These multivalued amplitude and frequency ranges increase as the average density of the cylinder approaches the density of the fluid to which the cylinder is exposed. (from Author's abstract)

The author suggests that although the Reynolds number of the approach velocity is less than the critical Reynolds number defining the transition region for stationary cylinders, the actual fluid velocity may be in the transition region where vortex shedding is more random. The tests were performed on specimen with natural frequencies less than .05 Hz.

6. D. W. Sallet, *On the Reduction and Prevention of the Fluid-Induced Vibrations of Circular Cylinders of Finite Length*, Shock and Vibration Bulletin 41(6), 31 (1970)

A method which prevents the unsteady pressure distribution around the cylinder, and therefore fluid-induced vibrations, is discussed. A potential flow model is presented to illustrate that a splitter plate will prevent attached vortices from shedding. Designs and experiments for more realistic fluids are presented. The data shows the splitter plate to be very effective in inhibiting flow-induced vibrations due to vortex shedding in water. For cylinders without the splitter plate, the data shows large amplitudes over a wide range of Reynolds numbers ($0.4 - 3 \times 10^5$).

7. R. J. Glass, *Final Report: A Study of the Hydroelastic Vibrations of Spring Supported Cylinders in a Steady Fluid Stream Due to Vortex Shedding*, Ohio Northern University (AD-721073) (1970)

The steady state amplitude and frequency response for the vortex-induced transverse vibrations of a circular cylinder mounted on linear springs in a steady fluid stream was considered. The tests were conducted in water and the range of variations were: aspect ratio, 16.5 to 29.9; the ratio of cylinder density to fluid density, 0.718 to 8.67; Reynolds number, 1727 to 4317. The nondimensional frequency response was found to be a strong function of the cylinder-to-fluid density ratio ($\bar{r}$). The nondimensional amplitude response ($\bar{A}$-amplitude/diameter) was found to be a function of cylinder-to-fluid density ratio, Reynolds number (N_R), and the dimensionless ratio of the free stream velocity divided by the product of natural frequency and cylinder diameter. The maximum nondimensional amplitude response ($\bar{A}_m$) was analyzed for the form of dependency, and empirical equations were developed:

$$\left[\bar{A}_m = 0.0268\,(\bar{r})^{-0.191}\,(N_R)^{0.462} \right] .$$

8. S. Umemura, T. Yamaguchi, and K. Shiraki, *On the Vibration of Cylinders Caused by Karman Vortex,* Bull. Jap. Soc. Mech. Engrs. 14(75), 929 (1971)

Wind tunnel tests were carried out in the subcritical Reynolds number range ($3 - 8 \times 10^4$) to investigate the vibrations of a rigid, spring-damper mounted (both ends) wood cylinder and the associated aerodynamic forces. Only motion in the lift direction was allowed. The velocity range over which vortex shedding frequency "locked into" the natural structural frequency and self-excited vibrations occurred was largest for small damping factors and decreased as damping increased. For a damping factor of 0.179 neither lock-in or self-excited vibrations occurred. Increased damping decreased resonant amplitudes; but neither frequency, spring constant, nor mass was found to affect resonant amplitude or calculated lift coefficient for the same diameter cylinders. Lift coefficients are significantly affected by resonant amplitudes, but not in any systematic manner. Variations in aerodynamic damping, which became negative around a structural Strouhal number of $S_t = 0.2$, was found to be a very sensitive function of the S_t and is cited as the source of the self-excited vibrations. End plates were used to approximate two-dimensional flow. Three-dimensional effects, surface effects, wind tunnel blockage, etc. are thought to be the cause of scatter in data.

9. R. T. Hartlen and I. G. Currie, *Lift-Oscillator Model of Vortex-Induced Vibration,* J. Engr. Mech., ASCE 96, 577-591 (1970)

Based on a review of existing experimental data, an analytical model for the transverse response of a spring-mounted rigid cylinder in crossflow is proposed to be governed by the equations for a linear mechanical oscillator. However, the lift coefficient in the forcing function is governed by a nonlinear oscillator (Vanderpol's equation) with a linear dependence on cylinder velocity. The many coefficients in the equations can be judiciously chosen to represent experimental trends and data. For a stationary cylinder, a constant lift coefficient at the vortex shedding frequency is shown to be predictable. For an oscillating cylinder, a lock-in range for the vortex shedding and structural natural frequency, a peak in amplitude, a sharp change in phase angle between amplitude and force, is predicted as well as peak amplitude vs. damping curve qualitatively similar to experimentally obtained results. Correlation of the model with specific data is shown to be good. The model does not predict multiple values of displacement which have been observed.

10. I. G. Currie, R. T. Hartlen, and W. W. Martin, *The Response of Circular Cylinders to Vortex Shedding*, IUTAM/IAHR Symposium on Flow-Induced Vibrations, Paper B1, Karlsruhe, Germany, August 1972.

The lift-oscillator model discussed above (Ref. 9) is modified to include qualitatively the possibility of multivalued displacements, which have been observed experimentally, by including a small nonlinearity in the spring in the mechanical oscillator. Also included in the paper is a stability diagram (method) which predicts, by analytical means, the range of wind speeds over which a given structure will be unstable.

11. G. Di Silvio, *Self-Controlled Vibrations of a Cylinder in a Fluid Stream*, J. Engr. Mech. Div., ASCE 95, 347-361 (1969)

An analytical model is proposed to represent the response of a spring-damper mounted rigid circular cylinder subject to crossflow. The wake width of the vibrating body is determined by assuming the effective breadth of the cylinder is the cylinder diameter plus twice the cylinder displacement when a new vortex begins to form (positive or negative displacements are possible). Then conventional stationary cylinder theory based on Von Karman vortex trails are employed to determine lift force and Strouhal frequency. For application to a particular system, one vibrational amplitude and corresponding Strouhal number must be known. Lock-in of vortex shedding and natural frequency is predicted as well as a critical velocity above which multiple values of displacements and phase angles (three branches) can occur. A good comparison is obtained with the results of Ferguson and Parkinson (Ref. 1).

12. O. M. Griffin, *Flow Near Self-Excited and Forced Vibrating Circular Cylinders*, J. Engr. Industry, Trans ASME 94, 539-547 (1972)

Two circular cylinders of equal diameter were used for experimentation: one was tuned to self-excite under the influence of lift forces (air), and the other was a rigid cylinder mounted in a shaker and forced to vibrate sinusoidally perpendicular to the mean flow direction under conditions that duplicated the Reynolds number (550 - 900), Strouhal number, motion amplitude, and relative frequency of the tuned cylinder. One finds the wake formation process to be similar for both cylinders under the same conditions of flow, and the amplitude and distribution of near wake velocity fluctuations also to be the same. A phase shift of ninety deg is observed between eighty and one hundred and ten percent of the peak self-excited resonance condition, with the phase angle between the velocity fluctuation and cylinder motion signals being equal for both means of excitation. The critical relative frequency that corresponds to peak resonant conditions is less than unity. The independent parameters that govern the vibrations are not the same for the two means of excitation, and the bounds for the forced and self-excited motions are discussed in terms of the present results and those reported in the literature. (from Author's abstract)

13. O. M. Griffin, *The Unsteady Wake of an Oscillating Cylinder at Low Reynolds Number*, J. Appl. Mech., Trans ASME 93, 729-738 (1971)

The flow (Reynolds number of 120-350) in the wake is controlled by suitable transverse vibrations of the cylinder at, and near, the natural vortex shedding frequency. The size of the vortex formation region is substantially influenced both by cylinder frequency and amplitudes, velocity fluctuations in early wake are increased, and flow is correlated in wake. The initiation of turbulence downstream of the vortex formation is suppressed, and the limiting Reynolds number for the formation of a laminar-stable vortex street is extended well beyond the usual (stationary cylinder) limiting (Reynolds number) value, $R_e = 150$ to $R_e = 350$. The bands of cylinder frequency and amplitude which control wake are limited. (from Author's conclusions)

14. D. W. Sallet, *Suppression of Flow-Induced Vibrations by Means of Body Surface Modifications*, Shock and Vibration Bulletin 42(4), 215-228 (1972)

The flow-induced vibrations of an elastically supported (rigid) cylinder which is exposed to crossflow can be reduced by changing the flow around the cylinder. This report discusses at length the effects of surface modifications on the flow-induced vibrations. It is seen that surface modifications can reduce the amplitudes of the flutter motions. (from Author's abstract)

15. R. A. Skop and O. M. Griffin, *A Model for the Vortex-Excited Resonant Response of Bluff Cylinders*, J. Sound Vib. 27, 225-233 (1973)

An analytical lift-oscillator model for the vortex-excited resonance response of spring-damper mounted rigid cylinders is formulated by modifying the Vanderpol equation which determines the lift coefficient in the model of Hartlen and Currie (Ref. 9). Appropriate choices are made for the four arbitrary model constants to fit the stationary lift coefficient, the peak amplitudes, the flow velocities at which peak amplitude occurs, and damping for four sets of wind tunnel experimental data having different system parameters. For the same experiments, good quantitative agreement with theory is shown for dynamic lift coefficients, phase angles, and vortex frequencies over the lock-in region. Empirical relations are postulated for the arbitrary model constants based on curve fitting. The validity of the model and the empirical relations is tested by predicting amplitudes based on different system parameters for which additional sets of data obtained in the same experimental facility are available. Correlation is excellent.

16. G. V. Parkinson, C. C. Feng, and N. Ferguson, *Mechanisms of Vortex-Excited Oscillations of Bluff Cylinders*, Paper 27, Symp. Wind Effects on Build. and Structures, Loughborough, England, 1968.

Transverse vibration amplitudes, vortex shedding frequencies, surface pressure distributions and phase angles were obtained for rigid circular and D-shaped cylinders, spring-damper mounted and subjected to cross flow. The lock-in of vortex shedding frequency with natural frequency is observed near a critical velocity based on stationary cylinder Strouhal numbers. Although the pressure distributions remain nearly constant for different velocities during lock in, the pressure magnitude increases dramatically as does the vibration amplitude. Also, multiple values of displacement were found depending upon whether the wind speed is increased while the cylinder is oscillating or at rest. Sudden drops in pressure and amplitude were observed when lock-in ceased. Large damping was found to suppress peak amplitudes and pressures as well as to eliminate multiple values. Qualitatively the responses of the D shaped and circular section were the same. Quantitatively, the response of the D section was always stronger and more sensitive to variation in system parameters. The expected strong spanwise correlation of vortex shedding due to the sharp edge of the D section is suggested as the reason for the differences.

17. Y. N. Chen, *The Orbital Movement and the Damping of the Fluidelastic Vibration of Tube Banks Due to Vortex Formation; Part 1: The Interplay Between the Self-Excited Vibration of the Single Circular Cylinder and the Karman Vortex*, Presented at ASME Vibrations Conference, Cincinnati, Ohio, 1973.

In the present paper a series of experimental results obtained by several authors on the phenomena of the vortex street behind a vibrating cylinder are analyzed. From this we can establish a flow model for the relationship between the vortex shedding, the cylinder movement, the vortex lift and the variation in the position of the separation point. This relationship reveals that a close synchronization of the vortex shedding and the lift generated by it will arise when the flow velocity enters the lock-in region. Furthermore, the flow model will enable us to predict the narrowing of the vortex street shed by a vibrating cylinder for certain Reynolds number ranges. The theory can thus qualitatively explain the corresponding phenomena observed by Koopmann, Griffin, and Votaw. (From Author's abstract)

18. J. D. Hardwick and L. R. Wootton, *The Use of Model and Full-Scale Investigations on Marine Structures*, Paper No. 127, Proc. International Symposium on Vibration Problems in Industry, Keswick, England, April 1973.

A model was used to investigate the drag direction, water crossflow-induced vibrations of a circular cylinder as a means of understanding unexpected motion of prototype jetty piles. Excitation at a Strouhal number of 0.65 was determined to be due to symmetric vortex shedding (Reynolds number $\sim 5 \times 10^3$). The same phenomenon was observed by King, Prosser, and Johns (see Ref. 3, Sec. IIA4-1). The applicability of the model experiment and possible explanation of the excitation mechanisms are given. Quantitative, but not qualitative, changes in response appear to occur with variation in Reynolds number.

19. O. M. Griffin, R. A. Skop, and G. H. Koopmann, *The Vortex-Excited Resonant Vibrations of Circular Cylinders*, J. Sound Vib. 31, 235-249 (1973)

Measurements were made of the vibration amplitude and frequency for Reynolds numbers between 350 - 1000 at synchronization between vortex shedding and vibration frequencies. Observed was increased spanwise correlation of shedding and increases of 75% in drag between stationary and resonating cylinders. A mathematical nonlinear wake oscillator model was shown to correlate well on the basis of magnitudes of displacement and resonant frequencies.

3. *Rigid, Forced Oscillations*

1. G. H. Toebes and A. S. Ramamurthy, *Fluid Elastic Forces on Circular Cylinders*, Proc. ASCE, J. Engr. Mech. 92, 1-19 (1967)

   Fluid (water) force spectra acting on a rigid circular cylinder moving transverse to the flow with prescribed harmonic oscillations were obtained for the flow Reynolds number range (30-53) x 10^3 for various amplitude/diameter and forced frequency/Strouhal frequency (stationary cylinder) ranges. The lift forces showed sharp resonant response at some forced frequency slightly less the Strouhal frequency, which depended nonlinearly upon both Reynolds number and amplitude of vibration. The resonant (maximum) lift forces were found for the highest Reynolds number and amplitudes which could be tested. The large changes in phase angle between the displacement and the component of the lift force at the displacement frequency, as well as the corresponding maximum energy transfer (including inertia effects), are calculated. The energy can be used in determining maximum response of an equivalent self-excited system; however, from a design point of view, much more data is needed. Based on data, governing equations of motion for response of a self-excited cylinder at resonance are formulated (nonlinear oscillator) and the solution is discussed.

2. G. H. Toebes, *The Unsteady Flow and Wake Near an Oscillating Cylinder*, J. Basic Engr., Trans ASME, Series D 91, 493-505 (1969)

   Extensive velocity, pressure, and correlation measurements in the turbulent wake and adjacent unsteady potential flow region of a circular cylinder under prescribed (forced) sinusoidal motion are presented for air flow in the Reynolds number range (0.2 - 1.2) x 10^5. Vortex shedding or Strouhal frequency, which always contained some random variations up to 15%, are found to be modulated by cylinder motion (beat frequency observed) when the forcing frequency is not near a simple multiple or fraction of the shedding frequency. Near a shedding frequency harmonic, the vortex shedding was found to lock-in with the forcing frequency. During lock-in, the strength of the vortex is suggested to be stronger than for a stationary cylinder. Also, spanwise shedding frequency correlation is found to increase significantly with both synchronization of frequencies and amplitude of motion. Further, the change in location of the separation point, often associated with increases and decreases in lift and drag forces, is found to be much large during forced motion than for a stationary cylinder.

   Much information is included in this paper on the wake structure as well as a review of the associated literature.

3. R. E. D. Bishop and A. Y. Hassan, *The Lift and Drag Forced on a Circular Cylinder Oscillating in a Flowing Fluid,* Proc. Roy. Soc. London, Series A, 51 (1964)

   Early observations of fluctuating lift forces were obtained for a cylinder undergoing forced oscillations in flowing water in a Reynolds number range of 6000 - 10,800. The results can only be considered qualitative because of the questionable method of obtaining the lift force. Lock-in or synchronization of the vortex shedding to the exciting frequency was observed over a range around the exciting frequency . Sudden large amplitude lift force (resonance effect) occurred during lock-in, and near resonance, large phase shifts between the force and displacement were observed. Force magnitudes and Strouhal number at resonance were observed to be displacement amplitude and Reynolds number dependent. Different values (hysteresis effects) were obtained for increasing velocity tests in comparison to decreasing velocity tests, although the qualitative behavior was the same. Outside of the lock-in range the force amplitude was observed to have a beat modulation comprised of the forcing frequency and the vortex shedding frequency.

4. Y. C. Fung, *Fluctuating Lift and Drag Acting on a Cylinder at Super Critical Reynolds Numbers,* J. Aerospace Sciences 27(11), 801 (1960)

   See Ref. 5, Sec. IIA1-2.

5. O. M. Griffin, *Flow Near Self-Excited and Forced Vibrating Circular Cylinders,* J. Engr. Industry, Trans ASME 94, 539-547 (1972)

   See Ref. 12, Sec. IIA2-5.

6. A. Protos, V. W. Goldschmidt, and G. H. Toebes, *Hydroelastic Forces on Bluff Cylinders,* J. Basic Engr., Trans. ASME 90, 378-386 (1968)

   Fluid (water) force spectra acting on three different rigid cylinders prescribed to move transverse to the flow in sinusoidal oscillation were obtained for a flow Reynolds number of 45,000. The resonant lift force response amplification, phase angles and energy transferred to the cylinders from the fluid for an equilateral triangular cross section with apex into flow (least bluff cylinder), a circular cylinder, and an equilateral triangular cross section with apex away from flow (bluffest cylinder) were qualitatively the same as previously reported for circular cylinder (See Ref. 1). However, more accurate values over a wider range of amplitudes and frequencies are claimed. Smaller lift force amplifications, although larger absolute lift forces, were observed for the bluffer cylinders. Added mass coefficient for a triangular cylinder is reported to be ∿ 1.5.

7. G. H. Koopmann, *The Vortex Wakes of Vibrating Cylinders at Low Reynolds Numbers*, J. Fluid Mech. 28(3), 501-512 (1967)

The effect of the transverse (forced) motion of a cylinder in airflow (Reynolds number = 200) is visually observed at different amplitudes for the range of frequencies wherein the vortex shedding locks into the driving frequency. Observations were: Above a determined threshold amplitude, coherence of the separation points along the span was induced; the frequency limits of the lock-in range are amplitude dependent; cylinder motion decreases the lateral spacing of the vortices in comparison to the stationary cylinder. Excellent photographs of the shed vortices and spanwise correlation are provided.

8. G. W. Jones, Jr., *Unsteady Lift Forces Generated by Vortex Shedding About a Large, Stationary, and Oscillating Cylinder at High Reynolds Numbers*, ASME Paper No. 68-FE-36.

See Ref. 8, Sec. IIA1-3.

9. M. Funakawa, *The Vibration of a Cylinder Caused by Wake Force in a Flow*, Bulletin of JSME 12(53), 1003 (1969)

See Ref. 4, Sec. IIA2-2.

10. O. M. Griffin, *The Effects of Synchronized Cylinder Vibrations on Vortex Formation and Strength, Velocity Fluctuations, and Mean Flow*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

Measurements (in air) have been made in a cylinder wake with a hot wire anemometer for Reynolds numbers between 120 and 350 where vibrations at and near the Strouhal frequency of shedding both synchronize the flow and delay the initiation of turbulence. The changes that occur in the amplitude and distribution of both mean and fluctuating velocities are discussed and with the vortex formation length are related to a shedding parameter defined by the amplitude and frequency of the vibrations. It is demonstrated that synchronized cylinder vibrations of half a diameter result in a 65 percent increase in vortex strength from the stationary cylinder value, and a correspondence is shown between the smaller formation region and substantially increased vortex strength for several conditions of forced excitation at a Reynolds number of 144.

There is a relation between the fluid forced on a bluff body and the distance downstream at which vortices are shed, there being an increase in base underpressure and drag as the formation region decreases in length. It is thus possible to relate the increased vortex strength to the greater drag that accompanies resonant vibrations and the increased pressure and lift forces that act periodically with the same frequencies as those of the vibrations.

(from Author's abstract and summary)

11. P. Bublitz, *Measurements of the Unsteady Pressure and Forces Acting Upon an Oscillating Cylinder*, IUTAM/IAHR Symposium on Flow-Induced Vibrations, Karlsruhe, Germany, August 1972.

    Extensive experimental studies of the airflow phenomena arising with the forced oscillated circular cylinder at DFVLR, AVA Göttingen, Germany are summarized. Many of the subcritical range results performed elsewhere are confirmed: lock-in of vortex shedding and oscillating frequency occurs, the band width of the lock-in range is dependent upon displacement amplitude, the force (pressure) amplitudes increase during lock-in, the flow separation point is shifted somewhat upstream, and out of the lock-in range the vortex shedding forces are unaffected by cylinder oscillation. In the supercritical range the force (pressure) spectra are random whether oscillations are forced or not. Also, the oscillating cylinder pressure spectrum results indicate that boundary layer transition (laminar to turbulent) Reynolds number is lower than for the stationary cylinder.

12. C. W. Votaw and O. M. Griffin, *Vortex Shedding from Smooth Cylinders and Stranded Cables*, J. Basic Engr., Trans. ASME 93, 457-460 (1971)

    The character of vortex shedding and wake characteristics in air were not found to be significantly different for smooth vs. stranded cables so long as the projected area of the cable is not rough (e.g., either the helix angle or the ratio of strand and total diameters of the cable remain small). The cables were tested at Reynolds numbers of 240 and 500 for both stationary and forced oscillation conditions.

13. G. H. Toebes, *Fluidelastic Features of Flow Around Cylinders*, Wind Effects on Buildings and Structures Conference (University of Toronto Press, 1968), pp. 323-341.

    The paper presents results of a study of the (air) flow field near an (rigid) oscillating circular cylinder. It provides proof for a number of notions about fluid-structure interaction effects. These are that cylinder motion near the Strouhal frequency increases the local circulatory lift force and increases the structuredness of the wake flow. In addition, the local lift is shown to be non-harmonic and under all conditions is a narrow-band, random disturbance. The fluidelastic nature of the flow field is demonstrated convincingly by means of correlation diagrams. (from Author's abstract)

14. J. R. Dale and R. A. Holler, *Secondary Vortex Generation in the Near Wake of Circular Cylinders,* AIAA Paper No. 69-755, CASI/AIAA Subsonic Aero- and Hydro-Dynamics Meeting, Ottawa, Canada, July 1969.

Forced oscillation of a circular cylinder, transverse to relative water flow, has disclosed two shedding regimes in which the vortices are shed with a fixed phase relation to the motion. Oscillation amplitudes from 0.04 to 0.31 diameters were used over a freestream Reynolds number range $330 < R < 2700$. Hydrogen bubbles were used for direct flow visualization. The lower frequency regime was related to the Strouhal frequency and the higher frequency regime was related to the frequency of transition waves in the free shear layers. Transition vortices appeared to evolve from the transition waves and preceded the laminar to turbulent transition zone. The vorticity of the transition vortices was enhanced during forced oscillation in the higher frequency regime. Scaling criteria were formulated for the limits of the higher frequency regime. (Authors' abstract)

4. *Elastically Deformable*

1. L. R. Wootton, M. H. Warner, and D. H. Cooper, *Some Aspects of the Oscillations of Full-Scale Piles*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper F1, August 1972.

   The shedding of vortices from a stationary pile was found to be regularly periodic up to the highest Reynolds numbers studied ($R \approx 1.5 \cdot 10^6$) with a shedding frequency of $nD/V = 0.22$. As the flow speed increased from zero, the piles started to oscillate when the shedding frequency was close to 1/3 of their natural frequency. Symmetrical shedding could be observed from behind the pile when it was responding in the flow direction under these conditions. At a reduced velocity of about 2.0, the cause of the response changed radically with vortices being shed alternately from the sides of the cylinder. At much higher flow speed still, the well known crossflow response occurred, though this is not discussed in this paper. (Authors' abstract)

2. J. Vellozzi and Edward Cohen, *Dynamic Response of Tall Flexible Structures to Wind Loading*, Wind Loads on Buildings and Structures, Nat. Bureau of Stand. Build. Sci. Series 30, 115-128 (1970)

   Methods of calculating the dynamic response of tall, flexible (mainly circular) structures to wind loads are presented. Design methods based on extensive experimental data (see Ref. 10, Sec. IA-4) are referenced and discussed as adequate for avoiding self-excited lateral response due to vortex shedding in the subcritical Reynolds number range. The theory of random excitation is employed to yield expressions for the RMS deflection (fundamental mode) in the supercritical Reynolds number range based on RMS lift coefficients and power spectral densities obtained by Fung (see Ref. 5, Sec. IIA1-2). The response due to air turbulence is calculated again utilizing random excitation theory and the more elaborate information available on spectral characteristics of wind turbulence.

3. R. King, M. S. Prosser, and D. J. Johns, *On Vortex Excitation of Model Piles in Water*, J. Sound and Vibration 29, 169-188 (1973)

   Vortex shedding flow-induced vibration observations of cantilevered cylinders at various water depths revealed three ranges of flow velocity in which resonance (instability) occurred. Maximum in-line (fundamental and second mode) amplitudes occurred at reduced velocities v/fD (v = flow velocity, f = beam frequency, D = beam diameter) of ~ 2.2, and lock-in did not occur. Symmetric vortex sheddings were observed to occur. Another maximum occurred for in-line vibrations at a reduced velocity of ~ 3.2 where lock-in did occur. Transverse oscillation maximums and lock-in were observed for reduced velocities of 5.5 - 7.5. Constants for a stability design criteria were successfully evaluated from the data. The criteria indicate the range of flow velocities to be avoided and the minimum (structural-nonfluid) damping allowable if large oscillations are to be avoided. The stability criteria was originally developed for design of smokestacks (see Ref. 10, Sec. IA-4).

4. R. King, *Flow Induced Vibrations*, The British Hydromechanics Research Association Report RR 1093 (January 1971)

   A cylinder, mounted with its axis vertical and fixed as a cantilever to the floor of a water channel has been tested to observe the resulting flow-induced vibrations when the water velocity in the channel was varied.

   Investigations revealed that vibrations, at the fundamental natural frequency in the direction of flow were initiated at reduced velocities (V/ND) as low as 1.2. In the cross-stream direction forced vibrations at the vortex shedding frequency were detected at a reduced velocity of 0.6.

   It was observed that the addition of mass and stiffness to the cylinder free end affected the resulting vibrational mode (fundamental or second harmonic) and that (again) the reduced velocity was not a sufficient criterion to determine whether or not in-line vibrations would occur. (from Author's summary)

5. R. King, *The Stability of Piles in Flowing Water*, Dock and Harbor Authority <u>53</u>, 352-355 (1973)

   The stability criteria developed previously (see Ref. 3) for avoiding cross flow, vortex induced, drag direction, vibrations is explained,and a practical application is illustrated.

6. J. R. Dale and Roger A. Holler, *Spanwise Vortex Wakes from Circular Cylinders*, 2nd Canadian Cong. Appl. Mech., Univ. of Waterloo, 227-228 (1969)

   Observations in air of the vortex wakes for both stationary rigid circular cylinders and self-excited flexible circular cylinders in the Reynolds number range of 30-550 were made. A cellular spanwise vortex structure due to inate velocity gradients along the span (also see Ref. 7, Sec. IIA3-3) were found for the stationary cylinder. For the oscillating cylinder, lock-in occurred at the coincidence of the vortex shedding frequency and the fundamental and second harmonic, as well as strong uniform spanwise correlation of the vortex shedding. Around the node point of the second mode, vortex shedding did exhibit characteristics similar to that of a stationary cylinder.

7. J. Dale, H. Mevzel, and J. McCandless, *Dynamic Characteristics of Underwater Cables Flow Induced Transverse Vibrations*, NADC-AE-6620 (Sept 1966)

   Crossflow vortex excitation of smooth cylindrical hydrophone cables was documented. The lock-in of vortex shedding and structural natural frequencies and associated peaking of amplitudes was observed. An empirically determined modification of the Strouhal number

   $$S_T = f_v d/(u \sin\theta)^n$$

   was presented as the form which correlated best with data from several different size cables (diameter d and frequency f) over various velocity (u) ranges (Reynolds numbers 200-3000), amplitudes of motion (0-30 diameters), and yaw angles (θ). An analytical model to predict response was constructed for a particular cable mass system.

8. J. R. Dale and R. A. Holler, *Vortex Wakes from Flexible Circular Cylinders at Low Reynolds Numbers*, NADC-AE-7011, (1970)

Smooth cables were towed in water tanks at Reynolds numbers from 30-500, and hydrogen bubbles were employed to observe the wakes. For an oscillating cable in crossflow with sufficient amplitude, uniform spanwise shedding was observed, except around nodes, in comparison to wavy lines of shedding for a stationary cable. For a stationary yawed or curved cable, the vortex shedding was wavy and, at any given instant, the mean line of the vortices was not parallel to the length of the cable. The Strouhal relation was valid based on velocity and shedding frequency normal to the rod. For oscillating yawed or curved cables, shedding at the vibrating frequency was uniform and parallel to the cable for sufficiently large oscillations. A definite dependency between amplitude of vibration and the existence of uniform or wavy vortex shedding was established.

9. R. King and M. J. Prosser, *Criteria for Flow-Induced Oscillations of a Cantilevered Cylinder in Water*, Paper No. E5, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

A series of experiments were performed to determine conditions of drag direction oscillations of cylinders in various water depths. The terms of the stability criteria employed in design of smoke stacks (see Ref. 10, Sec. IA-4) were modified to account for the significant added mass of water, water damping, and depth of water. An analytical method for calculating still water damping, based on pure viscous effects, is given. In a flowing fluid, damping was found to be amplitude and flow velocity dependent.

10. A. J. Dutt, *Dynamic Response of a Vertical Cantilevered Structure in Natural Wind*, Strain 9, 11-18 (1973)

Both response due to vortex shedding (transverse vibrations) and wind gusts (drag direction vibrations) were predicted (linear analysis) and compared to experiment with good correlation for the circular cylinder. The fluctuating component of the wind (gusts) was measured with a hot wire anemometer at the same time deflections were measured. The fluctuating drag force was calculated on the basis of the velocity record and a steady drag coefficient obtained in a wind tunnel test. Lift forces due to vortex shedding were assumed to be equal to the average dynamic pressure varying sinusoidally at the vortex shedding frequency: The lift coefficient was taken to be one. Equivalent mechanical damping was measured in a separate test. Drag direction air damping based on relative velocity of air with respect to vibrating cylinder was included, also.

11. B. J. Vickery and R. D. Watkins, *Flow Induced Vibrations of Cylindrical Structures*, Proc. 1st Aust. Conf., Univ. West. Aust., MacMillan (1964), pp. 213-241.

Single, circular, cantilevered cylinders were tested for response due to crossflow vortex shedding in water and air when vortex and structural natural frequencies coincide. Based on linear single degree of vibration theory for which damping energy dissipated is equal to the driving energy, a functional relation between maximum amplitude and the parameter $\frac{M\delta}{\rho D^2} = \Delta$ is proposed, where D is the cylinder diameter, δ the log decrement of damping, ρ the fluid density, and M is the effective mass. Experimental response data for a wide range of mass and damping did reduce to a single curve when plotted as a function of Δ.

Appropriate helical strakes practically eliminated vibrations for a single cylinder, but were far less efficient when wake buffeting from an adjacent cylinder occurred. Significant drag direction vibrations were observed for lightly damped structures. Downstream cylinders for a set of in-line cylinders experienced greater response than a single cylinder.

12. G. Koopman, *Wind Induced Vibrations of Skewed Circular Cylinders*, AD 717 739 (1970)

A general discussion of the various techniques used to measure the oscillating lift coefficients of wind-induced vibrations of circular cylinders is presented. The discussion is summarized with a brief outline of the various categories of research efforts being conducted on fluid-induced vibrations. Each cateogry is referenced to an appropriate group of papers which exist in the literature. A simple method for determining the oscillating lift coefficient for the wind-induced vibration of a circular cylinder is developed and applied to a typical problem where the longitudinal axis of the cylinder is skewed relative to the direction of the oncoming flow. (Author's abstract)

Cylinders skewed beyond ∿ 15° to the flow were reported to exhibit random oscillations two orders of magnitude less than the periodic oscillations observed for flow normal to the cylinder axis.

13. C. R. Gerlach and F. T. Dodge, *An Engineering Approach to Tube Flow-Induced Vibrations*, ASME Symp. Flow Induced Vib. Heat Exchangers, 18-26 (1970)

A review of crossflow, vortex induced vibrations of circular tubes was made. Information necessary to make analytical predictions, which are not presently available, is identified. A design method is given which requires minimal experimental data from like structures. The method is equivalent to that used by designers of tall smokestacks (see Ref. 10, Sec. IA-4).

14. N. Ellis, *A Technique for Evaluating the Fluctuating Aerodynamic Forces on a Flexible Building*, Paper No. 312, Proc. International Symposium Vibration Problems in Industry, Keswick, England, April 1973.

See Ref. 11, Sec. VB5-4.

B. Yawed Circular Cylinders in Uniform Flow

1. A. R. Hanson, *Vortex Shedding from Yawed Cylinders*, AIAA J. 4, 738 (1966)

   The frequency of vortex shedding is determined over the Reynolds number range 40 tc 150. Basing the Reynolds and Strouhal numbers on the component of air velocity normal to the yawed cylinder (taut wire) yields results which are the same as for an unyawed cylinder. However, an unexplained large change in the data occurs for large yaw angles greater than 72° (see Ref. 2). The Reynolds number at which vortex shedding begins is given as a function of yaw angle also.

2. C. W. Van Atta, *Experiments on Vortex Shedding From Yawed Circular Cylinders*, Tech. Note, AIAA J. 6, 931 (1968)

   Experimental data in air for determining the relation between vortex-shedding frequency (Strouhal number S_n) and yaw angle are presented for the Reynolds number range $50 \leq R_n \leq 150$. The R_n and S_n are calculated on the basis of the velocity normal to the rigid cylinder. The S_n was found to be approximately constant for yaw angles up to 30°; for larger yaw angles, a significant monotonic increase was observed. These results are in disagreement with those of Hanson (Ref. 1). Hanson's results are believed to be incorrect because of lock-in with structural vibrations.

3. W. S. Chiu and J. H. Lienhard, *On Real Fluid Flow Over Yawed Circular Cylinders*, J. Basic Engr., Trans. ASME 89, 815-857 (1967)

   Based on classic boundary layer theory, the boundary layer separation point is shown to be independent of yaw angle. Subsequently, the conclusions are made that the Strouhal number (therefore, vortex shedding frequency) and the pressure drag coefficient (lift also) can be evaluated for the crosswise component of flow, as though the spanwise flow did not exist, for Reynolds numbers greater than 100. Vortex shedding frequency data are presented for the Reynolds number range 4,000 to 20,000, to support the first conclusion. The second conclusion supports the experimental results of E. H. Relf and C. H. Powell (not obtainable for review).

   Discussion by A. Roshko and later work (see Ref. 4) point out that classic boundary layer theory is probably not relevant when the flow in the wake is not laminar, although the conclusions may be correct. The later work gives data in the Reynolds number range 2,000 to 15,000, which shows variation of the pressure drag coefficient with yaw angle.

4. R. A. Smith, W. T. Moon, and T. W. Kao, *Experiments On Flow About A Yawed Circular Cylinder*, J. Basic Engr., Trans. ASME 94, 771 (1972)

   Experiments were performed in air to evaluate the influence of yaw angle on circular cylinder pressure drag and near wake characteristics in the range of Reynolds numbers 2000 to 10,000. It was found that the transition in the wake from laminar to turbulent motion was significantly promoted as the angle of yaw increased. As a result, wake properties such as base pressure and position of transition to turbulence do not obey the Independence Principle which requires that properties be dependent only on the normal component of the free-stream conditions. (Authors' abstract)

   The vortex shedding frequency obeys the Independence Principle, however the energy associated with the shedding frequency becomes less dominant with increased yaw angles.

5. E. H. Relf and C. H. Powell, *Tests On Smooth and Stranded Wires Inclined To the Wind Direction and a Comparison of the Results On Stranded Wires In Air and Water*, British ARC, R and M 1917, Report No. 307.

   Not obtainable for review.

6. J. Dale, H. Menzel, and J. McCandless, *Dynamic Characteristics of Underwater Cables Flow Induced Transverse Vibrations*, NADC-AE-6620 (Sept 1966)

   See Ref. 7, Sec. IIA4-2.

7. J. R. Dale and R. A. Holler, *Vortex Wakes from Flexible Circular Cylinders at Low Reynolds Numbers*, NADC-AE-7011 (1970)

   See Ref. 8, Sec. IIA4-3.

C. Plates in Uniform Flow

1. G. Heskestad and D. R. Olberts, *Influence of Trailing-Edge Geometry On Hydraulic-Turbine-Blade Vibration Resulting Form Vortex Excitation*, J. of Engineering for Power, Trans. ASME 82, 103-110 (1960)

Effects of trailing edge geometry on the vortex-induced vibrations of a model blade designed to simulate the conditions of a hydraulic (water) turbine blade were studied. Strouhal numbers were determined (non-resonance) for ten different edges. Amplitude and frequency responses were similar in character to that of most blunt bodies excited by vortex shedding, except the lock-in of vortex shedding and structural natural frequencies was not distinct. The maximum amplitude of vibration, for a given flow velocity, was thought to increase with an increase in the ratio of the distance (perpendicular to flow) between boundary layer separation points to the boundary layer thickness plus the solid shielding thickness (provided by the trailing edge) between regions of vortex growth. The boundary layer thickness was the same order of magnitude as the blade thickness. Non-resonant Strouhal numbers can be calculated from the data.

2. G. H. Toebes and P. S. Eagleson, *Hydroelastic Vibrations of Flat Plates Related to Trailing Edge Geometry*, J. of Basic Engineering, Trans. ASME 83, 671-678 (1961)

Vortex-induced vibrations of thin flat plates are studied as a function of trailing edge geometry. The vibrations are considered as hydroelastic phenomena and an equation of motion is formulated. Some expected features of its solution are set forth. A detailed experimental determination is made of the amplitude spectra of various rigid thin plates mounted at zero mean angle of incidence in the test section of a water tunnel and suspended by a torsion spring through their leading edge. Qualitative vibrational characteristics are similar to those for a circular cylinder. The trailing edge geometries significantly influence vibrational amplitudes. Reentrant edges produce orders of magnitude smaller vibrations than rounded edges. The extent of the after body is thought to be a major factor in correlating vortex shedding along the trailing edge and producing the associated large amplitudes. Well streamlined bodies (separation point near edge) with little afterbody produce only small vibrations.

3. P. S. Eagleson, G. K. Noutsopoulos, and J. W. Daily, *The Nature of Self-Excitation in the Flow-Induced Vibration of Flat Plates,* J. of Basic Engineering, Trans. ASME 86, 599-606 (1964)

Flow-induced vibrations of flat plates are studied in water. An equation of motion of a single degree of freedom plate-spring system is formulated incorporating the hydrodynamic loads given by the linearized potential theory, and the unknown, vortex-induced, forcing moments. The moment is evaluated for plates with different trailing edges using experimental measurements of vibrational amplitude and frequency, and the nature of its dependence on vibration is shown to be equivalent to a negative damping. Bounds of the zone in which large vibrational ("singing") motion occurs are predicted. Criteria are offered for the design of systems to avoid these self-excited vibrations. (from Authors' abstract)

Variation of amplitude and vibrational frequency with flow velocity is similar to that of circular cylinders. Fluid damping (viscous) coefficients are determined in still water. Classical flutter is shown to be highly unlikely for usual mass of metallic plates.

4. R. Brepson and P. Leon, *Vibrations Induced By Von Karman Vortex Trail In Guide Vane Bends,* IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

Research on vaned bend vibration at SOGREAH has shown that the vanes behave as a two-dimensional plate, and especially that the trailing edge configuration is most important and that one must know the natural vane frequencies in order to ensure that they are not the same as the excitation frequencies. A programme has been developed for the computation of natural vane frequencies and the associated modes, and the numerical data and results of (water) tests on an actual vanes bend have been compared. The theoretical and experimental data agreed closely and yielded design data enabling the vibration risk for guide vane bends to be reduced to a minimum. (from Authors' summary)

5. C. J. Wood, *Discussion of Paper C5 In Opening Addresses, Discussions, and Contributions, Pg 59,* IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

Reintrant edges on trailing edge geometries of plates are claimed to reduce vibrations because of the increased fluid damping ability due to motion. Evidence is given that indicates rigid stationary plates with a square or reinstrant edge produce the same vortex trail.

6. R. Parker, *Resonance Effects In Wake Shedding From Parallel Plates: Calculation of Resonant Frequencies*, J. Sound Vib. 5(2), 330-343 (1967)

   It has been shown previously by experimental methods that, when a fluid flows over a series of parallel plates, periodic wakes of the plates can excite a sequence of acoustic reasonances, each of which has a clearly defined mode. This paper presents a method of calculating the resonant frequencies and the corresponding pressure amplitude distributions. For each mode there is a critical value of the plate chord/pitch radio. Below this value the mode does not exist. At values just above the critical the regions of maximum amplitude are large and decay gradually in the upstream and downstream directions. At values much larger than the critical the decay is rapid and large pressure amplitudes only occur between the plates. Correlation with experimental results is good. (Author's abstract)

7. D. S. Weaver, N. Kouwen, and W. M. Mansour, *On the Hydroelastic Vibration of a Swing Check Valve*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Paper No. C6, Karlsruhe, Germany, August 1972.

   The paper reports the decaying oscillation of a swing check valve (gravity door) upon pump shut down. Attempts to force the valve shut (spring load) and damp only aggravated the vibration by establishing long term larger amplitude vibrations. The vibration excitation is linked to the change in pressure upstream and downstream of the valve when flow is nearly choked resulting in reopening, reestablishment of flow, reclosing, etc. The addition of a spring and damping only serve to organize an otherwise random decaying process.

8. R. C. Leibowitz and A. Kilcullen, *Experimental Determination of Structural and Still Water Damping and Virtual Mass of Control Surfaces*, Shock and Vibration Bulletin 42(4) (1972)

   An experiment has been designed for determining the damping constants and virtual mass for the control surface systems (e.g. rudder) of USS ALBACORE (AGSS 569) and USS SAMPSON (DDG 10); theoretical methods for determining the virtual inertias (including virtual mass) of these control surfaces are also given. The theoretical foundation for the experimental design and the procedure for analyzing the experimental data to obtain the parameters are described. These damping and inertial parameters are essential to the performance of a hull-control surface vibration and/or flutter analysis.

9. D. J. Maull and R. A. Young, *Vortex Shedding From a Bluff Body In a Shear Flow*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper No. H2, August 1972.

   The vortex shedding frequency and base pressures are measured on a (∿ 15 x 20 x 2.5 cm) cantilevered rigid plate subjected to uniform and shear air flow (Reynolds No. ∿ 3×10^4 at center line flow, 25% different at tunnel walls) at zero angle of incidence. The leading and trailing edges have elliptical and rectangular cross sectional shapes, respectively. The base pressures for uniform flow were significantly different (generally lower) for the half of the plate including the tip in comparison to a plate spanning the wind tunnel. For uniform flow vortex shedding occurred at nearly the same frequency all along the plate. In shear flow the vortex shedding frequency was nearly constant (25% lower than for uniform flow) over the half of the plate containing the base. The vortex shedding frequency for the half of the plate containing the tip was nearly constant (15-25% higher than for uniform flow), also. Along the middle region of the plate length both frequencies occurred.

10. D. R. Miller and R. G. Kennison, *Theoretical Analysis of Flow-Induced Vibration of a Blade Suspended in a Flow Channel*, ASME Paper 66 - WA/NE-1, 1966, 17 pp

    A rigid-plate suspended in a flow channel by pivoting at the trailing edge and providing rotational springs and damping is analyzed for self-excited oscillations and instabilities. Approximate one-dimensional fluid theory is employed to calculate pressure moments on the blade as a function of motion. Frequency analyses of the equation of motion of the blade show that either static divergence, a form of stall flutter (galloping), or decaying vibrations may occur depending on the flow rate and length of blade assuming other parameters are constant. The theory does not correlate well with water table test results other than a region of divergent vibrations does occur.

11. M. W. Wambsganss, *Flow-Induced Vibration in Reactor Internals*, Power Reactor Technology and Reactor Fuel Processing <u>10</u>, 2-5 (1966)

    The results given in Ref. 10 are clearly summarized and used to interpret failures observed in nuclear reactors.

12. E. H. Dowell, *Panel Flutter: A Review of the Aeroelastic Stability of Plates and Shells*, AIAA J. <u>8</u>, 385-399 (1970)

    The state-of-the-art in panel flutter is reviewed and pertinent references which provide access to the large literature are given.

13. R. C. Leibowitz, *Methods for Computing Fluid Loading and the Vibratory Response of Fluid-Loaded Finite Rectangular Plates Subject to Turbulent Excitation-Option 3*, Naval Ship Research and Development Center, Report No. 2976C, AD-737203 (September 1971)

Various methods are presented for computing heavy or light fluid loading (i.e., added mass) of thin finite rectangular plates. Based on the results, preferred methods of computation are recommended. These methods and a corresponding computer program--Option 3--are of particular value in extending previously formulated digital computer programs for obtaining the vibroacoustic response (high frequency) to turbulence excitation of a plate. Computer results are given for a particular case which includes the effect of fluid loading on the vibratory response of a plate subject to turbulence excitation. (Author's abstract)

14. D. J. Maull and R. A. Young, *Vortex Shedding from Bluff Bodies in a Shear Flow*, J. Fluid Mech. 60, 401-409 (1973)

See Ref. 9.

15. M. E. Greenway and C. J. Wood, *The Effect of a Bevelled Trailing Edge on Vortex Shedding and Vibration*, Dept. Eng. Science Report No. 1052/73 (Univ. Oxford, 1973); Also J. Fluid Mech. 61, 323-335 (1973)

In the absence of vibrational motion of the body, a bevelled trailing edge has very little effect upon the strength of the vortex shedding. However, it does appear to destabilize the wake vortex trail and lead to intermittency and a consequent reduction in the excitation.

Under vibrating conditions the effect of a trailing edge bevel is to destroy the amplification ordinarily experienced by blunt based aerofoils. Not only is the mean vortex strength reduced to the quiescent level, but also an asymmetry is introduced in which the vortices from the acute corner become stronger than those from the obtuse corner. Its effect is to cause a serious instability in the vortex trail which vanishes within one or two cycles and causes a greatly reduced vibration excitation.

These effects of decreasing the trailing edge angle are progressive. Satisfactory damping appears to be achieved for angles of 30 degrees or less. (from Authors' conclusions)

16. D. R. Miller, *Flow-Induced Instability of a Thin-Walled Cylindrical Shell*, Proc. Conf. Flow-Induced Vib. in Reactor System Components ANL-7685 (1970), pp. 312-320.

A bibliography on flow-induced collapse of flat plates in channels is included.

17. J. Novak, *Strouhal Number and Flat Plate Oscillation in an Air Stream,* ACTA Tech. CSAV 18, 372-380 (1973)

This paper describes the results of an experimental investigation of Strouhal number S and the oscillation of a flat plate in an air stream as a function of Reynolds number Re, the intensity of turbulence I, and the angle of attack a. The following intervals were used: Re = 0.60 to 2.67 x 10^4, I = 2.4 and 15%,and a = 15 to 90°. The width of the plate was 20 mm.

Strouhal number of plate S, characterizing vortex shedding from the plate, is practically independent of the Re number but decreases with the growing angle a. Strouhal number S also slightly drops with rising turbulence intensity I,and is identical for both sides of the plate, regardless of Re, I,and a.

The plate oscillates in the air stream practically with its natural frequency or close to this value irrespective of Re, I,and a. The plate oscillation amplitude grows with the Re number and angle a,but practically does not depend on I. The oscillation amplitude changes relatively at random. The degree of this randomness grows with the Re number, slightly with the intensity of turbulence I, and with the decreasing angle a in an interval in which periodical vortex shedding from the plate passes into a random one.

(from Author's abstract)

D. Bluff Cylinders in Uniform Flow

1. G. V. Parkinson and T. Jandali, *A Wake Source Model for Bluff Body Potential Flow*, J. Fluid Mechanics 40(3), 577-594 (1970)

   See Ref. 13, Sec. IIA1-5.

2. R. C. Binder, *The Flutter or Galloping of Certain Structures in a Fluid Stream*, Shock and Vibration Bulletin 39(Part 3) (Jan 1969)

   This paper presents a first-order (flutter) analysis for one case that has not been presented in the literature. The particular case is taken in which the center of gravity coincides with the elastic axis. A closed form solution is obtained.

   In a range of velocities the motion of the system is bounded and no dangerous torsional or translational displacement amplitude is involved. At one particular velocity, however, the characteristic roots are equal, and the vibration amplitude increases with time; this condition might be classed as a critical flutter or gallop. At this critical condition the flutter frequency equals the natural translation frequency. At a higher approach velocity the characteristic equation gives at least one positive root, which means an amplitude build-up, and an unstable condition.

   The transmission line galloping data reported by several different investigators check the main features of the foregoing analysis very closely.

   (from Author's abstract)

3. P. W. Bearman, *Turbulence-Induced Vibrations of Bluff Bodies*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper H1, August 1972.

   Measurements are presented of the fluctuating pressure recorded at the stagnation point on a stationary, two dimensional flat plate mounted normal to the flow. The effects of the distortion of the approaching turbulence are examined. Some measurements of the response of a flexibly mounted bluff body (triangular cross section) of finite aspect ratio where the scale of turbulence was three times the width of the body are reported. It is shown that the response in the drag direction, at the resonant frequency, can be predicted to good accuracy by the method of Davenport (see Ref. 20) over a range of values of the structural damping. There is evidence, however, of a complex interaction between the stream turbulence and the wake flow at low frequencies. (from Author's abstract)

4. G. H. Toebes and A. S. Ramamurthy, *Lift and Strouhal Frequency for Bluff Shapes in Constricted Passages*, Proc. Conf. Flow-Induced Vib. Reactor Sys. Components, ANL-7685 (1970), pp. 225-247.

   This note presents initial data on Strouhal frequency and lift for circular and triangular cylinders and for blockage between 7% and 44%. It is found that, in that range, a simple continuity argument can account for blockage effects on the Strouhal number. The same argument is not satisfactory for correcting the oscillatory lift. For high blockages the oscillatory lift for steady cylinders decreases relative to the drag. The tendency towards self-excitation, however, may well increase when vortex-induced vibration gives way to a single-degree-of-freedom flutter. (from Authors' abstract)

5. C. F. M. Twigge-Molecey and W. D. Baines, *Measurements of Unsteady Pressure Distributions Due to Vortex Induced Vibration of a Cylinder of Triangular Section*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper E1, Aug 1972. Also, ASCE 99(EM4), 803-818 (1973)

   A wind tunnel investigation was conducted on a long cylinder of equilateral triangle cross section the point being directed upstream. Instantaneous pressure was recorded at twenty points around the section and from this data root mean square pressure fluctuation and phase relative to the lift force were determined. Measurements were made for the cylinder fixed rigidly and for the cylinder mounted on springs. The pressure distributions were subsequently integrated to give the rms lift coefficient. It was found that the frequency of shedding of the vortices was independent of the cylinder motion. The lift coefficient was virtually constant except near resonance where a minimum occurred for wake frequency slightly less than the natural frequency of the cylinder and support system and a maximum occurred for the wake frequency slightly greater than the natural frequency. (Authors' summary)

6. A. Protos, V. W. Goldschmidt, and G. H. Toebes, *Hydroelastic Forces on Bluff Cylinders*, J. Basic Engr., Trans. ASME 90, 378-386 (1968)

   See Ref. 6, Sec. IIA3-2.

7. A. S. Mujumdar and W. J. M. Douglas, *Vortex Shedding from Slender Cylinders of Various Cross Sections*, J. Fluids Engr., Trans. ASME, 474-476 (1973)

   Vortex shedding frequencies were measured for a number of cylinders of various geometrical shapes by placing a hot-wire sensor in the near (air) wake and autocorrelating the turbulence signal. Strouhal numbers are presented for D-section cylinders with the flat face facing both upstream and downstream, isosceles triangular prisms, axially corrugated and helically grooved circular cylinders. For the triangular prisms effect of angle of attack was also studied. Effect of surface roughness on shedding from circular cylinders was observed to be negligible. (Authors' summary) Re < 16,000

8. P. W. Bearman and D. M. Trueman, *An Investigation of the Flow around Rectangular Cylinders*, The Aero. Quart. 23, 229-237 (1972)

   Measurements are presented of the base pressure coefficient, drag coefficient and Strouhal number of (stationary) rectangular cylinders. The results confirm a finding in Japan that the drag coefficient rises to nearly 3 when the depth of the section is just over half the width. The flow around the sections is found to be strongly influenced by the presence of the trailing edge corners. (Authors' summary)

   Drag coefficients were R_e dependent in the air flow range (4-12) x 10^4.

9. G. V. Parkinson, C. C. Feng, and N. Ferguson, *Mechanisms of Vortex-Excited Oscillation of Bluff Cylinders*, Symp. Wind Effects on Build. Struct., Paper No. 27, Loughborough, England, 1968.

   See Ref. 16, Sec. IIA2-7.

10. G. V. Parkinson, *Mathematical Models of Flow-Induced Vibrations of Bluff Bodies*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

    See Ref. 15, Sec. IA-5.

11. G. V. Parkinson and J. D. Smith, *The Square Prism as an Aeroelastic Non-Linear Oscillator*, Quart. Journ. Mech. and Applied Math. XVII(Pt. 2) (1964)

    A quasi-steady analysis is made of the transverse galloping of a long prism of square section in a normal steady wind. Experimental stationary aerodynamic forces are used in the theory, which leads to an ordinary differential equation with small non-linearity for the displacement. This is solved by the first approximation method of Krylov and Bogoliubov, and it is found that some characteristics of non-linear oscillators unusual in a mechanical system are predicted, in particular the occurrence of oscillation hysteresis over a range of wind speeds. Quite accurate quantitative agreement between these predictions and wind tunnel measurements on an elastically mounted square prism is described. (Authors' summary)

12. M. Novak, *Galloping Oscillations of Prismatic Structures*, J. Eng. Mech. Div. ASCE 98, 27-46 (Feb 1972)

    A widely applicable galloping theory assuming a general form of an aerodynamic force, which includes most experimentally observed, is formulated assuming two-dimensional flow, no vortex shedding interaction, and only lateral motion. Emphasis is placed on solving the governing equations of motion and the energy balance expression, and interpreting the regions of amplitude and velocity for which galloping occurs in terms of the coefficients in the force expression. Each different type of galloping is discussed via example utilizing experimental data. The suppression of or increased tendency toward galloping because of flow turbulence is discussed. The paper provides a good overview.

13. G. V. Parkinson and T. V. Santosham, *Cylinders of Rectangular Section as Aeroelastic Nonlinear Oscillators*, ASME Paper No. 67-VIBR-50 (March 1967)

A quasi-steady two-dimensional theory of galloping oscillation of bluff cylinders is applied to a cylinder of rectangular section with section aspect ratio 2 in uniform air flow. Force measurements on the stationary cylinder, needed for the theory, were made using a wind-tunnel balance, and observations of galloping in the wind tunnel were made on two sizes of rigid cylinder mounted on springs, using several levels of damping over a range of wind speeds. Wake vortex frequency measurements by hot-wire anemometer helped to define the wind speed range of validity of the galloping theory, and within this range, good agreement is found between theory and experiment. An extension of the theory to include effects of the wake vortices leads to a prediction of asynchronous quenching of galloping oscillation of a cylinder of square section in water flow. (Authors' abstract)

14. M. Novak, *Galloping Oscillations of Prisms in Smooth and Turbulent Flows*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper H8, August 1972.

Research on the effects of turbulence on galloping is reviewed, with the conclusion that galloping in turbulent flows must be studied in similar turbulent flow wind tunnels since, for example, some structures galloping in smooth flow have been found not to gallop in turbulent flows, and vice versa.

15. T. L. Shaw, *On the Nature of Fluctuating Circulation, Lift and Flow-Induced Structural Vibrations*, J. Sound Vib. 14(2), 251-261 (1971)

It is commonly considered that periodic oscillations of a structure in relative motion through a fluid result from vortices being shed into the wake of the body. It is contended that this concept accounts for the observed vibration of cables, stacks, towers and the like, even though the similar behaviour of other structures, such as sluice gates, may not similarly be explained. This paper reconsiders the fluid-mechanic phenomena accompanying flow past two-dimensional bodies of various forms, and concludes that vortex shedding is associated with, but not the cause of, pressure fluctuations and structural vibrations. (Author's summary)

16. R. H. Wilkinson, J. R. Chaplin, and T. L. Shaw, *On the Correlation of Dynamic Pressures on the Surface of a Prismatic Bluff Body*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper E4, August 1972.

The authors give attention to instantaneous pressure distributions over the side faces of prismatic square cylinders. Correlation measurements suggest that the line of transition to turbulence in the shear layer may have a wave-like form, so that cells of coherent shedding may be detected close to the cylinder. Transverse cylinder oscillations are also studied. (Authors' summary)

17. V. J. Modi and J. E. Slater, *Quasi-Steady Analysis of Torsional Aeroelastic Oscillators*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Paper D2, August 1972.

The galloping, aeroelastic instability of bluff cylinders in torsion is analyzed using a quasi-steady approach. The analysis indicates the presence of various singularities which are generally centers or foci. Furthermore, there exist limit cycles, the stability of which can be determined from the Liapunov criterion. The amplitude of the galloping motion increases with wind velocity accompanied by a slight shift in oscillation frequency. The experimental results on a structural angle substantiate the analysis. (Authors' summary)

18. W. P. Mortenson and L. V. Schmidt, *Aeroelastic Problems as Found in a Large Antenna System*, ASME Paper No. 67-VIBR-39 (March 1967)

In air crossflow ($R_e \sim (1\text{-}6) \times 10^5$), the response of a rigid-spring mounted model with square and rectangular cross sections was controlled by the corners: an increase in corner radius resulted in a decrease in motion amplitude, probably due to change in flow requirements. Estimates of unsteady lift force showed a strong tendency to be motion dependent.

19. Y. Nakamura and T. Mizota, *Galloping and Vortex Excitation of a Rectangular Block*, Reports of Research Institute for Applied Mechanics XIX, 64 (1972)

Galloping and vortex excitation were experimentally investigated in a wind tunnel on a rectangular block of a side ratio 2:1 which was free to oscillate transversely in a uniform flow. The mean angle of attack of the model was varied from zero to 90 deg. The limit-cycle amplitude of model oscillation and the aerodynamic damping coefficient of unsteady lift force were obtained by a free oscillation technique. (from Authors' abstract)

Quasi-steady aerodynamic theory for galloping was found to be useful for velocities above twice the reduced velocity for vortex shedding. Effects of vortex shedding are discussed. An unexplained instability occurred for very low velocities and zero mean angle of attack.

20\. A. G. Davenport, *The Application of Statistical Concepts to the Wind Loading of Structures,* Proc. The Institution of Civil Engineers Session 1960-61, 19, Paper No. 6480 (1961)

The statistical concepts of the stationary time series are used to determine the response of a simple structure to a turbulent, gusty wind. This enables the peak stresses, accelerations, deflexions, etc., to be expressed in terms of the mean wind velocity, the spectrum of gustiness, and the mechanical and aerodynamic properties of the structure. An expression for the spectrum of gustiness near the ground is given, which takes into account its variation with mean wind velocity, roughness of the terrain, and the height above ground level. The statistical distribution of peak values over a large number of years is related to the statistical distribution of mean values by means of a so-called "gust factor."

As an illustrative example, the wind loads which might arise on a flexible arc-lamp standard and a rigid water tower are compared. This emphasizes the considerable differences which may arise in the effective wind loads owing to differences in the local ground roughness and the dynamic characteristics of the structure. (from Author's synopsis)

21\. A. S. Ramamurthy and C. P. Ng, *Effect of Blockage on Steady Force Coefficients,* J. Eng. Mech. Div., ASCE 99(EM4), Proc. Paper 9905, 755-772 (Aug 1973)

The variation of the steady force coefficients for a two-dimensional circular cylinder and a triangular prism due to wall interference are reported here for a large range of blockage ratios. The effect of wall constraint on the Strouhal frequency is also examined for a limited range of blockage ratios. A simple choice of the scales of velocity and lengths constituting the force coefficients and the Strouhal number for constrained flows is proposed to include blockage effects. (Authors' abstract)

22\. S. M. Gorlin, *Effect of Initial Turbulence on the Flow Around Bodies and on Their Aerodynamic Characteristics,* Nauchnyye Trudy, Institut Mekhaniki (No. 1), 34-45 (1970) (in Russian), and FTD-HT-23-0212-73 (English translation)

Effects of initial turbulence in significantly lowering the transition Reynolds number and changing lift and drag coefficients for bluff bodies are reviewed. Methods of achieving wind tunnel turbulence are included.

23\. A. S. Ramamurthy and P. M. Lee, *Wall Effects on Flow Past Bluff Bodies,* J. Sound and Vibration 31, 443-451 (1973)

Drag coefficients corrections for large wind tunnel blockage ratios were characterized for a centrally located rigid, stationary cylinder and equilateral triangle. Blockage corrections for eccentrically located bodies in the tunnel were possible, if the gap between the body and the wall was larger than the effective body diameters. For smaller gaps, erratic trends were observed associated with deflected flow and variations in boundary layer separation and reattachment point locations.

E. Circular Cylinder Arrays

1. H. J. Connors, Jr., *Fluidelastic Vibration of Tube Arrays Excited by Cross Flow*, Flow-Induced Vibration in Heat Exchangers (ASME, 1970), p. 42.

Fluid (air) flowing past the tubes in single-row and multi-row model arrays causes the tubes to vibrate with large whirling motions. The vibrations initiate abruptly when the flow velocity exceeds a critical value. Measurement of the forces that act on stationary tubes as they are displaced point-by-point to simulate a cycle of vibration show that the tubes extract energy from the fluid by means of a fluid-elastic, time-independent, displacement mechanism. A stability criterion for predicting the critical flow velocity above which the displacement mechanism causes severe tube vibration in single-row arrays is developed by a quasi-steady analysis. Stability test results for single-row model arrays of spring-mounted tubes having a wide range of natural frequency and damping are in good agreement with the quasi-steady prediction. Tube vibrations caused by vortex shedding are also discussed. (from Author's abstract)

2. P. R. Owen, *Buffeting Excitation of Boiler Tube Vibration*, J. Mech. Engr. Sci. 7, 431 (1965)

The origin of the vibration generated within an extensive bank of tubes that run transverse to the direction of gas flow through a boiler shell and whose movement is small enough in amplitude to have no perceptible effect on the motion of the gas, is examined on the supposition that, sufficiently deep inside the bank, the flow is essentially turbulent and, except for a general drift through the bank, exhibits no regular feature. Conditions of this kind are thought to be appropriate to certain types of heat exchangers used in nuclear power stations and operating at large Reynolds numbers.

The source of vibration, either structural or gaseous, is associated with the randomly fluctuating forces imposed on the tubes by the turbulent eddies, and a simple argument is put forward to account approximately for the length scale of the most energetic of these eddies and consequently the frequency with which they encounter the tubes. It is further argued that the tubes are aerodynamically discriminating in their force response which is thereby narrowed spectrally and confined to the neighbourhood of the frequency corresponding to the energetic eddies. The subsequent structural or acoustic response is even more sharpened spectrally, owing to the small damping inherent in the system.

A relation between the dominant frequency of the force fluctuations, the gas velocity and the geometrical arrangement of the tubes, that emerges from the argument, agrees in form with published observations of the sound emission from boilers under resonant conditions. A disposable constant appearing in the relation is also satisfactorily predicted in order of magnitude.

The analysis applies to only one possible form of the vibration phenomenon; other forms, aero-elastic and vortex-excited, may appear under suitable conditions dependent upon Reynolds number, structural stiffness, and damping. (Author's abstract)

3. Y. N. Chen, *Frequency of the Karman Vortex Streets in Tube Banks*, J. Royal Aeronautical Society 71, 211-214 (March 1967)

The influence of the transverse and longitudinal (with respect to flow direction) spacing of tube banks on the frequency of vortex shedding is discussed. The frequency is measured with a hot-wire anemometer exposed to airflow in tube banks of rigidly mounted tubes. Results of previous investigators are correlated. Presented are charts for the Strouhal number as a function of transverse and longitudinal spacing for both in-line (square pattern) and staggered tube banks.

4. Y. N. Chen, *Flow-Induced Vibrations and Noise in Tube-Bank Heat Exchangers Due to von Karman Streets*, J. Eng. for Ind., Trans. ASME, Series B 90, 134-146 (1968)

The literature relating Strouhal vs. Reynolds number for a single stationary circular cylindrical tube and stationary banks of tubes is reviewed, including an extensive bibliography. Based on previous work, an expression is derived for in-line tube banks which relates the vortex shedding frequency to the flow velocity, and tube spacing. The theory is compared to the available data and the discrepancies discussed.

Experimental results (10% accuracy claimed) are presented for staggered (in flow direction) stationary tube banks. Strouhal numbers for a wide range of spacings for both finned and unfinned tubes are given. The Strouhal numbers were found to be constant for a given tube bank spacing over the Reynolds number range investigated, $(1.5 - 6.0) \times 10^4$. Reasons for Strouhal number variation with tube spacing are given.

The vortex shedding frequency was measured downstream from a tube which was elastically mounted (non-stationary) and strain gauged such that tube loads and tube vibrations could be measured, also. Experimentally determined lift and drag coefficients for a single staggered tube bank geometry were given as a function of Reynolds number. The results for two modes of vibration of a single tube were extrapolated to predict coefficients for other stiffness tubes. The vibration amplitudes and tube loads always possessed a character of a beat of two components, one having the vortex shedding frequency and one the structural natural frequency. Amplitudes, lift, and drag forces were a nonlinear function of Reynolds number with peaks occurring when the natural and vortex frequency coincided. Excitation sources were thought due to general wake turbulence rather than vortex-structural synchronization observed for single tubes.

Methods of detuning heat exchangers to avoid transverse gas-column vibrations excited by vortex shedding are discussed also.

One should be aware that the author has subsequent to this paper published additional work on the subject including new data, flow models, and theoretical analyses.

5. Y. N. Chen, *Fluctuating Lift Forces of the Karman Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 3 - Lift Forces in Tube Bundles,* J. Eng. for Ind., Trans. ASME, Series B 94(2), 623 (1972)

   The trend of the fluctuating lift coefficient C_L and the dimensionless shedding frequency S (Strouhal number) of the vortex in tube bundles at higher Reynolds numbers R will be predicted by the course of the steady pressure drag coefficient C_D at the corresponding R ranges. Furthermore, some measurements of the vortex lift forces in tube bundles will be given. It reveals that the lift force for certain small transverse tube spacings possesses a strong second harmonic. The tubes and, therefore, the transverse gas column in the tube bundle channel can be excited to vibrate in resonance either at the critical flow velocity or at its half value. Finally, the coupled vibration between the vortex shedding and the transverse gas column will be covered with some experiments. (Author's abstract)

6. Y. N. Chen, *Flow-Induced Vibrations in Tube Bundle Heat Exchangers with Cross and Parallel Flow, Part 2, Cross Flow,* Flow-Induced Vibration in Heat Exchangers (ASME, 1970)

   Based on the theory developed for the relation between the Strouhal number of the Karman vortex and the steady drag coefficient for the cross flow past a single circular cylinder, the Reynolds number effect on the Strouhal number and the lift coefficient for the tube bundle are presented. The damping of the flow, the influence of the channel width, and the behavior of the irregularity of the tube spacing are explored by some experiments.

   The mixed type of the flow in the tube bundle (cross and parallel) can be treated as well with the theory developed. An example is presented. (Author's abstract)

7. A. R. J. Borget, *Vortex Shedding Frequencies of the Flow through Two-Row Banks of Tubes,* J. Mech. Engr. Sci. 11, 498-502 (1969)

   For a single stationary row of identical rigid circular cylinders, crossflow vortex shedding was found unstable for a gap less than one tube diameter. For a gap larger than one diameter, single cylinder shedding frequencies were observed. The shedding frequencies are given for various gaps for two rows in tandem and two rows staggered. Some Reynolds number effects (range 7×10^3 to 8×10^4) were observed only for the tandem rows.

8. M. M. Zdravkovich, *Flow Induced Vibrations in Irregular Staggered Tube Bundles, and their Suppression*, Paper No. 413, International Symposium Vibration Problems in Industry, Keswick, England, April 1973.

   Vibrations of a flexible tube by the flow of fluid may be greatly enhanced by the proximity of other tubes. The paper presents a study of the effect of irregularly staggered arrangements and banging of adjacent tubes on such vibrations. The pressure distribution around the central tube indicates that the flow in the gaps is dependent on the Reynolds number. Some methods of reducing such vibrations are discussed. (Author's summary)

F. Cylinders in Nonuniform Flow

1. C. Dalton and F. D. Masch, *Influence of Secondary Flow on Drag Force,* J. Engr. Mech. Div., Proc. ASCE, 94, 1249-1257 (1968)

   Rigid, stationary cylinders are subject to a flow field which varies linearly along the cylinder axis. Circumferential pressure distributions are measured and local drag coefficients computed. Pressure distributions and local drag coefficients are found to be different from a corresponding uniform flow by ∿ 25-50%. Local secondary flow along the cylinder axis due to the velocity gradient and channel walls is cited as the mechanism creating the drag coefficient differences. Also, the length/diameter ratio change from 4 to 7 was shown to effect the coefficient values (∿ 75%). Above 7 little effect was expected.

2. S. D. Savkar, *Oscillations of Cylindrical Rods and Cables in Shear Flows,* J. Sound Vib. 16(2), 161-172 (1971)

   The oscillations of elastic strings and rigid rods in a fluid undergoing uniform shearing motion (normal to string or rod axis) are considered. It is shown that the oscillations can become unbounded, in the sense of the linearized analysis, when a parameter designated as the shear frequency exceeds the unaffected natural frequency. With the above theory founding the basis of qualitative considerations, an empirical quasi-static analysis is devised for a more realistic situation analoging the wake-induced oscillations of high voltage transmission line bundles. An empirical equivalent of the shear frequency is derived from the analysis. This latter expression has an advantage in the sense of being a simple criterion and requiring only one piece of empirical information, the maximum static lift coefficient. The results are compared with experiments conducted in a wind tunnel using two in-line cables with the leeward cable in the wake of the windward cable. Self-induced oscillations leading to galloping are observed above a critical velocity calculated from the shear frequency criterion. (Author's abstract)

3. J. F. Wilson and H. M. Caldwell, *Force and Stability Measurements on Models of Submerged Pipelines,* J. Engr. Ind., Trans. ASME 38, 1290-1298 (1971)

   Mean drag and lift coefficients were measured for two stationary parallel pipes, parallel to a flat plane, subject to a nominally uniform flow. The flow velocity, the buoyancy, the height above the plan, the yaw angle of the pipe axis to the flow direction, and the separation distance between the cylinders were the parameters varied. Also, for non-yawed, flexible cylinders, the flow velocity at which instability (sic) due to vortex shedding was determined. The drag coefficients were significantly sensitive to all parameters as was the instability velocity. The flow field across the test section, especially near the wall, was not specified and not enough instability velocities were determined to separate out the effect of different parameters. Enough data was obtained for application to oil pipeline design, for which an example is given.

4. C. F. Chen and B. J. Mangione, *Vortex Shedding from Circular Cylinders in Sheared Flows*, AIAA J. 7, 1211-1212 (1969)

Vortex shedding for rigid-stationary circular cylinders in sheared flow (normal to cylinder axis) was found to correlate with that of uniform flow when based on local velocities.

5. F. D. Masch and W. L. Moore, *Drag Forces in Velocity Gradient Flow*, J. Hydraulics Div., ASCE 86, 1-11 (1960)

1. A longitudinal velocity gradient in the (water cross) flow approaching a (rigid, stationary) circular cylinder induces longitudinal currents in the wake zone and along the upstream element, thus altering the local drag coefficient at various positions along the cylinder. 2. The local drag coefficient is reduced (e.g., 40%) at sections subject to highest stream velocity due to the rise in pressure as fluid is supplied into the wake from the regions of lower stream velocity. 3. The magnitude of the above effect increases as the magnitude of the velocity gradient increases. (Reynolds number $\sim 10^4 - 10^5$) (from Authors' conclusions)

G. Wake Buffeting (sheltering)

1. B. J. Vickery and R. D. Watkins, *Flow-Induced Vibrations of Cylindrical Structures*, Proc. First Aust. Conf. on Hydr. and Mech.-1962, (New York: Pergamon Press, 1964), pp. 213-241.

   Four in-line, rigid, circular cylinders cantilevered from an elastic base with viscous damping were analyzed for resonant response due to vortex shedding and wake buffeting in air and water crossflow. The upstream cylinder was found to respond similar to a single cylinder, but downstream cylinders were greatly affected by the spacing between cylinders and the angle of incidence of the flow with the line of cylinders. The farthest downstream cylinder had the highest amplitudes. The amplitude of response was found to increase with spacing in the range of 2-6 diameters. Maximum response with respect to wind direction occurred at about 30° wind direction with respect to the line of the cylinders. The use of helical strakes which were shown to effectively reduce amplitudes for a single cylinder were not as successful for the in-line cylinders. Pitch to diameter ratio for cylinders $\sim$ 4-5.

2. W. A. Mair and D. J. Maull, *Aerodynamic Behavior of Bodies in the Wakes of Other Bodies*, Phil. Trans. Roy. Soc. London, Series A 269, 425-437 (1971)

   The wake dynamics behind a rigid stationary single bluff body in uniform, nonturbulent air flow is reviewed in order to define regions with significantly different flow. The inadequacy of response theory for aerofoils several diameters away from a bluff body is employed as an example to illustrate difficulties to be expected for two bluff bodies. Some of the experimental data for bluff bodies in the wake of other bodies is reviewed to indicate the significant changes in response which occur because of small changes in geometry or flow.

3. M. M. Zdravkovich, *Flow Induced Vibrations of Two Cylinders in Tandem, and Their Suppression*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

   The large observed motion of a rigid, spring mounted circular cylinder downstream from a similar rigid, stationary cylinder is attributed to the hysterisis of the flow switch through and around the gap between cylinders. The large motion could not be started for $2.5 < \text{gap/diameter} < 6$, where 6 was the largest ratio tested. Static pressure distribution measurements reported illustrate the displacement/diameter ratios for which excitation or restoration forces occurred. An axial rod shroud totally suppressed the vibration. ($R_e \sim 10^5$)

4. K. R. Cooper, *Wake Galloping, an Aeroelastic Instability*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper No. H7, August 1972.

   The flow velocities and spatial positions for which a cylinder undergoes large amplitude motion in the wake of an identical rigid, stationary, circular cylinder are determined. A minimum flow velocity was necessary for any motion to occur. Generally, more motion occurred in the drag than in the lift direction. Combinations of wind shear and turbulence appeared to suppress the onset of motion to higher flow velocities over that for smooth, uniform flow. The pitch/diameter ratios investigated appeared to be 5 to 50 and Reynolds numbers of $10^4 - 10^5$.

5. M. M. Zdravkovich, *Smoke Observations of Wakes of Tandem Cylinders at Low Reynolds Numbers*, Aero J. of Roy. Aero Soc. 76, 108-114 (1972)

   Observation of wake behavior via smoke filaments were made in the Reynolds number range 62-500. In comparison to a single cylinder, suppression of transition to turbulent wakes of the tandem cylinders was observed when spacing is less than four diameters, and promotion of transition when the plane containing the cylinders is inclined to the free stream.

6. J. F. Wilson and H. M. Caldwell, *Force and Stability Measurements on Models of Submerged Pipelines*, J. Engr. Ind., Trans. ASME 38, 1290-1298 (1971)

   See Ref. 3, Sec. IIF-1.

7. S. D. Savkar, *Oscillations of Cylindrical Rods and Cables in Shear Flows*, J. Sound Vib. 16(2), 161-172 (1971)

   See Ref. 2, Sec. IIF-1.

8. J. Armitt, *Vibration of Cooling Towers*, Proc. International Symposium Vibration Problems in Industry, Keswick, England, April 1973.

   See Ref. 12, Sec. VB5-4.

9. R. L. Wardlaw, K. R. Cooper, and R. H. Scanlan, *Observations on the Problem of Subspan Oscillation of Bundled Power Conductors*, Proc. International Symposium Vibration Problems in Industry, Keswick, England, Paper No. 323, April 1973.

   The mean aerodynamic forces on the conductors have been measured in wind tunnels for 2, 4, 6, and 8 conductor bundles. Dynamic response studies have been made using spring-mounted two-dimensional full-scale models and reduced scale aeroelastic models. Using the measured force data, the quasi-steady, linearized analytical approach has been shown to give reasonable predictions of the conditions for instability and the initial amplitude buildup rates. A conductor can become unstable only in a narrow region of the wake of an upstream conductor. The physical causes of the vertical aerodynamic force and the effects of terrain on the forces and the instability are discussed. (from Authors' summary) Pitch diameter ratios ≥ 1.5, and Reynolds numbers $\sim (10^4 - 10^5)$.

10. P. W. Bearman and A. J. Wadcock, *The Interaction between a Pair of Circular Cylinders Normal to a Stream*, J. Fluid Mech. 61(Pt. 3), 499-511 (1973)

This paper describes how the (air) flows around two (rigid) circular cylinders, displaced in a plane normal to the free stream, interact as the two bodies are brought close together. Surface pressure measurements at a Reynolds number of 2.5×10^4, based on the diameter of a single cylinder, show the presence of a mean repulsive force between the cylinders. An instability of the flow was found when the gap between the cylinders was in the range between one diameter and about 0.1 of a diameter. Correlation measurements of hot-wire outputs indicate how mutual interference influences the formation of vortex streets from the two cylinders. Spanwise correlation measurements show that the correlation length doubles as the cylinders are brought into contact. (Authors' abstract)

H. Other Configurations

1. F. A. Locher, *Some Aspects of Flow-Induced Vibrations of Hydraulic Control Gater*, AD 689457 (Feb 1969)

Characterization of the flow separation and fluid forces in water which occur at the edge of a stationary and oscillating control gate (rectangular cross section) are investigated. Flow away from the gate is two-dimensional and parallel to the flat surface from which the control gate is cantilevered. The length of the cantilever, b, and the thickness of the plate, d, are parameters. Results from stationary tests indicated that periodic forces developed in the range $2.5 < d/b < 4.5$ due to the unstable shear layer reattachment point after separating at the upstream edge. Random response was observed outside this range. Oscillations of the gate normal to the flow direction indicated increased force levels (order of 2-4) over the stationary gates. Data on the net force normal to the thickness of the gate in the form of DSD's and RMS values are given in addition to a physical interpretation of the fluid phenomenon.

2. F. A. Locher, *On the Role of Cavitation in the Flow-Induced Vibration of High-Head Gates*, Cavitation Forum (ASME, 1969), pp. 28-30.

A flow instability associated with a free shear layer of the leading edge of a flat gate (protruding into a conduit to control the discharge rate) induces an intense quasi-periodic force on the gate. Calling the gate thickness d and the projection into the flow b, the range of problem ratios was $\sim 2.5 \leq d/b \leq 4$. The paper treats cavitation effects on these loading forces.

With no cavitation the RMS values of the force remained constant for each configuration. However, the constant changed from one configuration to another. The higher values were associated with larger d/b ratio.

For cavitation flow velocities, the RMS values of force rise slowly and then drop with the formation of a vapor cavity behind the gate. The paper states that cavitation stabilizes the eddies produced and keeps them from breaking down for some d/b ratios, while it retards formation of periodic eddies for other configurations. Generally, cavitation reduces the magnitude of the fluctuating forces due to vortex shedding in the former instance, while increasing them in the latter. In addition, the effect of cavitation on the flow-induced forces acting on the gate is "strongly dependent upon the boundary geometry and the resulting flow pattern." Each case must be investigated separately for the effect of cavitation.

3. D. R. Miller, *Excitation of a Pure Tone by Flow Through an Orifice*, Proc. Conf. Flow-Induced Vib. Reactor System Components, ANL-7685 (1970), pp. 308-310.

Vortex rings may be shed periodically from the downstream side of an orifice. These vortices may excite acoustic resonances in a pipe. The characteristics of these jet tones and acoustic resonances are described. (Author's abstract)

4. C. B. Sharma and D. J. John, *Wind-Induced Oscillations of Circular Cylindrical Shells: An Experimental Investigation,* Department of Transport Technology, Loughborough University of Technology Report No. TT 7008 (July 1970)

Wind tunnel investigations of 12 models simulating smokestacks were made to determine relations between vortex shedding and excitation of cantilevered shell vibration modes. The observed critical flow velocities, less than given by a Strouhal number of 0.2, were associated with ovaling and breathing oscillations. Predicted natural frequencies were well correlated with those excited. Methods of suppressing the oscillations were discussed.

5. S. K. Bland, R H. Rhyne, and H. B. Pierce, *Study of Flow-Induced Vibrations of a Plate in Narrow Channel,* J. Engr. for Industry, Trans. ASME 89, 824 (1967)

The flow-induced vibrations of a two-degree of freedom flat plate (vertical translation and rotation about the leading edge) in a narrow air channel are investigated. The leading edge of the plate is rounded and the trailing edge is streamlined. Experiments showed that the flow rates (velocities) required to initiate oscillations (flutter) strongly depend upon channel width. A linear inviscid flutter theory analysis accounting for channel size correlated with experiment in some cases, while unconservative flutter speeds were predicted when the channel width was small in comparison to the plate length. Neglect of viscosity in the theory was suggested as the reason for the discrepancy. In the majority of the cases, the plates showed nonlinear behavior in that limited amplitude oscillations, sometimes at two different values, occurred over a wide range of flow rates.

6. H. N. Abramson, *Hydroelasticity: A Review of Hydrofoil Flutter,* Applied Mech. Reviews 22(2), 115-121 (Feb 1969)

The topical structure of this comprehensive review (87 references) is organized to make clear the differences between aeroelastic and hydroelastic flutter. Classical aeroelastic flutter methods have not been successful in predicting response for low solid to fluid mass ratios. The various modifications, refinements, and experiments directed toward developing a better theory are discussed under the categories: geometric parameters, finite-span hydrofoils, sweep hydrofoils, real fluid effects, cavitating hydrofoils, surface proximity effects, and hull motions. The author believes that flutter theory must account for the viscosity and circulatory contributions (real fluid effects) to the unsteady forces on the hydrofoil for an adequate theory. Such theories are still being developed and tested.

7. H. N. Abramson, *Hydrofoil Flutter: Some Recent Developments*, IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August 1972.

Reasons why aeroelasticity flutter methods predict nonconservative results, in comparison to experimental results, are discussed. Real fluid effects, involving both boundary layer and the wake, are suggested as the basic factors involved which are not included in aeroelasticity theories. Other factors include possible intermittent cavitation due to hydrofoil oscillation and the accompanying reduction in fluid damping (wetted surface). Approximate theories which account for some of these factors show promise in giving conservative flutter speed predictions. Flutter testing with models have given poor predictions. Simulation of flow conditions is thought to be the main problem. In addition, models are difficult and expensive to fabricate because of need to maintain mass ratio and static strength.

8. F. T. Dodge and A. F. Muller, *Viscous Flow-Induced Vibrations of a Flat Plate Suspended in a Narrow Channel*, AIAA Structural Dynamics and Aeroelasticity Specialists Conference, New Orleans, April 16-17, 1969.

Previous classical ideal fluid analyses of flow-induced vibrations of elastically restrained plates contained in flow channels accurately predicted the plate vibrations for wide channels but, not for narrow ones. It has been hypothesized that viscous stresses and other real fluid effects are the causes of this breakdown of the potential flow analysis. Consequently, in the analysis given here, a one-dimensional viscous flow theory is used to calculate the flow variables; friction factors and energy loss coefficients at channel area changes are computed on the basis of a steady velocity equal to the instantaneous value of the actual unsteady velocity. Results show that the critical velocity decreases as the channel height decreases; this agrees substantially with the previous classical theory, but not with experimental data. (Authors' abstract)

9. A. Powell, *On the Edgetone*, J. Acoust. Soc. Am. 33(4), 395-409 (1961)

The feedback mechanism of classical low-speed edgetones in which the action at the edge is interpreted as an acoustical source is developed in detail. A theoretical development indicating that the acoustic field is primarily due to the dipole associated with the fluctuating fluid force on the edge has been verified. It is the hydrodynamic field of the dipole which disturbs the jet, whose instability characteristics are shown to depend acutely on the Reynolds and Strouhal numbers, and the orifice-edge distance. The gain criterion is developed in detail, it being shown how the eigenfrequencies (which can form no algebraic sequence) arise; the lower limit to the orifice-edge distance is discussed, yielding an estimate of the "linear" instability of the stream. The amplitude of the established edgetone depends on the nonlinear behavior of large-amplitude stream disturbances, and the corresponding upper limit to the edge force proves to be in satisfactory agreement with measurements, thus yielding acceptable expressions for the sound pressure. Multiple tones and the circumstances of the hysteretic frequency jumps are discussed. The basic action depends only on Reynolds number for geometrically similar systems, while the sound power depends on the cube of the Mach number also. (Author's abstract)

10. L. F. East, *Aerodynamically Induced Resonance in Rectangular Cavities*, J. Sound Vib. 3(3), 277-287 (1966)

Experiments have shown that in deep rectangular cavities of large aspect ratios at low Mach numbers, oscillations of discrete frequencies can be produced. These oscillations are primarily of the fundamental acoustic depth mode, and the values of the non-dimensional quantity (fd/a) are in close agreement with a published theory. An additional shear layer resonance is inferred from the fact that the noise level reaches obvious maxima at certain Mach numbers, yielding two bands of Strouhal numbers, with a suggestion of a third. The similarity between this shear layer flow and that of edge tones is supported experimentally.

Thus the phenomenon of aerodynamically induced cavity resonance is considered to result from the simultaneous doubly tuned amplification of the shear layer unsteadiness by both the shear layer "edge tone" effect and the cavity enclosure acting as an acoustic resonator. (Author's abstract)

11. C. R. Gerlach, *Vortex Excitation of Metal Bellows*, J. Engr. Ind., Trans. ASME 94, 87-94 (1972)

The present paper extends the results presented in an earlier paper, and pertains to the prediction of vibratory amplitudes and stress levels resulting from flow-induced vibrations of metal bellows. Included is visual verification of the vortex shedding-bellows convolution coupling phenomena. Two methods for predicting flow excitation amplitudes are described. One method, called a "Stress Indicator" method is a simplification of the other, and allows rapid estimates of bellows dynamic stress values. This simplified method is complemented by a plot of "Stress Indicator" versus number of cycles to failure, obtained from experimental data for actual bellows failures. The influences of bellows damping and acoustical resonances are discussed. (Author's abstract)

12. C. R. Gerlach, *Flow-Induced Vibrations of Metal Bellows*, J. Engr. Ind., Trans. ASME 91, 1196-1202 (1969)

Results are given of an experimental and analytical study of longitudinal vibrations resulting from internal flow in metal bellows. It is shown that vortex shedding from the convolutions is the fluid excitation mechanism responsible for the vibrations. An N-degree-of-freedom spring-mass mechanical model is presented which is useful for predicting the bellows frequencies, and methods for estimating the fluid added mass for use in the model are discussed. Results of experiments designed to determine the vortex shedding forces are presented. An argument is given advocating the use of an effective vortex shedding force coefficient for excitation problems because of inaccuracies in experimentally obtained vortex amplitude and phase angle data. (Author's abstract)

13. N. Abramson et al., *Hydroelasticity with Special Reference to Hydrofoil Craft*, Naval Ship Research and Development Center, Washington, D. C. Report AD 682 946 (1967)

Report gives extensive development of current theory and bibliography.

14. *Hydrofoils,* Defense Documentation Center, Alexandria, Virginia, Report AD 737 300 (Feb 1972)

    Report is extensive abstract bibliography on hydrofoils.

15. E. Naudascher and F. A. Locher, *Flow-Induced Forces on Protruding Walls,* J. Hyd. Div., Proc. ASCE 100, 295-313 (1974)

    See Refs. 1 and 2.

III. PARALLEL FLOW-INDUCED VIBRATIONS OF SIMPLE STRUCTURES

A. External Flow

1. *Circular Cylinders*

1. D. Burgreen, J. J. Byrnes, and D. M. Benforado, *Vibration of Rods Induced by Water in Parallel Flow*, Trans. ASME 80(5), 991-1003 (1958)

   This is the first paper on parallel-flow-induced vibrations. An experiment was performed to determine the response of simulated fuel rods subjected to parallel water flow. The rod vibration was considered to be self-excited. Based on dimensional analysis, a correlation was proposed and the resulting equations give a good fit with the test data. The semi-empirical equation can serve as an aid in the design of fuel rods, but the proposed mechansim of excitation, self-excitation, is open to debate.

2. E. P. Quinn, *Vibration of Fuel Rods in Parallel Flow*, GEAP-4059 (July 1962)

   An experimental and theoretical investigation of parallel-flow-induced vibrations was presented. Lateral fuel rod vibration was determined experimentally to be a maximum of 0.2 mils displacement near 50 cps in a prototype element. An analytical model for a single rod in single phase flow was postulated on the basis that the mechanism was self-sustained oscillation.

3. E. P. Quinn, *Vibration of SEFOR Fuel Rods in Parallel Flow*, GEAP-4966 (September 1965)

   Tests were performed with a full-scale SEFOR fuel rod assembly to determine the rod vibration due to parallel flow.

4. M. P. Paidoussis, *The Amplitude of Fluid-Induced Vibration of Cylinders in Axial Flow*, AECL-2225, Chalk River, Ontario (1965)

   An empirical correlation for the vibration amplitude of cylindrical rods in axial flow was developed based on reported empirical observations made before 1965. This paper used an engineering approach which did not delve into the actual mechanisms of flow-induced vibrations.

5. M. P. Paidoussis, *Vibration of Flexible Cylinders with Supported Ends, Induced by Axial Flow*, Proc. Inst. Mech. Engrs. 180(Pt. 3J), 1-11 (1965)

   This paper is essentially a combination of References 4 and 6. The stability of a pinned-pinned rod was studied, and an empirical expression was given for the amplitude of subcritical vibration which was postulated to be excited by crossflow components of flow and other departures from steady, uniform, and perfectly axial flow.

6. M. P. Paidoussis, *Dynamics of Flexible Slender Cylinder in Axial Flow; Part I: Theory; Part 2: Experiment,* J. Fluid Mech. 26(Pt. 4), 717-751 (1966)

   In the first part of the paper, a linear equation of motion was derived for the small, free, lateral motions of a flexible cylindrical rod immersed in an axial flow; the added mass, viscous forces, and axial force were considered. Two approximate methods of analysis were used to study the stability. It was found that the rod may lose stability by buckling and flutter. In the second part of the paper, experiments were conducted with rubber cylinders in water flow. The conditions of instability were determined for pinned-pinned and clamped-free rods and compared with the theory. The observations were in fair agreement with the theory. The main contribution of this paper is the equation of motion which can be used for investigating the flow-induced vibrations of fuel rods. (See Ref. 27)

7. R. T. Pavlica and R. C. Marshall, *An Experimental Study of Fuel Assembly Vibrations Induced by Coolant Flow,* Nuclear Engineering and Design, 4, 54-60 (1966)

   Tests of a sixteen-rod assembly in a water loop were described. The amplitude data agreed well with predictions based on Paidoussis' formula (Ref. 4). But the responses in this loop were much smaller than those in Burgreen's experiments (Ref. 1).

8. Y. Takada and T. Egusa, *Vibration of the Fuel Assembly of a Marine Reactor,* Nuclear Engineering and Design, 7, 578-584 (1968)

   A full size model of the fuel assembly of a light water ship propulsion reactor was tested on a vibration test machine. The results were used in the design for avoiding the ship-full-motion-induced vibration. An analytical study was also made to calculate the frequency.

9. M. W. Wambsganss, Jr. and B. L. Boers, *Parallel-Flow-Induced Vibration of a Cylindrical Rod,* Paper No. 68-WA/NE-15.

   The fundamental aspects of the flow-induced vibration of reactor core components were studied with an integrated theoretical-experimental investigation of the parallel-flow-induced vibration of a cylindrical rod. The problem was treated as a random vibration problem. Flow tests were performed and the spectral density functions and RMS values of the responses were presented as functions of mean flow velocity. Initiating an integrated theoretical-experimental study in a systematic way and recognizing the importance of other system design parameters are the important contributions of this study.

10. M. P. Paidoussis, *Stability of Towed, Totally Submerged Flexible Cylinders*, J. Fluid Mech. 34(Pt. 2), 273-287 (1968)

    A general theory is presented to account for the small, free, lateral motions of a flexible, slender, cylindrical body with tapered ends, totally submerged in liquid and towed at steady speed V. It is shown that the system is subjected to both buckling and flutter, and that for maximum stability the system must have: (a) a streamlined nose, (b) a blunt tail, (c) a fairly slender cylinder, and (d) a short tow-rope. Some experiments are conducted with rubber cylinders in a water loop, and observations are generally in qualitative agreement with theory.

11. A. K. Addae and H. Fenech, *Experimental Determination and Analysis of Vibrations Induced by Flow Noise in Tubes*, Trans. ANS 10, 651 (1968)

    This paper describes an experiment which suggests that boundary-layer turbulence is adequate in accounting for the observed response, provided the near-field effect and the far-field effect associated with boundary-layer turbulence are duly accounted for. The measured RMS response was found to be in good agreement with the prediction by Reavis' expression (Ref. 14).

12. D. Basile, J. Faure, and E. Ohlmer, *Experimental Study on the Vibration of Various Fuel Rod Models in Parallel Flow*, Nuclear Engineering and Design 7, 517-534 (1968)

    The vibrations of a single rod in parallel flow were investigated in air and in water. The test data were compared with other experimental data. The effects of flow asymmetry, pumps, and grids were also reported. From the results, it can be realized that the technical parameters in parallel-flow-induced vibration of fuel rods are not clearly identified.

13. M. P. Paidoussis, *An Experimental Study of Vibration of Flexible Cylinders Induced by Nominally Axial Flow*, Nucl. Sci. & Eng 35, 127-138 (1969)

    Experiments for parallel-flow-induced vibration were performed for three cases: (1) single cylinders in normal flow conditions; (2) single cylinders in flows with strong disturbances; and (3) a bundle of cylinders. Based on the test data, a previously derived empirical expression for vibration amplitude (Ref. 4) was revised. In the rod bundles, it was found that the vibration amplitude is high at low flow velocities, and there is very little increase in vibration with flow.

14. J. R. Reavis, *Vibration Correlation for Maximum Fuel-Element Displacement in Parallel Turbulent Flow*, Nuclear Science and Engineering 38, 63-69 (1969)

    The response of a hinged-hinged beam to turbulent boundary-layer-pressure fluctuations was calculated using a one mode approximation. The theoretical RMS displacement was found to be much lower than the existing experimental data; therefore, a coefficient was introduced to correlate the experimental data with the theory.

15. D. J. Gorman, *The Role of Turbulence in the Vibration of Reactor Fuel Elements in Liquid Flow*, Atomic Energy of Canada Report AECL-3371 (1969)

An experimental and theoretical investigation of the fuel rod vibration induced by the turbulent-boundary-layer pressure fluctuations was reported. The analysis is similar to that of Reavis (Ref. 14) except for the forcing function which was obtained from the tests. Although fairly good agreement between experiment and theory was achieved, the cross-correlation is contrary to that obtained by other experimenters. It was suggested that in the test section, the acoustic pressure is uniform and of no significance with respect to structural vibration. In the reactor channels, the acoustic pressure is not necessarily uniform and is a possible excitation mechanism.

16. R. M. Kanazawa, *Hydroelastic Vibration of Rods in Parallel Flow*, Ph D Thesis, University of Illinois, Urbana (1969)

A cylindrical rod excited by parallel flow is studied theoretically and experimentally. The analysis is based on a mathematical model for the rod subjected to a random pressure field. An empirical expression for the RMS rod displacement is presented.

17. C. R. Ortloff and J. Ives, *On the Dynamic Motion of a Thin Flexible Cylinder in a Viscous Stream*, J. Fluid Mech. 38, 713-720 (1969)

The stability and response of a flexible cylinder with zero bending rigidity set in a viscous stream are examined. It is found that a cylinder fixed at the upstream end and free at the downstream end is always unstable, and the displacement increases without bound as time is increased. This is a mathematical paper containing no significant physical insight.

18. K. Namatame, *Theoretical Analysis of Fuel Rod Vibration Induced by Parallel Coolant Flow*, J. Atomic Energy Soc. (Japan) 11, 63-69 (1969)

The response of a cylindrical rod to turbulent pressure fluctuations was obtained. The model for the pressure field used in this paper is questionable.

19. G. P. Cali, P. Grillo, and G. Testa, *Fuel Rod and Bundle Vibrations Induced by Coolant*, Trans. ANS 13(1), 333-334 (1970)

The two-phase flow-induced vibration of a sixteen-rod bundle was investigated experimentally. It was concluded that steam quality does not seem to have any remarkable influence on rod vibration amplitude. This is contrary to that of Gorman's experiment (Ref. 30).

20. A. K. Addae and H. Fenech, *Experimental Determination and Analysis of Vibrations Induced by the Near-Field Flow Noise in Tubes*, Proc. Conf. on Flow-Induced Vibrations in Reactor System Components, ANL-7685 (1970), pp. 32-46.

The response of a tube conveying fluid, which is taken as the model of a rod subjected to parallel flow, is determined experimentally. The measured RMS response is found to be of the same order of magnitude as the RMS response predicted by the boundary-layer turbulence wall pressure correlation. However, the maximum amplitude predicted by Paidoussis' empirical correlation (Ref. 4) is a factor of 4 to 15 times greater than the measured RMS response. This paper points out the significance of the far-field noise.

21. R. M. Kanazawa and A. P. Boresi, *Calculation of the Response of Rods to Boundary-Layer Pressure Fluctuations*, Proc. Conf. on Flow-Induced Vibrations in Reactor System Components, ANL-7685 (1970), pp. 47-63.

The Bernoulli-Euler beam theory and random pressure field on flat plates were used for calculating the RMS response of cylindrical rods.

22. Y. N. Chen, *Turbulence-Induced Instability of Fuel Rods in Parallel Flow*, Sulzer Technical Review (Switzerland), 72-84 (1970)

A theory is given for the tube-bundle subjected to an axial flow. The tubes are postulated to be excited by the pulsating components of turbulence. Although the theory shows good agreement with the experimental results by using a correction factor, the proposed mechanism of excitation is open to doubt.

23. Y. N. Chen, *Flow-Induced Vibrations in Tube Bundle Heat Exchangers With Cross and Parallel Flow*, Part 1, Parallel Flow, Proc. Flow-Induced Vibration in Heat Exchangers (ASME, 1970), pp. 57-66.

This paper summarizes the results given in Ref. 22, and simplifies the original theory.

24. J. Kadlec and K. D. Appelt, *Flow-Induced Rod Vibrations of Fast Reactor Subassemblies*, Nuclear Engineering and Design 14, 136-150 (1970)

An integrated theoretical-experimental approach (Ref. 9) was used to study the flow-induced vibration of fuel pins of fast reactor subassembly. The procedure used includes analytical and experimental verification of normal modes, experimental investigation of resonance curves, experimental determination of spectral density functions of the strain, and calculation of the spectral density function of bending strain and displacement for locations on the pin where peaks in the spectral density function are expected. This study concerned multi-span rods. A one-mode approximation was suggested as a good approximation, which is contrary to what one could expect.

25. S. A. Knudson and G. M. Smith, *Dynamic Response of Slender Tubes in Parallel Flow When Subjected to Time varying Boundary Conditions,* Proc. Conf. on Flow-Induced Vibrations in Reactor System Components, ANL-7685 (1970), pp. 64-90.

The response of slender rods in parallel flow with induced motion of the rod support structure were investigated. The experimental data show that in the case of a clamped-free rod, the parallel flow velocity appears to have a significant damping effect on rod vibrations; and in the case of clamped-pinned rod, the damping mechanism is essentially independent of the flow velocity. Theoretical studies of several damping models reveal that the response of support excited rods in parallel flow corresponds quite closely to a viscous type damping model.

26. S. A. Knudson and G. M. Smith, *Vibration of Supported Excited Tubes in Coaxial Flow,* J. Eng. Mech. Div., Am. Soc. Civil Eng. 97(EM6), 1039-1060 (1970)

See Ref. 25.

27. S. S. Chen and M. W. Wambsganss, *Response of a Flexible Rod to Near-Field Flow Noise,* Proc. Conf. on Flow-Induced Vibrations in Reactor System Components, ANL-7685 (1970), pp. 5-31.

An analytical solution is obtained for the displacement statistics of a simply-supported rod in parallel flow. The derived model is successful in predicting the basic trends and essential features of parallel-flow-induced vibration. Numerical examples are given for comparison with the experimental measurements. A parameter study is also made for the ranges associated with typical reactor components. The study shows theoretical predictions and experimental correlations to be in good agreement.

28. S. S. Chen, *Discussion on the Paper "Vibration of Support Excited Tubes in Coaxial Flow" by S. A. Knudson and G. M. Smith,* J. Eng. Mech. Div., Am. Soc. Civil Eng 98(EM5), 1579-1582 (1971)

The damping mechanisms of cylindrical rods subjected to parallel flow were discussed. The mathematical model predicts the correct trend of the damping on flow velocity, and the results verify the experimental data presented in Ref. 26.

29. J. Kadlec and E. Ohlmer, *On the Reproducibility of the Parallel-Flow-Induced Vibration of Fuel Pins,* Nuclear Engineering and Design 17, 355-360 (1971)

A bundle of 37 pins was tested in Karlsruhe and Ispra water loops for the purpose of understanding the influence of the test loop on parallel-flow-induced vibration of fuel pins. The experiments were performed in the test sections of flow loops with several modifications. It was observed that in different experimental arrangements, the ratio of maximum to minimum value of the measured pressure was approximately 10, while comparatively moderate scatter (50%) of the vibration magnitude and a slight variation in the characteristics of the vibration response were observed.

30. D. J. Gorman, *An Analytical and Experimental Investigation of the Vibration of Cylindrical Reactor Fuel Elements in Two-Phase Parallel Flow*, Nuclear Science and Engineering 44, 277-280 (1971)

An experimental-theoretical approach (Ref. 15) was used to study the response of a single fuel element subjected to two-phase (water/air) parallel flow in a circular annulus. Statistical properties of the pressure fluctuations were taken with highly sensitive differential pressure transducers mounted on diametrally opposite points on the wall of test section. These pressure data were used as forcing functions in the analytical model for predictions of vibration amplitude. Good agreement was found between the theoretical results and experimental data. It was shown that (a) a high peripheral correlation of the driving force is primarily responsible for the larger vibrations encountered in two-phase flow; (b) the longitudinal spectral correlation rises rapidly with quality to reach a first peak at 12% simulated quality; and (c) the RMS displacement also rises rapidly and peaks at a simulated quality of 12%. This paper is the most extensive study on two-phase flow-induced vibrations.

31. S. S. Chen and M. W. Wambsganss, *Parallel-Flow-Induced Vibration of Fuel Rods*, Nuclear Engineering and Design 18, 253-278 (1972)

A mathematical model is proposed to describe the phenomena of parallel-flow-induced vibrations of a flexible rod, and a solution is obtained for a rod with arbitrary end conditions; the solution can be used for fixed, hinged, cantilevered, and other elastically supported end conditions.

Comparisons between model predictions and flow-test data for rods with fixed and cantilevered end conditions show that the model successfully predicts the essential features of the system behavior: (1) the adjacent rods and duct wall may considerably increase the added mass; (2) the fundamental frequency may increase or decrease with flow velocity, depending on the end conditions; (3) the system damping increases with increasing flow velocity, and is attributed to the normal drag force and the Coriolis acceleration; (4) the RMS rod response increases with flow velocity and follows an approximate power function relationship; and (5) the increase in rigidity at the ends tends to reduce the RMS response.

B. Internal Flow

1. *Straight Tubes*

1. H. Ashley and G. Haviland, *Bending Vibrations of a Pipe Line Containing Flowing Fluid,* J. Appl. Mech., Trans. ASME 72, 229-232 (1950)

   This is the first theoretical investigation into the phenomenon of transverse vibrations of pipes conveying fluid. Both free and forced vibrations were studied. Since the derived equation of motion is incorrect, the conclusions drawn from this study are also wrong.

2. G. W. Housner, *Bending Vibrations of a Pipe Line Containing Flowing Fluid,* J. Appl. Mech. 19, 205-208 (1952)

   The equation of motion for a fluid-conveying pipe was derived utilizing Hamilton's principle. The natural frequency and the steady-state response of a simply-supported pipe were studied by an approximate method. It was found that when the flow velocity reaches a certain value, the pipe is subjected to buckling-type instability. This paper corrected the errors in Ref. 1; however, as Benjamin (Ref. 7) pointed out, Hamilton's principle used in this paper is valid for conservative systems only.

3. F. Z. N. Niordson, *Vibrations of a Cylindrical Tube Containing Flowing Fluid,* Trans. of the Royal Institute of Technology, Stockholm 73 (1953)

   The free vibration of a fluid-conveying tube was investigated analytically using a shell theory and potential flow theory. The detailed analysis was carried out for beam-mode motions. The effect of fluid compressibility was taken into account.

4. R. H. Long, Jr., *Experimental and Theoretical Study of Transverse Vibration of a Tube Containing Flowing Fluid,* J. Appl. Mech. 22, 65-68 (1955)

   The free transverse vibrations for the fundamental mode of a single-span tube containing a flowing fluid were investigated analytically and experimentally for several end conditions. The experimental results agree reasonably well with approximate power series solutions. For small flow velocities, the simply-supported tube performs free oscillations, while the fixed-free tube performs damped oscillations.

5. G. H. Handelman, *A Note on the Transverse Vibration of a Tube Containing Flowing Fluid,* Quart. Appl. Math. 13, 326-330 (1955)

   A perturbation technique was employed to study the characteristics of a tube conveying fluid for various support conditions. The results obtained for small flow velocities and large flow velocities agree qualitatively with those obtained by other methods.

6. G. Heinrich, *Vibrations of Tubes With Flow*, Zeitschrift für Angewandte Mathematik und Mechanik 36, 417-429 (1956)

   The paper deals with small transverse vibrations of cylindrical tubes through which a liquid is flowing. The wave propagation - which is anisotropic - is studied in detail for a non-dispersive system in the form of a "string with flow." For dealing with the free oscillations of such a system fixed at two points, a graphic as well as an analytic method is given. (From Author's summary)

7. T. B. Benjamin, *Dynamics of a System of Articulated Pipes Conveying Fluid: I. Theory; II. Experiment*, Proceedings of the Royal Society, London 261 (Series A), 457-499 (1961)

   This paper presented a theoretical and experimental study of the dynamics of a chain of fluid-conveying rigid pipes. Hamilton's principle was derived to account for the energy flux which is very important in nonconservative systems. Two types of instability were recognized: buckling and flutter (Benjamin was the first to report on the phenomenon of flutter instability). An experiment was conducted with water and air, and the results stand to confirm the theoretical formulae. This excellent paper gives a very clear description of the fluid-pipe interaction characteristics and will be interesting to those considering the fluid-pipe problems.

8. T. Li and D. D. DiMaggio, *Vibration of a Propellant Line Containing Flowing Fluid*, AIAA Fifth Annual Structures and Materials Conference CP-8: Am. Inst. Aeron. Astronaut., 194-199 (April 1964)

   The natural frequency of a simply-supported pipe conveying fluid was studied analytically. The frequency equation, the determinate of a fourth-order system of equations, is reduced to the third-order by a simple transformation, and the latter is further simplified to a transcendental equation which can be expressed as a power series. Numerical results agree well with the experimental data of Long (Ref. 4).

9. H. L. Dodds and H. L. Runyan, *Effect of High-Velocity Fluid Flow on the Bending Vibrations and Static Divergence of a Simply Supported Pipe*, NASA-TN-D-2870 (1965)

   Two pipes, constructed of aluminum alloy and conveying water, were tested to study the effect of fluid velocity on the fundamental bending frequency, and to determine the critical flow velocity. The results are in good agreement with the theory. This is the first experimental investigation involving high flow velocities.

10. S. Nemat-Nasser, S. N. Prasau, and G. Herrmann, *Destabilizing Effect of Velocity-Dependent Forces in Nonconservative Continuous Systems*, AIAA J. 4(7), 1276-1280 (1966)

    A cantilevered pipe conveying fluid was studied analytically. It was shown that the Coriolis force, and internal and external damping may have a destabilizing effect. It is also demonstrated that the Galerkin method with a two-term approximation may lead to erroneous results for the critical flow velocities.

11. R. W. Gregory and M. P. Paidoussis, *Unstable Oscillation of Tubular Cantilevers Conveying Fluid: I. Theory and II. Experiments*, Proceedings of the Royal Society, London 293(Series A), 512-542 (1966)

    A theoretical and experimental study of the unstable oscillation of a cantilevered tube conveying fluid was presented. The stability curve was constructed by finding solutions to the equations of motion using an exact method and an approximate method. It was shown that both internal and external damping may destabilize the system. Experiments were conducted mainly with rubber tubes conveying water or air and with metal tubes conveying oil. The experiments appear to confirm the predictions of the analysis.

12. G. Herrmann and S. Nemat-Nasser, *Instability Modes of Cantilevered Bars Induced by Fluid Flow Through Attached Pipes*, Int. J. Solids Structures 3, 39-52 (1967)

    A cantilevered bar of uniform cross section with flexible pipes conveying fluid attached to it is considered. For certain cross sections of the bar stability may be lost by either torsional divergence or torsional flutter, depending upon the location of the pipes with respect to the center of gravity of the cross section. In addition, transverse flutter can also occur. This paper is of academic interest.

13. A. S. Greenwald and J. Dugundji, *Static and Dynamic Instabilities of a Propellant Line*, AFOSR 67-1395 (May 1967)

    The stability of tubes with clamped-free and clamped-hinged ends was studied analytically and experimentally. Reasonably good agreement was found between the experimental flutter and divergence phenomena, and the theory.

14. S. Naguleswaran and C. J. H. Williams, *Lateral Vibration of a Pipe Conveying a Fluid*, Journal Mechanical Engineering Science 10(3), 228-238 (1968)

    The transverse vibration of pipes conveying fluid was studied theoretically and experimentally. An exact solution for the natural frequency and axial phase distribution for various end conditions was found. Several approximate solutions (Galerkin, Rayleigh-Ritz, and Fourier Series) were obtained and compared with the exact solution. Tests with a neoprene pipe conveying water were conducted; the results are in good agreement with the theory at low flow velocities but show considerable deviation from the theory at high flow velocities. This paper presents a clear description of the phenomena.

15. A. L. Thurman and C. M. Mote, *Nonlinear Oscillation of a Cylinder Containing a Flowing Fluid*, Trans. ASME 81, 1147-1155 (1969)

The fundamental and second periods of transverse oscillation of a cylinder containing a flowing fluid are analytically determined for the approximate solution of two, coupled, nonlinear partial differential equations describing the transverse and longitudinal motions.

16. P. Srinivasan and V. Lakshminarayanan, *Vibration of Pipe Carrying Flowing Fluid*, Transportation Engineering Journal, ASCE 96(TE2), 165-174 (1970)

Two approximate methods (Dunkerley's method and Ritz's method) to find the natural frequencies of a pipe conveying fluid were described. Long's (Ref. 4) data were used to provide justification for the proposed procedures. Despite the authors' claims, both methods are no more simpler to use than methods proposed by other investigators.

17. J. L. Hill and C. P. Swanson, *Effects of Lumped Masses on the Stability of Fluid Conveying Tubes*, J. Appl. Mech. 37, 494-497 (1970)

The effects of adding lumped masses to fluid conveying tubes were studied. The lumped masses, in general, destabilize the system, and in some particular cases, stabilize the system.

18. J. M. Clinch, *Prediction and Measurement of the Vibrations Induced In Thin-Walled Pipes by the Passage of Internal Turbulent Water Flow*, J. Sound and Vibration 12(4), 429-651 (1970)

A theoretical analysis based on the application of random vibration theory was developed for predicting the response of thin-walled pipes to the turbulent wall pressure field at high mode orders and frequencies. Measurements of the vibrational response of a thin-walled pipe were made in narrow frequency bands. The results obtained showed good agreement with the predicted values of the response over a wide range of flow speeds and frequencies. The proposed method can be applied to high frequencies only.

19. J. M. Diaz and R. K. Jain, *Vibration Analysis of Pump Discharge Lines*, J. Hydraulics Division, ASCE 96(HY11), 2279-2296 (1970)

A method is described for designing pump discharge lines to avoid detrimental vibrations induced by pump pulsations. This paper also describes practical design problems.

20. S. S. Chen, *Forced Vibration of a Cantilevered Tube Conveying Fluid,* J. Acoustical Society of America 48(3), 773-775 (1970)

The problem of the forced vibration of a cantilevered tube conveying fluid is solved for time-dependent loading and arbitrary initial conditions. The solution is obtained by making use of the properties of the linear operator and its adjoint operator intrinsic to the governing differential equation of motion and boundary conditions.

21. R. A. Stein and M. W. Tobriner, *Vibration of Pipes Containing Flowing Fluids,* ASME Paper No. 70-APM-SSS.

The propagation of flexural waves in an infinite tube conveying fluid and supported by an elastic foundation was considered. The effects of foundation modulus, flow velocity, and internal pressure on the dynamic stability, frequency response, and wave-propagation characteristics were discussed. The main contributions of this paper are the deviation of the pressure term and the interpretation of the wave-propagation phenomenon.

22. M. P. Paidoussis, *Dynamics of Tubular Cantilevers Conveying Fluid,* J. Mechanical Engineering Science 12(2), 85-103 (1970)

A cantilevered tube conveying fluid was reconsidered, with the objective to study Benjamin's paradox: Buckling is possible in case of vertically hanging articulated cantilevers conveying water; yet buckling does not occur if the fluid is air (Ref. 7). In this paper, it was found that buckling instability is not possible at all in the case of continuous hanging cantilevers. Qualitative and quantitative agreement between theory and experiment was satisfactorily good.

23. M. P. Paidoussis and E. B. Deksnis, *Articulated Models of Cantilevers Conveying Fluid: The Study of a Paradox,* J. Mechanical Engineering Science 12(4), 288-300 (1970)

The paradox (Ref. 22) was studied analytically and experimentally. It was found that the higher modes of the articulated model, no matter how large the number of degrees of freedom, do not model closely the corresponding modes of the continuous system; moreover, the disagreement becomes exaggerated with flow. As buckling is associated with the higher modes of the articulated system, it is not possible to model the higher modes of the continuous system by the articulated system. This paper is of academic interest.

24. L. H. Jones and B. E. Goodwin, *The Transverse Vibrations of a Pipe Containing Flowing Fluid: Methods of Integral Equations,* Quart. Applied Mathematics matics 29, 363-374 (1971)

An integral equation method was discussed and applied to the vibration of a simply-supported pipe conveying fluid. Approximate solutions were obtained for low and high flow velocities. This paper is mathematical and does not give additional insight into the physics.

25. A. Kornecki, *On Application of Galerkin's Method to Non-Self-Adjoint Equations*, Israel Journal of Technology 9, 189-194 (1971)

This note demonstrates that Galerkin's method can be applied successfully to a typical non-conservative system, a cantilevered tube conveying fluid, but one must always examine the rate of convergence. This analysis confirms earlier conclusion in Ref. 10.

26. S. S. Chen and G. S. Rosenberg, *Vibration and Stability of a Tube Conveying Fluid*, ANL-7762 (March 1971)

This report analyzes the free vibration, forced vibration, and parametric response of a simply supported tube conveying fluid; the effects of initial curvature and Coriolis force are included and evaluated.

27. S. S. Chen, *Flow-Induced Instability of an Elastic Tube*, Paper 71-Vibr-39 presented at the ASME Vibrations Conference, Toronto, Canada, September 8-10, 1971.

A fluid conveying tube, clamped at the upstream end and supported by a displacement spring at the other, is studied theoretically. It is shown that when the flow velocity exceeds a certain value, depending on the spring constant, the tube becomes subject to flutter-type instability, buckling-type instability, or both, with multiple stable and unstable ranges of flow velocity. The conditions of stability are calculated, and unstabilized regions are constructed. One of the interesting features of this system is that the spring may have a destabilizing effect on the tube for certain ranges of parameters.

28. S. S. Chen, *Dynamic Stability of Tube Conveying Fluid*, J. of the Engineering Mechanics Division, ASCE 97(EM5), 1469-1485 (1971)

The parametric resonance of a simply supported tube is studied analytically. By employing Galerkin's method, the equation of motion is reduced to a system of coupled Mathieu-Hill-type equations with multiharmonic coefficients. The stability-instability region boundaries are constructed by the methods of Hsu and Bolotin. The results obtained by Hsu's first approximation show that combination resonance is possible and that the coupling terms do not influence the principal and second instability regions. The higher order approximation is obtained by Bolotin's method, which shows that the effect of the coupling terms is to lower, in frequency, the instability regions; they have no effect on the size of the instability regions.

29. S. S. Chen, *Vibrations of Continuous Pipes Conveying Fluid*, Presented at the International Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper No. G-1, August 1972.

This paper presented a theoretical investigation of the transverse vibrations of continuous pipes conveying fluid. A general dynamic three-moment equation is derived, including the effects of fluid forces and axial force. The three-moment equation is then used to study the free waves and the response to harmonic pressure in a periodically supported pipe. Finally, the free and forced vibrations of multiple span pipes are analyzed; the effects of various parameters on natural frequencies are studied.

30. D. S. Weaver and T. E. Unny, *On the Dynamic Stability of Fluid-Conveying Pipes*, ASME Paper 72-WA/APM-7 (1972)

The shell mode and beam mode instabilities of a finite length, fluid-conveying pipe were studied using the Flugge-Kemper equation and potential flow theory. The critical flow velocities for short, thin shells are associated with a number of circumferential waves. This number reduces for thicker and longer shells until the instability is in a beam mode.

31. M. P. Paidoussis and J. P. Denise, *Flutter of Thin Cylindrical Shells Conveying Fluid*, J. Sound and Vibration 20(1), 9-26 (1972)

The existence of flutter-type instabilities of circular cylindrical shells conveying fluid was demonstrated experimentally and established theoretically, and the conditions of stability are determined for some possible physical systems. Theory and experiment are in fair agreement.

32. A. A. Lakis and M. P. Paidoussis, *Prediction of the Response of a Cylindrical Shell to Arbitrary or Boundary-Layer-Induced Random Pressure Fields*, J. Sound and Vibration 25(1), 1-27 (1972)

A general theory is presented for the response, to an arbitrary random pressure field, of a uniform or axially-non-uniform thin cylindrical shell. The theory is then specialized to the case where the pressure field originates from the turbulent boundary layer of a subsonic internal flow.

The basic formulation of the dynamical problem is in terms of a hybrid classical/finite element theory in which the finite elements are cylindrical frusta and the displacement functions are determined from the shell equations; the pressure forces are lumped at the nodes of the finite elements.

The cross-correlation spectral density and the mean square value of the displacements of the shell are obtained for an arbitrary pressure field and for a boundary-layer pressure field. Some calculations of the latter case are conducted to illustrate the theory. In one case the theory is compared with experiment, and agreement is found to be quite good.

33. S. S. Chen and G. S. Rosenberg, *Free Vibrations of Fluid-Conveying Cylindrical Shells* (To be presented at the 1973 ASME Vibrations Conference)

This paper treats the free vibrations of cylindrical shells conveying fluid. The shell motion is described by the Flugge's equations, whereas the hydrodynamic forces are described by the linearized potential flow theory. Frequency spectra are presented for symmetric and asymmetric modes, and the effect of flow velocity and other parameters are discussed. In the low frequency range, a modified water hammer theory and an approximate bending frequency equation, including the effect of the flowing fluid, are developed.

2. *Curved Tubes*

1. T. E. Unny, E. L. Martin, and R. N. Dukey, *Hydroelastic Instability of Uniformly Curved Pipe-Fluid Systems*, J. Appl. Mech. 37, 817-822 (1970)

   The instability of uniformly curved pipes conveying fluid with clamped-clamped and hinged-hinged ends was considered. Since the derived equation of motion is erroneous, the conclusions are also not valid.

2. S. S. Chen, *Vibration and Stability of a Uniformly Curved Tube Conveying Fluid*, J. Acoustical Society of America 51(1), 223-232 (1972)

   This paper presents a theoretical study of the vibration and stability of a uniformly curved tube containing flowing fluid. The assumption of the inextensibility of the tube is applied to derive the equation of motion. A solution for the natural frequency is obtained and numerical results are presented. The effects of flow velocity, fluid pressure, and the Coriolis force on the natural frequency are discussed. It is shown that when the flow velocity and fluid pressure exceed a certain value, the tube becomes subject to buckling-type instability. Critical loads in terms of the flow velocity and fluid pressure are presented for fixed-fixed, hinged-hinged, and fixed-hinged end conditions.

3. S. S. Chen, *Flow-Induced In-Plane Instabilities of Curved Pipes*, Nuclear Engineering and Design 23, 29-38 (1972)

   The equation of motion of curved pipes conveying fluid is derived from Hamilton's principle. Depending on the end conditions, the system may be conservative. It is shown that when the flow velocity exceeds a certain value, the conservative system becomes subject to buckling-type instability and the nonconservative system becomes subject to fluttering-type and buckling-type instabilities. The critical flow velocity at which the pipe loses stability is computed for four end conditions.

4. S. S. Chen, *Out-of-Plane Vibration and Stability of Curved Tubes Conveying Fluid*, ASME Paper No. 72-WA/APM-36 (To appear in Journal of Applied Mechanics)

   A general theory is presented to account for the out-of-plane motion of uniformly curved tubes containing flowing fluid. The systems are grouped as conservative and nonconservative according to the support conditions. A general solution for the natural frequency is obtained and numerical results are presented. The effects of the flow velocity and Coriolis force on the natural frequency are discussed. It is shown that when the flow velocity exceeds a certain value, the tube becomes subject to the buckling-type instability for conservative cases and the fluttering-type instability for nonconservative cases. In the subcritical range of flow velocity, the conservative system performs free oscillations, while the nonconservative system performs damped oscillations.

IV. REACTOR SYSTEM ASSEMBLY VIBRATIONS

A. Reactor Vessel Components

1. C. Lesueur, D. Milan, and G. Payan, *Study of Random Vibrations of Hydrodynamic Origin in Certain Structures of the Phenix Reactor Block,* Nuc. Eng. Design 18, 279-303 (1972)

Random analysis methods for calculation of reactor shell response to random pressure fluctuations in the boundary layer are illustrated. Several representations of the pressure fluctuation field are compared to data from 1/10 and 1/5 reactor component scale models. The shells considered are very thin, thickness/radius ∿ 0.003, the natural frequencies low, 0.1 - 5.0 Hz, and the flow velocities small, 1 ft/sec. Methods of accurately computing effective masses are referenced. Damping calculated by assuming laminar flow was in error by a factor of 10 from the damping ratio measured (16%), which seemed very high. Forced response calculations are shown to well represent the response measured in an experiment where a thin cylinder was subjected to axisymmetric jets.

Fluid damping is considered very difficult to simulate or calculate, and is found to be flow rate dependent. Calculation of an upper bound on response based on a pressure PSD is claimed possible. References are given. Pressure data from a 1/4-scale model, constructed in Reech-Froude similarity, are used to predict the response for Phenix Reactor primary and secondary vessels.

2. E. O. Hooker, *Design of Reactor Internals and Incore Instrument Nozzles for Flow-Induced Vibration,* Babcock & Wilcox Topical Report BAW-10051 (Sept 1972)

The redesigned reactor internals and incore instrument nozzles have been analyzed for operational, flow-induced loadings. The results of the analyses show that the reactor internals and incore instrument nozzles are structurally adequate for long-term operation. (Author's abstract)

Bases for design criteria are discussed in BAW-10050 (see Ref. 3). Each critical compon is analyzed. Where applicable, structural natural frequencies are separated from vortex shedding frequencies by a factor of 3, vibratory stresses due to flow-induced vibrations are specified to be less than endurance limit of material, and all components must meet ASME code requirements for normal operating conditions. In some instances (thermal shield) maximum displacements were assumed when forcing functions could not be approximated.

3. *Evaluation of Oconee Reactor Component Failure,* Babcock & Wilcox Topical Report BAW-10050 (Sept 1972)

An investigation was conducted to evaluate the failure of several Oconee 1 reactor components during hot functional tests in early 1972. The investigation intends: (1) To supplement the Reactor Coolant System Incident Report, (2) To describe B&W's evaluation of the damage, (3) To present the results of this evaluation, and (4) To set forth the criteria for redesigning the failed components.

Failures were due primarily to hydraulically induced forces and each component's failure was independent of others.

4. D. E. Thoren and R. J. Harris, *Prototype Vibration Measurement Program for Reactor Internals - 177-Fuel-Assembly Plant,* Babcock & Wilcox Topical Report BAW-10038 (Sept 1972)

   In accordance with Safety Guide 20, B&W has developed a vibration measurement program to be used at the Oconee 1 reactor site. This report describes the details of the program and the plans for recording and analyzing the required data. (Authors' abstract)

   A limited number of accelerometers, strain gauges, and pressure transducers are proposed to monitor critical components. Types of instrumentation and location are described. Predictions previously made (BAW-10051), assuming estimates of fluid forcing functions, will be compared to measurements from strain gauges and accelerometers. Previously estimated vibration levels, which served as a basis for design, will be compared to actual measurements, also. No indication is given as to what use will be made of the pressure measurements.

5. G. J. Bohm, *Natural Vibration of Reactor Internals,* Nucl. Sci. Eng. 22, 143-152 (1965)

   The transfer matrix method is used to determine the eigenvalues and eigenfunctions needed to obtain the response of nuclear power reactor internals to dynamic excitations. Transfer matrices and delta matrices are developed for a particular closed-cycle pressurized-water-reactor (PWR) configuration. Two cases are studied: (1) where the internals are rigidly supported near the bottom by the vessel walls; and (2) where the vessel elastically supports the internals requiring that the combined structure be analyzed. The analysis takes into consideration structures with different cross sections and masses that are connected in series and/or parallel. Results obtained with a digital computer are shown.

   The method and the results obtained in this paper can be used for a complete reactor dynamical analysis of most PWR internals, since their structures are similar in design. (Author's abstract)

   Components are idealized as equivalent beams. No comparison to experimental results are made.

6. D. Haensel, *Vibration Measurements in a 3-Loop PWR-Instrumentation, Analysis, Results,* Advances in Instrumentation 26(Part 2), Instrument Society of America Annual Conference, 1971, p. 624; Also, ISA Trans. 11, 299-303 (1972)

   Vibration measurements of reactor vessel and reactor internal components were carried out at a typical 3-loop PWR. The instrumentation and the data acquisition system are described briefly. An outline of the data reduction and analysis methods used is given. The description of two particular vibration sources, flow induced vibration of guide tubes and forced excitation of the structure caused by pump generated pressure pulsations, concludes the discussion of results. (Author's abstract)

   The flow-induced vibrations magnitude and bandwidth of response are associated with the energy content of eddies, the size of the components, and therefore the Reynolds number and the geometry of the flow path.

7. A. W. Graves and C. R. Davidson, *Elementary Rod Vibration Measurements in a Hexagonal Array of 19 Wire Wrapped Fuel Rods with Parallel Flow*, Advances in Instrumentation 26(Part 2), Instrument Society of America Annual Conference, 1971, p. 625.

A 19-rod assembly was instrumented in an elementary fashion and tested for flow induced vibration at 17 to 45 ft/sec water flow velocity. The geometry was prototypic of proposed LMFBRs. The 5-ft long rods were wire wrapped on a 12-inch helical pitch. Each rod had a diametral looseness of 0.005-inch.

The instrumentation was kept simple by utilizing the impedance change in an electrolyte caused by a change in probe separation. Electrodes were flush mounted in selected weight simulated rods and in the adjacent hexagonal flow tube wall. The signals were monitored for both amplitude and frequency of rod motion induced by the parallel water flow. The signals had been calibrated to known rod displacements.

Power spectral density analysis of the data was performed. Generally, the signals were buried in the noise background, and no signals were recorded with equivalent amplitudes greater than 0.0003-inch. The absence of potentially damaging rod vibration was further verified by inducing rod displacements with an impact energy input at the base of the flow tube and recording the resulting signals. The natural frequency was about 70 Hz, and the periodic vibration signals damped to the noise background in less than one second for all test conditions. (Authors' abstract)

8. M. Carteus and R. Gopal, *Vibration Measurements in a PWR - Instrumentation*, Advances in Instrumentation 26(Part 2), Instrument Society of America Annual Conference, 1971, p. 639.

The instrumentation system for measuring the mechanical vibration behavior of a PWR is described. Instrumentation layout as well as signal preamplification conditioning and processing are detailed. Separation of the instrumentation system into a preamplification system and a signal conditioning-processing system is illustrated and its advantages over a centralized (inside the vapor containment) system are shown. Further, a description is given of both on-site and off-site signal analysis techniques. Advantages of on-site signal analysis are shown with regard to test optimization. The last section relates to the system sensitivity and the resolution obtained from the off-site data reduction techniques. (Authors' abstract)

9. E. Lansiti, L. Lazzeri, and G. Messore, *Calculating and Testing the Performance of Nuclear Reactor Internals,* Performance of Nuclear Power Reactor Components (Vienna: International Atomic Energy Agency, 1970), pp. 185-197.

Analytical models are presented which model the vibrations of a PWR core barrel, surrounding thermal shield, and the fluid in the annular region between the two components. The fluid is assumed ideal. The structures are assumed rigid but able to vibrate in pendular motion because of an assumed elastic base for two cases. A third case assumes the core barrel to vibrate in combinations of normal shell modes. Natural frequencies which account for the "added mass effect" of the annular region are compared to those in air. Measurements in a scale model agree with calculation. Damping characterization, and therefore displacements, are said to be difficult to determine. A very general description of the exciting force as due to "some pulsation in velocity" is suggested.

Model testing criteria stated as being successful are simulation of Strouhal number, the velocity field, use of same materials in the model and the prototype, and geometric scaling. The similarity of stresses, strains, pressure, damping, etc., are claimed for such a model, but no data or references are given. Some unknown errors in scaling are suggested to be those due to a distorted Reynolds number and the inability to scale pump noise. A scale model is considered to give qualitative results and cannot replace prototype testing.

Methods of prototype testing are discussed in general. Measurements can only be practically made during preoperational tests with accelerometers, strain gauges, etc. The reactor should be operated for a sufficient period before vibration measurements are made because the damping has been observed to change considerably. Preoperational tests should be very complete because of the difficulty in obtaining information after operations begin. Operational and shutdown testing are discussed briefly.

10. K. D. Appelt, et al., *Experimental Investigation of Loop Caused Influences on Parallel Flow Induced Vibration of Fuel Pins,* Kernforschungszentrum, Karlsruhe, KFK 1385 EUR 4574e (March 1971)

The influence of the test loop on parallel flow-induced vibration of fuel pins of the Na-1 fast reactor design was investigated. The experiments were performed with the same subassembly mock-up, mounted in the test section of four different flow loops with several modifications.

Different experimental arrangements differ considerably in rms-values and spectral densities of pressure fluctuations at the channel entry. Pressure fluctuations pass through the subassembly and modify the fluctuating pressure field in the pin bundle. By different experimental arrangements and identical mean values of hydrodynamic quantities in our experiments the rms-values of pressure fluctuations in the pin bundle reached 7 to 30% of the value of dynamic pressure of the flowing coolant. These values are at least 7 to 30 times higher than the corresponding values measured in "ideal" channels. In accordance with the grade of correlation of fluctuating pressure forces with vibration modes of pins, different response is to be expected by otherwise identical mean values of hydrodynamic parameters. In our experiments the variation of rms-values of fuel pin vibrating strain was found to 1:3. (from Authors' abstract and summary)

11. G. Bohm, *Analytical Problems Associated with Core Support Structures of PWR*, Nuclear Eng. Des. 18, 305-321 (1972)

General steps to be used by analysts in studying flow induced vibrations were outlined. Limited specific techniques, forcing functions, data, or analyses were presented. Inference was made that scale model testing correlation with analytical models and prototypes have been accomplished, including the determination of forcing functions. Blowdown analysis and seismic analysis are discussed in a similar fashion. Forty-three references are given.

12. A. J. Kuenzel, *Westinghouse PWR Internals Vibration Summary 3-Loop Internals Assurance*, WCAP-7765 (Sept 1971)

Information on other reactors (prototype and scale models) are given as evidence why instrumentation for the 3-loop plant is not proposed. The prototype units for each size reactor are R. E. Ginna (RGE), H. G. Robinson (CPL), and Indian Point Unit 2 (IPP).

The experience of Westinghouse in measuring and designing around flow-induced vibrations are reviewed,including thermal differential expansion, hydraulic forces, and flow-induced vibrations. However, all quantitative information, including instrumentation placement, has been deleted as proprietary. Thus, the report is very difficult to read. The ability to measure necessary vibrational characteristics and predict behavior from different size plants and their scale models is implied. The (heavily instrumented) 4-loop IPP Plant data scheduled for spring 1972 is hoped to provide additional assurance of 1/7 scale model prediction methods.

13. G. C. Millman, G. R. McCoy, and J. P. Thompson, *Analysis of Flow-Induced Vibrations: Maine-Yankee Precritical Vibration Monitoring Program* (Non-Proprietary Version), Combustion Engineering Report CENPD-55 (Feb 1973)

Analysis methods and hydraulic pressure variation models are formulated and used in predicting the response of the thermal shield and core barrel to pump and turbulent boundary layer flow induced vibrations. Normal structural vibration modes are assumed, determined, and employed to calculate forced response.

Comparison to measured values are made and general test procedures and instrumentation described. The general conclusion is that flow-induced vibrations are acceptable and predictions can be made that are conservative. However, little evidence is given that the forcing functions assumed are physically valid or would lead to conservative predictions in other systems. The data for Maine-Yankee is held proprietary and is not presented.

14. H. J. Fortune and D. E. Thoren, *Prototype Vibration Measurement Results for B&W's 177-Fuel Assembly, Two-Loop Plant,* Babcock & Wilcox Topical Report BAW-10039 (April 1973)

Accelerometers, strain gauges, and bench top tests were described and used to measure acceleration, displacements, stresses and strains, and associated power spectral density plots. Measured responses were acceptable and less than that previously predicted for Oconee I's flow distribution, instrument nozzles, thermal shield supports, and guide and surveillance tubes. Measured response of the thermal shield was within established acceptance criteria. No use was made of the pressure measurements that evidently were part of the test program. Program is part of compliance with AEC Regulatory Guide 1.20.

15. U. R. Wetzel, C. S. Duckwald, and M. A. Head, *Vibration Analysis and Testing of Reactor Internals,* General Electric Co., San Jose Report APED-5453 (1967)

Method of analysis of reactor internals consists of assuming mode shapes, frequencies, and maximum stresses; then allowable displacements are calculated and both displacements and modal assumptions are compared to experimental data. The program for the Oyster Creek Reactor is discussed in particular.

16. J. E. Corr, *Big Rock Point Vibration Analysis,* Conf. Flow-Induced Vibration in Reactor System Components, ANL-7685 (1970), pp. 272-289.

The symptoms of the unacceptable rigid body thermal shield lateral motion is outlined. A mathematical model relating seal leakage at the bottom of the shield to shield motion is derived and used to explain the method of excitation, instabilities, and corrective procedures employed. Long term operation has confirmed the validity of the design fixes.

17. E. Kiss, *Analysis of the Fundamental Vibration Frequency of a Radial Vane Internal Steam Separator Structure,* Conf. Flow-Induced Vibration in Reactor System Components, ANL-7685 (1970), pp. 335-343.

The analysis of the fundamental vibration frequency of a Radial Vane Internal Steam Separator has been performed, considering the effect of the entrapped fluid between the idealized structure and pressure vessel wall. The hydrodynamic or "virtual" mass associated with a vibrating finite length cylinder is presented in terms of a correction factor to be used with the calculated two-dimensional "mass" effect. Finally, the lateral frequency or a radial vane separator assembly has been measured and compared with the predicted value. (Author's abstract)

18. Nuclear Safety Information Center, Oak Ridge National Laboratory, P. O. Box Y, Oak Ridge, Tennessee, 37830 (615/483-8611, ext. 7253)

See Ref. 13, Sec. IA-4.

B. Heat Exchanger and Steam Generator Components

1. W. Kellar, *Tube Support Damping Fort St. Vrain Steam Generator*, Gulf General Atomics Report GAMD-9735 (1969)

   Damping characterization of helical tubes and support combinations (sleeves were pressed on tubes at baffle support locations for wear protection) were required in order to determine lift coefficients from existing experimental data and to make predictions of response for Fort St. Vrain steam generator. Straight sections of tubing were mechanically excited and damping measured for different prescribed loads at the supports representing interaction of helical tubes and baffle plates due to differential thermal expansion. Damping was determined by the bandwidth technique and an energy technique which is described.

   Damping was assumed to be entirely due to material distortion and specific material damping energy calculated. Existing techniques for obtaining magnification factors for other geometries and mode shapes are outlined. The reader is cautioned to account for other kinds of damping (joint damping, air damping, etc.) if they become significant for a particular application.

2. W. J. Kellar, *An Engineering Method for the Evaluation of Steam Generator Vibrations*, Gulf General Atomics Report GA-8292 (1969); Presented at USAEC/RDT Sponsored Meeting on Heat Exchanger Vibrations, Feb 1969.

   Method involves four tasks for gas/steam generators. First, vortex shedding coupling with acoustic standing waves are avoided. Second, excitation strengths (lift forces) are determined for prototypic tube bundles. Stress levels, tube natural frequencies, and the fluid Strouhal number are measured as well. Observed vortex shedding was not organized but similar to random turbulence. The lift coefficient was a function of Reynolds number as well as response frequency. Third, damping or magnification factors (see Ref. 1) were determined in bench tests using bandwidth methods. Fourth, lift coefficients vs frequency and Reynolds number are derived from experimental data. The lift coefficients and damping information is used in conjunction with linear modal analysis computer codes to predict tube vibrations in production steam generators.

3. M. J. Pettigrew, J. L. Platten, and Y. Sylvestre, *Experimental Studies on Flow Induced Vibration to Support Steam Generator Design, Part II: Tube Vibration Induced by Liquid Cross-Flow in the Entrance Region of a Steam Generator*, Chalk River Nuclear Laboratories Report AECL-4515; Proceedings International Symposium Vibration Problems in Industry, Keswick, England, April 1973.

   A full scale model of a steam generator was employed to assess tube bundle vibrations induced by water cross flow at a Reynolds number of approximately 2×10^4. Eight strain gauges and one accelerometer monitoring response showed no evidence of periodic vortex shedding, but indicated first and second mode structural vibration response likely induced by broad-band random fluid forces. Changes in tube support conditions with vibration (free to simple), and a nearly constant viscous damping coefficient at both structural frequencies, were observed. Tube vibration amplitudes were generally less than 0.001 in. (RMS).

4. M. Weber, *Flow-Induced Vibrations in Tube Bundle Heat Exchangers with Cross and Parallel Flow, Part 3, Design Problems in Conjunction with Vibrations in Tubular Heat Exchangers,* Flow-Induced Vibration in Heat Exchangers (ASME, 1970)

   Some constructive solutions for the detuning and damping of tube vibrations in heat exchangers of a number of atomic reactors, e.g., at Würenlingen (Switzerland), St. Vrain (U.S.A.), St. Laurent I and EDF EL-4 (France), are given. The experiences with helical bundle heat exchangers reveal the greatly favorable behavior of this type of design in regard to the suppression of the vibrations. (Author's abstract)

5. L. J. Cohan and W. J. Deane, *Elimination of Destructive, Self-Excited Vibrations in Large, Gas and Oil-Fired Utility Units,* Trans. ASME 87, 223-228 (1965)

   As oil and gas-fired steam generators have grown in size, instances of self-excited vibrations have increased. This paper deals with the steps taken by one manufacturer to study the source of these vibrations, and then eliminate them through prebaffling of sensitive gas passes. The method of determining baffle spacings for various gas-pass widths is detailed, together with the necessary mathematical background.

6. R. L. Colt, C. C. Peake, and A. Lohmeier, *Design and Manufacture of Large Surface Condensers - Problems and Solutions,* Proc. Amer. Power Conf. 28, 469 (1966)

   Among other problems discussed, condenser tube failure due to impacting between adjacent tubes is described. The vibrations occurred very nearly at the tube natural frequency after a "critical flow" was attained. Below the critical flow, vibrations were not perceptible. A design formula is presented which relates system geometry, flow velocity, and damping to a "severity factor." The severity factor was determined for the extreme operating conditions of similar systems which did not indicate vibration damage.

7. R. C. F. Dye and C. G. H. Abrams, *An Investigation of the Aerodynamic Stability of a Cross-Flow Type Finned Tube Heat Exchanger,* ASME Paper No. 68-WA/HT-19 (1968)

   Subject to air crossflow, staggered rows of dense arrays of high finned circular tubes were found to shed vortices at two distinct frequencies for both a wind tunnel model and a prototype.

8. S. Mirza and D. J. Gorman, *Experimental and Analytical Correlation of Local Driving Forces and Tube Response in Liquid Flow Induced Vibrations of Heat Exchangers*, Paper F6/5, First Int. Conf. on Structural Mechanics in Reactor Technology, Berlin, Germany, September 1973.

Selected tube displacement response was investigated for triangular tube bundles subject to water crossflow. Both in-line and out-of-line arrays with a pitch to diameter ratio of 1.33 were tested. In all cases, motion was observed to be random, with peaks at the lowest structural frequencies. Out-of-line upstream tubes were thought to respond to both vortex shedding and fluid-elastic mechanism, with interior and downstream tubes showing significantly smaller response. Force measurements for interior tubes indicated a random forcing function. In-line upstream and interior tubes exhibited very large response. Vortex shedding excitation was suspected. proposed prediction methods for determining response correlated well with limited data. The method requires knowledge of damping, force spectral densities, and force spectral correlations.

9. H. A. Nelms and C. L. Segaser, *Survey of Nuclear Reactor System Primary Circuit Heat Exchangers*, Oak Ridge National Laboratory Report No. ORNL-4399 (1969)

Problems resulting from excessive tube vibration in certain primary-circuit heat exchangers in reactor systems for which the USAEC Division of Reactor Development and Technology is technically responsible are evaluated in this report. Of the 19 reactor systems surveyed, problems in primary exchangers resulting from tube vibration hydrodynamically induced by the shell-side fluid flow were experienced in 9 of the 17 plants that have been operated. The results of a detailed vibration analysis that was based on well-known procedures and information available in the literature tend to support the general conclusion that if the designs for these exchangers had been critically examined for tube vibration prior to fabrication, the possibility of failure would have been judged too great to accept and the problems could have been averted by design modifications. (Authors' abstract)

10. P. M. Moretti, *A Critical Review of the Literature and Research on Flow-Induced Vibrations in Heat Exchangers*, Paper 86D, A.I.Ch.E. 74th Nat. Meeting, New Orleans, March 1973.

The current literature in flow-induced vibrations is summarized and analyzed with respect to its applicability to heat exchangers. The different types of vibration and excitation are classified and the calculation methods for each class identified. Suggestions are made regarding needed research and data analysis. (Author's abstract)

V. SCALE MODEL TESTING

A. Similitude Theory

1. D. E. Hudson, *Scale Model Principles*, Shock and Vibration Handbook, Volume 2, Data Analysis, Testing, and Methods of Control, C. M. Harris and C. E. Crede (eds.) (New York: McGraw-Hill Book Company, 1961)

   Both general principles and examples are given. After a brief introduction to dimensional analysis, principle of dynamic similarity, distorted model theory, and how to use known equations of motion in model design, model materials are discussed. Examples presented include model tests of Tacoma Narrows Suspension Bridge (geometric model scale factor of 100 and 10) with quite accurate model frequencies. Also applications to a generator stator frame and airplane wing flutter are discussed. Included are 23 references, all dated prior to 1959.

2. D. F. Young, *Basic Principles and Concepts of Model Analysis*, Experimental Mechanics 11, 325-336 (1971)

   Presented as an educational lecture, both dimensional analysis (π-theorem) and analysis of the characteristic equations of the systems are employed to illustrate determination of similarity relationships. Very basic examples are illustrated. The results of a model study simulating soil-structure interaction are discussed. Fluid-solid interaction is not considered.

3. H. L. Langharr, *Dimensional Analysis and Theory of Models* (New York: John Wiley and Sons, 1951)

   The work represents a standard text on the subject. Buckingham's Pi theory is rigorously proved, and a systematic procedure for determination of dimensionless parameters is developed via linear algebra theory. Numerous detailed examples are given in all areas of fluid mechanics, except for the dynamic interaction of fluids and deformable bodies. Several applications are given in the areas of deformable bodies, heat theory, and electromagnetic theory.

4. G. Murphy, *Similitude in Engineering*, (Ronald Press, 1950)

   An axiomatic development of Pi theorem is presented along with detailed applications which clearly outline procedures that could be employed in any dimensional analysis. The determination of information from static and dynamic testing of structural models is covered thoroughly. General methods of obtaining information from distorted models are discussed, with particular applications to statically loaded structures. Fluid flow models receive similar considerations, but with less attention to details. The fluid-solid interaction problem is not discussed. The book is an excellent tutorial text.

5. R. C. Pankhurst, *Dimensional Analysis and Scale Factors,* (London: Chapman and Hall Limited, 1964)

Dimensional analysis based on the π theorem is intuitively motivated using the indicial method of determining dimensionless parameters for homogeneous equations. Direct derivation of dimensionless products from explicit physical equations is also considered. Applications to problems in fluid mechanics, including pipe flow, drag over stationary bodies, channel flow, and general incompressible viscous flow are made using both methods. Heat transfer and response of elastic structures are treated in similar manner but with fewer details. No detailed examples are given for scale model testing. Partial (distorted) similarity is discussed in general.

Specifically, the similarity requirements for ideal testing of fluid-elastic solid dynamic interaction are presented with some development. No scale model tests are discussed. The distortion of Reynolds No. during wind tunnel tests is mentioned as an example of partial simulation. Aerodynamic force and moment coefficients for bluff bodies are claimed to be relatively insensitive to variations in Reynolds Numbers.

6. R. Sutherland, *Engineering Systems Analysis,* (Addison-Wesley, 1958)

Undergraduate text devoted to developing theory for simple electrical and mechanical systems and analogous behavior. Single chapter devoted to dimensional analysis which assumes the π theorem and rigorously makes dimensional analysis of simple mechanical, electrical, and fluid systems. Good tutorial introduction to dimensional analysis.

7. L. I. Sedov, *Similarity and Dimensional Methods in Mechanics,* (New York: Academic Press, 1959)

Dimensional analysis based upon π theorem is rigorously developed. Simple examples of pendulum motion, fluid motion in pipes, motion of a body in a fluid, heat transfer, etc., are given where intuitive motivation is used to derive dimensionless parameters. The motion of an elastic body in a nonviscous, compressible fluid, in a steady infinite flow field is treated. Turbulence theory of fluid flow is developed with use of dimensional analysis. Compressible fluid flow is discussed in relation to blast waves. Book treats fluid flow problems as examples, in general.

Flutter is treated for a nonviscous, incompressible fluid flow of an elastic body in an infinite flow field with steady velocity at infinity. Physical parameters defined are geometric length ℓ, elastic modulus E, shear modulus G, elastic body mass m, fluid density ρ, fluid velocity v. The similarity parameters are $\frac{\rho v^2}{E}$, $\frac{G}{E}$, $\frac{m}{\rho \ell^3}$, $\frac{vt}{\ell}$. Few details or references are given on the flutter problem.

8. A. Ezra, *Scaling Laws and Similitude Requirements for Valid Model Work*, Colloq. on Use of Models and Scaling in Shock and Vibration (ASME, 1963)

Basic concepts of scaling are presented regarding the determination of π groups and what to do if 1, 2, or many π groups cannot be maintained equal between the model and prototype. In particular, the scaling laws for a vibrating Euler beam are derived, and the use of the equations of motion to account for distorted scaling is illustrated. Consideration is given to cases where the equations of motion are not available, also. Similitude requirements can be relaxed if one π term at a time can be varied in the model; testing determines its relation to the dependent π group. An example from explosive forming is discussed in detail.

9. H. N. Abramson and G. E. Nevill, *Some Modern Developments in the Application of Scale Models in Dynamic Testing*, Use of Models in Shock and Vibration (ASME, 1963), pp. 1-15.

The paper reviews, with example results, the then existing literature on problems involving coupling between structures and their surroundings. Cases of extreme loading are considered also. Among the subjects discussed are the response of aerospace structures to vibratory and impulsive loading (plastic deformation), the fluid-structure coupling as represented by fuel sloshing in a launch vehicle, airplane wing flutter, soil-structure coupling, and aerothermoelasticity. In most instances the similarity parameters are simply stated and detailed motivation and derivation left to the references.

10. A. Fortier, *General Considerations of the Problems of Aero- and Hydroelasticity*, La Houille Blanche (no. 5), 383-390 (1971) (in French)

Similitude relations are derived by consideration of the governing equations and boundary conditions for two classes of low velocity flow problems: (i) flow wherein the interfacing solid boundaries are fixed, and (ii) flow wherein the interfacing solid boundaries vibrate and affect the flow. Reynolds number is thought to be an important flow parameter in both cases only for very low velocities. In general, Froude similarity is considered necessary when free surfaces are involved. Strouhal similarity is stipulated to be most important when fluid-solid interaction occurs; and Mach number similarity is required when the flow velocities are near the speed of sound or when nonstationary, internal, flow phenomena (e.g., vortex shedding) occur with correlation lengths (distance over which pressure pulsations are considered correlated) on the order of magnitude of the body under consideration. On the basis of the last requirement it is suggested most of the wind tunnel data on bluff bodies do not represent prototypic behavior of flow in an infinite field.

11. W. E. Baker, P. S. Westine, and F. T. Dodge, *Similarity Methods in Engineering Dynamics*, (Rochelle Park, New Jersey: Hayden Book Co., 1973)

Emphasis is placed on the complete consideration of specific dynamic engineering problems. The book is an outgrowth of several short courses taught on modeling weapon effects. Model laws are derived from governing differential equations or the Pi theorem, selection of significant parameters are discussed, and in most cases, comparisons of model and prototype data are made. Most of the problem areas dealt with represent the recent interest of the authors and the Southwest Research Institute. General concepts of similarity and modeling are reviewed. Included among the large number of applications discussed are scaling of blast waves and structural response to blast waves, penetration of projectiles, propellant sloshing in fuel tanks and associated launch vehicle vibrations, and modeling explosive excavations and vehicle mechanics on soils. The case histories given provide excellent example approaches to wide areas of applications and indications of the practical limitations encountered in obtaining data.

B. Vibrations of Solids in Fluids

1. *Simple Structures*

1. R. J. Glass, *Final Report: A Study of the Hydroelastic Vibrations of Spring Supported Cylinders in a Steady Fluid Stream due to Vortex Shedding,* Ohio Northern University Report AD-721073 (1973)

   See Ref. 7, Sec. IIA2-3.

2. R. J. Glass and C. L. Sayre, *Amplitude and Frequency Response and Laws of Similitude for Vortex-Induced Vibrations of Spring Supported Cylinders in Subcritical Flow,* Can. Congress Appl. Mech., 2a-086 (1967) (Abstract only)

   Tests in air showed that maximum amplitude did not depend upon Reynolds number. Empirical relations relating maximum amplitude-to-diameter ratio as a function of fluid-to-cylinder density ratio are given.

3. G. H. Toebes and A. S. Ramamurthy, *Fluid Elastic Forces on Circular Cylinders,* Proc. ASCE, J. Engr. Mech. 92, 1-19 (1967)

   See Ref. 1, Sec. IIA3-1.

4. G. H. Toebes, *The Unsteady Flow and Wake Near an Oscillating Cylinder,* J. Basic Engr. Trans. ASME, Series D 91, 493-505 (1969)

   See Ref. 2, Sec. IIA3-1.

5. R. E. D. Bishop and A. Y. Hassan, *The Lift and Drag on a Circular Cylinder Oscillating in a Flowing Fluid,* Proc. Roy. Soc. London, Series A, 277, 51 (1964)

   See Ref. 3, Sec. IIA3-2.

6. E. Naudascher, *Discussion of "Flow-Induced Structural Vibrations," by G. H. Toebes,* Proc. ASCE, J. Engr. Mech. 92(4), 80-86 (1966)

   Toebes concludes in his article that model testing is the only feasible solution to most cases of flow-induced vibrations. Naudascher points out difficulties and directions in model testing. Because of the extreme sensitivity of flow-induced response to small changes in parameters, hardly another class of model studies is claimed to exist for which model design and instrumentation requirements are more demanding. A dimensional analysis of a one-degree-of-freedom system is made to illustrate the numerous pertinent laws of similarity which must be satisfied for proper testing, their often mutual incompatibility, and the difficulty in physically simulating damping and elastic effect. The similarity laws developed assumed excitation is governed by viscosity (Reynolds number). The large reduction in experimental testing requirements for rigid-stationary models and rigid forced oscillation models is noted, and the suggestion is made that these model tests precede complete fluid-elastic modeling in order to gain significant insight. However, the acquisition of design information through such testing is questionable because the test implicitly assumes superposition is valid, which is not the case for most fluidelastic systems.

7. J. Dale, H. Menzel, and J. McCandless, *Dynamic Characteristics of Underwater Cables Flow Induced Transverse Vibrations*, NADC-AE-6620 (Sept. 1966)

Crossflow vortex excitation of smooth cylindrical hydrophone cables was documented. The lock-in of vortex shedding and structural natural frequencies and associated peaking of amplitudes was observed. An empirically determined modification of the Strouhal number $S_T = f_V d/(u \sin\theta)^n$ was presented as the form which correlated best with data from several different size cables (diameter d and frequency f_V), over various velocity (u) ranges, amplitudes of motion (0-3 diameters), and yaw angles (θ). An analytical model to predict response was constructed for a particular cable mass system.

8. B. J. Vickery and R. D. Watkins, *Flow Induced Vibrations of Cylindrical Structures*, Proc. 1st Aust. Conf. Univ. West. Aust., 1964, pp. 213-241.

See Ref. 11, Sec. IIA4-4.

9. G. V. Parkinson, *Wind-Induced Instability of Structures*, Phil. Trans. Roy. Soc. London, Series A, 269, 395-409 (1971)

See Ref. 11, Sec. IA-4.

10. C. Scruton, *Wind-Excited Oscillations of Structures*, Proc. Inst. of Civil Engineers 27, 673-702 (1964)

See Ref. 10, Sec. IA-4.

11. C. Scruton and E. W. E. Rogers, *Steady and Unsteady Wind Loading of Buildings and Structures*, Phil. Trans. Roy. Soc. London, Series A, 269, 353-383 (1971)

See Ref. 9, Sec. IA-3.

12. J. D. Hardwick and L. R. Wootton, *The Use of Model and Full-Scale Investigations on Marine Structures*, Proc. International Symposium Vibration Problems in Industry, Paper No. 127, Keswick, England, April 1973.

See Ref. 18, Sec. IIA2-7.

2. *Reactor Components*

1. P. Lambert and P. Leon, *Experimental Determination of Fluctuating Hydrodynamical Forces in the Tanks of the Phenix Reactor*, La Houille Blanche (No. 6), 499-503 (1971) (in French)

Simulation of a free surface (Froude similarity) in the primary tank as well as flow velocity simulation (Strouhal similarity) were considered as the two main requirements thought important for the 1/4 scale model. Since construction of a scale model simulating both Froude and Strouhal number is not possible, an indirect method of vibration analysis was employed. Pressure fluctuations for rigid models in Froude similarity were measured and were used as forcing functions in an analytical vibration analysis. The pressure fluctuations on the main vessel containing the main flow were found to be of a homogeneous and isotropic turbulence nature in the low frequency range (below 24 Hz). The magnitude of the pressure fluctuations were quite small (.002 atmospheres). Unexpectedly, the pressure fluctuations varied with velocity rather than velocity squared. Valid relations of transfer of data to the prototype were not resolved.

2. D. K. Schmitt, *Fast Flux Test Facility Test Report Secondary Set/Isolation Valves Vibration Testing*, Westinghouse Advanced Reactor Systems Report No. 2171-31 (Dec 1972)

The procedures for testing an 8-inch sodium valve in water are presented. Scale modeling criteria employed are the same as those of H. J. Connors (see Ref. 3). Full-scale geometric modeling was used. Simulation of damping was of the most concern.

3. H. J. Connors, *Scaling Laws and Similitude Requirements*, An Experimental Investigation of the Flow-Induced Vibration of Tube Arrays in Cross Flow, Ph.D. Thesis, University of Pittsburgh, 1969, p. 49.

Scaling laws are rigorously derived for a one-dimensional, rigid, spring mounted tube bank subjected to crossflow, periodic external forces, and periodic boundary displacements. Assuming geometric similarity and fixed boundaries, tube displacements are shown to be functions of Reynolds number, fluid damping, mass ratio, and the Strouhal number for the structural natural frequency. Vortex shedding displacements, frequencies, tube oscillation frequency, and fluid forces are functions of the same dimensionless parameters.

4. G. Hetsroni, *Use of Hydraulic Models in Nuclear Reactor Design*, Nuclear Science and Engineering 28, 1-11 (1967)

Successful experimental studies were conducted on two scale models to determine the effects of various internal geometries on the flow distribution. Vibration response was not considered. Geometric similarity was maintained while Reynolds number, which was at a high value, was distorted.

5. F. S. Fahy, *Noise and Vibration in Nuclear Reactor Systems*, J. Sound Vib. 28, 505-512 (1973)

Research work at Institute of Sound and Vibration, Southampton, England, is described; specifically, work defining the applicability of statistical energy analysis for the analysis of gas-cooled reactor problems.

3. *Hydroelastic Components*

1. C. E. Brown, *The Use of Ship Model Basins for the Study of Vortex Wake Phenomena*, Hydronautics Inc. Tech. Report 7115-2 (1973)

   The use of water channels to simulate response of streamlined air wing profiles was found possible as long as Mach numbers are low enough (< .7). Surface and cavitation effects were found to be easily avoidable. Model Reynolds numbers are stated as being large enough when trailing edge flow can be insured to remain attached.

2. J. Andrews and J. Church, *A Model for Simulation of Wave Impact Loads and Resultant Transient Vibration of a Naval Vessel*, David Taylor Model Basin ASME Colloq. on Use of Models and Scaling in Shock and Vibration (Nov. 1963)

   Discusses similitude parameters in general for ship towing test modeling. Presents prediction equations, example data, model construction, and instrumentation when Froude number similarity is maintained.

3. W. A. Lecher, *Consideration of Similarity for Hydroelastic Vibrations*, Proc. Inst. Mech. Engrs. 18, 25 (1967)

   Proposes without derivation that the Strouhal number, generalized Froude number, Reynolds number, and cavitation number, in addition to the usual structural parameters, are the most important parameters for hydroelastic simulation. The generalized Froude number is the ratio of inertia energy to the potential energy or head of the fluid. Regarding Reynolds number similarity as being unnecessary at the high Reynolds number found in most machines, modeling and prediction laws are derived based on similarity of the Strouhal number, generalized Froude number, and structural parameters.

   Calculations of strains from test models are discussed. Differences between model and prototype materials, size, and hydraulic heads are accounted for. Model test results for a pump turbine are presented, prototype predictions made, but no prototype test results are presented to test the validity of the prediction equation.

4. M. K. Ochi, *Ship Slamming - Hydrodynamic Impact between Waves and Ship Bottom Forward*, Fluid-Solid Interaction, Naval Ship Res. and Dev. Center (ASME, November 1967)

   The paper accepts, without any discussion, the use of Froude number for relating impacting properties of ships of all sizes including models. Theoretical discussion of how to solve for the pressure of impact is included. The problems are many, but an accurate relation for added mass of water is one of the most difficult. The effects of flexibility of ship, shape of ship entering water, and sea wave irregularities are studied and very approximate functional relations developed. Not enough data has been taken to define an accurate functional relation.

5. H. Nolle, *Determination of Structural Natural Frequencies of a 215,000 gpm Water Pump Using a Dynamic Model,* Israel J. Technology 11(4), 205-216 (1973), Proc. Seventh Isr. Conf. Mechanical Engineering (June 1973)

The structural dynamic characteristics of a 215,000 gpm vertical shaft water pump design have been investigated experimentally using a 1/20-scale model and the pump prototype. Special attention has been paid to possible resonances in the low frequency region. The pump is reduced to its dynamic equivalent and model scale factors are derived. The effect on frequencies of structural support flexibility, shaft bearing stiffness and water inertia are ascertained from tests. Results of vibration tests are presented in terms of natural frequencies and corresponding flexural mode shapes. On the basis of these results the pump main casing design was modified for the purpose of spacing out critical and operating speeds. Field measurements, made subsequently on the pump in situ are described and compared with predicted values. Overall accuracy of modelling was found to be better than 10%, confirming the validity of the technique. (Author's abstract)

4. *Aerospace Structures*

1. A. G. Rainey, *Progress on the Launch-Vehicle Buffeting Problem*, J. Spacecraft and Rockets, 2, 289 (1965)

Fluctuating pressures are shown to be very dependent upon the upstream configuration of a launch vehicle where flow separation occurs. Examples are cited where pressure fluctuations differ by 50% between machined and smooth lapped surfaces. However, scaling pressure power spectral density according to reduced frequency (Reynolds No. distorted) is concluded as giving reasonably valid results as long as the same flow regime occurred in model and prototype. Although, model predictions of prototype response were sometimes off by orders of magnitude, no better correlation existed between data from different flight tests. The dimension chosen for scaling was associated always with the source of the buffeting pressure fluctuations. Thus, for complicated structures, the choice of the dimension was the major problem.

Response problems are discussed also. Determination of local high frequency structural response depends almost entirely upon aeroelastic modeling. Low frequency (bending mode) response is determined by use of a combination of experiment for aerodynamic moments and damping, for instance, and an appropriate analytical model. Qualitative agreement is the best to be expected in all cases.

2. P. N. Hanson and G. W. Jones, *On the Use of Dynamic Models for Studying Launch Vehicle Buffet and Ground Wind Loads*, Proc. Symp. Aero and Dyn. Modeling Tech., RTD-TDR-63-4197 (1963), pp. 334-387.

Scaling relations are given for determining gross bending response (first three modes) due to buffeting. Reynolds number is distorted during testing. The Mach and Strouhal numbers are simulated. Aerodynamic damping is assumed proportional to velocity (laminar flow) and scaling relations are given to account for the Reynolds number distortion. Damping and moment time histories are measured from the model and scaled to predict prototype response. No comparison to prototype data is made.

Reynolds number is maintained above 50,000, and Mach number below 0.4, to avoid compressibility distortion effects, for ground wind load model testing. Loading is assumed to be due to steady drag, vortex shedding, and wind gusts. Strouhal number, the mass ratio, damping ratio, and surface roughness are simulated as best as possible. Artificial model damping is quite commonly necessarily introduced to simulate prototype damping (requiring prior knowledge of prototype damping). Base bending moments are measured and scaled to prototype. Since wind gusts and turbulence are not simulated in the wind tunnel, results of a linear elastic analysis based on wind gust data are superimposed upon scaled model results. Again, no prototype data was available for comparison.

3. D. H. Ross, *Aerodynamic Noise Investigation in a Short-Duration Shock Tunnel*, Shock and Vib. Bull., 37(Pt. 3), 203-217 (1968)

   The use of a short-duration shock tunnel to determine the pressure loading on a cylindrical Titan III, 1/30 scale, rigid model due to a shock wave produced by attached fuel tanks is described.

   Frequency/(Strouhal No. based on body dia.) and (pressure fluctuations)/(free stream dynamic pressure) are assumed similar in model and prototype. Excellent comparisons of model and prototype sound pressure level data were obtained. Except for the effect of the shock wave, care was taken to ensure a fully developed turbulent attached boundary layer by increasing (distorting) the length of model's cylindrical segment between the nose cone and the pressure transducers. In addition, two "Hama" type boundary-layer trips were used at the nose cone. Ambiguities such as which length, body diameter or boundary layer thickness should be used to determine Strouhal number are discussed but not resolved.

4. G. W. Jones and J. T. Foughner, Jr., *Investigation of Buffet Pressures on Models of Large Manned Launch Vehicle Configurations*, NASA TN D-1633 (May 1963)

   Buffet problem areas on large manned launch vehicles were identified and associated with flow separation due to geometry and/or shock waves via testing of reduced scale rigid models. Thus, buffeting was found highly velocity and geometry dependent. Pressure fluctuations were found to be independent of Reynolds numbers above 4.5×10^6 (where most testing was done), but quite sensitive below 4.5×10^6. Scaling relations (so-called reduced frequency scaling) for frequency and pressure PSD's implicitly assume no dependence between random measures and motion. Two different model data (1.6% and 8.0%) were extrapolated to prototype size via the scaling relations and comparison was good. Note, however, both models were tested at the same Reynolds Nos. The data indicate that the relations would be invalid for Reynolds numbers below 4.5×10^6 (a different flow regime).

5. D. E. Cooley and R. F. Cook, *Dynamic Modeling, Its Past and Future*, Proc. of Symp. on Aero. and Dynamic Modeling Tech., RTD-TDR-63-4197 (1963), pp. 13-48.

   This paper covers, first, the historical background of dynamic modeling and the evolution to the current state-of-the-art of modeling methods and uses. A review and discussion of recent research efforts dealing with various modeling problems, including flutter models for inflatable structures, high angles-of-attack, high temperature environments, vibration and sonic fatigue prediction are presented. Also included are remarks concerning future requirements and problem areas where research is needed to assure the availability of adequate modeling technology for the potential dynamic problems of advanced flight vehicles. (From Authors' abstract)

6. H. C. Peterson and A. A. Ezra, *Analysis of Similitude Requirements and Scaling Laws for Transonic Buffeting*, Proc. Symp. Aero. and Dyn. Modeling Tech., RTD-TDR-63-4197 (1963), pp. 49-79.

   Similitude and distorted scaling requirements are discussed in great detail for small scale testing of response due to buffeting. Corresponding scaling relations are given including those for most random response measures. Significant to the application of the relations is that the pressure field is assumed to be independent of the motion of the model (modal random analysis is valid). Tests at different scales but similar Reynolds and Mach numbers show good correlation. The effect of distorting Reynolds numbers, etc., remains to be investigated.

7. F. T. Abbott, *Some Current Techniques in Experimental Aeroelasticity*, Fluid-Solid Interaction (ASME, 1967), p. 144.

Techniques are discussed for testing models in wind tunnels for buffeting in flight and launch ground wind loads. Tricks and methods of mounting are described and illustrated. Similitude relations are not discussed. Described is a test of a 7% scale Saturn with gantry tower subjected to ground wind gusts from all compass directions. Some qualitative data on bending response is provided. Description concerns how the test was performed rather than discussion of scaling laws. However, structural damping is indicated as being one of the most difficult modeling problems in all NASA programs. Artificial dampers were necessary in many cases in order to simulate prototype damping. Nine references which also appear to deal primarily with test techniques rather than model scaling or data interpretation are given.

8. I. E. Garrick, *A Survey of Aerothermoelasticity*, Aerospace Engineering, <u>22</u>, 140 (1963)

The purpose of the paper is to describe some known problems of aerothermoelasticity and to indicate methods of obtaining quantitative information for attacking or resolving them. Particular example problems found in the then new concepts in flight structures such as the X-15 are presented. Methods of accounting for high temperature effects on materials, natural frequencies, and panel flutter are discussed. Seventeen references are given. Scale modeling is not discussed.

9. J. Dugundji, and J. M. Calligeros, *Similarity Laws for Aerothermoelastic Testing*, J. Aerospace Sciences, <u>29</u>, 935 (1962)

The similarity laws for aerothermoelastic testing are determined for the range $M_\infty < 3.5$, $T < 1{,}000°F$ by making nondimensional the appropriate governing equations.

For the general aerothermoelastic model, where the model is placed in a high-stagnation-temperature wind tunnel, similitude is shown to be very difficult to achieve for a scale ratio other than unity. The primary conflict occurs between the free-stream Mach number M_∞, Reynolds number Re_∞, aeroelastic parameter $\rho_\infty V^2/E_0$, heat conduction parameter k_∞/K_0, and thermal expansion parameter $\alpha_0 T_0$.

Means of dealing with this basic conflict (for streamlined bodies) are presented. These include (1) looking at more specialized situations, such as the behavior of wing structures and of thin solid plate lifting surfaces, and panel flutter, where the aerothermoelastic similarity parameters assume less restrictive forms, (2) the use of "incomplete aerothermoelastic" testing in which the pressure and/or heating states are estimated in advance and applied artificially to the model, and (3) the use of "restricted purpose" models investigating separately one or another facet of the complete aerothermoelastic problem.

Some numerical examples of modeling for the general aerothermoelastic case as well as for the specialized situations mentioned in Ref. 1 above are given.

Finally, extension of the aerothermoelastic similarity laws to higher speeds and temperatures is discussed. (from Authors' abstract)

10. A. R. Regier, *The Use of Scaled Dynamic Models in Several Aerospace Vehicle Studies*, Colloquium on Use of Scale Models and Scaling in Shock and Vibration, ASME, 34 (1963)

NASA related research is reviewed. A tutorial section dealing with the pertinent similitude parameters (not derived) for a variety of problems is included. Qualitative descriptions of models tested, results, and references are given. Large increases in bolted joint damping with decreasing model size is cited as a significant difficulty in proper scale modeling. Simulation of Reynolds number is deemed important in modeling separated flow induced forces produced on blunt launch vehicles by ground winds. A 1/9 scale model of the launch vehicle was found to predict low structural natural frequencies well, but higher frequency simulation would require a replica model. An extensive bibliography (73 references) dealing mainly with aeroelastic modeling is included.

11. J. S. Mixson, J. J. Catherine, and A. Arman, *Investigation of the Lateral Vibration Characteristics of a 1/5-Scale Model of Saturn SA-1*, NASA Technical Note D-1593 (January 1963)

Resonant frequencies and associated mode shapes and damping of the model were determined at weight conditions simulating five points in the launch trajectory of the full-scale vehicle. The model was supported in a vertical position by a two-cable suspension system to simulate the free-free condition. The results show the unusual frequency spectrum and mode shapes associated with the clustered configuration of the Saturn SA-1 launch vehicle. In some modes the booster tank deflections at a particular station are all approximately the same; these modes are similar to more conventional bending modes. In other modes, however, the booster outer tanks deflect in the opposite direction from the center tank; these unusual modes are termed cluster modes. (Authors' abstract)

Both natural frequencies and damping were found to be functions of shaker forces and vibration amplitude. Comparison to prototype test results are planned.

12. C. Scruton, and N. C. Lambourne, *Similarity Requirements for Flutter Model Testing*, Manual on Aeroelasticity 4, (AGARD) (1968), Chapt. 6.

Comprehensive listing of similarity laws for flutter model testing of various structures under several environmental conditions are presented without derivation. Distorted model testing is discussed and the conditions for which parameters can be distorted are discussed. In particular, the distortion of Reynolds number and structural damping is discussed in detail because both are distorted in most model testing. Reynolds number has to be simulated as close as possible in stalling flutter, buffeting, and control surface flutter because they depend on the position of flow separation and/or the thickness of the boundary layers. All classic types of flutter have been found insensitive to small changes in geometry and changes in Reynolds number, provided it does not fall below one million based on wing chord.

13. P. E. Sandorff, *Principles of Design of Dynamically Similar Models for Large Propellant Tanks*, NASA Technical Note D-99 (January 1960)

A study is made of the similitude conditions existing between a full-scale propellant tank such as would be used for a large rocket vehicle and a dynamically similar, reduced scale model. Scaling laws are derived which permit the design of such a model for a large 40-foot-diameter liquid-oxygen JP-4 tank used as an example. Permutations of different design combinations for the model are examined to determine their suitability and practicability. It is concluded that dynamically similar reduced scale models offer a practical means of studying and developing solutions for large elastic-wall propellant tanks. (Author's abstract)

Problems were indicated that must be overcome before reduced scale modeling results would be useful. Any model fluid would exit disproportionately large viscous damping effects. Since viscous effects are of major importance, a test program to evaluate scale effects is necessary. Among other parameters, simulations of Reynolds, Froude, and Strouhal numbers were deemed necessary.

14. H. N. Abramson and G. E. Ransleben Jr., *Simulation of Fuel Sloshing Characteristics in Missile Tanks by Use of Small Models*, J. American Rocket Society, 603-612 (July 1960)

Similitude theory is applied to the problem of fuel sloshing in accelerated tanks to establish criteria for the design of model experiments. It is found that dynamic modeling is possible even if liquid viscosity is considered, and the ranges of significant parameters and the selection of model liquids are discussed. The results of experiments made with small models are compared with those obtained with full-scale tanks, for two different types of damping devices. (Authors' abstract)

Tanks are assumed rigid. The damping produced by the slosh-depressant devices was definitely dependent upon the equivalent Reynolds number defined. Damping for prototype, although distorted in model, was extrapolated by performing several scale model tests.

15. H. L. Runyan, H. G. Morgan, and S. S. Mixson, *Role of Dynamic Models in Launch Vehicle Development*, Experimental Techniques in Shock and Vibration (ASME, New York, 1962), pp. 55-69.

Paper summarizes methods of launch vehicle model testing performed by NASA. Scale models are usually constructed to simulate one type of vibration only: lateral vibration, longitudinal vibration, panel flutter, etc. Exact geometric testing is found to be difficult to fabricate and instrument, and is also expensive.

Some of the structural dynamic similitude parameters are given for several categories of vibrations. Those included are lateral, longitudinal, local, sloshing, buffeting, flutter, and wind load vibrations. Each of these categories is discussed briefly and applicable references given.

Model tests for gross buffeting of the entire launch vehicle during flight are described as being useful. However, local buffeting of panels, struts, etc., is described as being difficult to simulate either because of replication of boundary conditions or simulation of prototype turbulence environment. Present methods include measuring pressures on small rigid models for subsequent use as forcing functions in an analytical investigation.

Model and full scale response to crossflow wind testing are compared. The model results are in considerable error (conservative) unless the launch tower is immediately upstream from the launch vehicle. This suggests that difficulty in modeling air turbulence is the cause for the error observed.

16. U. L. Peterson et al., *Static and Dynamic Aerodynamics of Space Shuttle Vehicles*, NASA Space Shuttle Tech. Conf. III, NASA-TM-X-2272 (1971), pp. 311-374.

The large amount of aerodynamic data obtained for space shuttle configurations at NASA Ames Research Center is discussed. Objectives include describing configurations tested; comparing aerodynamic forces for different Mach numbers, Reynolds numbers, streamlining, and angle of attack; and presenting new analytical and test methods. In particular, at small Mach numbers, (0.3), the D-shaped body cross section flow-induced forces were found (see Ref. 18) to vary by orders of magnitude with the amount of rounding of the sharp edge (chine radius). The same magnitude change occurred for the rounded bodies when the Reynolds number was changed from 0.6 to 2.5×10^6 (based on body width), or the angle of attack was changed from 0 to 60°. The sharp-edged bodies were not sensitive to Reynolds number variation.

17. R. W. Hess, W. H. Reed, and J. T. Foughner, *Recent Studies of Effects of Ground Wind Loads on Space Shuttle Vehicles*, NASA Space Shuttle Technology Conference, 3, 155 (1971)

Single degree of freedom torsional instabilities (stop sign flutter) and translational instabilities (galloping), both due to the occurrence of negative total damping, are determined for specific shuttle configurations by the use of models. The significance for full-scale vehicles is examined. Galloping instabilities are found to be very Reynolds number dependent over the range 4×10^5 to 4×10^6, whereas the drag coefficient remained nearly constant for the same Reynolds number range.

18. T. B. Sellers, *Consideration of Reynolds Number Simulation for Subsonic Shuttle Tests*, NASA Space Shuttle Tech. Conf. III, NASA-TM-X-2272 (1971), pp. 423-454.

The aerodynamic force coefficients necessary for stability analysis of the D-shaped cylindrical body of the space shuttle are known to be sensitive to angle of attack and Reynolds numbers. Based on data for flat plates, delta wings, square cylinders with rounded edges, and yawed circular cylinders, an analytical model is constructed which categorizes expected flow mechanisms, Reynolds number sensitivity, and force and moment coefficients as a function of yaw angle. For yaw angles between 30° - 60°, the largest forces and greatest Reynolds number sensitivity is expected because of bound vortices produced at the nose. Above 60°, the nose vortex is expected to break down, with an associated reduction in forces and Reynolds number sensitivity. Data is deemed sufficient for bounding coefficient magnitudes of existing designs. More quantitative results for existing designs or bounds for more rounded D-shaped designs would require additional experimental data at simulated Reynolds number.

19. H. L. Runyan and R. C. Goetz, *Space Shuttle - A New Arena for the Structural Dynamicists*, Dynamic Response of Structures (New York: Pergamon Press, 1972), pp. 115-138.

The particular problems associated with the space shuttle vehicle during launch and flight are discussed in general. The use of holographic techniques via pulsed lasers are being investigated for vibration measurements at high temperatures (1000°F - 3000°F). Two ground wind load instabilities have been identified: stop sign (stall) flutter, and a galloping instability. This galloping instability has been found (see Ref. 17) to be Reynolds number dependent, and further tests in high speed wind tunnels will be performed. Also, references are made to the buffeting (see Ref. 16) and flutter problems expected for existing shuttle designs.

20. P. J. Grimes et al., *Advancements in Structural Dynamic Technology Resulting from Saturn V Programs*, Vol. II, NASA CR-1540 (June 1970)

Included is a discussion of the utility of a 1/10 replica scale model. It was useful in assessing Saturn V design changes and definition of instrumentation for full-scale testing. The scale model was used to refine mathematical modeling by showing where stiffness simulation, structural-fuel coupling, etc., were inadequate. Correlation between model and prototype response was never achieved mainly because replica (exact geometric scaling) of joints did not simulate prototype stiffness. Further damping was not simulated because full scale testing showed it to be amplitude dependent. Acceptable simulation of prototype response would have required artificial modeling of several joints based on knowledge of prototype response. The joint simulation was never made.

The major simulation of Saturn V was a mathematical representation which was developed based on parameter (damping, etc.) knowledge gained from full scale shaker testing. Most refinements were made on the basis of simulating shaker testing. No mention is made of predictions of flight response other than natural frequencies, mode shapes, and damping.

21. H. Himelblau, C. M. Fuller, and T. D. Scharton, *Assessment of Space Vehicle Aeroacoustic-Vibration Prediction, Design, and Testing*, NASA CR-1596 (1970)

An assessment of scale model testing for vibration response is included along with a discussion of similarity parameter selection. Mechanically transmitted vibration is best simulated using modeled engines, pumps, etc. Methods are given for characterizing a substitute model source. The vibration response to mechanical transmission requires structural damping scaling. Material damping similitude is found to be impracticable and requires different model and prototype materials. Bolted joint damping requires same static as well as dynamic coefficient of friction, which is usually impossible to achieve. Based on a review of literature (examples are cited), highly complex structure testing was found inadequate. However, when the model was simple, adequate correlation could be obtained.

22. J. W. Wissmann, *Dynamic Stability of Space Vehicles, Structural Dynamics Model Testing,* NASA CR-1195 (1968).

    Tutorial presentation of π similitude parameter calculations is presented. Similitude relations and difficulties are stated with little development. Buffeting, ground wind loads, and flutter model testing require Strouhal simulation. The first two require Reynolds number simulation as well. Surface roughness simulation is assumed critical in buffeting scaling. Damping simulation is very difficult. Elastic structural similitude parameters are discussed, also.

23. E. E. Ungar, R. E. Jewell, and H. J. Bandgren, *Rocket-Sled Model Study of Prediction Techniques for Fluctuating Pressures and Panel Response,* Shock and Vib. Bull. 41(Part 7), 1-7 (1970)

    The distortion of Reynolds No. and wall effects common to most wind tunnel studies were avoided by model testing (1/10 scale Saturn V, upper stage) on a rocket sled. Methods for predicting and experimentally obtaining fluctuating pressures under turbulent boundary layers and particular subsonic separated flows are summarized and shown to compare favorably. Key to predicting reasonable response is the identification of the flow regime and availability of applicable empirical pressure data for each regime.

24. C. E. Lemley and R. E. Mullans, *Buffeting Pressures on a Swept Wing in Transonic Flight - Comparison of Model and Full Scale Measurements,* Presented at Dyn. Spec. Conf.-AIAA, McDonell Air. Report MCAIR 73-005 (1973)

    For various angles of attack, RMS pressure and power spectral shapes compared well with full scale and 10% rigid model results, when data were plotted as a function of reduced (Strouhal) frequency and nondimensional power spectral density.

25. *The Need for Large Wind Tunnels in Europe,* AGARD-AR-60 (1972)

    Arguments are made for obtaining a wind tunnel which gives prototypic Reynolds number so that flow patterns during boundary layer transition, separation, and the interaction of shock waves and boundary layers can be simulated.

26. D. A. Sherman, D. L. Motycka, and G. C. Oates, *Experimental Evaluation of a Hypothesis for Scaling Inlet Turbulence Data,* AIAA Paper No. 71-669, AIAA/SAE 7th Prop. Joint Spec. Conf., Salt Lake City, Utah, 1971.

    The turbulence acting on compressor face due to complex flow through a jet inlet duct is shown to be nearly independent of Reynolds number, although the source of the turbulence is expected to be Reynolds number dependent. The apparent insensitivity to Reynolds number variation is due to the presence of a region in the inlet where nearly isotropic turbulence is established with little turbulence production.

27. L. P. Parlett, C. C. Smith, Jr., and J. L. Megrail, *Wind-Tunnel Investigation of Effects of Variations in Reynolds Number and Leading-Edge Treatment on the Aerodynamic Characteristics of an Externally Blown Jet-Flap Configuration,* Report No. NASA TN D-7194 (August 1973)

In general, the aerodynamic characteristics of the model were not significantly affected by changes in Reynolds number through the range tested (0.47×10^6 to 1.36×10^6), except above the stall where the highest Reynolds number data showed the lowest rolling and yawing moments for the engine-out condition.

The use of a 25-percent-chord leading-edge slat was found to be more effective than a 15-percent-chord leading-edge slat or a 30-percent-chord leading-edge flap in extending the stall angle of attack and in minimizing the loss of lift after the stall. The large slat was also effective in reducing the rolling moments that occurred when the engine-out wing stalled first. (from Authors' summary)

5. *Civil Engineering Structures*

1. T. S. Katra and D. B. King, *Noise Control Design Using Scale Model Tests*, J. Sound and Vibration <u>7</u>(1), 14-21 (1973)

Wind-tunnel tests are performed on a 1/20-scale model of a large turbine type air compressor to determine effectiveness of various noise-reduction techniques. Very little discussion on modeling is given.

2. J. D. Raggett, *Modeling Problems in the Study of Bridge Flutter*, Princeton University, 1971.

The main objective of the study was to investigate the dependence of the aerodynamic force on bridge structures as a function of Reynolds number in order to support or refute the common scale modeling practice of operating at greatly reduced Reynolds number. The assertion is made that although the steady drag forces over stationary bodies are known to exhibit Reynolds number independence, the interaction between a shed vortex and a vibrating model, and hence unsteady aerodynamic forces, has not been shown to exhibit Reynolds number independence. The shed vortices were considered to be due to bridge lift and/or a von Karman type flow separation mechanism.

Three different scale model sections were tested where the motion of the section was prescribed. All other dimensionless quantities being fixed, the results indicated that for the unsteady force and moment components over a change in Reynolds number from 3×10^4 to 6.5×10^5 the lift coefficient increased 10%, the phase angle between force and displacements decreased by one-half, and the moment coefficient doubled. The above conclusions were the same for each model.

3. B. J. Vickery and R. D. Watkins, *Flow-Induced Vibrations of Cylindrical Structures*, Proc. First Aust. Conf. on Hydr. and Mech.-1962 (New York: Pergamon Press, 1964), pp. 213-241.

Scale model experiments were conducted to determine the maximum response of a single cantilevered circular cylinder and four in-line cylinders subject to vortex shedding cross flow in air and water. The cylinders were rigid and elastically supported at the base with viscous damping. The experiment was designed on the basis of dimensional analysis and further specified with the assumption that damping energy lost equals energy absorbed from the disturbing fluid forces. The dimensionless variables simulated were the Strouhal number, the mechanical damping log decrement δ, and an effective modal mass ratio term M. Reynolds number was not simulated (10^4 - 10^5 in model, compared to 10^7 in prototype) and arguments were made that the scale tests would overestimate prototype response. When the nondimensional response was plotted versus M , the data collapsed to a single curve with little deviation. No comparisons to prototype response were made.

4. B. J. Vickery, *On the Reliability of Gust Loading Factors*, Wind Loads on Buildings and Structures, Nat. Bur. Stand. Building Science Series 30, 93-104 (1970)

   A simplified mathematical model between the time variation of wind loads and the ratio of peak to mean loads (gust factor) is proposed. The wind turbulence characterization, vibration mode shape, and damping are required input. The load pressure is assumed proportional to local velocity squared and mass density. Comparison with model data (no scaling relations given) indicated good agreement in the drag direction. The model is not expected to make predictions in the lateral direction where wake pressures are significant.

5. W. A. Dalgliesh, *Experience with Wind Pressure Measurements on a Full-Scale*, Wind Loads on Buildings and Structures, Nat. Bureau Stand. Building Science Series 30, 61-71 (1970)

   Wind pressure measurements made over a 4-year period on a 34-story building in downtown Montreal were used to obtain data for checking and improving wind tunnel techniques of modeling flow characteristics of wind and aerodynamic behavior of buildings.

   The major problems involved in making field measurements and in comparing them with wind tunnel measurements were found to be:

   (a) difficulty of establishing a static reference pressure and its relation to the static pressure in the wind tunnel;

   (b) inadequacy of wind velocity information, which in this case consisted of one anemometer and wind vane located 1,500 ft southwest of the building;

   (c) lack of stationarity and homogeneity of the velocity field as compared with the wind tunnel situation.

   Comparisons with model measurements are made on the basis of mean pressures, rms pressures, power spectra, and the correlation between selected pairs of pressures measured at various points on the building. Examples have been found of excellent agreement in almost all respects, but for some wind directions the comparisons gave unsatisfactory correlation. The lack of agreement is attributed mainly to differences between indicated and actual on-site wind direction, but this cannot be shown conclusively because of incomplete wind information. (from Author's abstract)

   Scaling laws are not given, but are referenced. Rigid stationary models were employed.

6. J. E. Cermak, W. Z. Sadeh, and G. Hsi, *Fluctuating Moments on Tall Buildings Produced by Wind Loadings,* Wind Loads on Buildings and Structures, Nat. Bureau Stand. Building Science Series 30, 45-59 (1970)

Wind loading on a 1:384 scale model of a building 666 ft high was studied experimentally in a thick-boundary-layer wind tunnel. Measurements of mean velocity and turbulence intensity upstream of the model building verified that the wind tunnel flow was an adequate simulation of atmospheric-surface-layer flow over an urban area.
Mean pressure distributions and local pressure fluctuations were measured for a variety of upstream roughness conditions and wind directions. Emphasis was placed on direct measurement of mean and fluctuating overturning moments by means of a strain-gage dynamometer. Peak values of the moment fluctuations were found to have a magnitude of ± 34% of the mean moment. Root-mean-square values of the moment fluctuations also were determined in an effort to relate the moment fluctuations to the measured pressure fluctuations. (from Authors' abstract)

Pressure fluctuation measurements indicated that for the Reynolds number tested ($\sim 10^5$), where the structures of interest had sharp edges, the flow was essentially Reynolds number independent. The structures were rigid.

7. S. H. Abu-Sitta and M. G. Hashish, *Dynamic Wind Stresses in Hyperbolic Cooling Towers,* J. Struc. Div., Proc. ASCE 99, 1823-1835 (1973)

An analysis of cooling tower model response is made, based on measured pressure fluctuations on a rigid model, and compared to response previously measured on a similar aeroelastic model. Prototype predictions are also made, without comparison to actual data. The analysis neglects inertial response of structure (a pseudo-dynamic analysis) on the basis that the frequency content of the wind pressure is far below the structural natural frequencies. Comparisons with the aeroelastic model response are good. Differences in the model and prototype static pressure and the location of the wake separation are significant due to distortion of Reynolds number, surface roughness, and wind tunnel turbulence. However, analyses based on model pressures are thought to give conservative prototype response.

8. C. Scruton, *Aerodynamics of Structures,* Int. Res. Sem. on Wind Effects on Buildings and Structures 1 (Toronto: University of Toronto Press, 1967), pp. 115-161.

Theme (review) article covers research on structural response to time averaged wind loads, to fluctuating forces due to wind, and to wind conditions which result in oscillatory and divergent instabilities. The magnitude of the Reynolds number, the character of the free stream turbulence, body geometry, and the presence of nearby bodies are cited as quantities whose variation can produce significant variations in the response to wind excitation. Many examples are discussed and referenced. Design requirements and prediction methods are summarized. The most importance is given to the use of aeroelastic models. However, simulation of Reynolds number, wind turbulence scale, and structural damping similarity is cited as being difficult but necessary, if meaningful data is to be obtained.

9. H. J. Leutheusser and W. D. Baines, *Similitude Problems in Building Aerodynamics*, J. Hyd. Div., Proc. ASME 93, 35-49 (1967)

From review of the current status of bluff-body building aerodynamics relating to static wind loading it becomes abundantly clear that the entire problem of similitude of flow about sharp-edged objects is poorly understood. In particular, contrary to the basic premise of model studies on sharp-edged three-dimensional bodies, Reynolds number is not always an insignificant parameter.

Following a dimensional argument, a new model law for flow about bluff bodies has been derived and substantiated. The significant similitude parameters appearing therein are relative boundary roughness and degree of boundary layer immersion. (from Authors' conclusions)

10. N. Isyumon, S. H. Abu-Sitta, and A. G. Davenport, *Approaches to the Design of Hyperbolic Cooling Towers against the Dynamic Action of Wind and Earthquake*, Int. Asso. Shell Struct. Bull. 48, 3-22 (1972)

Model and full scale studies provide an example where Reynolds number effects pressure distribution, boundary layer separation point location, and stresses. The effect of surface roughness in reducing Reynolds effects is also included.

11. N. Ellis, *A Technique for Evaluating the Fluctuating Aerodynamic Forces on a Flexible Building*, Proc. International Symposium Vibration Problems in Industry, Keswick, England, Paper No. 312, April 1973.

Flexible scale models and analysis techniques are developed which provide a means of measuring the spatial distribution and coherence of fluctuating aerodynamic forces. The technique requires measurement of the spatial distribution of the bending strain and acceleration for the model. The equations of motion are used to relate the measured response time history to the desired load time history. Attempts to obtain the random load spectra from the displacement spectra failed, because small errors in the measured response were shown to produce large errors in the loads.

12. J. Armitt, *Vibration of Cooling Towers*, Proc. International Symposium Vibration Problems in Industry, Keswick, England, Paper No. 311, April 1973.

Wind tunnel tests to determine wind induced stresses in a cooling tower employ aeroelastic models for which the power station site, wind turbulence and velocity gradient, Reynolds number, Strouhal number, structural material density, structural damping, and geometry are all simulated. Tests for a model of the Ferrybridge "C" power station show significant stresses at structural natural frequencies, which increase as the fourth power of wind speed upstream turbulence.

C. Vibration of Solids

1. *Material Properties*

1. S. H. Crandall, *On Scaling Laws for Material Damping,* NASA Tech. Note NASA TN D-1467 (Dec 1962)

   See Ref. 3, Sec. IB-2.

2. B. R. Hanks and D. G. Stephens, *Mechanisms and Scaling of Damping in a Practical Structural Joint,* Shock and Vibration Bulletin 36(4) (1967)

   See Ref. 6, Sec. IB-3.

2. *Simple Structures*

1. W. Sodel, *Similitude Approximations for Vibrating Thin Shells*, J. Acoust. Soc. America 49, 1535-1541 (1971)

General classical shell equations and boundary conditions are written and nondimensionalized for free and forced vibrations. So-called "true similitude parameters" are obtained by inspection of the coefficients. For free vibrations of a plate, the in-plane (membrane) dimensions and the plate thickness only appear together in the frequency similitude parameter. Thus, the true plate parameters allow the use of models where surface dimensions can be distorted with respect to plate thickness. For shells, other true parameters exist which require exact similitude scaling of the surface and thickness dimensions. In line with certain simplifying assumptions often made in shell problem solutions, membrane effects or bending effects are assumed to dominate and the appropriate governing equations used to obtain "approximate similitude parameters" for each assumption. The approximate parameters only include surface and thickness dimensions in the frequency parameters.

Forced vibration simulation is discussed and the example of a cylindrical shell given. The important point is made that most vibrations consist of both membrane and bending normal modes so that distortion of geometry is not valid generally.

When rotary inertia and shear effects are included, approximate similitude parameters cannot be determined which have surface and thickness dimensions only in the frequency parameter.

2. V. R. Kristiansen, W. Soedel, and J. F. Hamilton, *An Investigation of Scaling Laws for Vibrating Beams and Plates with Special Attention to the Effects of Shear and Rotary Inertia*, J. Acoust. Soc. America 20, 113-122 (1972)

The natural frequency model to prototype scaling laws were derived from classical beam and plate equations of motion,as well as those including shear and rotary inertia. For the classical equations,membrane geometry and the thickness only appeared together in the natural frequency similitude parameter. Thus analytically, the separate scaling (distortion) of membrane and thickness dimensions seemed feasible. The validity of the relations were examined for several compressor reed plates with complex cutouts. The geometry was the same for each,except for thickness. The classical scaling law predictions were accurate, except at high frequencies. The similitude parameters which account for shear and rotary inertia showed that distorted geometry scaling was not possible. Approximate correction factors for the classical laws were obtained from analytical solutions of simply supported beams and rectangular plates,which included shear and rotary inertia effects.

3. *Complex Structures*

1. D. V. Wright and R. C. Bannister, *Plastic Models for Structural Analysis*, Shock and Vibration Digest 2 (1970)

   The use and fabrication of plastic models in determining the static and dynamic response of complex structures is discussed. Examples of steam condensors, turbines, and ship structures are given. Advantages and disadvantages are discussed. Cost is claimed to be less than computer analysis. Simulation of flow-induced vibrations is difficult because of need to simulate solid/fluid densities, etc. Natural frequency, off resonant amplitudes, and resonant amplitudes were found to be accurate within 5%, 10%, and 100-200% respectively. Joint damping was found difficult to simulate and damping simulation is discussed extensively.

2. R. C. Bannister, *Comparison of the Dynamic Response of a Complex Plastic Model with its Prototype*, J. Acoust. Soc. America 43, 1306-1310 (1968)

   Comparisons were made between natural frequencies and modal shapes obtained from a plastic model and prototype twin turbine generator sets that were installed on a common bedplate. Model-prototype prediction laws were given. Only the low frequencies were investigated where the major machine components could be considered rigid bodies and the relatively simple beam framework bedplate deformable. The systems were driven with electrodynamic shakers placed symmetrically on the turbines or the framework. The natural frequency and mode shape variations between model and prototype ranged between 5 to 15%. Only one frequency and associated mode shape could be excited at one time because the speed of sound, and therefore the scaling laws, were functions of frequency for the viscoelastic model material.