AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

DOE/ER/14/68--T1

CORNELL
UNIVERSITY

**NONLINEAR DYNAMICS OF
FLUID-STRUCTURE SYSTEMS**

Annual Technical Report to

**U.S. Department of Energy
Office of Basic Energy Sciences**

**Francis C. Moon
Principal Investigator**

**George Muntean
Graduate Research Assistant**

**Sibley School of Mechanical and Aerospace Engineering
Cornell University
Ithaca, New York 14853**

January 1994

**RECEIVED
MAY 31 1994
OSTI**

MASTER

JFB

Nonlinear Dynamics of Fluid-Structure Systems

Summary

We are investigating the nonlinear dynamics of a row of cylindrical tubes excited by the cross flow of fluid. Both experimental and analytical/numerical studies have been conducted. The goal of this research is to look for low dimensional dynamic models in flow-induced vibrations using modern methods of dynamical systems and chaos theory. The experimental study uses a 25 cm x 25 cm wind tunnel with flow velocity in the range of 15 m/sec. The use of a wind tunnel to explore dynamic phenomenon compliments the work of Chen at Argonne National Laboratory who also is conducting experiments with a water tunnel.

The principal nonlinearities studied are impact constraints due to gaps in the cylinder supports and nonlinear fluid forces.

Background

Fluid-elastic problems come in several classes such as flow over slender bodies flows around bluff bodies or flows in elastic tubes. Nonlinear studies of flow over slender bodies or flow over curved or flat elastic panels have been studied by Dowell and co-workers. (Dowell, 1975; Dowell and Ilgamova, 1988). The study of internal flows in elastic bodies such as tubes or pipes using modern methods of nonlinear analysis has received a lot of attention from both analysts and experimentalists. Examples of theoretical studies include those of Bajaj and Sethna (1984, 1991) and Troger and coworkers (1988). Experimental studies of chaotic and other nonlinear dynamic behavior of elastic tubes with internal flow have been performed by Paidoussis and Moon (1988) and Copeland and Moon (1992).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Fluid-elastic flows around bluff bodies such as cylinders in heat exchangers present a formidable challenge because of flow separation which can form regular and nonregular vortex patterns in the wake or other complex forms of turbulent flows. Fluid-elastic studies of these problems have been mainly empirical as are represented in the book by Blevins (1986).

Linear models for the dynamic behavior of tube array vibrations in cross and parallel flows have been presented by Chen and Co-workers at Argonne National Laboratories (1983, 1985). Nonlinear models for a single bluff body include the wake-oscillator model (Hartlen and Currie, 1970) in which the fluid dynamics is represented by a second order differential equation with nonlinear damping and coupled to a mechanical oscillator representing the elastic system.

While the wake-oscillator model seems to be an ad-hoc theory, from the prospective of modern nonlinear dynamical systems theory, the existence of low order dynamic models in high dimensional spatio-temporal systems is quite natural in dissipative dynamical systems. In such problems, the concept of a finite dimensional center manifold in the state space on which the motion evolves has been discussed by many theoreticians (See e.g. Guckenheimer and Holmes, (1983). For chaotic behavior, the use of the fractal dimension measure as well as other techniques such as Lyapunov exponents and false-nearest-neighbors have provided a tool to place a bound on the essential dimension of a state space that is required to describe a nonlinear system. (See e.g. the recent book by the Principal Investigator (1992), or the work of Kennel et. al, 1992.) Thus in the problem of nonlinear vibrations of elastic tube arrays in external flow it is natural to try to apply these new experimental techniques to try to establish the existence of low dimensional nonlinear models for complex dynamical behavior. Low dimensional models not only enable the investigator to uncover the bifurcation sequence from simple to complex behavior but they are essential in being able to design some effective vibration control scheme whether it be passive or active.

One aspect of bluff body fluid elastic problems that is different from internal tube flow problems is the existence of low level turbulence excitations below the transition to self-excited fluid elastic vibrations. This can be seen in recent experiments at Cornell using a five cylinder tube

row in cross-flow of air. Very little work has been done on the interaction of random force excitation and deterministic nonlinear chaotic dynamics. (See e.g. Crutchfield and Farmer 1982). One approach has been to add a small amount of noise to a deterministic model and use the Fokker-Planck equation to derive a probability distribution function. There is also a body of literature in the stochastic and random vibration field concerning nonlinear systems. However our goal in this research is to try to use new tools of analysis to uncover relatively simple models that can predict complex behavior in fluid elastic systems and to see if these models can be useful in designing vibration inhibiting or damping of fluid-elastic motions.

Current Grant Progress Report

This section summarizes experimental work done to date on the dynamics of tube rows in cross flow. An air tunnel has been dedicated to the study and its performance results are included. The current testing consists of a row of five tubes with a Pitch/Diameter (P/D) ratio of 1.35 installed in a 25.6 x 25.6 cm² test section.

Facilities Description

The present investigation is being performed with a wind tunnel (Figure 1). The tunnel is a standard blower type tunnel powered by a 7.5 HP AC-Motor. Air velocity is controlled by adjusting the drive motor speed via a variable-frequency controller. The air is drawn down through a filter box into a six blade centrifugal blower via a standard bell-mouth. The blower is rated at 3425 cfm with 6 inches of water static pressure at 2504 rpm. The blower outlet (8.25" by 10") feeds into an acoustic muffler via a soft coupling (to remove mechanical vibrations). A primary diffuser is fitted with seven screens (0.0075" diameter, 0.35 solidity) to prevent flow separation. The diffuser is followed by a 48" by 48" settling chamber to produce a uniform flow with minimal turbulence. The flow is contracted via a seventh-order polynomial profile contraction section to a final cross-section of 10.125" by 10.125" (256mm by 256mm). The contraction section is connected to a three foot test section constructed of Plexiglas. Finally, the test section is

followed by a six foot wooden outlet section to prevent any exit conditions from influencing the test section.

As standard practice, the wind tunnel was evaluated for uniformity and turbulence level as measures of performance. The uniformity (measured with a pitot-static tube) was found to be 0.09% in the horizontal direction and 0.35% in the vertical direction, see Figure 2. The turbulence level was measured using a hot wire anemometer calibrated with a pitot-static tube. The flow velocity, hot wire voltage and hot wire voltage variations (rms) were averaged over periods of roughly 1 minute. After factoring out the baseline noise due to test equipment electronics, the maximum turbulence level was found to be 0.23%.

Description of Experiments

The ultimate objective of the current program is to understand and model the instability of tube arrays subject to crossflow. An arbitrary tube within an array can lose stability from a variety of mechanisms including buffeting, wake galloping, acoustic resonance, fluid-elastic instability and possibly vortex shedding. As a first step, it seems reasonable to try to isolate the particular mechanisms and understand them individually before studying them as a whole. To this end it was felt that a first step should include the study of the instabilities within a single tube row. In this configuration there exists no possibility of (upstream) turbulent buffeting or wake galloping. Furthermore, a review of the literature indicates that vortex shedding and acoustic resonances do not appear to be present in tube rows with P/D ratios below 1.5. By choosing a P/D ratio of 1.35 it is felt that all instability mechanisms are precluded with the exception of the fluid-elastic instability.

The current testing consists of a row of five tubes with a P/D ratio of 1.35 installed in a 256mm by 256mm test section. The tubes are 38mm diameter plexiglass tubes with a wall thickness of 3.5mm. The three center tubes can be mounted flexibly with linear springs. The spring rates of the tubes in the lateral direction can be adjusted independently of the spring rates in the inline direction.

In order to minimize the effects of the test section boundaries the two tubes closest to the walls are held rigid. A cross-section of the test section is shown in Figure []. The mounting of the tubes is shown in Figure []. The flexible tubes are supported on either end by 1/16" diameter steel rods. The rods are mounted rigidly to the tubes and pinned to the support structure thereby creating a cantilevered system. The tubes are mounted vertically thereby producing an additional effective spring rate due to gravity (pendulum effect). To compensate for this effect the upper cantilever was 300mm in length while the lower cantilever was 245mm in length. To adjust the inline spring rate two additional springs were added to the tubes (one above, one below) which acted only in the streamwise direction. The procedure for adjusting the spring rates consists of

first adjusting the transverse spring rates by varying the length of the cantilever supports and then adjusting the inline spring rates by adding the necessary additional tension springs.

The tension springs also allowed the static position of the flexible tubes to be held in the nominal position. As the flow velocity is increased, the static tension in the springs are increased to counteract the increased dynamic pressure on the flexible tube. This arrangement allows for the study of a true tube row with no offset.

Various configurations were tested including adjacent tubes restricted to only lateral motions. The final configuration used in this study consisted of a row of five tubes with only the center tube mounted flexibly. The center tube has two degrees of freedom with two distinct natural frequencies although the instability only excites the inline degree of freedom.

A summary of the system parameters is given below:

Table 1

mass of tubes:	0.19 kg
diameter of tubes:	38 mm
P/D:	1.35
mass damping ratio:	26.8
critical flow rate (upstream):	3 m/s & 4.2 m/s (measured) 3.16 m/s (calc. - Connors)
Reynolds Number:	40,000 max. @ instability
Natural frequency in still air	6.4 Hz (inline to flow), 2.8 Hz (transverse)
Damping ratio in still air	0.011 (inline to flow), 0.025 (transverse)

Bifurcation Diagram

The tube row configuration investigated is known to undergo a bifurcation known as the fluid-elastic instability. (Chen, 1983) At lower flow rates the tubes vibrate at a low amplitude that varies roughly linearly with the flow velocity. These oscillations are not periodic and have often been assumed to be of a stochastic nature. This pre-flutter vibration is likely due to instabilities in

the vortex flow behind the cylinders. As the flow rate increases past a certain point the tubes begin to oscillate violently in a roughly periodic fashion. Past this transition the amplitude of the motions no longer varies linearly with the flow rate but increase as some higher power. This Hopf-type bifurcation can clearly be seen in Figure 5.

Preliminary Results

In Figure 6 are shown typical time series, phase plane, pdf's and power spectrums of the strain signal for the small scale motions believed to be due to the buffeting of the tubes from the recirculation in the wake. These represent points on the bifurcation diagram below upstream flow velocities of 4 m/s. These represent points on the bifurcation diagram immediately below the sudden jump in amplitude.

The precritical motions appear quite random with a broad power spectrum (Figure 6c) and a single hump pdf (Figure 6b). Many investigators have assumed this motion to be turbulent buffeting and of a stochastic nature. The postcritical motions shown in Figure 7 shows the more periodic nature of the oscillations. The main frequency component is at 6.4Hz (very near the natural frequency of the tubes in still air).

Fractal Dimension Calculation

The ultimate objective of this study is to produce low order nonlinear models for the dynamics of flexible tubes in crossflow. Before this may be accomplished, however, it must first be determined how many active degrees of freedom are present in the dynamics. We have no information a-priori on the size of the attractors. In order to find bounds on the number of degrees of freedom we use a technique known as embedding. It is now well known that a phase space may be reconstructed from a single time series by plotting $x(\tau)$ versus $x(\tau + d\tau)$ where $d\tau$ is a delay time. By increasing the dimension of the embedding space and calculating the fractal dimension of the attractor in that space one can determine when enough degrees of freedom are present (since the dimension of the attractor will no longer increase).

Once the time series has been embedded, a variety of techniques can be used to calculate the fractal dimension of the attractor. Figure 8 shows the results from the computation of the correlation dimension at successively higher embeddings for the precritical behavior configuration #1 (this corresponds to the time trace shown in Figure 6a). The fractal dimension of the attractor is the slope of the curves in the linear regime. Figure 10 plots the fractal dimension as a function of the embedding dimension. The 45 degree line represents stochastic behavior since a random signal will fill any size embedding space. 200,000 points were used in the analysis ensuring fine resolution to at least 6 embedding dimensions. As is evident from the figure, the precritical buffeting does not appear to have a low order attractor. However, this analysis cannot confirm that the dynamics are truly stochastic. Figures 9 and 11 show the same data for the post-critical case. Here there does appear to be a leveling off indicating the possibility of low order dynamics. Furthermore, examination of figure 9 reveals a linear regime at large length scales with fractal dimension of 1.1. This indicates that the attractor appears to be nearly one dimensional when the fine scale dynamics are neglected. Recently a new method has been published by a group at U. Cal at San Diego under Professor H. Abarbanel called "False Nearest Neighbors" (Kennel, et. al, 1992). We plan to try this technique on the flow-induced vibration data in order to check the results of the fractal dimension calculations. Further planned tests in the coming months include using flow visualization to investigate the nature of the flow behind the flexible tubes, especially in the pre-flutter regime.

Proposed Research

The research at Cornell will be coordinated with that of Dr. Chen at Argonne National Laboratory. The focus will be on the dynamics of a row of cylinders in cross flow. The Cornell facility built in 1993 involves a wind tunnel with speeds of up to 15 m/s. At present we are studying a five cylinder tube row with one, two or three on elastic constraints. The Argonne facility is using a water tunnel. These tests are complimentary in that they look at different flow regimes.

The Cornell program will focus on the following aspects of the nonlinear dynamics of fluid-elastic motions of the cross flow problem.

This project will be a continuation of the study of nonlinear dynamics in fluid elastic problems centered around the crossflow around a row of cylinders. The methods used will involve modelling, analytical and computational methods and experimental studies using a wind tunnel. The principal nonlinearities will be impact constraints due to gaps in the cylinder supports as well as nonlinear fluid-elastic forces. The goal will be to look for low-dimensional dynamic models using modern methods of dynamical systems and chaos theory. Current research results have shown the existence of pre-flutter vibrations in the tubes presumably generated by vortex instabilities in the preflutter flow. Our current thinking is to develop a lift-oscillator model similar to the Hartlen and Currie Model (1970) in which the lift and drag coefficients on the cylinder depend on time and are themselves governed by differential equations of the Van-der Pol type (See also Blevins, 1986). This phenomenological approach has been used successfully on the single cylinder. For the multi-cylinder case, Chen of Argonne National Laboratory, has developed force estimates for the cylinder-cylinder interaction that can predict the onset of flutter. It is believed that using both a lift oscillator concept along with the Chen theory, one will be able to produce a model that will simulate both preflutter and post-flutter dynamic behavior. In these studies several types of investigation will be used:

- a) Bifurcation analysis
 - b) Quasiperiodic excitation and multifractals
 - c) Interaction of random and deterministic forces
 - d) Use of control to suppress fluid-structure vibration
-
- a) Bifurcation analysis

Here we are seeking to understand the transition from one type of dynamical motion to another as the flow velocity changes and as a function of tube geometry and constraint parameters. We will use both experimental as well as analytical models in this study. In fact we hope to use the

experimental bifurcation study as a proof test of proposed analytical models. Thus we will observe changes in vibration modes (eigenvalues, and eigenfunctions), power spectra, fractal dimension, and probability distributions as a function of flow speed both in the pre- and post-flutter regimes. In earlier studies (e.g. Paidoussis and Moon, 1989, and Copeland and Moon, 1993) both periodic, quasi-periodic and chaotic dynamics were observed in elastic pipe flow problems. In this study the existence of several elastic cylinders will likely produce quasi-periodic vibrations. Of interest here is how these quasiperiodic motions transition into chaotic dynamical behavior.

b) Quasiperiodic excitation and multifractals

In an earlier paper resulting from research under the present grant (Muntean and Moon, 1992) multifractal probabilities distribution functions in the phase space of the flow were observed for vibration of a long elastic tube with internal flow. Such multifractal properties seem to be a precursor to the transition from quasiperiodic motion to chaotic motion as can be seen in the study of the simple circle map (e.g. Halsey et. al 1986). Multi-fractal behavior has also been observed in a number of fluid flow problems such as Rayleigh-Benard flow. Therefore, it is natural to see if we can measure such a transition in the cross-flow problem around a row of tubes.

c) Interaction of Random and Deterministic Forces

As discussed above, experiments on the cross-flow around cylinders in a low turbulence wind tunnel have shown a preflutter excitation of the cylinders due to unstable fluid flow (possibly jet switching between cylinders). Preliminary measurements of fractal dimension seem to indicate a low order attractor for the pre-flutter dynamics. However we expect that in the post flutter regimes, the fluid forces will exhibit a high order turbulent component that might be modelled with a random (pink noise) excitation. There are few studies on the interaction of deterministic chaos and random excitation (see e.g. Crutchfield et. al 1982). Our effort will not be a major study but if we can produce a good model for the deterministic dynamics, then we will look at the behavior of this model under random forces as well as to compare the results with experiments.

d) Control of Chaos and Fluid-elastic Vibrations

The principal investigator has had a long history of studying control of flutter (Moon & Dowell, 1970, Horikawa, et. al 1978). Also Chen of Argonne has also attempted to control fluid-elastic vibrations. Recently studies out of the University of Maryland have shown promise in applying new ideas in the control of chaotic vibrations. Here use is made of the existence of a low dimensional stochastic attractor and the use of digital control or maps. We believe it is worthwhile to explore these new ideas as well as other possibilities of controlling fluid elastic vibration especially by controlling the motion of the cylinder supports. For example, in the case of cylinder impact on supports with gaps we will explore the use of actively taking out energy at the support during an impact as a way to try to control or influence the fluid-elastic motions.

Collaboration with Argonne National Laboratory

The current project has been in cooperation with Argonne National Laboratory and Dr. S.S. Chen. This cooperation began with a short course on chaotic dynamics by the Principal Investigator that was presented at Argonne to Dr. Chen and other Argonne staff. Since then both the P.I. and his student, Mr. George, Muntean, have visited Dr. Chen on different occasions to consult on the progress of this research. As a result of these visits it was decided to build a wind tunnel at Cornell to study flow-induced vibrations as a complement to the water channel test being done at Argonne.

In the renewal proposal we plan to continue this collaboration. In particular we are interested in using a fluid force model of Dr. Chen in our simulation model and to compare it to experimental tests on our wind tunnel, especially bifurcation sequences from steady to chaotic motions. We also intend to transfer to Argonne new techniques on signal processing of chaotic signals, such as the "false nearest neighbors" test for dimension of Abarbanel. It is also planned that the effort to design control for fluid-structure dynamics will be a collaborative effort.

References

- Bajaj, A.K., and Sethna, P.R.(1984). "Flow induced Bifurcations to Three-dimensional Oscillatory Motions in Continuous Tubes," *SIAM J. of Applied Mathematics*, **44**(2), 270-286.
- Bajaj, A.K., and Sethna, P.R. (1991). "Effect of Symmetry-breaking Perturbations on Flow-Induced Oscillations in Tubes," *J. Fluids and Structures*, **5**, 651-679.
- Blevins, R.D. (1986). *Flow-Induced Vibration*, Krieger, Malabar, Florida, 2nd Ed.
- Cai, Y., and Chen, S.S. (1992). "Chaotic Vibrations of Nonlinearly Supported Tubes in Crossflow," *ASME Publication, PVP- Vol. 242*, 223-241.
- Chapman, G.T., Yates, L.A., and Szady, M.J. (1992). "Atmospheric Flight Dynamics and Chaos: Some Issues in Modeling and Dimensionality," Chapter 4 in *Applied Chaos*, John Wiley & Sons, Inc.
- Chen, S.S. (1983). "Instability Mechanisms and Stability Criteria of a Group of Circular Cylinders Subjected to Cross-Flow," *J. Vibration, Acoustics, Stress and Reliability in Design*, **105**, 51-58.
- Chen, S.S., and Jendrzejczyk, J.A. (1985). "General Characteristics, Transition and Control of Instability of Tubes Conveying Fluid," *J. Acoustical Society of America*, **77**, 887-895.
- Chen, S.S. (1987) "Flow-Induced Vibration of Circular Cylindrical Structures," Hemisphere Publishing Co., New York.
- Chen, S.H., and Chen, S.S. (1993). "Chaotic Vibration in Fluidelastic Instability of a Tube Row in Crossflow," Presented at the 1993 ASME PVP Conference, Denver, Co.
- Chen, S.H. and Chen, S.S. (1993). "Nonlinear Fluid-Stiffness-Controlled Instability of Tube Row in Crossflow," to be submitted for presentation at Asia-Pacific Vibration Conference '93, November 14-18, 1993, Kitakyushu, Japan.
- Copeland, G.S. and Moon, F.C. (1992). "Chaotic Flow-Induced Vibrations of a flexible Tube with End Mass," *J. Fluids and Structures*, **6**, 705-718.
- Crutchfield, J.P. and Farmer, J.D. "Phys. Rep **92**(2), 45-82.
- Cusumano, J.P. (1990). "Low-Dimensional, Chaotic, Nonplanar Motions of the Elastica: Experiment and Theory, " Doctoral Dissertation, Department of Theoretical and Applied Mechanics, Cornell University.
- Dowell, E.H. (1975). *Aeroelasticity of Plates and Shells*, Noordhoff International Publ.
- Dowell, E.H., and Ilgamova, M.(1988). *Studies in Nonlinear Aeroleasticity*, Springer-Verlag.
- Glazier, Jensen, Libchaber, and Stavans (1986) "Structure of Arnold tongues and the f(a) spectrum for period doubling: Experimental results," *Physical Review A*, **34** #2.
- Grassberger, P. and Proccacia, I., (1985). "Measuring the Strangeness of Strange Attractors, *Physica* **9D**, 189-208.

- Guckenheimer, J., and Holmes, P., (1983). *Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields*., Springer-Verlag, New York.
- Halsey, Jensen, Kadanoff, Procaccia, Shraiman, (1986). "Fractal measures and their singularities:: The characterization of strange sets," *Physical Review A*.
- Hartlen, R.T., and Currie, I. G. (1970). "Lift Oscillation Model for Vortex-induced Vibrations of Bluff Bodies", *J. Engineering Mechanics Division*, ASCE, 96 577-591.
- Horikawa, H., Dowell, E.H., and Moon, F.C. (1978). "Active Feedback Control of a Beam Subjected to a Nonconservative Force", *Int. J. Solids and Structures*, **14**, 821-839.
- Kalmbach, C.F., Dowell, E.H., and Moon, F.C. (1974). "The Suppression of a Dynamic Instability of an Elastic Body Using Feedback Control," *International J. Solids and Structures*, **10**, 361-381.
- Kennel, M.B., Brown, R. and Abarbanel, H.D.I. (1992). *Physical Review A*, **45**(6), 3403-3411.
- Lever, J.H. and Weaver, D.S. (1982). "A Theoretical Model for Fluid-Elastic Instability in Heat Exchanger Tube Bundles", *J. Pressure Vessel Tech.*, vol. **104**, 147-158.
- Moon, F.C., and Dowell, E.H., (April 1970). "The Control of Flutter Instability in a Continuous System using Feedback," Proc. AIAA-ASME 11th Structure and Materials Conf., 48-65.
- Moon, F.C., (1992). *Chaotic and Fractal Dynamics*, Wiley-Interscience, New York.
- Muntean, G.G., and Moon, F.C. (1992). "Multifractals in Flow-Induced Vibrations", to appear in *J. Fluids and Structures*, Presented at the 10th Symposium on Energy Engineering Sciences, Argonne National Laboratory.
- Païdoussis, M.P. (1980). "Flow-induced Vibrations in Nuclear Reactors and Heat Exchangers", *Practical Experiences with Flow-induced Vibrations* , 1-81, Edited by E. Naudascher and D. Rockwell, Berlin, IAHR/IUTAM, Springer-Verlag.
- Païdoussis, M.P., and Moon, F.C. (1988). "Nonlinear and Chaotic Fluidelastic Vibrations of a Flexible Pipe Conveying Fluid," *Journal of Fluids and Structures* **2** 567-591.
- Roberts, B.W. (September 1966). "Low Frequency, Aeroelastic Vibrations in a Cascade of Circular Cylinders," M.E.S.M. **4**.
- Sethna, P.R. and Shaw, S.W. (1987). "On Codimension-three Bifurcations in the Motion of Articulated Tubes Conveying a fluid," *Physica* **24D** 305-327.
- Simiu, E., and Cook, G.R. (1991). "Chaotic Motions of Self-excited Forced and Autonomous Square Prisms," *J. Engineering Mechanics* **117**(2) 241-259.
- Skop, R.A., and Griffin, O.M.(1973). "A Model for Vortex-excited Vibrations of Bluff Bodies," *J. Sound and Vibration* **27**(2) 225-233.
- Southworth, P.J., and Zdravkovich, M.M.(1975). "Cross-flow-induced Vibrations of Finite Tube Banks in in-line Arrangements," *J. Mechanical Engineering Science* **17**(4), 190-198.
- Steindl, A., and Troger, H.(1988). "Flow-Induced Bifurcations to Three-Dimensional Motions of Tubes with an Elastic Support," *Trends in Applications of Mathematics to Mechanics*, 128-138.

Tanaka, H., and Takahara, S. (1981). "Fluid Elastic Vibration of Tube Array in Cross Flow," *J. Sound and Vibration* **77**(1).

Toebe, G.H. (1969). "The Unsteady Flow and Wake near an Oscillating Cylinder," *J. Basic Engineering* 493-505.

Grant Related Publications

1. Moon, Francis C., "Experimental Measurement of Chaotic Attractors in Solid Mechanics", *J. Chaos*, **1** (1), pg. 31-41, 1991.
2. Moon, Francis C., Chaotic and Fractal Dynamics, John Wiley and Sons, October, 1992.
3. Copeland, G.S., Moon, Francis C., "Chaotic Flow-Induced Vibration of a Flexible Tube with End Mass", *J. of Fluid and Structures*, **6**, pg. 705-718, 1992.
4. Muntean, G.G., Moon, Francis C., "Multifractals in Elastic Tube Vibrations Due to Internal Flow", *J. of Fluids and Structures*, to appear.
5. Muntean, G.G., Ph. D. Dissertation expected July 1994, experimental study nonlinear vibrations of a row of elastic cylinders in cross flow.

Figure 1 "Low Turbulence Air Tunnel"

Figure 2 "Air Tunnel Performance Characteristic"

Figure 3.

Figure 4.

Figure 5 "Bifurcation Diagram"

Figure 6.a

Figure 6.b

4/10/94 afternoon 9:30

Figure 6.0

7/21/94 2:16:00 PM

Figure 6.d

Figure 7.a

Figure 7.b

4/11/84 afternoon 99m

4.5 m/s

Figure 7.c

4/21/64 afternoon 9gm

10%

Figure 7.d

Figure 8

Figure 9

Figure 10.

Figure 11.

**DATE
FILMED**

6/23/94

END