NONLINEAR DYNAMICS OF FLUID-STRUCTURE SYSTEMS

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SUMMARY

Detailed results of research under this grant were reported in several annual Progress Reports to DOE as well as in numerous published research papers. A list of research papers, books and dissertations completed during this grant period are listed in the Appendices. Some of these publications were as a result of direct DOE support while others benefited from indirect support as well as from other sources.

The technical research was directed at problems involving the dynamics of fluid flow and elastic structures. Such problems occur in heat-exchange systems in energy generating plants. Fluid excited vibrations of structures can result in unwanted impact forces which can lead to metal fatigue failures. Mathematical theories based on linear models have been used for several decades. In this research we explored the phenomenon associated with nonlinear effects using experimental models, mathematical models and numerical computation. Two principle geometric configurations were examined; flow inside a flexible tube and external cross flow around a row of cylindrical tubes.

A number of nonlinear effects were observed experimentally including chaotic dynamics, multi-fractal Poincaré maps, quasi-periodic vibrations, subcritical Hopf bifurcations, helical waves in a tube row and spatial localization. Flow visualization methods were used as well as video recording of tube row dynamics. For example, these methods revealed the importance of multiple, fluid jet configurations in the wake behind the tube row on the dynamic stability of the tubes. New nonlinear mathematical models were identified using techniques from nonlinear dynamics including center manifold theory, normal form theory and harmonic balance.

In addition to the research results, two Ph.D. students received training under this grant. Both are working in American industry.

APPENDIX I: LIST OF PUBLICATIONS

Books

F.C. Moon, *Chaotic & Fractal Dynamics*, J. Wiley & Sons, 1992.

Editorial Proceedings

F. C. Moon, Editor, *Proceeding fo IUTAM 1997*, Kluwer Publishing, 1999.

Published Papers related to DOE grant

G.S.Copeland, F.C.Moon, "Chaotic Flow-Induced Vibration of a Flexible Tube with End Mass",
J. Fluids and Structures **6**, (1992) 705-718.

B.F. Feeny, F.C. Moon, P.Y. Chen and S. Mukherjee, "Chaotic Mixing in Rigid, Perfectly Plastic Material," Int'l. Journal of Bifurcation and Chaos **5** (1) (1995) 133-144.

G.G. Muntean and F.C. Moon, "Multifractals in Elastic Tube Vibrations Due to Internal Flow,"
Journal of Fluids and Structures **9** (1995) 787-799.

B. Feeny and F.C. Moon, "Chaos in a forced dry-friction oscillator: experiments and numerical modelling," J. of Sound and Vibration **170** (3) (1994) 303-323.

F.C. Moon, M.A. Johnson and W.T. Holmes "Controlling Chaos in a Two-Well Oscillator,"
Int'l. J. of Bifurcation and Chaos **6** (2) (1996) 337-347.

V. Bhatt and F.C. Moon "Measures of Robust Dynamical Behavior and Fractal Basin Boundaries for Two- and Three-Well Potential Problems," AMD 192, DE 78, Nonlinear and Stochastic Dynamics, ASME (1994).

M.A. Davies and F.C. Moon, "Transition from Soliton to Chaotic Motion During Impact of a Nonlinear Elastic Structure," *Chaos, Solutions & Fractals* **4** (2) (1994) 275-283.

M. Thothadri and F.C. Moon, "Helical Wave Oscillations in a Row of Cylinders in Cross Flow,"
J. Fluids & Struct. **12** (1998) 591-613.

APPENDIX II: ABSRACTS OF DISSERTATIONS

Thesis Publications

Ph.D -- George Muntean, 1995

IIA

M.S. -- Mani Thothadri, 1996

IIB

Ph.D -- Mani Thothadri, 1999

IIC

INFLUENCE OF FLUID WAKE STRUCTURE ON THE DYNAMICS OF A FLEXIBLE TUBE ROW IN CROSS FLOW

George Gabriel Muntean, Ph.D.

Cornell University 1995

The basic tenet of this dissertation is that an understanding of the structure of the flow field is vital to the understanding of the fluid-elastic instability in cylinder rows subject to a cross flow. Wind tunnel testing, with smoke-wire visualization, was conducted on a row of five circular cylinders with a pitch to diameter ratio of 1.35. The central cylinder, mounted elastically, was found to undergo a subcritical Hopf bifurcation as the flow rate was increased. The post-critical oscillations were on the order of magnitude of the cylinder diameter and in line with the upstream flow direction. Direct measurement of the fluid forces in tandem with the flow visualization revealed a strong dependence of the cylinder dynamics on the behavior of the planar jets emanating from the gaps between cylinders.

Flow visualization testing was done using a unique long duration technique. It was found that the jets emanating from between the cylinders coalesce with one another in several unique configurations. Four stable

states were found to exist and their affect on the cylinder stability established. The flow visualization results suggest a new instability mechanism by which the jet structure in the wake produces a delayed feedback between the pressure field and the cylinder dynamics. However, detailed analysis of this instability mechanism was not undertaken here.

Static and dynamic fluid force measurements were taken. It is shown conclusively that the fluid force stiffness and damping coefficients depend critically on the wake structure and, in particular, the jet configuration. These measurements confirmed the loss of stability through a negative damping mechanism. The fluid force data were used to construct linear and nonlinear models for the instability.

The dynamics of the cylinder were described with time series, power spectrum, pdf, autocorrelation, phase plane and embedding dimension analysis. Three distinct behaviors were identified including apparently stochastic motions at low flow rates, periodic 'limit cycle' oscillations at high flow rates and intermittent 'bursting' type behavior at intermediate flow rates.

Manivannan Thothadri, M.S.

Cornell University 1996

ABSTRACT

A row of cylinders oscillating due to cross flow in a wind tunnel is investigated. An experimental setup with a row of nine cylinders, with fixed cylinders at each end is built. The coupling between the cylinders is provided only by the air flowing past the cylinders. It is observed that for small flow velocities, the oscillation amplitude of the cylinders is small and the oscillations are mostly stochastic. As the flow velocity is increased past a threshold, called the critical flow velocity, the small amplitude oscillations of the cylinders loses stability in a sub-critical Hopf bifurcation. The modal patterns of the limit cycle oscillations of the cylinders are obtained. It is also observed that as the number of oscillating cylinders in the cylinder row is increased, the critical flow velocity decreases.

The system is modelled as a set of coupled, linear, two degrees of freedom oscillators, with the interactions of the structure with the fluid providing the coupling between the cylinders. The forces exerted by the fluid on the cylinder are approximated as linear functions of the relative motions between adjacent cylinders and flow velocity. The component of the fluid force along each degree of freedom of any cylinder, consists of two parts; one due to relative motion along the degree of freedom (direct coupling) and the other transverse to it (cross-coupling). The direct coupling terms are measured experimentally and the cross-coupling terms are fit, by analyzing the instability mechanisms, to match the experimental

observations. The Auto Regressive Moving Average (ARMA) process of the system identification theory is used in the experimental measurements.

The linear model is analyzed by obtaining a travelling wave solution for the propagation of a disturbance in the periodic, infinite cylinder row. The dispersion relations between the frequency and the wave numbers of the waves propagating through the medium are obtained. The solution for the finite cylinder row is obtained as a boundary value problem and the results of the analyses are compared with the experimental results.

NONLINEAR SYSTEM IDENTIFICATION AND CONTROL OF
FLUID-ELASTIC VIBRATIONS OF A CYLINDER ROW USING
BIFURCATION THEORY

Manivannan Thothadri, Ph.D.

Cornell University 1999

A row of flexible cylinders in a cross flow undergoes sudden large amplitude vibrations when the flow velocity is increased past a critical value. This change in dynamical behavior can be characterized as a sub-critical Hopf bifurcation that occurs at the critical flow velocity. The hysteretic behavior of the cylinder amplitude with flow velocity has resulted in extensive damages to commercial systems such as heat exchangers and nuclear reactors.

In this study, nonlinear system identification and control are used to eliminate the undesired hysteretic region in the fluid-elastic vibrations of a cylinder row. The system identification is effected on single degree of freedom and two degrees of freedom systems using experimental data and bifurcation theory. A nonlinear system identification technique based on the method of harmonic balance (Harmonic Balance Nonlinear Identification - HBNID) is extended to multi-degree of freedom systems and its performance is evaluated on two theoretical models. HBNID performs well in cases where the structure of the nonlinearities in the physical system is known and a large number of harmonics of the periodic motion are available.

HBNIID, however, does not capture all the characteristics in experimental systems where the nonlinearities are not well known or experimental noise corrupts higher harmonics. In order to improve this aspect, center manifold and normal form analysis and a rough experimental estimate of the unstable limit cycle amplitude are used to obtain a set of constraints which are enforced on the unknown parameters. This new methodology, called Bifurcation Theory System IDentification or BiTSID, is used along with experimental data to obtain models for the single degree of freedom and two degrees of freedom systems. These models match the experimentally observed response very well and also capture the bifurcation behavior of the systems. Various analyses of these models are performed to fully understand their bifurcation characteristics outside the experimental region.

An optimal, adaptive, nonlinear control strategy is devised to eliminate the hysteresis region due to the sub-critical Hopf bifurcation. This is done by using the center manifold and normal form analysis to identify the minimal nonlinear feedback that converts the sub-critical bifurcation behavior into a super-critical one. The control feedback is applied to just one of the vibrating cylinders and worked successfully on the two degree-of-freedom system with three different nonlinear feedbacks.

The system identification methodology (BiTSID) developed in this study is a general technique that can be applied to any physical system with a limit cycle response. The minimal control strategy devised is useful in the nonlinear control of a sub-critical Hopf bifurcation into a super-critical Hopf bifurcation.

Finally, the two degrees-of-freedom system is extended to a seven degree-of-freedom system which is then numerically analyzed. The response of this seven degrees-of-freedom system is shown to exhibit spatially localized limit cycles and co-existing limit cycles observed in the experiments.