ANL/MCT/TMS--1

DE93 003191

FLOW-INDUCED VIBRATION – 1992

by

S. S. Chen

Materials and Components Technology Division
Argonne National Laboratory
Argonne, Illinois 60439
USA

Prepared for

Taiwan Power Company
Taipei, Taiwan
Republic of China

(ANL Contract No. 31-109-ENG-38-85540)

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1 INTRODUCTION

In October 1984, the American Institute in Taiwan and the Coordination Council for North American Affairs of Taiwan signed a comprehensive agreement on joint United States/Taiwan cooperation in civilian uses of nuclear energy and related technical and scientific fields. This agreement also established a joint committee to encourage this cooperation. In a meeting of this committee in 1987, attended by a representative of Argonne National Laboratory (ANL), the subject of flow-induced vibration (FIV) problems in power plants was given high priority. A joint program on FIV was established in July 1988 between Taiwan Power Company (Taipower or TPC) and ANL.

The main objectives of the program are to provide a technology transfer program on FIV for Taipower staff and to assist Taipower with various aspects of FIV including evaluation of reports and proposals, review of designs, resolution of design issues, recommendation for design modifications, and selected research studies. During the first two years (July 1, 1988, to June 30, 1990), the following tasks were accomplished (Refs. 1 and 2):

- A technology transfer program on FIV was completed and key Taipower staff members were prepared to handle future problems in the subject area.

- The modified component cooling water (CCW) heat exchangers were assessed and the basis for a license from the Taiwan Atomic Energy Council (AEC) was established (Ref. 3).

- The seismic reanalysis of Chin Shan spent-fuel racks was assessed and a report was submitted to the Taiwan AEC.

- Fluid/structure interaction activities were coordinated and provided a list of potential bidders for a fluid transient project and related publications and a recommendation for purchasing technical data on fluid coupling, and assisted in the promotion of Taipower/INER (Institute of Nuclear Energy Research)/University cooperation.

- Flow-induced vibration of tube arrays was reviewed and the needs of Taipower in the area of fluid/structure interaction were identified as were the procedures necessary for Taipower to accomplish its goals (Ref. 4).

- A computer program, ARRAY, was established to compute the added-mass matrices for tube arrays (Ref. 2).

Taipower expressed interest in extending the joint program so that ANL could provide continuing assistance. The program was extended for several years (May 1, 1991, to June 30, 1994). Work from May 1, 1991, through June 30, 1992, summarized in this report, included technology transfer, assessment of sensing-line and valve vibrations, literature survey, and tests on motion-dependent fluid forces acting on tube arrays in crossflow.

2 TECHNOLOGY TRANSFER PROGRAM

A Taipower engineer, F. Y. Lai, was at the Thermal and Mechanical Sciences Section of ANL for the month of June 1991. He participated in several programs: chaotic dynamics of loosely supported tubes in crossflow; unsteady flow theory for fluidelastic instability of tube arrays; and FIV of heat exchanger tubes. This provided him the opportunity to learn how to construct a test facility and instrumentation, how to develop a test plan and test procedure, and how to analyze and apply experimental data. In addition, Lai also participated in many technical discussions on various topics about fluid/structure interaction. His performance at ANL was excellent and contributed significantly to the success of the joint program between Taipower and ANL.

To develop their capabilities and to establish future cooperation, two engineers from INER, C. N. Fan and J. J. Shyr, through Taipower, also visited the Thermal and Mechanical Sciences Section of ANL for approximately two weeks in June 1991. In addition to INER participation in the test program on chaos of fluid/structure systems, a series of technical discussions was held on future cooperation among Taipower/INER/ANL on FIV. These discussions have facilitated the establishment of future joint programs.

A short course on FIV was given at Taipower on June 1 and 2, 1992. Participants included Taipower's staff, engineers from Taiwan AEC and industries, professors from various universities, and engineers from several research institutes.

2.1 Features of Short Course on Flow-Induced Vibration

Flow-induced vibration is a subject of current interest and has received continuing attention. FIV problems have been experienced in many fields, including the aerospace industry, civil engineering, power generation and transmission, and offshore and undersea technology. The source of the problems has usually been improper design. In most cases, a structural or mechanical component becomes a problem or causes other problems when undesired effects of a flow field have not been accounted for in the design. When a FIV problem is

noted in the design stage, the engineer has various options to eliminate the detrimental vibration. In many situations, however, the problems occur after the components are already in operation; modification is usually very costly.

The objective of the short course on FIV is to provide a general background for, and an approach to solving FIV problems in different fields. The emphasis is on understanding the phenomena, analytical modeling, and experimental techniques. The main purpose is to develop diagnostic skills and an ability to establish effective remedies for existing FIV problems, and more importantly, to develop an ability to anticipate and eliminate problems at the design stage. Common features of classes of problems are presented and the concepts are illustrated with specific examples from a wide variety of applications. In addition, future research needs are discussed.

Upon completion of this seminar, the participants should understand the fundamental concepts of FIV, various phenomena, analytical models, experimental techniques, available design guides, and the state of the art of the subject.

The information presented is organized into the following areas:

- Coupled fluid/structure vibration in stationary fluid
  - Added mass and fluid damping
  - Sloshing
  - Coupled modes and response
  - Computer programs

- Vortex shedding
  - Strouhal numbers
  - Lock-in oscillations
  - Acoustic resonance
  - Examples

- Fluidelastic instability
  - Divergence
  - Damping-controlled instability
  - Stiffness-controlled instability
  - Parametric resonance and combination resonance
  - Examples

- Tube/support interaction in heat exchangers
  - Wear
  - Mathematical models
  - Experimental data
  - Prediction and design considerations
  - Examples

- Chaotic vibration
  - General description
  - Tubes conveying fluid
  - Tube arrays in crossflow
  - Examples

- Design guides
  - ASME (American Society of Mechanical Engineers) Codes
  - TEMA (Tubular Exchanger Manufacturer's Association) Standards
  - PVRC (Pressure Vessel Research Committee of Welding Research Council) guideline
  - Future development

- Discussion
  - Practical examples
  - Techniques to eliminate excessive vibration

In addition, nine video tapes were shown to illustrate different vibration mechanisms: (1) sloshing of water in a storage tank; (2) pipes conveying fluid; (3) vortex-induced vibration of two tubes in tandem; (4) parametric resonance and lock-in oscillations; (5) instability of tube arrays in crossflow; (6) nonlinear response of tube rows in crossflow; (7) tube/support interaction; (8) chaotic vibration of simple mechanical systems; and (9) weir instability. A simple experiment on the chaotic vibration of a two-degree-of-freedom system was demonstrated.

2.1.1 Benefits to Participants

Upon completing the short course on FIV, the participants should understand

- The fundamental concepts of FIV and instability.
- Various phenomena of fluid/structure interaction.
- Various mathematical models and vibration mechanisms.
- How to compute structural motion in response to flow.
- How to specify vibration tests for fluid/structure systems.

- The significance of structural response, i.e., how to translate vibration specifications to design decisions.
- The state of the art of the subject and current developments in different countries.
- Available design guidelines.

From my discussions with some of the participants, the short course appears to have been well received. Taipower is in a good position to solve FIV problems in the future, based on the materials presented at the short course.

3 VIBRATION OF SENSING LINES AND RHR SYSTEM COMPONENTS

A preliminary evaluation of Taipower sensing lines and residual heat removal (RHR) system components was performed, based on discussions with Taipower staff, analytical results and experimental data obtained by General Electric Co. (GE), experimental data obtained by Taipower staff, damage evaluation reports by INER, and a series of other reports provided by Taipower. The main objectives of this evaluation were to identify the potential root causes of vibration and to recommend a plan to alleviate vibration problems.

Upon performing a series of tests to measure the responses of RHR pumps, sensing lines, risers, valve F017, and fluid pressure, Taipower found that another nuclear power plant had experienced problems similar to theirs; I had discussed the problem with the project engineer at the Susquehanna Nuclear Power Plant and had met with the contractor who replaced valve F017 in February 1991.

3.1 Experimental Data, Analytical Results, and Observations

Important data and information used to identify the excitation sources are summarized below.

- In some cases, sensing line vibration amplitude for one pump operating with a valve opening of 7% is approximately six times that for two pumps operating with a valve opening of 15%. The results show that valve F017 is the critical component and is the excitation source.

- The dominant response frequencies f_s of all sensing lines with one pump operating are ≈ 17 N, where N = 1, 2, 3, 4, and 5. The dominant frequencies changed dramatically when two pumps were used. Comparison of typical frequency spectra of a sensing line obtained with one and two pumps shows that all sensing lines are excited by the same source, and that RHR pumps are the probable source. The excitation of

all sensing lines can be transmitted by fluid or risers. Because of unsteady flow, the mechanism may be forced vibration of the sensing lines due to riser vibration and unsteady flow.

- RHR pumps, which are operated at 1780 rpm (30 Hz), are understood to have two stage impellers, one with five vanes and the other with seven vanes. For a seven-vane impeller, the pump excitation frequency f_p is 210 Hz. It is noted that

$$f_s = f_p/N, \quad N = 12, 6, 4, 3, \tag{1}$$

which shows that RHR pumps are one of the probable sources of excitation.

- According to Taipower staff, the F017 valve stem had been replaced several times. This is an indication that severe vibration of the valve is a potential cause of RHR piping vibration. Normally, unsteady flow will induce valve vibration but its vibration amplitude is not very significant. It is believed that the valve is subjected to fluidelastic instability with a small opening of 7%.

- RHR piping supports were damaged; the damaged supports are located within ≈25 ft of valve F017. This shows that the damage is most likely associated with the valve. One of the most likely mechanisms is fluidelastic instability of the valve with a small opening.

- According to a Taipower engineer who was standing next to a riser during the testing of the RHR shutdown cooling mode, vibration amplitudes of the risers are very small while the vibration amplitudes of sensing lines are extremely large. Two observations can be made:

  - If riser vibration is indeed very small while that of the sensing line is extremely large, resonance of the sensing line in response to riser excitation becomes questionable.

  - If sensing lines are not excited by riser vibrations, they are most likely excited by fluid pulsations. Flow pulsations may be associated with RHR pumps, valve F017, and sensing-line orifices. If sensing lines are not excited by riser oscillations, parametric resonance is a possible mechanism.

- The shape of valve F017 had been modified to control flow rate more accurately at small valve openings. The current shape of the valve is

susceptible to fluidelastic instability, which will cause large vibration and may amplify flow pulsations and excite loop vibration.

- Crack initiation occurred on the OD of the pipe. The first crack initiation of sensing line N2E was at the 3 o'clock position, followed by initiation at the 9 o'clock position. Crack growth occurred by cyclic stresses. This shows that large-amplitude vibration is a cause of tube breakage and that bending vibration in the out-of-plane direction is a critical mode.

- The time history of sensing line N2E shows a dominant frequency of 17 Hz. The maximum amplitude for N2E is ≈0.5 in. However, there are multiple frequency peaks at 17 N (N = 1, 2, 3, 4, 5) Hz. This implies two possibilities. (1) RHR pumps are probable excitation sources. (2) Because some U-bolt supports may not provide firm support (there is clearance between support and sensing line), chaotic vibration may exist due to nonlinear boundary conditions.

3.2 Root Causes of Sensing-Line and RHR System Vibration

Based on the available data, the following conclusions can be made. Sensing lines are excited by forced vibration and possibly by unsteady flow caused by valve F017 because of fluidelastic instability of the valve. The RHR pump is also a contributing factor. The mechanisms are believed to be forced vibration due to risers and possibly the parametric resonance associated with pulsating flow.

The vibration of RHR piping is believed to be excited by fluidelastic instability of the valve and unsteady flow. The original source of unsteady flow is due to RHR pumps; however, the dominant excitation force is due to fluidelastic instability of valve F017.

It is emphasized that to avoid further damage to sensing lines, two pumps can be used to reduce vibration amplitudes for loop B, because in loop B, vibration amplitudes for operating with two pumps are much smaller than those with one pump. For loop A, available information appears to be contradictory. In GE tests with two pumps, the amplitudes of the sensing-line vibration appear to be about the same as those in loop B operating with two pumps. However, the engineer at the plant reported higher vibration with two pumps running. In any case, a best condition of pump and valve opening in loop A should be set to avoid excessive vibration.

It is noted that the side effects of operating two pumps should be considered and the effects on other components such as heat exchangers should be assessed.

3.3 Course of Action to Remedy Sensing-Line and RHR System Vibrations

Step 1: Restoration of the Structural Integrity of all Affected Components

Damaged sensing lines, cracked pipes, and supports should be repaired to satisfy ASME Codes. GE personnel, who have performed analyses and tests, should be asked to verify that their results are applicable for operating with one or two pumps.

Step 2: Modification of Valve F017

Three methods are generally used to eliminate detrimental vibration.

- Fluid dynamic attenuation, in which the flow field is modified so that fluid excitation forces are eliminated, weakened, or modified.

- Structural dynamic attenuation, in which the structural component is modified so that it is less susceptible to vibration.

- Combination of fluid dynamic and structural dynamic attenuation, in which both flow field and structure are modified to reduce the vibration to a tolerable level.

In the case at Taipower, the excitation sources are associated with valve F017 and partially with the RHR pumps. Valve F017 is the most critical component. The RHR pumps induce unsteady flow; but alone, oscillations appear to be insignificant. Therefore, valve F017 components can be changed, or a new valve that will not be subjected to fluidelastic instability at small openings should be used.

Based on the experience of the Susquehanna Nuclear Power Plant, a CCI Drag Valve appears to alleviate the problem. It is recommended that Taipower consider the replacement of valve F017 with CCI Drag Valves.

This program involves engineers from several departments with different specialties. Communication among different departments becomes very important. Taipower appears to have a strong line management system. In each project, a project manager, who follows the matrix system, may be appointed to enhance coordination within Taipower and interaction with outside consulting firms.

4 VALVE VIBRATION

On June 4, 1992, T. K. Lee, Head of the Mechanical Division of Taipower's Nuclear Engineering Department, and a group of engineers visited TPC Third NPS units 1 and 2. The purpose was to have S. S. Chen present a lecture on FIV and to discuss valve vibration. The meeting participants included T. K. Lee and F. Y. Lai of Taipower, S. S. Chen of ANL, C. N. Fan of INER, staff of TPC Third NPS, and Taipower contractors.

Taipower has found that valve EF-HCV 127 must be replaced yearly. During the June 4 meeting, possible excitation mechanisms, diagnostic techniques, and design modifications were reported to the company (Appendix A).

Valve vibration in the nuclear industry is an important topic. The engineers in Taipower's Nuclear Engineering Department, Third Station, and monitoring and maintenance group working together with INER will be able to identify the excitation mechanisms and choose the most appropriate contractor to eliminate the excessive vibration permanently.

5 LITERATURE SURVEY

5.1 Dynamic Tube/Support Interaction

In Ref. 5, Chen reviews the dynamic tube/support interaction that occurs in heat exchanger tubes. He points out that the supports for heat exchanger tubes are usually plates with drilled holes; however, other types of supports have also been used. To facilitate manufacture and allow for thermal expansion of the tubes, small clearances are used between tubes and tube supports. The dynamics of tube/support interaction in heat exchangers is fairly complicated. From a practical point of view, what is needed is a design guide to predict the useful life of tubes under specific design flow conditions. To achieve this goal, it is necessary to understand tube dynamics, tube/support interaction characteristics, impact and wear due to flow excitations, wear rate, and effects of various system parameters. Chen (Ref. 5) conducted a survey and summarized the current state of the art of this subject and identified future research needs. Specifically, he discusses dynamics of loosely supported tubes, tube/support gap dynamics, tube response in flow, tube damage and wear, design considerations, and future research needs.

The following topics are of particular importance:

- Linear-flow theories are no longer applicable to fluid effects with relatively large oscillation amplitudes. Nonlinear effects of the fluid in

the tube/support clearance are not well understood. An integrated analytical/ experimental study of the nonlinear effects is needed.

- Wear rates for different oscillations induced by different mechanisms including subcritical vibration and fluidelastic instability, are not well quantified. To predict tube life, wear rate is a key parameter. Extensive studies are needed to quantify the wear rate as a function of different system parameters and excitation mechanisms.

- Tubes with loose supports are intrinsically nonlinear. Their response includes periodic oscillations, chaotic vibration, and random vibration. Very limited studies have been performed to understand the nonlinear behavior. A systematic study, including analysis and experimentation, is needed.

It is expected that dynamic tube/support interaction will be a subject of continuing research for some years to come. The review was presented at the International Conference on Flow-Induced Vibration in Brighton, England (Appendix B).

5.2 Flow-Induced Vibration of an Array of Cylinders

Flow-induced vibration in cylinder arrays has been a subject of extensive studies during the last decade for several reasons. Many system components consisting of a group of cylinders still experience failure due to FIV and can result in significant repair costs; design guides to prevent FIV are still being developed or are not well developed and the state of the art is such that many key parameters in the analysis are not well quantified (Refs. 6 and 7).

Several topics are important and must be studied to resolve unsettled issues of FIV and to provide the basis for developing prediction methods and design guides:

- Flow field: Flow velocity distributions in cylinder arrays, such as heat transfer equipment.

- Fluid excitation forces: Power spectral density of fluid excitation forces, axial and peripheral correlation of fluid pressure fluctuations, and effects of other system parameters on fluid excitation forces.

- Motion-dependent fluid forces: Fluid damping and stiffness as a function of reduced flow velocity and cylinder pattern, as well as oscillation amplitude.

- Cylinder response: Mathematical models that incorporate all fluid effects, simplified equations for different excitation mechanisms, and response as a function of system parameters.

- Design guides: Design guides for predicting cylinder response acceptance criteria and design modification techniques.

Flow-induced vibration in an array of cylinders is a worthwhile topic for future research and an important subject in practical applications. It is expected to receive continuing attention for some time to come. Details of this review are published as feature articles of Shock and Vibration Digest (Appendix C).

6 UNSTEADY-FLOW THEORY FOR FLUIDELASTIC INSTABILITY OF TUBE ARRAYS

Many system components, such as heat exchangers and steam generators, consist of a group of tubes submerged in crossflow. Fluid flow is a source of energy that can induce vibration and stability. In general, the excitation forces can be divided into two groups. When a tube array is rigid, it disturbs the flow field. The fluid forces acting on the tubes result from the fluid flow. These fluid forces are called fluid excitation forces. For example, steady and fluctuating drag and lift forces are typical fluid excitation forces. If the tubes of a tube array oscillate in a flow, the motion will disturb the flow field. The fluid forces acting on the tubes will depend on tube motion. All fluid force components that are a function of tube motion are called motion-dependent fluid forces. Typical examples are fluid added mass, fluid damping, and fluid stiffness.

Fluid forces will excite tube vibration and fluid excitation forces will cause forced vibration and resonance. In general, they do not change tube characteristics. On the other hand, motion-dependent fluid forces can change the tube characteristics and may induce instability. Mathematically, it can be stated that fluid excitation forces appear in the right-hand side of the differential equations to describe a coupled fluid/tube system, while motion-dependent fluid forces appear on the left-hand side of the equation. The main objective of the study described below is to present the motion-dependent fluid forces acting on a tube array.

6.1 Motion-Dependent Fluid Forces

Consider a group of n tubes vibrating in a row as shown in Fig. 1. The axes of the tubes are parallel to one another and perpendicular to the x-y plane. Each tube has the same radius R, and the fluid is flowing with a gap flow velocity U.

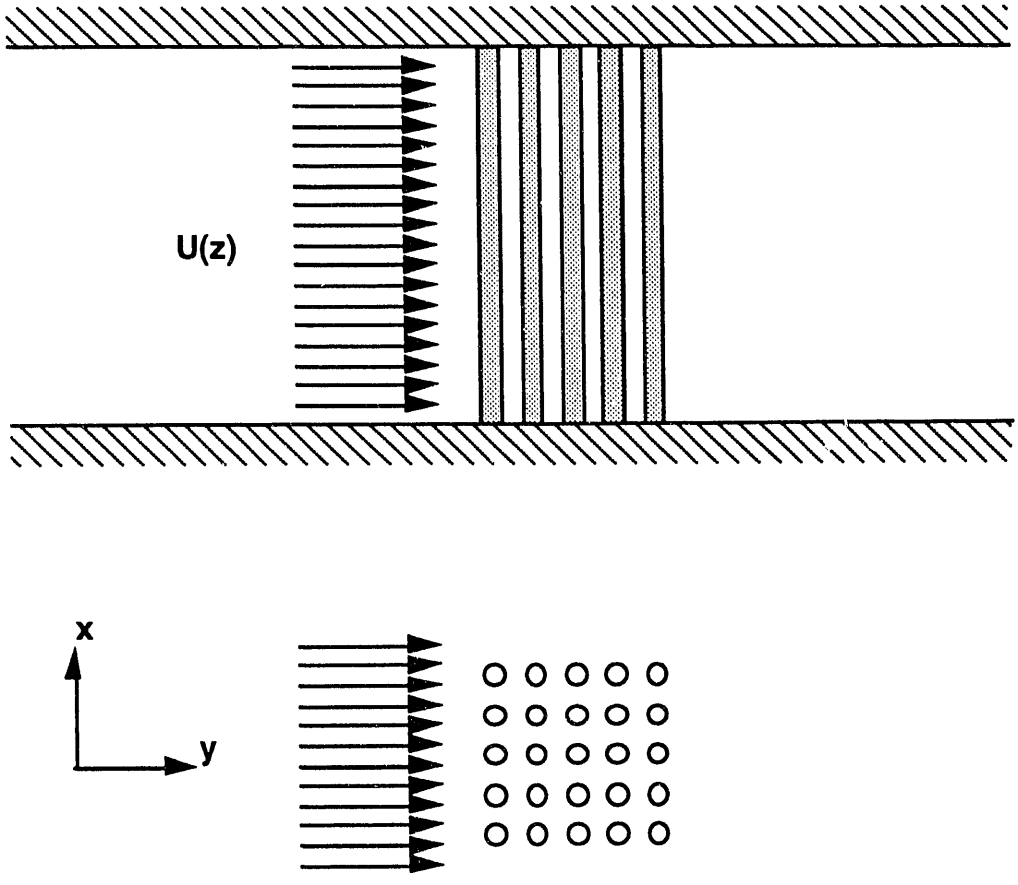

Fig. 1. Tube Array in Crossflow

The displacement components of tube j in the x and y directions are u_j and v_j, respectively. The motion-dependent fluid-force components acting on tube j in the x and y directions are f_j and g_j, respectively; f_j and g_j are given as (Ref. 8)

$$f_j = -\rho\pi R^2 \sum_{k=1}^{n}\left(\alpha_{jk}\frac{\partial^2 u_k}{\partial t^2} + \sigma_{jk}\frac{\partial^2 v_k}{\partial t^2}\right) + \frac{\rho U^2}{\omega}\sum_{j=1}^{n}\left(\alpha'_{jk}\frac{\partial u_j}{\partial t} + \sigma'_{jk}\frac{\partial v_k}{\partial t}\right)$$

$$+\rho U^2 \sum_{j=1}^{n}\left(\alpha''_{jk}u_k + \sigma''_{jk}v_k\right), \qquad (2)$$

and

$$g_j = -\rho\pi R^2 \sum_{k=1}^{n}\left(\tau_{jk}\frac{\partial^2 u_k}{\partial t^2} + \beta_{jk}\frac{\partial^2 v_k}{\partial t^2}\right) + \frac{\rho U^2}{\omega}\sum_{k=1}^{n}\left(\tau'_{jk}\frac{\partial u_j}{\partial t} + \beta'_{jk}\frac{\partial v_k}{\partial t}\right)$$

$$+\rho U^2 \sum_{j=1}^{n}\left(\tau''_{jk}u_k + \beta''_{jk}v_k\right), \tag{3}$$

where ρ is fluid density; t is time; ω is circular frequency of tube oscillations; α_{jk}, β_{jk}, σ_{jk}, and τ_{jk} are added mass coefficients; α'_{jk}, β'_{jk}, σ'_{jk}, and τ'_{jk} are fluid-damping coefficients; and α''_{jk}, β''_{jk}, σ''_{jk}, and τ''_{jk} are fluid-stiffness coefficients.

Three flow theories have been used for fluid-force coefficients: quasi-static-flow theory, quasi-steady-flow theory, and unsteady-flow theory. In this study, the unsteady-flow theory is used.

Fluid-force coefficients can be determined by measuring the fluid forces acting on the tubes due to oscillations of a particular tube. For example, tube k is excited in the y direction; its displacement in the y direction is given by

$$v_k = v\cos\omega t. \tag{4}$$

The fluid force acting on tube j in the x direction can be written

$$f_j = \frac{1}{2}\rho U^2 c_{jk}\cos\left(\omega t + \phi_{jk}\right)v, \tag{5}$$

where c_{jk} is the fluid-force amplitude and ϕ_{jk} is the phase angle that the fluid force acting on tube j leads the displacement of tube k.

Using Eqs. 2 and 4, we can also write the fluid force component as

$$f_j = \left(\rho\pi R^2\omega^2\sigma_{jk} + \rho U^2\sigma''_{jk}\right)v\cos\omega t - \rho U^2\sigma'_{jk}v\sin\omega t. \tag{6}$$

Comparing Eqs. 5 and 6 yields

$$\sigma''_{jk} = \frac{1}{2}c_{jk}\cos\phi_{jk} - \frac{\pi^3}{U_r^2}\sigma_{jk}, \tag{7}$$

and

$$\sigma'_{jk} = \frac{1}{2} c_{jk} \sin\phi_{jk}, \tag{8}$$

where U_r is the reduced flow velocity ($U_r = \pi U/\omega R$).

The added-mass coefficient α_{jk} in Eq. 7 can be calculated by the potential flow theory (Ref. 8). Then σ'_{jk} and σ''_{jk} can be calculated from Eqs. 7 and 8 when the force amplitude c_{jk} and phase angle ϕ_{jk} are measured. Other fluid-force coefficients can be obtained in the same manner.

Fluid force coefficients depend on tube arrangement, tube pitch, oscillation amplitude, oscillation frequency, and flow velocity. For a given tube array, fluid-force coefficients are functions of oscillation amplitude (A/D) and reduced flow velocity (U_r), where A is vibration amplitude, and D is tube diameter. For small-amplitude oscillations, fluid-force coefficients can be considered a function of the reduced flow velocity only.

6.2 Experimental Setup

The test channel is shown in Fig. 2. Water is pumped into an input tank. The flow passes through a series of screens and honeycombs and then into a rectangular flow channel. The water level is controlled by standpipes in the output tank and the flow is controlled by the running speed of the pump motor.

Flow velocity is measured by a turbine flowmeter. The velocity profile in the test area is measured with a turboprobe flowmeter.

An array of tubes is assembled in the test area (see Fig. 3) and one group of tubes is active while the others are dummy tubes. The relatively rigid main bodies of the tubes are constructed from stainless steel tubing with a 2.54-cm (1-in.) OD, a 0.071-cm (0.028-in.) wall thickness, and a 38.1-cm (15-in.) length (Fig. 4). Thin brass caps are soldered to both ends of each tube and a smaller, relatively flexible tube, with a 0.635-cm (0.25-in.) OD, and a 0.089-cm (0.035-in.) wall thickness, and a 12.07-cm (4.75-in.) length, is fastened to the upper end cap of each tube. All tubes except Tube 1 are clamped to a support plate with a nut attached to the smaller supporting tube. Tube 1 is not attached to the support plate, but passes through a circular hole in the support plate and is connected to an electromagnetic shaker, which provides the support for Tube 1. In addition, prescribed oscillations can be imported to Tube 1 in the x or y direction. Both the oscillation amplitude and frequency of the shaker can be controlled in the appropriate range.

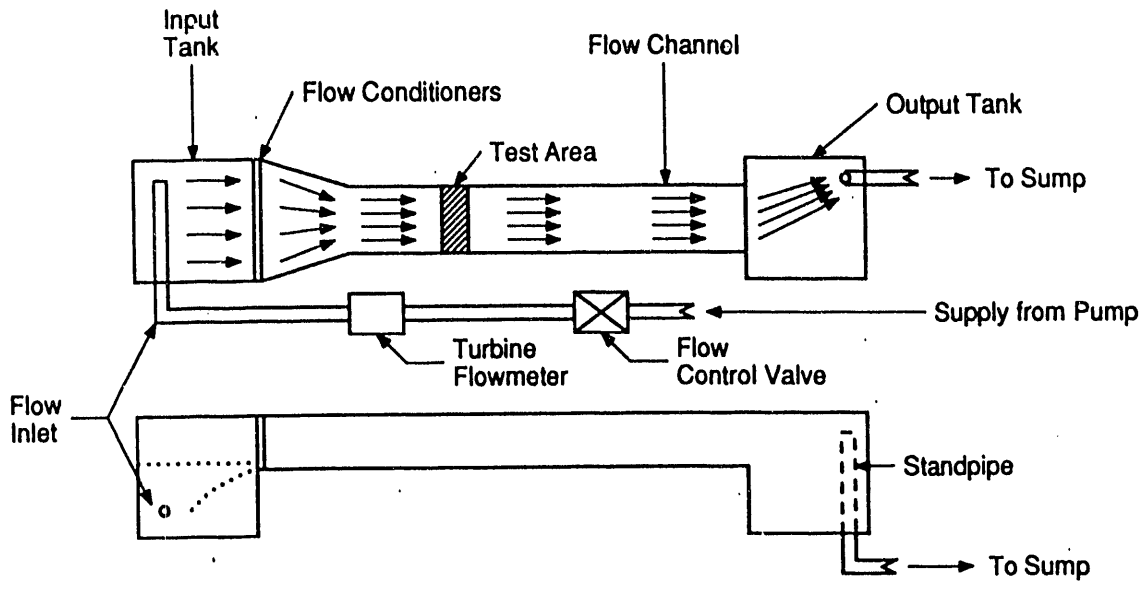

Fig. 2. Test Channel

For the active tubes, two sets of strain gauges are placed on the outer surface of the smaller tube where the outer surface of the tube has been machined to a smaller diameter. The two sets of strain gauges measure the force components in the two perpendicular directions with a sensitivity of ≈1 volt for 0.18 Newtons (0.04 lb) of force acting on the middle of the active tubes.

During tests, the water surface is kept at such a level that the active length of the tubes is submerged in the flow. Normally, only a small portion of the supporting tube (less than 1.3 cm) is submerged in water. Therefore the strain gauges do not require waterproofing.

6.3 Test Procedure and Data Analysis

The force transducers (active tubes) are calibrated by two methods—static and dynamic.

- Static method in air: The active tube is held fixed at the supported end and a given force is applied at the middle of the active length.

- Dynamic method in air and in water: The tube is excited at a given frequency and amplitude in air or in water. Then, the inertia force due to the sinusoidal oscillations is used to determine the calibration constant.

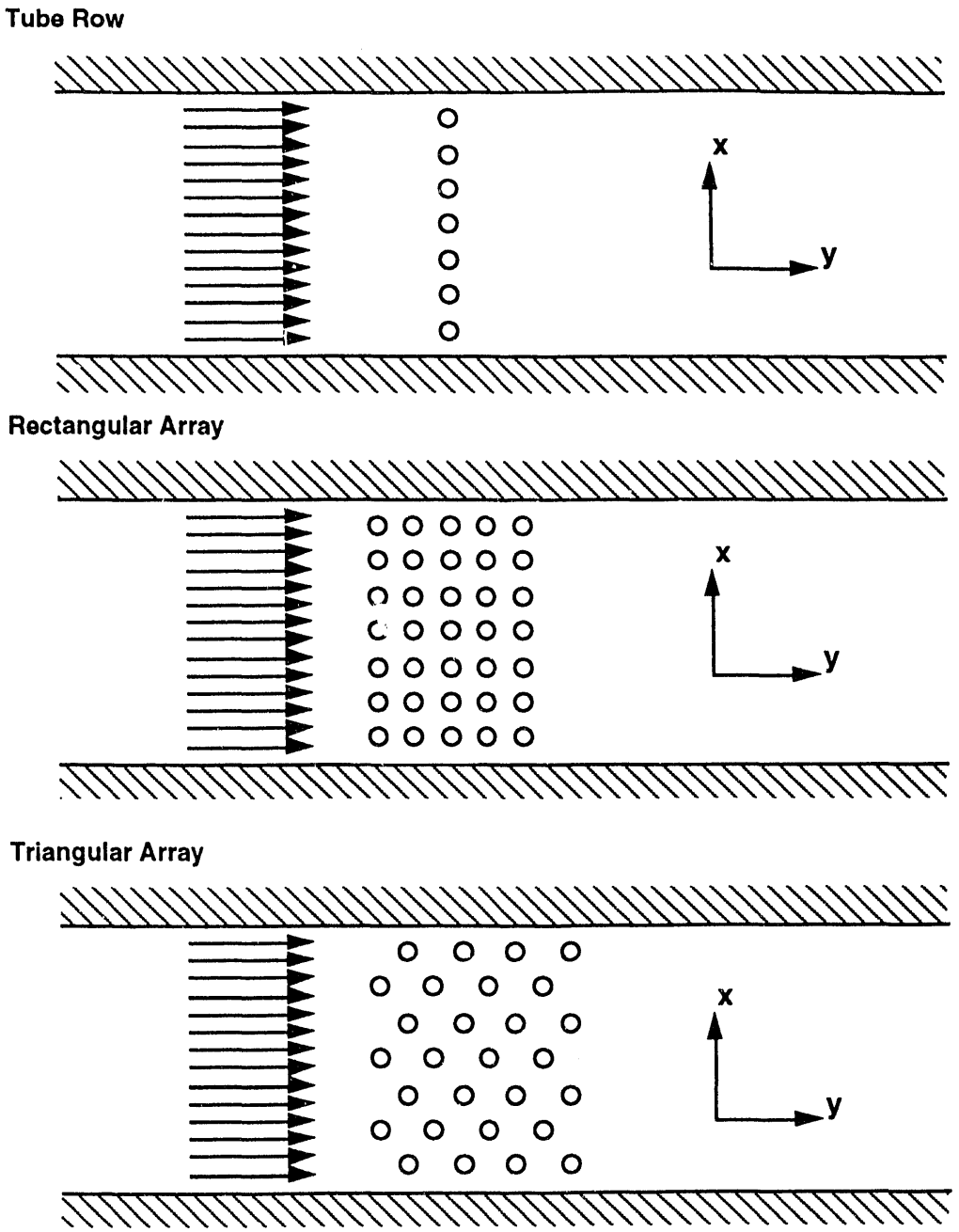

Fig. 3. Tube Arrangement

In general, fairly consistent results are obtained. In application, the calibration constant from the dynamic method is used.

Motion-dependent fluid forces are measured for active Tubes 1, 2, and 3, with Tube 1 oscillating in the lift or drag direction.

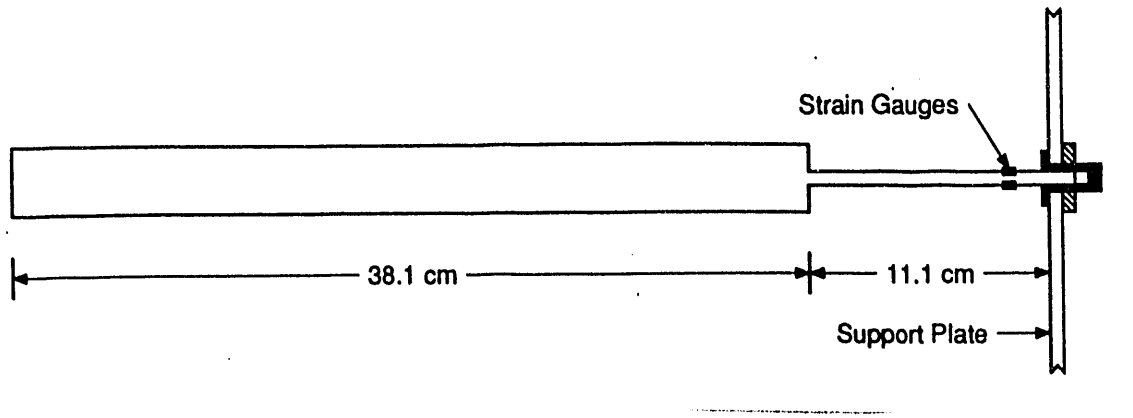

Fig. 4. Schematic Representation of an Active Tube

A flow diagram of the instrumentation and exciter is shown in Fig. 5. The exciter provides sinusoidal displacement at a frequency varying from ≈0.1 to 2.0 Hz. Displacement and force signals are filtered by band-pass filters to eliminate low- and high-frequency noises and then are digitized and stored in the fast fourier transform analyzer. These signals are analyzed to obtain the oscillation displacement of the tube, the magnitude of the forces acting on the active tubes, and the phase between the motion-dependent fluid force and tube displacement.

The test facility, instrumentation, and data analysis systems are ready for a series of tests. The first tube array is a row of tubes with a pitch-to-diameter ratio of 1.35. Tests of the tube row are in progress. The experimental data will be reported in the near future.

This task is also being sponsored by ANL; the test facility, including the water channel, instrumentation, and analyzer, are provided by ANL. The experimental data obtained are expected to be very useful.

7 CLOSING REMARKS

The joint program between Taipower and ANL has been very beneficial. It provides an opportunity for Taipower staff to learn the state of the art of FIV and resolution of some FIV problems. Upon completion of the third year of the program, Taipower has accomplished the following:

- Completed another technology transfer program on FIV, and has key staff members, as well as engineers from industry, universities, and research institutes, in a good position to handle future FIV problems more effectively.

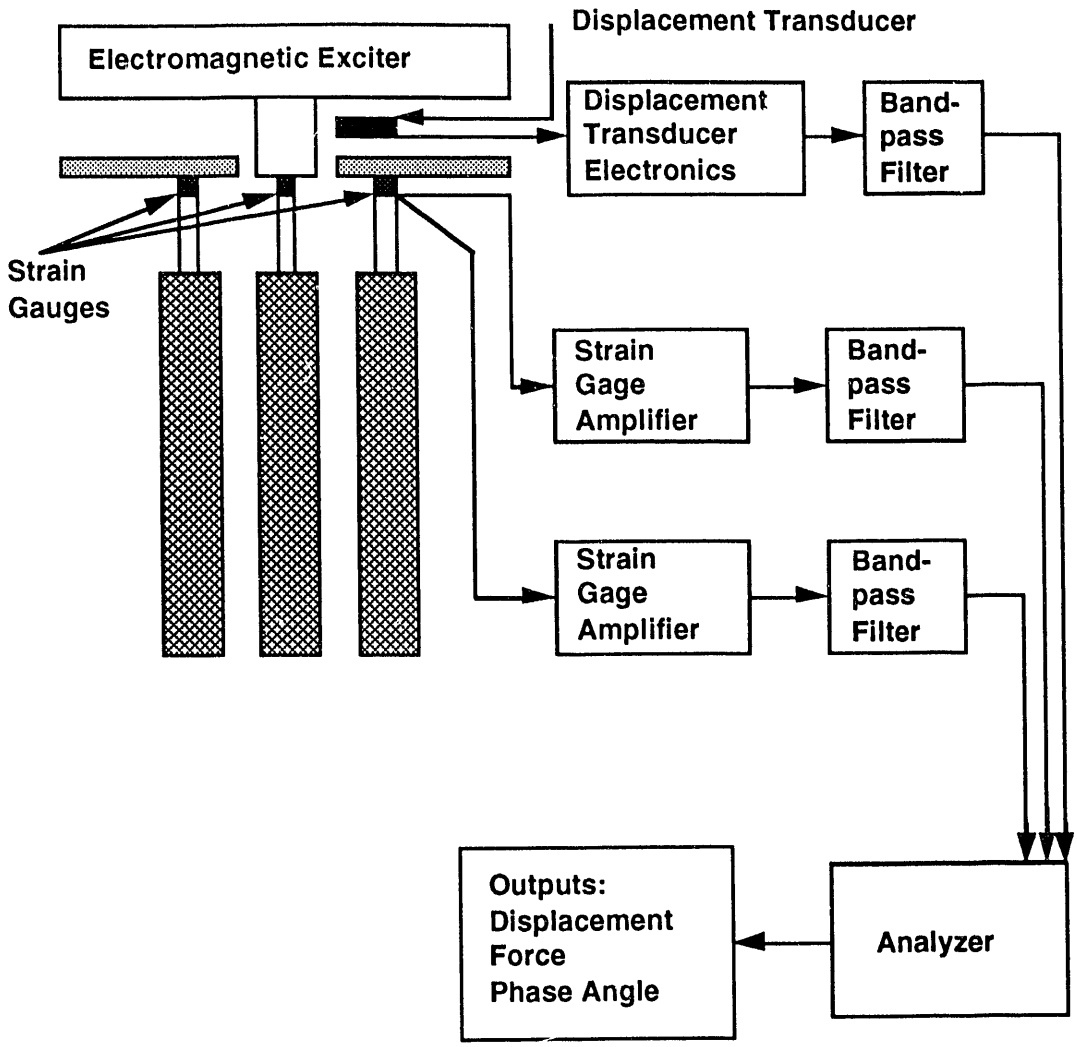

Fig. 5. Flow Diagram of Data Analysis Instrumentation

- Completed preliminary assessments of the vibration of sensing lines and valves and recommended future courses of action.

- Completed reviews of FIV of an array of cylinders in crossflow and dynamic tube/support interaction, and identified future research needs to achieve Taipower's goals.

- Completed the setup of a test facility to measure motion-dependent fluid forces. This facility is expected to be very useful to Taipower and the FIV community.

Continuing cooperation between Taipower and ANL in this subject area is expected to be very fruitful.

ACKNOWLEDGMENTS

This work was sponsored by Taiwan Power Company under an agreement with the U.S. Department of Energy under Contract Agreement 31-109-Eng-38-85540.

Many engineers in the Nuclear Engineering Department of Taiwan Power Company have contributed to various aspects of the program; among them are P. C. Chen, Y. H. Cheng, T. K. Lee, P. C. Kao, F. Y. Lai, and H. H. Lee.

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