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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

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PIPEAU-2

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D.J. GORMAN

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River
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D.J. Gorman
Department of Mechanical Engineering
University of Ottawa

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D.J. Gorman
Département de génie mécanique
Université d'Ottawa

Résumé

PIPEAU-2 est un code machine mis au point dans les Laboratoires nucléaires de Chalk River pour l'analyse des vibrations engendrées par les écoulements dans les faisceaux de tubes des échangeurs de chaleur et des générateurs de vapeur. Il peut effectuer cette analyse pour les tubes droits et en 'U'. Tout le travail théorique étayant le code est analytique plutôt que numérique en nature. On peut donc obtenir une évaluation très précise de la fréquence des vibrations libres et des formes des modes. En employant les plus récents paramètres déterminés expérimentalement, l'analyse des vibrations libres est suivie d'une analyse des vibrations forcées. On détermine la réaction des tubes à la turbulence des fluides et aux tourbillons ainsi que la vitesse critique des fluides associée à une instabilité fluido-élastique.

Ce code machine, ainsi qu'un rapport technique décrivant la théorie sous-jacente est maintenant disponible dans le commerce. Toutes les demandes de renseignements doivent être envoyées au chef du Département de recherche en ingénierie, EACL, Chalk River, Ontario, Canada.

Département de recherche en ingénierie
Laboratoires nucléaires de Chalk River
Chalk River, Ontario, KOJ 1J0

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ABSTRACT

PIPEAU-2 is a computer code developed at the Chalk River Nuclear Laboratories for the flow-induced vibration analysis of heat exchanger and steam generator tube bundles. It can perform this analysis for straight and 'U' tubes. All the theoretical work underlying the code is analytical rather than numerical in nature. Highly accurate evaluation of the free vibration frequencies and mode shapes is therefore obtained. Using the latest experimentally determined parameters available, the free vibration analysis is followed by a forced vibration analysis. Tube response due to fluid turbulence and vortex shedding is determined, as well as critical fluid velocity associated with fluid-elastic instability.

This computer code, along with a technical report describing the underlying theory, is now available on a commercial basis. All inquiries should be addressed to the Branch Head, Engineering Research Branch, AECL, Chalk River, Ontario, Canada.

Engineering Research Branch
Chalk River Nuclear Laboratories
Chalk River, Ontario, KOJ 1J0
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1. INTRODUCTION

The widespread introduction of nuclear power generation gave rise to a need for analytical means of assuring the mechanical integrity of tube bundles used in nuclear station heat exchange systems. It is well known that excessive fluid cross-flow velocities can cause tube vibrations, ultimately leading to tube failures and costly station shutdown. During the past two decades numerous experiments have been performed in various countries to gain an understanding of the mechanisms whereby fluids impart vibratory energy to the tubes. Much effort has also been devoted to developing design criteria that constrain tube vibrations to acceptable limits during the planned life of the heat transfer equipment.

Published test data from numerous tube bundles subjected to controlled laboratory flow conditions are available to designers. These data are not immediately useful for design purposes because of the large number of geometries and flow conditions encountered in different industrial heat exchanger designs. As well, most experimental data have been obtained from tests on straight, single-span tube bundles, whereas design problems normally occur in multi-span bundles with straight or U-shaped tubes.

These experimental data, along with field measurements on existing units, have been used to develop design criteria for tube susceptibility to flow-induced vibration. The computer code, PIPEAU-2, developed at the Chalk River Nuclear Laboratories, uses these design criteria in its assessment of the tube vibration response. PIPEAU does this by first conducting a free vibration analysis of the tubes, to obtain the free vibration frequencies and mode shapes. This is followed by a forced vibration analysis using existing experimental data and classical modal analysis. All the calculations are based on analytical rather than numerical methods. Even the integrals for the modal analysis are obtained through the exact integration of analytical functions. The output of the code is a printout of the tube natural frequencies, the predicted tube response amplitude due to vortex shedding, the predicted rms tube response due to fluid turbulence and the ratio of gap velocity to critical velocity used to assess susceptibility to fluid-elastic instability. If requested, the code will also provide a graphical representation of the modes of vibration and the rms tube response.

This report provides an overview of the capabilities of PIPEAU-2. The details of the underlying theory and equations are given in a separate, lengthy and detailed report [1] provided with the code. Further information on the availability of the code can be obtained by contacting the Branch Head, Engineering Research Branch, AECL, Chalk River, Canada.

2. FREE VIBRATION ANALYSIS

2.1 Straight Tubes

The theory of free vibration of straight tubes, presented in [2] was utilized in developing the straight tube vibration analysis capability in PIPEAU-2. The ends of the tube may be clamped, simply supported or free. It is assumed that all internal supports impart simple support to the tube. There is no limitation on the number of tube spans or on the distribution of span lengths.

2.2 U-Tubes

The free vibration analysis of U-tubes is based on work reported in [3-5]. This analysis is much more complicated than that for straight tubes, as can be seen from the detailed theoretical descriptions in [1]. Aspects of the U-tube free vibration behaviour that make it much more complicated than that of straight tubes are,

(i) Unlike straight tubes, there are two distinct families of U-tube free vibration modes: out-of-plane where the lateral motion in the curved tube region is perpendicular to the plane of the U, and in-plane where the lateral motion is in the plane of the U. These modes are independent of each other.

(ii) There are three distinct analytical solutions for the free vibration modes in each of the two vibration mode families. The applicable solution depends on the range into which the tube frequency falls. For the straight tube there is one solution only.

(iii) Each analytical solution for a U-tube free vibration mode contains six coefficients to be evaluated, whereas each solution for a straight tube contains only four.

3. FORCED VIBRATION ANALYSIS

In the forced vibration analysis, PIPEAU-2 computes the steady-state response of the tubes to excitation forces arising from fluid flowing through the bundle. It is generally agreed that for single phase cross-flow there are three significant excitation mechanisms:

(i) Excitation due to fluid turbulence.

The response of tubes to this type of excitation is random in nature. Accordingly, only the statistical properties of the tube response is computed, through well established means [6].

(ii) Tube response to resonant vortex shedding.

The excitation of cables, bridge decks, etc., due to resonant vortex shedding has been understood for many years. Vortex shedding can occur in tube bundles subjected to single phase cross-flow, particularly in tubes located where fluid enters the bundle.

(iii) Fluid-elastic instability

It has been well demonstrated that tube bundles subjected to fluid cross-flow, will reach fluid-elastic instability if the fluid velocities are sufficiently high. Beyond this critical velocity, the tubes undergo extremely large amplitude vibrations, making continued operation of the equipment impossible.

PIPEAU-2 can determine the tube response to fluid turbulence as well as vortex shedding. It also computes the critical velocities at which fluid-elastic instability starts, using the latest experimentally determined parameters available. The computational methods employed are now briefly outlined.

First the code computes and stores the information related to the free vibration modes and frequencies, whether the tubes are straight or of the U-type. These mode shapes are normalized for use in the modal analysis to determine the forced vibration response. The inputs required for these calculations include the flow distribution, flow density, lift coefficient, damping and fluid-elastic instability coefficient. Numerous integrals along the tube excited regions are solved analytically in the modal analysis [7]. These integrals involve the square of the mode shape function, the function itself, and the absolute value of the function. The latter is required for vortex shedding studies. Results of these integrations are stored for use in subsequent computations.

Using this information the code computes the rms amplitude of the tube response to fluid turbulence. This response is the result of a summation of contributions associated with each free vibration mode and combinations of the products of these modes [6]. Analytical expressions for the power-spectral-density of the driving forces are used in the computation. These expressions are stored in the code and are based on the latest test data. There is a built-in option that allows the user to consider the driving forces in the various spans to be correlated, or un-correlated. The number of normalized mode shapes (eigen-functions) employed in the analysis may be varied but 10 modes are usually employed. Having completed the calculations related to response to fluid turbulence, the code plots a curve of rms tube response against distance along the tube.

In computing the response to vortex shedding, each of the free vibration modes of interest is examined separately. It is considered that shedding occurs at the natural frequency of the mode (resonance) and that the resulting resonant driving forces are correlated all along the excited portion of the tube. The tube harmonic response for each mode shape is computed using the integral of the absolute value of the mode shape function. The results are output as a plot of normalized displacement versus distance, with the tube maximum displacement printed below each mode shape.

Critical fluid cross-flow velocities for fluid-elastic instability are computed using well recognized techniques. The mathematical formulation of the instability criterion used is based on work by Connors, as discussed in [6]. First the code evaluates and stores the integrals of the square of the mode shape function over the excited region. It then uses these integrals along with experimentally determined damping ratios and an instability coefficient to compute a critical velocity for each of the free vibration modes. The ratio of the specified velocity to critical instability velocity is printed for each of the free vibration modes analyzed.

4. USE OF PIPEAU-2

Despite the complexity of the problem, in so much as it can involve both straight and U-tubes, the computer code is developed for easy use. Input data is entered using a concise and logical format. It includes tube mechanical properties, number of straight spans and curved spans and their respective lengths. Boundary conditions at the outer ends of the tube must also be specified through input symbols provided. Provision is also made in the input section for specifying the coordinates of the excited tube regions and their fluid cross-flow velocities. Designers may wish to examine several tubes in a bundle, where, for example, different tubes have different fluid velocities. In the case of U-tube bundles, it may be desirable to compare the behaviour of the outer tubes of large radii of curvature with the inner tubes of much smaller radii.

5. CONCLUSIONS

The computer code PIPEAU-2 is comprehensive in nature. It can perform both a free and forced vibration analysis for straight or U-shaped tubes subjected to fluid cross-flow in heat exchangers or steam generators. All computations of the free vibration modes and their frequencies, as well as the integrals used in the forced vibration analysis, are analytical in nature. Problems characteristic of numerical methods, such as the finite element method, are thereby eliminated. The code uses the latest experimentally determined parameters, where such parameters are required in the analysis. Modification of these parameters presents no difficulty, should further experimental work warrant it. This code, which is already proving to be invaluable for design purposes, represents the culmination of ten years of concerted experimental and theoretical effort.

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