IMPROVEMENTS TO AECL'S CAPABILITY TO PREDICT FLUID-INDUCED VIBRATION BEHAVIOUR OF STEAM-GENERATOR TUBES

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Abstract

Degradation of components in nuclear power reactors due to flow-induced vibration remains an important issue affecting service life. This paper presents the recent upgrade of the VIBIC code to use measured quasi-static force coefficients for predicting fluidelastic instability in steam-generator tubes.

1. Introduction

The susceptibility of components to flow-induced vibration (FIV) and consequent fretting wear (FW) has always been an important consideration in the safety of nuclear power reactors. Steam-generator tube failure mechanism continues to be an active area of research. Recently, unusually severe FW damage caused a leak in a steam-generator tube at San Onofre NGS Unit 3 and resulted in the permanent shutdown of both Units 2 and 3. FIV and FW damage has been identified as a key cause of fuel failure as well.

Atomic Energy of Canada Limited (AECL) was one of the first research organizations in the nuclear sector to study and solve FIV and FW problems. As part of this work, computer codes such as VIBIC [1-3] and PIPO [3] were developed in the 1970s. PIPO was upgraded to its current version, PIPO-FE, in 2000. These codes have been continually updated with the latest analytical techniques and experimental findings. This paper presents the most recent upgrade to the VIBIC code and briefly reviews the development of AECL's existing FIV and FW analysis technology.

2. Development of FIV and FW Assessment Technology

AECL has studied FIV and FW in nuclear components for over 40 years. Because of the complicated nature of vibration in steam generators and fuel assemblies, experimental measurements have played a key role in characterizing the underlying mechanisms. Based upon studies conducted by AECL and others, AECL's recommended design guidelines have been developed for FIV and FW analysis in steam generators. PIPO-FE and VIBIC, both of which use beam-type finite elements, have been developed to perform FIV and FW analyses using linear and nonlinear approaches, respectively.

PIPO-FE uses a linear-analysis approach in which supports are simulated as pinned and the tube sheet is simulated as a clamped support. Neglecting the support clearance greatly simplifies calculations of the tube vibration response. A simulation run with PIPO-FE can typically be completed within several minutes for a typical CANDU®[1]-type steam generator tube analysis. A nonlinear approach is used in VIBIC to analyze vibrations of a steam generator tube with clearance supports. Tube and support intermittent contact makes the problem nonlinear. A VIBIC simulation requires a much longer time due

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[1] CANDU® (Canada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

to calculations of the dynamic interaction between a tube and its supports.

Using Archard's wear correlation, the fretting wear damage caused by turbulence excitation is estimated in PIPO-FE based on an energy approach, and in VIBIC by integrating the energy dissipated at contacts. Archard's wear correlation implies that the wear rate is linearly related to the power dissipated by friction through a constant wear coefficient. Therefore, besides the work-rate due to friction calculated in the codes, the reliability of the wear damage prediction of a steam generator is also largely dependent on wear coefficients derived from experimental studies. Many of the nuclear industry's most relevant tests of material wear properties were performed at AECL over the past four decades. Two types of test machines, room-temperature and high-temperature, have been used to conduct fretting-wear experiments. Early test programs at AECL involved exploratory tests at or near room temperature, to determine ranges of interest and trends of all the important wear parameters. Since the late 1980s, more complicated high-temperature machines have been used to test steam-generator materials at reactor secondary-side environmental conditions. In addition to wear studies, various experimental studies on excitation mechanisms, damping and the corresponding vibration responses of steam generator tubes have been carried out at AECL.

VIBIC was originally developed to analyze FIV and FW of steam-generator tubes. VIBIC's main feature is the detailed modelling of loose supports, which includes the effect of stick/slip friction and squeeze film dynamics. Another attractive feature is its fast calculation speed and ease of use compared to general-purpose codes developed in the same era. Largely because of these features and the extensive validation conducted, the code has been used to study vibration problems with fuel rods in PWRs, and fuel channels and fuel elements in CANDU reactors. Similar to vibration studies conducted on steam generators, parameters used in VIBIC fuel simulations are determined or confirmed through experiments.

3. VIBIC Upgrade

New nonlinear Fluidelastic Instability (FEI) analysis capabilities are brought to VIBIC through the current upgrade. Most attempts in the past to perform numerical simulations of FEI are based on a conversion of a frequency-domain formulation into a time-domain formulation. However, a frequency-domain formulation is better suited for a linear system with well-defined orthogonal modes. Since SG tubes are multi-span tubes with a gap at each support, the resulting mechanical system is nonlinear and has no clearly defined natural frequencies. Therefore, a purely time-domain formulation is desirable. In the current upgrade, a fully time-domain formulation based on the Quasi-Steady (Q-S) model is used to model the FEI effects.

The Q-S model was developed [4] based on the idea that the tube motion modifies the flow distribution around the tube, resulting in a variation of the lift and drag forces. Under certain flow conditions and depending on the tube mechanical properties such as its frequency and damping, this variation may result in energy transfer from the flow to the structure, causing large amplitudes of vibration known as fluidelastic instability. In the Q-S model, the fluid forces are theoretically expressed as functions of the tube displacement in the lift and drag directions, using Taylor expansion. In parallel, experimental measurements of the fluid forces are conducted in a tube array, providing the lift and drag coefficients and their derivatives with respect to position. Typical lift force data are presented in Figure 1 for various void fractions. These data were obtained in air-water two-phase flow by applying a finite static displacement to an instrumented tube and measuring the forces acting on it. It is also considered that the forces generated by the tube motion on the tube, do not act immediately but with a time delay. This time delay is also measured from experiments [5].

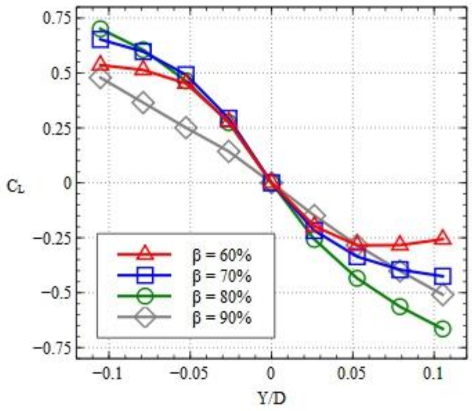

Figure 1 Quasi-static lift force coefficient versus dimensionless displacement in the lift direction (Y/D) for various void fractions [5]

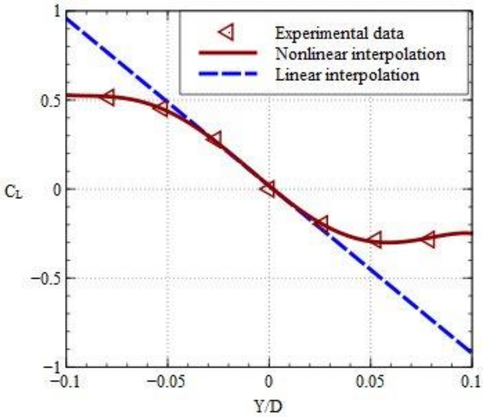

Figure 2 Comparison between the linear and nonlinear lift force coefficients for 60% void fraction

For small displacement magnitudes, linear fluid force expansion can be used, whereas for relatively large displacement, nonlinear fluid force expressions should be used. The difference between the linear and nonlinear fluid force approximations is shown in Figure 2. Both approximations as well as experimental data are plotted against dimensionless displacement in the lift direction. The linear approximation appears to be accurate only around the zero position. Therefore, this approximation should only be used to either assess tube stability or simulate vibration response for relatively small displacements. As a consequence, the nonlinear approximation is better for post-critical analysis for which tube displacement is relatively large. It is interesting to note that this model provides the capability to simulate the post instability behaviour as opposed to the linear model which can rigorously be used only to predict the critical velocity for FEI.

Due to the time delay, the equation of motion of the tube becomes a delay differential equation. This equation is solved numerically using a continuous extension of the Runge-Kutta method.

4. Validation

In this section, simulation results are compared against known theoretical and experimental results. Both simulations were performed for two-phase flow conditions. The theoretical case considered here is a single flexible straight tube subjected to 80% void fraction two-phase flow. The tube is supported in the transverse direction at its centre and two ends. One end is constrained in the axial direction. The tube is a stainless steel tube of 1.828 m long; its outer diameter is 15.85 mm; the wall thickness is 1.13 mm; the structural damping ratio is 0.3%; and its natural frequency is 48.2 Hz. The theoretical critical velocity for FEI given by the Q-S model is 3.14 m/s. An initial displacement is applied to the tube; then the response to the fluidelastic forces at a given flow velocity is simulated. Many simulation runs are conducted, starting with a flow velocity below the critical velocity. The critical velocity given by VIBIC simulation was 3.24 m/s, the difference being 0.1 m/s or 3%.

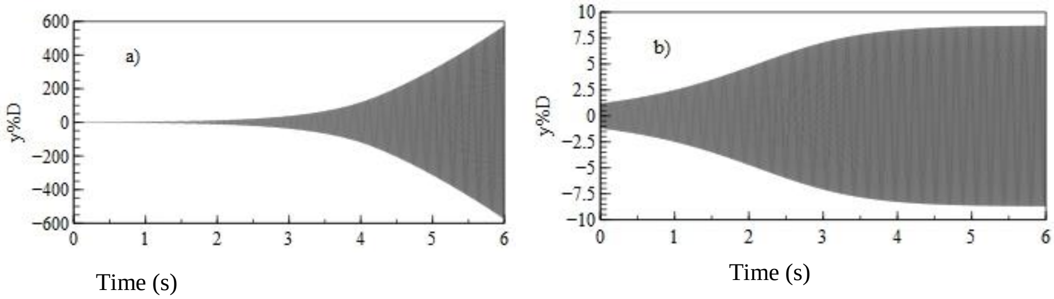

Figure 3 Comparison of the tube response to the: a) linear, and b) nonlinear fluid forces

Responses to the linear and nonlinear fluid forces are compared in Figure 3 for a relatively higher post-critical velocity. As shown in Figure 3, the use of nonlinear quasi-static forces yields more reasonable post-critical amplitude (7.5 % D) than linear fluid forces (theoretically unlimited). In the case of the nonlinear fluid force, the displacement reaches a limit cycle at instability. This is in accordance with experimental observations.

Comparisons were also made with experimental data acquired a few years ago at AECL Chalk River Laboratories. The data were obtained through stability tests on cantilever tubes in a rotated triangular array subjected to air-water flow. The experimental critical velocities were found to be 1.7 m/s and 2.1 m/s for 60% and 85 % void fractions, respectively. In comparison, the simulations results were 1.7 m/s and 1.8 m/s for 60% and 85% void fractions, respectively. This shows a good agreement, knowing that FEI results agree rarely with experimental data within 50%.

5. Conclusions

AECL has been analysing FIV/FW for over forty years and developed relevant assessment technology and computer codes such as PIPO-FE and VIBIC. A full time-domain fluidelastic force formulation has been developed and implemented in VIBIC recently. Both linear and nonlinear fluid forces based on the Q-S model are provided as options. Simulations results were compared to theoretical and experimental data for validation. The response of the tube to the nonlinear fluid force at a post-critical flow velocity reached a limit cycle in accordance with experimental observations. The order of magnitude of the displacement was also more realistic than when the linear fluid force was employed. The nonlinear fluidelastic force expression, which can be employed only in a full time-domain formulation, can, therefore, be used to investigate post-instability behaviour that might result from accident conditions such as a steam-line break.

6. References

[1] Rogers, R.J. and Pick, R.J., “On the Dynamic Spatial Response of a Heat Exchanger Tube with Intermittent Baffle Contacts”, *Nuclear Engineering and Design*, ***36***, pp. 81-90, 1976

[2] Rogers, R.J. and Pick, R.J., “Factors Associated with Support Plate Forces Due to Heat Exchanger Tube Vibration Contact”, *Nuclear Engineering and Design*, ***44***, pp. 247-253, 1977

[3] Han, Y. and Fisher, N.J., “Validation of Flow-Induced Vibration Prediction Codes – PIPO-FE and VIBIC Versus Experimental Measurements”, *Proceedings of the ASME International Mechanical Engineering Conference & Exposition*, Paper IMECE2002-32548, New Orleans, LA, USA, 2002 November 17-22

[4] Price, S.J. and Païdoussis, M.P., “A Single-Flexible-Cylinder Analysis for the Fluidelastic Instability of an Array of Flexible Cylinders in Cross-Flow”, *ASME Journal of Fluids Engineering*, ***108***, pp. 193-199, 1986

[5] Sawadogo, T. and Mureithi, N.W., “Fluidelastic Instability Study in a Rotated Triangular Tube Array Subject to Two-Phase Cross-Flow. Part I: Fluid Force Measurements and Time Delay Extraction”, *Journal of Fluids and Structures.DOI: 10.1016/j.jfluidstructs.2014.02.004*, 2014