APPLICATION OF FLOW-INDUCED VIBRATION PREDICTIVE TECHNIQUES TO OPERATING STEAM GENERATORS

R.G. Sauvé [1], M. Tabatabai [1], G. Morandin [1], M.J. Kozluk [2]

ABSTRACT

Analytical techniques for flow-induced vibration (FIV), such as those incorporated in available design tools, are routinely applied to process equipment at the initial design stage. Unfortunately, this does not always apply to the situation when problems, related to FIV, develop in crucial operating equipment, since design uses conservative methods, whereas in-service applications require more realistic assessments. Usually these problems appear in the form of severe through wall fret flaws or fatigue cracks that compromise the integrity of the tubes and possibly the complete unit. It is here where a somewhat different approach must be taken in the evaluation of tube response to FIV. Tube damage from fretting wear or fatigue crack growth must be estimated from actual in situ operating conditions. In this paper, an overview of the predictive methods used in the development and/or qualification of remedial measures for problems that occur in operating process equipment along with applications are described. The steps in the evaluation procedure, from the prediction of flow regimes, the development of the nonlinear computer models and associated fluid forcing functions through to the estimates of tube damage in operating heat exchangers and steam generators are presented. A probabilistic (i.e. Monte Carlo simulation) FIV approach that readily accommodates uncertainties associated with damage predictions is summarized. The efficacy of this approach comes from the fact that probabilistic methods facilitate the incorporation of field data, and that a large number of tubes and possible variations in geometry, process and support conditions, usually present in such equipment, can be addressed effectively.

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INTRODUCTION

Analytical techniques for flow-induced vibration (FIV) are routinely applied to process equipment at the initial design stage. Given the maturity of the field at the present time, methods can be applied with conservative approximations based on available databases (i.e. damping, turbulence forces, etc.) to evolve relatively reliable process equipment designs. Unfortunately, this does not always apply to the situation where problems related to FIV, that occur in the field, develop in crucial operating equipment. Usually these problems appear in the form of severe through wall fret flaws (Figure 1) or fatigue cracks (Figure 2) that compromise the integrity of the tubes and possibly the complete unit. In the case of significant safety and/or economic concerns, root cause investigations, design modifications and revised operating procedures are undertaken. It is here where a somewhat different approach must be taken in the evaluation of tube response to FIV. Tube damage from fretting wear or fatigue crack growth must be estimated from actual in situ operating conditions. For example, degradation of tube support plates due to corrosion may lead to changes in flow conditions and support conditions affecting the tube modal properties. Unlike the design stage, where conservative acceptance criteria (e.g. fluidelastic instability thresholds, tube response limits, etc.) based on guidelines are prescribed, damage estimates and remaining life predictions require advanced computational fluid dynamics and nonlinear flow-induced vibration simulations [1-3]. Predictive techniques used in FIV assessments, at either the design stage or for improved understanding of anomalous behaviour of operating equipment, generally require detailed information regarding geometry and flow conditions. During the design process, standards are used in conjunction with frequency domain methods such as modal superposition to evaluate the susceptibility of a design to FIV. This approach usually involves an eigensolution to generate natural frequencies and mode shapes of a particular tube configuration, followed by a frequency response analysis. This provides estimates of tube response to such mechanisms as periodic wake shedding and turbulent excitation. In addition, the potential for fluidelastic instability is determined, using the results of the modal analysis, by comparing the actual effective flow velocity, V, around a given tube to a critical velocity, V_c. This approach is supported by databases and guidelines for important parameters such as damping, random turbulence, etc.[4-9].

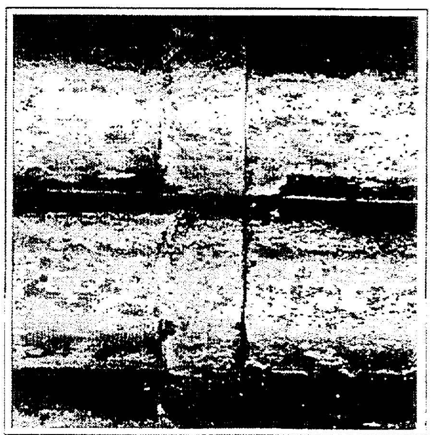

Figure 1
Heat Exchanger Tube Wear

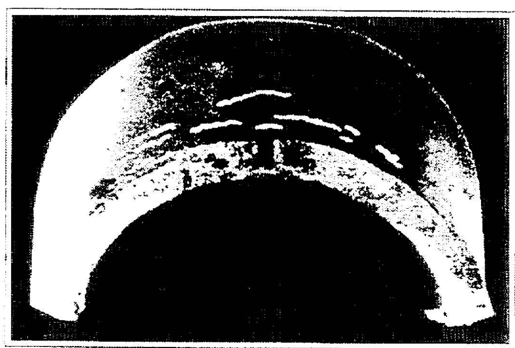

Figure 2
Crack Growth in a Heat Exchanger Tube

During operation, situations may arise where functional design performance is impeded by degraded tubes whose structural integrity is compromised due to flow-induced excitation. Whether it occurs due to fluid chemistry leading to corroded support conditions, loose tolerances causing wear, change in flow patterns or fatigue crack initiation followed by crack growth, the result is a damaged tube resulting from dynamic loading. Unlike the design stage, predictive methods must include details of FIV phenomena that permit more realistic estimates of tube displacements and stresses. An effective evaluation procedure such as that shown in Figure 3, must include an accurate prediction of flow regimes using three dimensional computational fluid dynamics models. The results of the fluid models (e.g. flow velocities, mass flux, quality) are utilized in the development of the associated time-dependent fluid forcing functions for turbulent excitation and fluidelastic forces that are applied to three dimensional nonlinear finite element models of the tube and supports. The nonlinearity arising from the tube to tube support interaction (i.e. clearance, friction) and the fluidelastic coupling necessitates time domain solutions of a set of nonlinear equations of motion for the tube. These solutions yield tube to tube support impact forces and work rates along with tube internal forces and moments versus time that can be used to obtain estimates of tube wear and/or fatigue crack growth in operating heat exchangers and boilers. These predictive methods are used in the development and qualification of remedial measures for problems that occur in operating process equipment.

The foregoing time domain solution for FIV represents a deterministic approach that works well when all key parameters are known with a fair amount of confidence. Unfortunately, there is usually a significant variability in the value of these parameters for a given design. For example, equipment that includes multi-supported tubes may have virtually interminable combinations of tube to tube support conditions (i.e. clearances, misalignment, preload), variability in fluid forces (i.e. fluidelastic parameters, power spectra of random turbulence), etc. One approach used to deal with this, is to combine the time domain FIV solution, described earlier, with a probabilistic method such as a Monte Carlo simulation [25]. Adapting the deterministic FIV solution to the Monte Carlo method requires a knowledge of the distribution functions of the critical parameters. These can usually be estimated from previous experimental data, compiled databases or previous inspection data. The efficacy of this approach comes from the fact that probabilistic methods facilitate the incorporation of field data and the large number of tubes and possible variations in geometry, process and support conditions, usually present in such equipment. In this paper, the key components of a procedure used in the assessment of tube damage due to FIV in process equipment is summarized. A probabilistic approach for evaluating damage due to FIV is presented through an application to an operating steam generator.

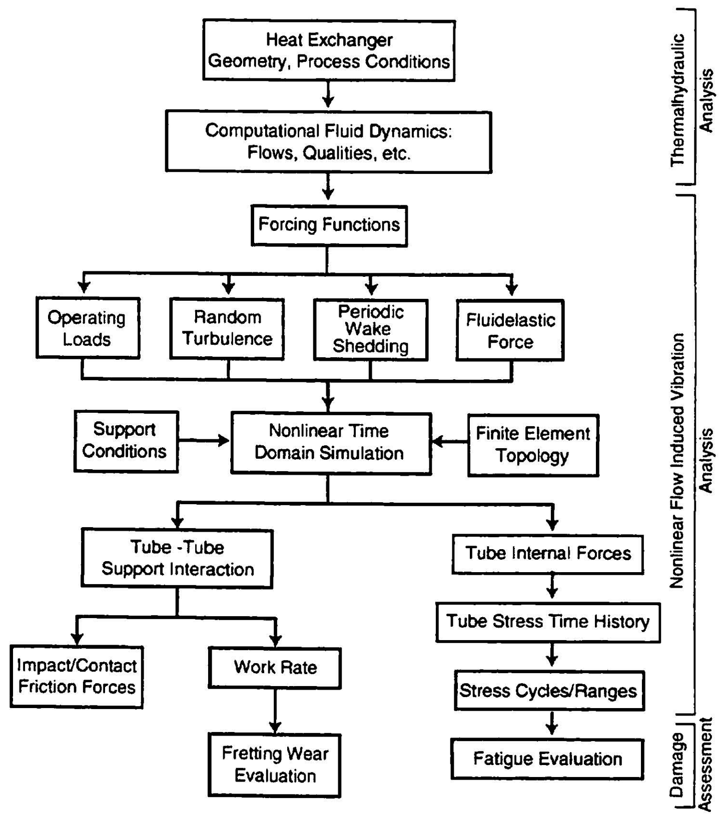

Figure 3
Tube Damage Assessment Procedure (FIV) for Process Equipment

COMPONENTS OF THE FIV EVALUATION PROCEDURE

There are numerous facets to a generic procedure for predicting tube damage from deleterious FIV mechanisms in process equipment. These range from computational fluid dynamics and nonlinear structural analysis to fatigue and fretting wear assessment. A systematic evaluation procedure, shown in Figure 3, is used to consolidate state-of-the-art simulation techniques and current understanding of FIV mechanisms with experimental and inspection data along with past operational experience. In addition, it provides an effective means of evaluating the impact of design modifications and accident scenarios on tube integrity in crucial operating process equipment. The following summarizes the key steps in the procedure.

Thermalhydraulic Analysis

The primary parameters of interest (e.g., density, velocities and void fraction) are obtained from one, two and three dimensional fluid models and are used to develop the tube forcing functions that are described later. The accuracy of the FIV analysis, therefore, depends heavily on the thoroughness of the thermalhydraulic analysis. One dimensional models are still used in some analysis (e.g. blowdown transients) and provide a global picture of flow acting on components. In order to obtain a more detailed spatial distribution of parameters, three dimensional (3D) models are necessary. A number of 3D thermalhydraulic codes are available, developed, mostly, using finite difference or finite element schemes [12,13]. The sophistication of the thermalhydraulic code, in addition to the algorithms used for the numerical formulation, depends on the empirical models used in the code, (e.g., loss coefficients, two-phase flow models, resistance models, etc.). Presently, steam generator models are developed using porous media assumptions, where the existence of tubes and plates in the steam generator are simulated by equivalent distributed resistances. The local details of the flow between tubes (e.g., gap velocities) are, then, approximated using the geometrical arrangement of the tubes. Figures 4 and 5 show typical results from the analysis of a nuclear steam generator and a preheater obtained using the porous media concept. Full 3D modelling of shell and tube type heat exchangers, including all the tubes and gaps, is currently not viable. However, with the rapid increase in the performance of the computers, that prospect can soon become a reality. Work is underway to improve the accuracy of FIV simulations through coupling of fluid and solid codes. This fully coupled approach represents the next step in modelling the interactions between the fluid and the tubes.

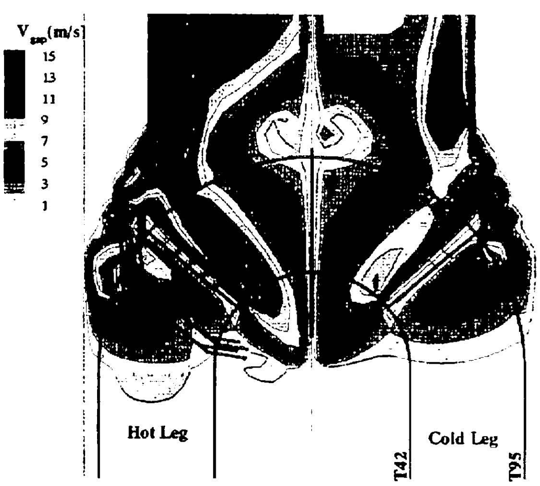

Figure 4
Steam Generator U-Bend Gap Velocity Contours

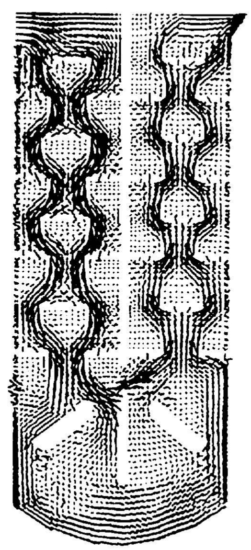

Figure 5
Velocity Vectors in a Stand-alone Preheater

Nonlinear Solution for Tube Dynamics

Since tube to tube support interaction and friction are generally present in operating process equipment, simulations must utilize a nonlinear computational scheme for tube structural dynamics similar to that described in [3,14,19,23]. Basically the discretized equations of motion describing a three dimensional nonlinear structural dynamic system representing a tube in loose supports, under time-dependent forces can be written in terms of convected coordinates x as follows;

$$M\ddot{x}^t + C_d\dot{x}^t + F^t_{int} = F^t_{ext} + F_f^t \tag{1}$$

Where $\dot{x}^t$, $\ddot{x}^t$ are the coordinate, velocity and acceleration vectors at time t respectively, M is mass, C_d is the damping. F_{ext} and F_f are the external (e.g. random turbulence, wake shedding, drag loads, etc.) and fluidelastic force vectors respectively. F^t_{int} is the internal force vector for a nonlinear system that includes nonlinear supports (i.e. contact force discontinuities arising from loose supports including normal impact and stick/slip friction models). For the explicit solution used herein, the following relation for F^t_{int} is used;

$$F^t_{int} = \int_V (B^T)^t \sigma^t dv + F^t_{NL} \tag{2}$$

where;

B^T	=	transpose of the matrix relating element nodal velocities to element velocity strains
σ^t	=	element stresses
V	=	element volume
F^t_{NL}	=	interface forces between contact surfaces described as a function of relative displacements U^t_a and clearance U_s between contact surfaces
	=	$f(U^t_a - U_s) \qquad U^t_a > U_s$
	=	$0 \qquad U^t_a < U_s$

The explicit central difference operator is used in the direct time integration of the equations of motion, since it has been shown to be highly efficient [14] for problems involving severe geometric and material nonlinearity. Unlike the modal superposition method used for nonlinear boundary conditions [1] the method considered herein includes the response in all frequencies of the discretized model and is appropriate for material and geometric nonlinearity. In the explicit integration scheme, all quantities such as accelerations $\ddot{x}$, velocities $\dot{x}$, coordinates x, displacements u, and internal element stresses σ, are known at time t. At time $t + \Delta t$, the external loads at a new time step are applied and the updated accelerations, $\ddot{x}$, along with velocities, $\dot{x}$, and coordinates, x, are obtained as shown in the solution strategy of Figure 6. In the updated configuration, the stresses are evaluated using appropriate constitutive laws and used in the discretized equilibrium equations to obtain updated accelerations. At each time step, all element constitutive calculations are evaluated in an updated configuration frame defined by current coordinates.

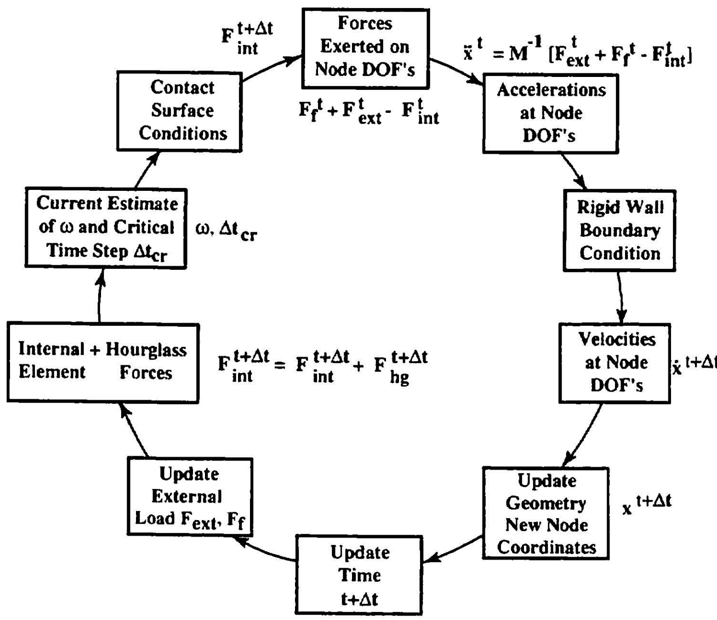

Figure 6
Explicit Nonlinear Computational Cycle for FIV

Using a lumped (i.e. diagonal) mass matrix, M, appropriate for the tube element formulation [23], avoids the need for a formation of system equations into a banded matrix and a system solver. This feature of the algorithm permits tractable solutions of large models (i.e. $>10^5$ degrees of freedom). This operator is conditionally stable so values of the time step must be maintained below a critical time step, based on the Courant stability limit.

Turbulent Excitation Forcing Function

The turbulent excitation component, $F(t)$, of the forcing function $F_{ext}(t)$ for the nonlinear analysis is established using the results of the thermalhydraulic analysis along with the time domain turbulent excitation model described in [16]. From the discrete representations of measured power spectral densities (PSD's) used in the steam generator design [7,15], the required forcing functions are generated using an inverse Fourier transform algorithm [16]. Since the discretized PSD of the forcing function is defined as the density of the mean square value of the forcing function in the interval $\Delta\omega$ at the frequency ω_i, an expression for the time dependent forcing function representing turbulent excitation of the tubes in the U-bend region of a steam generator can be accurately represented by a Fourier series of the form;

$$F(t) = \rho V d \sum_{i=1}^{N} [2\Delta f\, S(f_i)]^{0.5} \sin(\omega_i t + \Phi_i) \tag{3}$$

where;

ρV	=	mass flux (ρ = density, V= flow velocity)
d	=	tube diameter
$S(f)$	=	PSD deduced from experiments [7,15]
ω_i	=	frequency (radian) = $2\pi f_i$, where f_i = frequency (Hz) of each harmonic
Φ_i	=	phase angle
N	=	number of harmonics contributing to the total force

The value of the phase angle Φ_i lies between 0 and 2π and is selected randomly for each harmonic consistent with the random nature of turbulence. For a force distributed over an element length L_e, the force acting at each node $F'(t)$ is evaluated as $F'(t)=0.5\, L_e F(t)$ for the elements described in [23], assuming it to be fully correlated across each span. In the U-bend region of a typical steam generator, the flow regime is two-phase. Using an experimentally determined PSD for air-water, such as suggested in [15], to represent the actual steam-water regimes that exist in U-bend regions of operating boilers can be overly conservative. An approach for adjusting PSD's based on air-water data for two-phase regimes is given in [7].

Fluidelastic Forcing Function

As with the turbulent forcing function described in the previous section, the fluidelastic forcing function, F_f, is established using the results of the thermalhydraulic analysis. The particular form used replicates the instability predicted by the semi-empirical Connors' model for flow velocities that exceed a specific tube critical crossflow velocity. Alternate approaches [4,6] using a more rigorous theory, lack the experimental database needed to apply them to two-phase flow applications. In the present analysis, the time domain fluidelastic force $F_f(t)$ is based on the formulation described in [3]. It is an approach whereby nonlinear models of tubes can be driven by time dependent forces that predict the variation of damping with flow velocity that is consistent with Connors' equation. Considering the transverse tube motion in a mode of vibration, an expression for the time-dependent fluid destabilizing force F_f under a fluid cross-flow velocity V at time t is obtained as;

$$F_f^t = \left[\frac{4\pi}{(C_k)^2}\right]\frac{\rho^t(V^t)^2 L\dot{x}^t}{\omega} \tag{4}$$

where;

$\dot{x}$	=	the velocity of transverse tube motion
V	=	flow velocity assumed constant over the tube length L
ω	=	participating mode frequency at time t
L	=	tube length
C_k	=	empirical fluidelastic coefficient
ρ	=	fluid density

The calculation of the current participating mode frequency, ω, at each instant of the solution, is an important aspect of the formulation. Throughout each nonlinear time domain simulation, a modified form of Rayleigh quotient is used for estimating ω at time t. Use of equation (4) in conjunction with the equations of motion (1) provides a means of including fluidelastic forces with both spatial and temporal variations in ρ and V into the time domain. The fluidelastic forces are distributed over an element length L, and, as with the external forces, are applied to the three-dimensional beam model.

System Damping

An important parameter in any dynamic simulation is the damping that characterises the amount of energy dissipated from the system. Various estimates of damping in operating steam generators have been obtained from experiments and in-situ measurements. In [8,9] guidelines are suggested for evaluating the damping ratio, ξ, in terms of viscous, support and two-phase damping. Limited data is available for flow-regimes of steam-water [10]. Measurements of the total damping ratio for tubes in air have also been taken in operating steam generators [11]. The comparison of damping ratio versus frequency based on guidelines and measured values with the proportional damping formulation used in a typical simulation of steam generator FIV is shown in Figure 7.

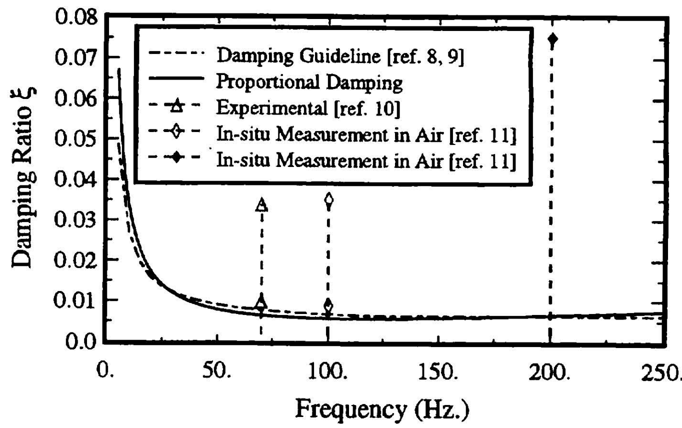

Figure 7
Damping in Steam Generator U-Bend Region

Support Conditions

In an operating boiler, the support conditions depend on the support geometry, manufacturing tolerances, operating conditions, tube and tube support material. The range of typical support geometries used in steam generators is depicted in Figure 8. The relative effectiveness of the support has a significant influence on the dynamic properties (and response) of the system. The shape of the support along with the magnitude of support clearance and misalignment can have a profound effect on the degree of tube wear at the support location. Thus, it is important to accurately model the tube to tube support interface if a nonlinear FIV simulation, representative of the particular operating steam generator, is to be obtained. Nonlinear supports are modelled using analog elements [24]. These elements describe the arbitrary support shapes shown in Figure 8, using a discretized unit normal vector approach.

The element tracks the trajectory of a point representing the neutral axes of the tube element on a constraint of arbitrary geometry. The interaction between the tube and supports is modelled with a stick/slip model based on a general three dimensional contact algorithm [17]. If the resultant tangential force is greater than the friction force, the tube slips on the support and wear results, otherwise it sticks to the support surface and does not move. The model accounts for static and dynamic friction. Representative coefficients of friction for this class of problem have been reported [18].

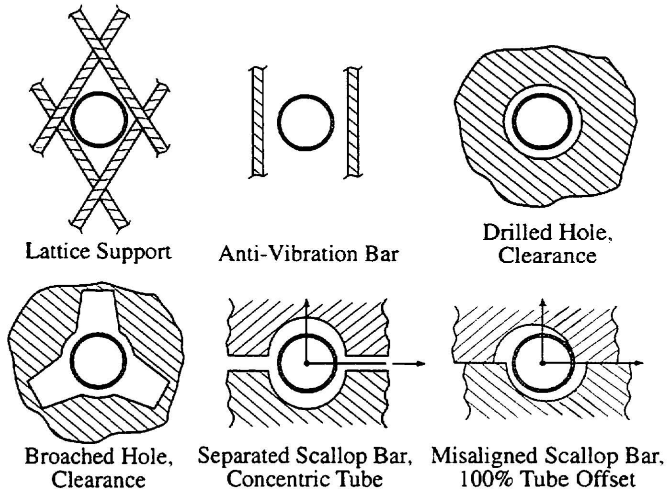

Figure 8
Typical Tube Support Conditions

Work Rate Definition and Wear Correlations

The potential for tube fretting wear damage is assessed using a time-averaged work rate parameter, $\dot{w}$. Wear data is generally correlated [2,20] with $\dot{w}$ and is usually defined as the time-averaged product of the normal component of impact force and sliding velocity:

$$\dot{w} = \frac{1}{t_t}\int_0^{t_t} F_n(t)\dot{x}_T(t)\,dt \tag{5}$$

where;

$F_n(t)$	=	normal impact force
t_t	=	total simulation time
$\dot{x}_T$	=	sliding distance per unit time

Using the system response, the work rates for the nonlinear elements representing the tube supports of interest are calculated. Since the work rate is related to wear rate, it provides a relative indication of which supports are more susceptible to fretting wear. The tangential sliding velocity $\dot{x}_T$, is obtained from an orthogonal tensor transformation of the global three dimensional tube response arising from the three dimensional excitation at the nonlinear support. The contact model [17] includes stick/slip friction and accounts for inelastic contact thus providing an accurate assessment of the tangential (e.g. sliding) motion and resulting work rate. The volumetric wear rate, $\dot{V}$, at the tube to tube support interface is obtained from experimental correlations with appropriate definitions of work rate [20].

Fatigue Crack Growth Model

Damage due to fatigue crack growth of postulated crack-like flaws, a_o, in process equipment tubes during steady state or transient FIV loading can be carried out using a linear-elastic fracture mechanics (LEFM) flaw model together with a fatigue crack growth rate model [21]. For linear-elastic stress states, the potential for non-ductile extension of a crack is characterized by the crack-tip stress intensity factor K_I. The value of K_I is a function of crack size, shape, orientation and the global stress state in the tube. The use of LEFM is warranted provided that the plasticity associated with the crack-tip does not extend through the remaining ligament. This requirement is met for high-cycle fatigue resulting from flow-induced random turbulent excitation. In the evaluation of steam generator tubes, the time histories of tube response in terms of internal moments and forces are obtained from the nonlinear time domain FIV simulation.

The number of cycles and the magnitude of stress ranges corresponding to each of these cycles is determined using an appropriate cycle counting algorithm such as the rainflow technique. For each of these cycles, the increment in crack growth, *da*, is evaluated using a flaw model in conjunction with a fatigue crack growth model [21] of the form;

$$\frac{da}{dN} = C(\Delta K)^n \quad \text{for } \Delta K > \Delta K_{threshold} \tag{6}$$

where;

da/dN = fatigue crack growth per cycle
C, n = material parameters: fatigue crack growth rate constant and exponent respectively [22]
ΔK = cyclic range of crack-tip stress intensity, K_I
$\Delta K_{threshold}$ = threshold value of ΔK below which no observable crack growth occurs

Equation (6) is used to evaluate the accumulated crack growth, *a*, over a specified time interval. In the case of steam generators, the evaluation period usually corresponds to the length of the transient, or, in the case of steady state operation, over the periodic inspection interval. The final length of the crack at the end of the simulation can then be compared to an allowable value to determine the remaining operating life of the tube.

PROBABILISTIC ASSESSMENT OF FLOW-INDUCED VIBRATION DAMAGE

The life management of process equipment requires predictive analyses to assess variations in support geometry, process conditions, environment and retrofits. It is essential to provide accurate estimates of tube integrity (i.e. fatigue, fretting wear) under the influence of these changes. In general, there will be a degree of uncertainty in much of the data required for these predictions. In some cases, probability distribution functions of critical parameters such as support clearance can be derived from actual inspection data. In others, the distribution can be estimated from experiments. Thus, a more realistic approach is to treat these parameters as random variables with probability density functions. The concepts previously described culminate in a probabilistic approach to the prediction of work rate (i.e. the main parameter in fretting wear) in the U-bend region of an operating nuclear steam generator. In [25] the nonlinear deterministic computational techniques described earlier are applied in Monte Carlo simulations in order to provide a probability density function (PDF) and cumulative distribution function (CDF) of wear work rate $\dot{w}$ for a tube support. This procedure may also be applied to other damage mechanisms such as fatigue produced by flow-induced vibration.

Monte Carlo Simulation

The Monte Carlo method considered herein, is designed to obtain the probability distribution of a general nonlinear function (i.e. work rate $\dot{w}$) from a set of independent random variables, Z. These variables and their probability distributions, $f_Z(Z)$, provide a convenient way of accounting for uncertainties. In the method, Z is obtained from a set of random numbers representing a sample of each of the critical parameters under consideration.

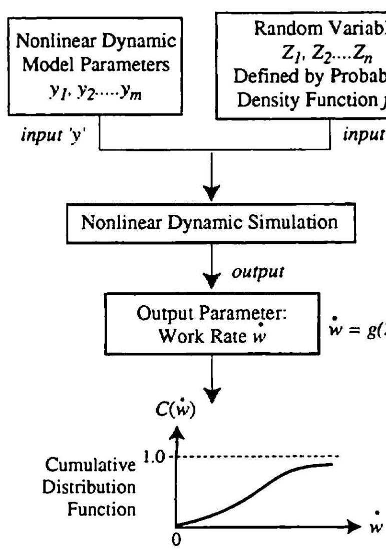

Figure 9
Monte Carlo Simulation Flow Diagram

In the application to FIV, the output function, $\dot{w} = g(Z)$, relating the output variable to the random input variable, Z_i, represents a complex relationship involving nonlinear behaviour. It is obvious that $\dot{w}$ is a nonlinear function of the various random parameters, Z, such as support clearance, tolerances, etc., and can be written as a function of Z required for the Monte Carlo simulation. Using Z as input, a nonlinear dynamic simulation is carried out to obtain the dependent random (i.e. output) variable, $\dot{w}$. This is repeated for N samples to obtain an estimate of the probability density function, $f_{\dot{w}}(Z)$, for the dependent random variable. As N approaches infinity, this function converges to the exact result. The Monte Carlo simulation is outlined in Figure 9. The output of this technique is the cumulative distribution function, $C(\dot{w})$, from which the probability of exceeding a specific value of $\dot{w}$ can be obtained. The expected value of $\dot{w}$ is approximated by the statistical average of the N samples of $\dot{w}$.

APPLICATION TO NUCLEAR STEAM GENERATORS

The efficacy of the procedure described in the preceding sections for applications involving operating process equipment is demonstrated by an application involving the U-bend region of a nuclear steam generator. In this example, a large radius U-bend tube, subject to two-phase flow, with scallop bar type supports at 40° in the hot and cold leg regions, at 90° and at 7th support plates is considered. The flow regime is determined from a thermalhydraulic analysis. Figure 10 shows the geometry of the finite element tube model along with the support data, boundary conditions, profile of the two-phase flow distribution and model parameters. In-plane (i.e. in the plane of the U-bend, directions X,Y) and out-of-plane (i.e. out-of-plane of the U-bend, direction Z) motions (full three-dimensional motion) are included. For each set of random variables, the nonlinear response time history is computed using the explicit module of a three dimensional nonlinear finite element computer code [24] for sampled steady state conditions over a four second time interval that is representative of steady state operating conditions. The location and local axis of the nonlinear supports are shown in Figure 10. In the simulations conducted herein, the following parameters are taken as the independent random variables: tube to support misalignment (e.g. offset), preload due to drag forces and manufacturing, radial clearance and friction.

The offset accounts for the position of the tube within its support, where 100% denotes initial contact of the tube with the support in the inplane direction. The empirical fluidelastic constant, C_k, is taken to be uniformly distributed within the range associated with this type of component. The effect of the variability in these parameters on the tube work rates at the supports is assessed using the probabilistic method and reported in [25]. In general, the probability distributions for some of these variables could be established from periodic inspection data. For the present work, uniform probability density functions are used, although alternate forms can be included as required. The range of values for the parameters used in each simulation is given in Table 1.

Parametric Analysis

In [25] the use of a probabilistic approach to perform sensitivity analyses is discussed. Unlike a traditional sensitivity analysis where the parameters are held constant with the exception of the one to be varied, all the independent parameters are varied randomly in the probabilistic analysis. The effect of each variable is determined by building a map of the output variable (e.g. work rate, fatigue crack growth) versus the parameter of interest. In [25], maps of this nature have been constructed for a number of parameters related to steam generator tube wear and the significance of each parameter is discussed. Of crucial importance to any Monte Carlo simulation of this kind, is the number of samples, N, used. Testing [25] has shown that a minimum of 1000 samples is sufficient for good statistical accuracy.

Variable	Min. Value	Max. Value
Friction, ν	0.05	0.50
Radial Gap (mm)	0.0127	1.27
Fluidelastic Coefficient, C_k	4.0	6.0
Preload (N)	0.0	22.24
Offset (%)	0.0	100.0

Table 1
Random Variable Support Data

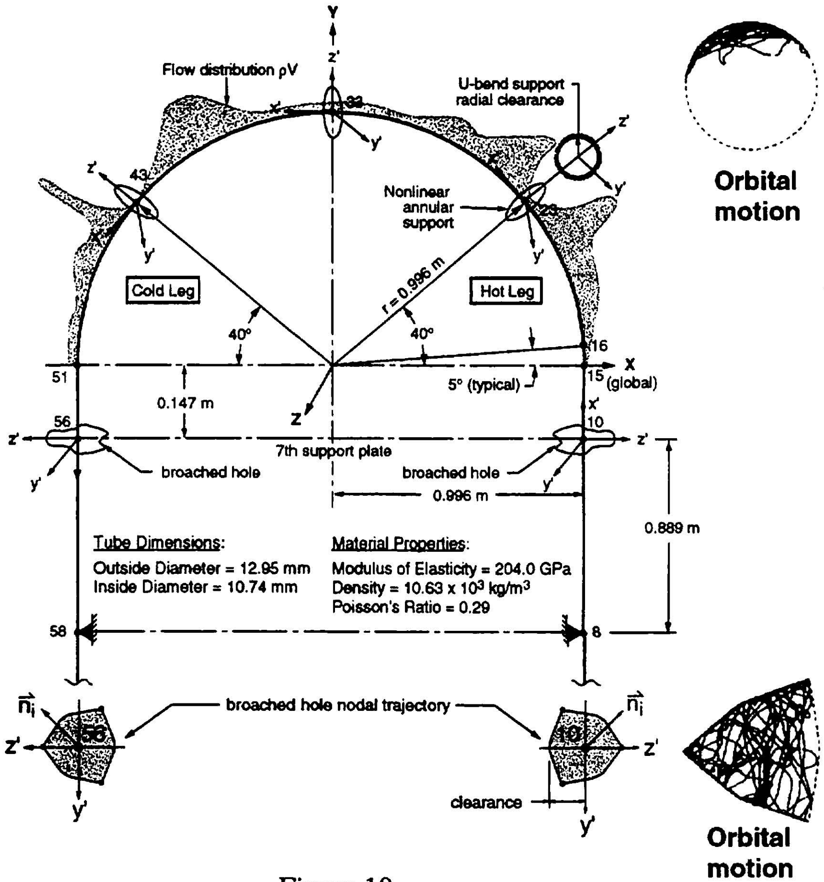

Figure 10
U-Bend Nonlinear Finite Element Model

Results

The probability density function (PDF) of work rate corresponding to 2000 samples for each distribution is given, along with its cumulative distribution function, for the 40° hot leg support as shown in Figure 11. The cumulative distribution and probability density functions of work rate provide the probability of exceeding specified values of work rate. In general, the results indicate that the work rate at this support will lie below 50 mW approximately 93% of the time. Similar results are obtained for the remaining supports. In very few cases involving a wide range of uniformly distributed random input parameters, excessive values of work rate are observed as shown in the cumulative distributions. Examination of the input parameters associated with the few events leading to unacceptably high work rates, can be used to identify the key contributors to damage in operating components.

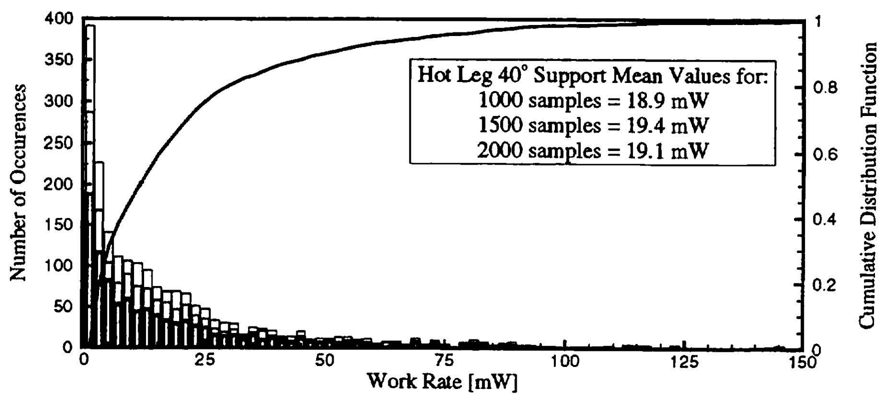

Figure 11
PDF and Cumulative Distribution Work Rate Function
Steam Generator Hot Leg Support

CONCLUSIONS

Significant advances have been made in computational methods for resolving FIV related problems in process equipment that can assist with the life management and maintenance of critical operating equipment. The Monte Carlo method provides a way of quantifying the effect of uncertainties in operating parameters on FIV related fretting and fatigue damage that is consistent with current inspection and licensing practices. Sustained research and development in the areas of fluid-structure coupling, and the compilation of global databases for FIV parameters used in establishing distribution functions and guidelines are paramount to the continued improvement in predictive capabilities.

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DISCUSSION

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Paper: Application of Flow-Induced Vibration Predictive Techniques to Operating Steam Generators

Questioner: D. Duncan, Lockheed-Martin

Question/Comment:

(1) What is the magnitude of the velocity in the U-bend?
(2) What type of velocity are you using for the modelling?
(3) Is the damping a function of void fraction?
(4) Are any thermal/hydraulic parameters used as variable in the Monte Carlo calculations?

Response:

(1) Maximum velocity is about 13 m/sec.
(2) Homogeneous mixture velocity based on the minimum gap.
(3) Yes, the two-phase damping is used as a part of 3-component damping calculation.
(4) Yes, the list presented in presentation includes only a limited number of parameters that are used in the Monte Carlo calculation.