Enclosure 6

GE-NE-0000-0048-1485-01, "Damping Value for Steam Dryer Hood Focused on a Single Frequency Regime" (Proprietary and Non-Proprietary)

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Non Proprietary Version

GE-NE-0000-0048-1485-01-NP
Class I
DRF Section 0000-0048-1485
November 2005

Damping Value for Steam Dryer Hood Focused on a Single Frequency Regime

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Damping Value for Steam Dryer Hood with Emphasis on 150 Hz Frequency Regime

Summary

For the dynamic analysis of the Quad Cities steam dryer subjected to fluid induced dynamic loading at the reactor operating environment, a technique of direct time-wise numerical integration of the equation of motion with Raleigh damping matrix was used. Corresponding to the Raleigh damping selected for dryer hood, the equivalent modal damping values are [[ ]], and about [[ ]] frequency regime.

From the Quad Cities 2 steam dryer start-up testing, the measured fluid induced dynamic loading has a major component near [[ ]] frequency regime. This frequency range will therefore be the main focus of the discussion on the appropriateness of using the equivalent modal damping value [[ ]] and the conservatism of subsequent Finite Element Analysis predicted steam dryer structural response.

This damping value is deemed appropriate based primarily on the following considerations:

(1) In the steam dryer test at an overseas BWR 5/251 plant, under actual reactor operating condition of steam environment, the steam dryer was subjected to rapid valve closures of the Turbine Stop Valve (TSV) and the Main Steam Isolation Valve (MSIV). The recorded strain responses have shown critical damping values from [[ ]] as measured on the hood.

(2) US NRC Regulatory Guide 1.61- Damping Values for Seismic Design of Nuclear Power Plants recommends, for welded structures, such as a steam dryer, critical damping values of 2% and 4% for the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) analyses, respectively. The Regulatory Guide also states that these modal damping values should be used for all vibration modes considered in an elastic spectral or time-history dynamic seismic analysis of the Seismic Category I structures or components. Although the recommended damping values are specifically for dynamic seismic analysis, there exists no prohibition against the use of these values for other dynamic loading analysis, such as flow induced vibration analysis, as long as the guidelines for the maximum combined stress response due to static, seismic, and other dynamic loading are satisfied. It should be noted that these recommended damping values are for structure in an air environment at room temperature and atmospheric pressure conditions. In a steam environment at the reactor operating condition (547^0 F and 1020 psia), the fluid portion of the damping mechanism is about [[

]] higher than that in an air environment at room temperature and atmospheric pressure conditions. The total critical damping values are estimated to be about [[ ]] for the OBE and SSE analyses, respectively, in a steam environment at the reactor operating condition.

(3) In the Quad Cities dryer hammer tests, the measured dryer hood damping values are in the ranges of [[ ]] at the low end of the frequency spectrum around [[ ]] and about [[ ]] toward the high end of the frequency spectrum around [[ ]]. The damping value at the actual reactor operating condition and under fluid flow induced dynamic loadings should be much larger than the hammer test measured damping values, especially the [[ ]] damping value at the [[ ]] regime. This conclusion is based on the following two considerations:(a) hammer tests were conducted in an air environment at ambient conditions (room temperature and atmospheric pressure). In a steam environment at reactor operating condition (547^0 F and 1020 psia), the fluid portion of the damping mechanism should be about [[ ]] higher than that in an air environment at ambient conditions, and (b) the structural portion of the damping mechanism depends on the magnitude of the structural deformation experienced; the larger the structure deforms, the larger the structural damping value will be. Through the new steam dryer start-up testing, it has been found that in the [[ ]] regime, the actual hood strain response is about [[ ]] higher than that induced by hammer tests. The total critical damping value at [[ ]], with these two factors taken into account, is estimated to be about [[ ]].

(4) Using the Raleigh damping for the dryer hood, which results in equivalent modal damping values [[ ]], and about [[ ]] of critical damping near the [[ ]] frequency regime, the Finite Element Analysis (FEA) predicted strain responses are closely matching and/or exceeding the start-up test measured strain responses.

Based on the above considerations, especially the close agreement between the analytical and test results (item 4 above), it can be concluded that the use of critical damping values of [[ ]] for the dryer hood near the [[ ]] frequency band is appropriate and technically justified. Details of this assessment are given in the following sections and references are provided.

1. Background

A structural dynamic system, such as the steam dryer, generally has three kinds of damping mechanism (Reference 1): material damping (due to yielding, heating, electromagnetic currents, and internal energy dissipation of materials), structural damping (due to friction, impact, scraping, and motion of trapped fluid within a joint, etc.) and fluid damping (due to fluid drag, viscous dissipation, and radiation to the surrounding fluid). These damping mechanisms result in energy dissipation while the structural system is responding to a dynamic loading. These damping and energy-loss mechanism are very complex, seldom fully understood and difficult to fully characterize, thus it is not feasible to analytically determine the exact damping values. The damping values are frequently determined directly by experimental methods.

Test measurements have shown that the magnitude of the structural damping depends not only on the type of joints or connections within the structure, but also on the magnitude of deformation experienced; the larger the structure deformation, the larger the structural damping value. As shown in Figure 1 (Reference 1), the damping increases with vibration amplitude.

Figure 1 Damping as a Function of Vibration Amplitude (Reference 1)

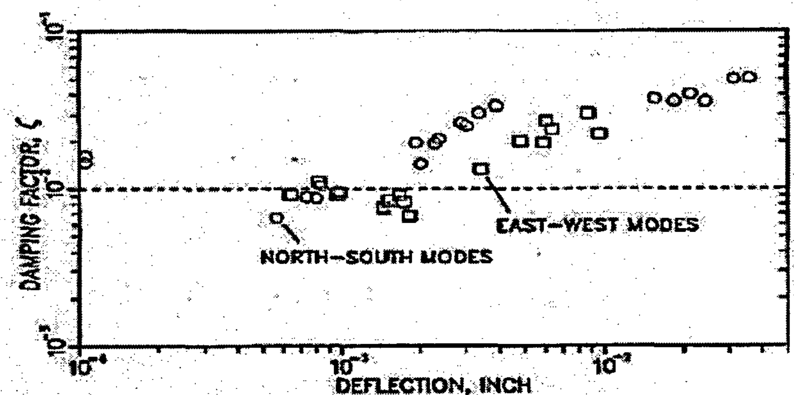

Fig. 8-20 Damping of a nuclear power plant steam generator as a function of amplitude of vibration (Hart and Ibanez, 1973).

Laboratory tests have also shown that the damping values are somewhat independent of the structural modal frequencies, as illustrated in Figure 2 (Reference 1). Note in Figure 2 that the upper bound frequency is about 600 Hz. Also, notice the large scattering of the test damping values for a given frequency both in air and in water. Damping values in water are generally higher than damping values in air.

Figure 2 Damping as a Function of Frequency of Vibration (Reference 1)

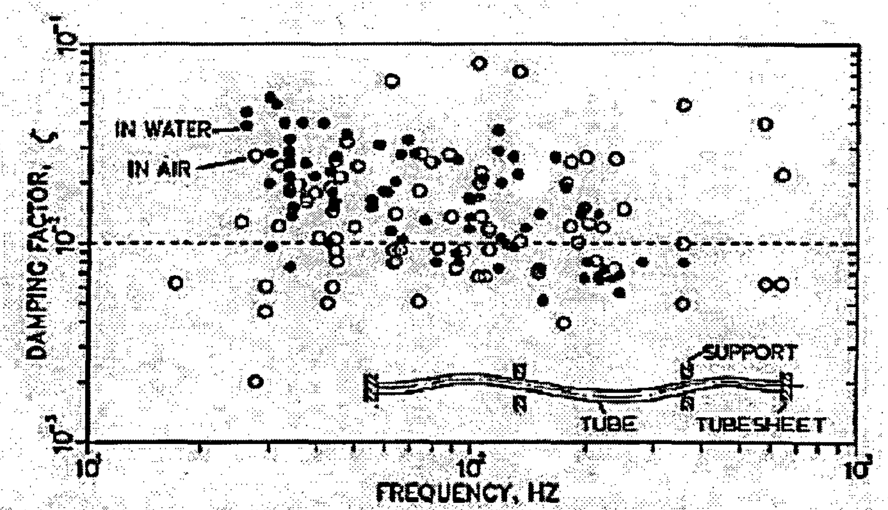

Fig. 8-19 Damping of multi-span heat-exchanger tubing (Pettigrew et al., 1986).

When performing a structural dynamic response analysis, energy dissipation is typically accounted for in one of two ways: (1) by specifying an amount of viscous damping via the percent of critical damping, if modal superposition analysis technique is employed, or (2) by specific the Raleigh damping, if a direct time-wise numerical integration of the equation of motion technique is used (Reference 2).

For the dynamic analysis of the Quad Cities steam dryer subjected to fluid induced dynamic loading, the technique of direct time-wise numerical integration of the equation of motion with Raleigh damping matrix was used. Corresponding to the Raleigh damping selected for the dryer hood, the equivalent modal damping values are [[ ]], and about [[ ]] of critical damping near the [[ ]] frequency regime, as shown in the upper curve of Figure 3 (References 3 and 4).

Figure 3 Modal Damping Equivalent to Raleigh Damping for Quad Cities Steam Dryer Structural Dynamic Analysis

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From the pressure loading measurements obtained directly during the Quad Cities 2 start-up testing, it has been observed that the major fluid loading component is near the [[ ]] frequency regime. Thus, this frequency range will be the main focus of the discussion on the appropriateness of using the equivalent modal damping value of [[ ]] and the conservatism of the subsequent steam dryer structural response predicted.

2. Steam Dryer Vibration and Valve Closure Responses at an Overseas BWR 5/251

At an overseas BWR 5/251 plant, the original steam dryer was damaged due to steam hammer forces resulting from the rapid closure of the turbine stop valve. Consequently, the original [[ ]] of the outermost dryer banks were modified to [[ ]]. Extensive instrumented tests were then performed on the modified dryer at transient conditions due to rapid turbine stop valve (TSV) and main steam isolation valve (MSIV) closures. The primary objective of the tests was to demonstrate the adequacy of the hood plate thickness modification. The transient forcing function characteristics and structural frequencies extracted from the tests were also reported (Reference 5).

For the present assessment of the modal damping value of the steam dryer, the recorded transient (time history) responses were reviewed and the damping values were calculated using the logarithmic decrement (free-vibration decay) method (Reference 2).

Figures 4 and 5 show the typical strain-time history records at the dryer hood for MSIV and TSV closures, respectively.

Figure 4Dryer Hood Strain-Time History Record due to MSIV Closure

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Figure 5 Dryer Hood Strain-Time History Record due to TSV Closure

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The peak measured strains, as shown in Figures 4 and 5, are about [[ ]], respectively. Using the logarithmic decrement method, the calculated critical damping values are about [[ ]] from Figure 4 and Figure 5, respectively.

3. Regulatory Guide 1.61- Damping Values for Seismic Design of Nuclear Power

For seismic design of nuclear power plants, modal damping values are recommended in NRC Regulatory Guide 1.61 (Reference 6). Table 1 lists the recommended damping values for various types of structures and piping.

Table 1 Damping Values (Reference 6)
(Percent of Critical Damping)

Structure or Component	Operating Basis Earthquake or ½ Safe Shutdown Earthquake	Safe Shutdown Earthquake
Equipment and large-diameter piping systems, pipe diameter greater than 12 inch	2	3
Small-diameter piping systems, pipe diameter equal to or less than 12 inch	1	2
Welded steel structures	2	4
Bolted Steel Structures	4	7
Prestressed concrete structures	2	5
Reinforced concrete structures	4	7

The Regulatory Guide states that the modal damping values as given in Table 1 should be used for the viscous modal damping for "all modes" considered in an elastic spectral or time-history dynamic seismic analysis of the Seismic Category I structures or components as specified in the table.

The Regulatory Guide also states that if the maximum combined stresses due to static, seismic, and other dynamic loading are significantly lower than the yield stress and ½ yield stress for SSE and ½ SSE, respectively, in any structure or component, damping values lower than those specified in Table 1 should be used for that structure or component to avoid underestimating the amplitude of vibrations or dynamic stresses.

The Regulatory Guide further states that "Damping values higher than the ones delineated in Table 1 of this guide may be used in a dynamic seismic analysis if documented test data are provided to support higher values".

Note that the steam dryer is a welded steel structure. A critical damping value of up to [[ ]] is recommended for the Safe Shutdown Earthquake (SSE) analyses. Although the recommended damping values are specifically for dynamic seismic analysis, there exists no prohibition against the use of these values for other dynamic loading analysis, such as the flow induced dynamic analysis, as long as the guideline for the maximum combined stress response due to static, seismic, and other dynamic loading is satisfied.

Also, note that these recommended damping values are for structures in an air environment at room temperature and atmospheric pressure conditions. For the steam dryer flow induced dynamic analysis, the fluid portion of the damping mechanism should be compensated for the steam environment at the reactor operating condition (547^0 F and

1020 psia). The fluid damping, ζ, consists two parts: form drag (affected by fluid density, ρ) and skin friction (due to viscosity effects, ν, kinematic viscosity) as (Reference 1):

$$\zeta \propto \rho\,(\nu)^{1/2}$$

At room temperature and atmospheric pressure conditions, air has the following properties (Reference 7):

ρ_{air} = 0.0765 lbm/ft^3 ν_{air} = 1.4208 E-04 ft^2/second

At the reactor operating condition of 547 °F and 1,020 psia, steam has the following properties (Reference 8):

[[ ]]

Thus,

$$\zeta_{steam} / \zeta_{air} = (\rho_{steam} / \rho_{air})\ (\nu_{steam} / \nu_{air})^{1/2}$$

$$= [[\quad]]$$

For the dryer in a steam environment at the reactor operating condition of 547^0 F and 1020 psia, the fluid portion of damping mechanism is about [[ ]] higher than that in an air environment at room temperature and atmospheric pressure conditions.

The Regulatory Guide recommended damping values for a welded steel structure of 2% and 4% for OBE and SSE analyses, respectively, are the total damping values including fluid, structural and material damping components. Since these values are for structures in an air environment, the fluid damping contribution to the total damping should be much smaller than that of the structural and material damping. Assuming the fluid damping contribution is [[ ]] of the total damping, i.e., [[ ]] fluid damping and [[ ]] structural damping for OBE and [[ ]] fluid damping and [[ ]] structural damping for SSE. In a steam environment at the reactor operating condition, the fluid damping increases by [[ ]], while the structural damping and material damping remain unchanged. Under this assumption, the total critical damping values are [[ ]] for the OBE and SSE analyses, respectively, in a steam environment at the reactor operating condition.

4. Quad Cities Dryer Hammer Tests Measured Dryer Hood Damping Values

Hammer tests were conducted on the Quad Cities new steam dryers (References 9 and 10). Hammer tests measured dryer hood damping values are in the ranges of [[ ]] at the low end of the frequency spectrum around [[ ]] toward the high end of the frequency spectrum around [[ ]] (as tabulated in Tables 2 and 3). Also notice the scattering of the test damping data.

Table 2 Dryer #2 Hood Damping Results at Low Water Level

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Table 3 Dryer #2 Hood Damping Results at Low Water Level

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Hammer tests were conducted in an air environment at the ambient conditions (room temperature and atmospheric pressure). For the steam dryer flow induced dynamic responses, the fluid portion of the damping mechanism should be compensated for by the steam environment at the reactor operating condition (547^0 F and 1020 psia). As derived in the previous section, for the dryer in a steam environment and at the reactor operating condition of 547^0 F and 1020 psia, the fluid portion of damping mechanism is about [[ ]] higher than that in an air environment and at room temperature and atmospheric pressure conditions.

The structural portion of the damping mechanism should also be compensated for the magnitude of the structural deformation experienced during hammer tests versus that experienced during the actual in-vessel operating condition.

Figures 6 and 7 show the typical hammer test measured strain time history and the corresponding Power Spectrum Density (PSD) at the hood region:

Figure 6 Hammer Test Measured Strain Time History – Hood

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Figure 7 PSD of Hammer Test Measured Strain Response – Hood

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Figures 8 and 9 show the start-up test measured strain time history and the corresponding Power Spectrum Density (PSD) at the hood region (Strain Gage S-9 of Reference 9):

Figure 8 Start-up Test Measured Strain Time History – Hood

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Figure 9 PSD of Start-Up Test Measured Strain Response – Hood

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Comparing Figure 7(b) with Figure 9(b), it can be seen that near the [[ ]] regime, the PSD of the strain response from the start-up test at in-vessel operating condition is about [[ ]] that of the strain response from the hammer test condition. In terms of strain response magnitude, the start-up test in-vessel operating condition strain is about [[ ]] that of the strain response magnitude from the hammer test condition. As noted earlier, the greater the structural deformation, the larger the structural damping value. The exact effects of strain response magnitude on the structural damping value cannot be quantified analytically. However, it can be assumed that:

[[ ]]

Where $\zeta_{structure}$ is the structural damping, ε is the strain response magnitude, n [[ ]] depending on test measurements, with an average value [[ ]].

Since the hammer tests were conducted in an air environment, the fluid damping contribution to the total damping should be much smaller then that of the structural and material damping. Assuming the fluid damping contribution is [[ ]] of the total damping, i.e., [[ ]] fluid damping and [[ ]] structural damping for a total damping of [[ ]] regime. In a steam environment at the reactor operating condition, the fluid damping increases by [[ ]] and the structural damping increases by [[

]]). The resulting total critical damping value at [[ ]], with these two factors taken into account, is estimated to be about [[ ]]

5. Finite Element Analysis Predicted Strains Compared with Startup Test Measured Strains

For the dynamic analysis of the Quad Cities steam dryer subjected to fluid induced dynamic loading at the reactor operating environment, a technique of direct time-wise numerical integration of the equation of motion with Raleigh damping matrix was used. Corresponding to the Raleigh damping selected for dryer hood, the equivalent modal damping values are [[ ]] of critical damping near the [[ ]] frequency regime (References 3 and 4).

The Finite Element Analysis (FEA) predicted strain responses are compared with the start-up test measured strain responses in Table 4 and Figures 10 through 14. In Figures 10 through 14, the left side plots show the Fast Fourier Transformation (FFT) and right side plot show the power spectrum density (PSD) of the time history responses. Also, the first row plots show the start-up test measured responses, and the second row, third row and the fourth row plots are FEA predicted responses corresponding to the [[ ]] of the time step size calculations, respectively.

It can be seen that using the Raleigh damping value, the FEA predicted strain responses are in general [[ ]] the start-up test measured strain responses. Thus, the Raleigh damping value as selected is conservative and technically justified. Of all the technical justifications enumerated above, this provides the most cogent argument for conservatism of the selected damping values.

Table 4 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

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Figure 10 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

(FFT and PSD Comparison - S1)

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Figure 11 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

(FFT and PSD Comparison - S5)

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Figure 12 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

(FFT and PSD Comparison - S7)

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Figure 13 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

(FFT and PSD Comparison - S8)

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Figure 14 Comparison of FEA Predicted Strain vs Startup Test Measured Strain

(FFT and PSD Comparison - S9)

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