Proceedings of PVP2005
2005 ASME Pressure Vessels and Piping Division Conference
July 17-21, 2005, Denver, Colorado USA

PVP2005-71666

VIBRATION DAMPING OF STABILIZED STEAM-GENERATOR TUBES

V.P. Janzen, Y. Han and B.A.W. Smith
Atomic Energy of Canada Limited, Chalk River Laboratories
Chalk River, Ontario
Canada K0J 1J0
janzenv@aecl.ca

S.M. Fluit
Babcock & Wilcox Canada
581 Coronation Blvd.
Cambridge, Ontario Canada N1R 5V3

ABSTRACT

The integrity of steam-generator tubes is an important aspect of the long-term reliable operation of nuclear power plants. In situations where a tube is judged to be at risk, it must be either plugged, or removed, or reliably stabilized in some manner to avoid excessive motion of the tube due to flow-induced vibration. The present work describes measurements of the effect of an internal cable-type stabilizer on the structural damping of steam-generator tubes. The free-vibration response of unstabilized and stabilized tubes was analyzed to provide damping ratios from frequency-domain spectral responses, time-domain logarithmic decrement ratios and time-domain vibration decay-curves. The structural damping ratios typically increased from approximately 1.6% to approximately 4.3% with the addition of the stabilizer. This last value is somewhat less than recently published values for stabilized tubes from a different type of steam generator, suggesting that tube stabilization, while effective, has limitations that need to be conservatively assessed.

NOMENCLATURE AND ABBREVIATIONS

A_0	amplitude at time $t=t_0$
f	frequency
f_1	principal-mode vibration frequency
f_{cutoff}	high-frequency cutoff
f_n	frequency of *n*th vibration mode
f_n/f_1	frequency ratio *n*th-to-lowest vibration modes
C_{offset}	constant offset in signal levels
n	number of cycles, or vibration mode
t	time
t_0	time at first peak following onset of vibration
δ	damping ratio
δ_n	"cumulative" damping ratio, measured over n cycles
y_n	peak vibration amplitude for the *n*th cycle

CANDU®[1]	CAnada Natural Deuterium Uranium
FFT	Fast Fourier Transform
I600	Inconel-600 alloy
ID	Inner Diameter
Log-Dec	Log-Decrement
OD	Outer Diameter
OTSG	Once-Through Steam Generator
SG	Steam Generator
TSP	Tube Support Plate

INTRODUCTION

During a recent outage, inspections of recirculating steam generators (SGs) at a CANDU® nuclear power plant showed that some of the tubes had become poorly supported – or perhaps even unsupported – at the location of the uppermost tube support plate (TSP), due to the long-term effects of flow-accelerated corrosion of the support-plate material. The affected tubes were thus at risk of being damaged over time because of excessive flow-induced vibration.

A suggested solution was to stabilize the affected tubes by inserting a wire-cable stabilizer inside most of the length of the tube. Stabilizers of this type are designed to protect the structural integrity of the tube, primarily by damping any motion of the tube due to flow-induced vibration. The vibration response of these stabilized tubes needed to be accurately predicted to assess the effectiveness of the repair. For this purpose, the structural damping characteristics of a section of steam-generator (SG) tubing were determined, with and without a wire-cable stabilizer installed inside the tube.

Damping is a result of energy dissipation during vibration. Under operational conditions, damping of steam-generator tubes has various forms and is often categorized as structural, viscous, flow-dependent, squeeze-film, friction,

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

tube-support, and two-phase damping [1]. The present tests were designed to measure the structural damping. The remaining components of damping required for any subsequent flow-induced vibration assessments are usually obtained from standard guidelines (*e.g.*, Pettigrew et al. [1]). A discussion of typical "in-flow" damping ratios is presented by Au-Yang [2].

Although the characterization of an energy-dissipation mechanism(s) can be reduced to a single parameter, the damping value or damping ratio, the measurement of damping is not necessarily simple. The industry uses a variety of testing and data-reduction methods to extract damping ratios based on a measured vibration response. The four commonly used data-analysis methods are: amplitude logarithmic decrement (log-decrement), frequency-domain spectral response (half-power), time-domain vibration decay (exponential-decay curve fit), and Nyquist plots (transfer-function two-point method). Comparisons between these methods have been made for piping systems [3] but not for steam generator tubes, which are relatively light and slender and are subject to external flow-induced forces.

The most recently available measurements of SG-tube structural damping ratios in the literature are between 8.6% and 12.7% for stabilized tubes [4]. If such high values are typical, the flow-induced vibration response of stabilized tubes effectively becomes a non-issue. However, these values were obtained with 15.9-mm (5/8") Once-Through Steam Generator (OTSG) tubing using a log-decrement analysis and unique tube-support conditions. It cannot be assumed that such high values apply either when a different tube-stabilizer combination is used, or when different support conditions or different analysis procedures are used.

In the present tests, all four of the common data-analysis methods were investigated. Due to time constraints, the Nyquist-plot method was not used to generate final results, since it required additional equipment and effort to properly set up and analyse.

DESCRIPTION OF TESTS

The following test conditions were specified by the customer:

- Tube: CANDU (or equivalent) SG tubing,
- Vibration mode: principal (i.e., lowest frequency),
- Vibration frequency: $f_1 = 15 \pm 2$ Hz,
- Support conditions: single-span, pinned supports,
- Stabilizer: Wound wire cable (supplied by customer)
- Four test series, with the following conditions:
    - with and without stabilizer,
    - tube filled with air and with water.

Preliminary tests were carried out to ensure that the test conditions were properly established, and that damping could be accurately measured for a single, principal vibration mode. This also involved trial runs using random excitation with a shaker and evaluating damping from the measured force-to-displacement transfer function.

Tube samples were mounted vertically in a multi-span vibration rig (see Figure 1). Support assemblies were built to hold the upper and lower parts of the tube with horizontal tapered screws (see Figure 2). With two opposing screws holding the tube, this design represented a pinned support condition. For tests with stabilized tubes, the stabilizer was inserted vertically in the tube, with the bottom end resting on a stopper at the bottom of the tube, and the top end as it naturally lay within a guide located above the tube (see Figure 1). The upper guide had a much larger diameter than the SG tube; the end result was that the semi-flexible stabilizer contacted the vertical wall of the SG tube in typically two places: one fairly close to the bottom, and the other towards the top end of the tube span.

Two accelerometers oriented horizontally, perpendicular to each other, were mounted on a block attached to the tube at midspan, with another two mounted on the tube 2/3 of the way up, to monitor X- and Y-vibration in the principal and higher modes. The accelerometer signals were amplified and fed into a PC-based data-acquisition system using National Instruments PC cards and customized LabVIEW® software. The software produced Fast Fourier Transform (FFT) acceleration and displacement spectra and allowed time and frequency data to be saved on disk. The accelerometers were calibrated with a hand-held calibrator, and the data-acquisition system was calibrated with a signal generator.

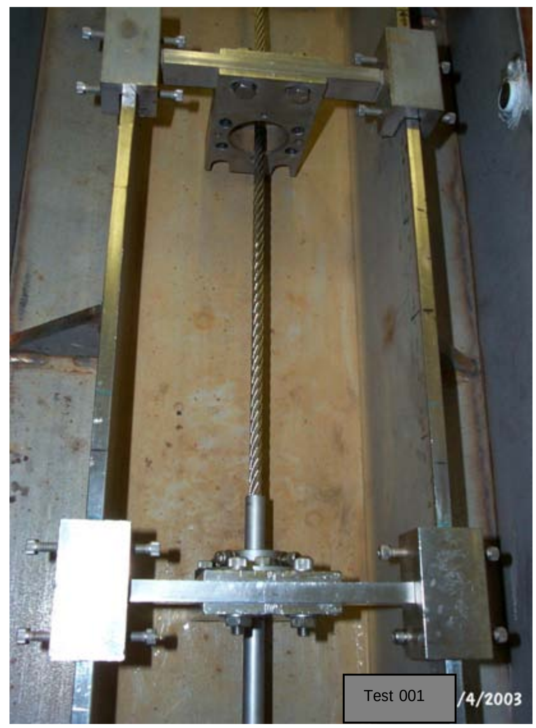

Figure 1 Test Rig (Upper Section)

Figure 2 Tube Support Assembly (Lower Section)

Preliminary tests were carried out with a 1.83-m long tube sample supplied by the customer. This tube was slightly curved, described as a "wow" of approximately 3 cm in the middle of the tube. This led to a vibration response with two principal modes, "in-plane" and "out-of-plane", each with its own natural frequency (5 Hz apart) and its own support conditions (quasi-pinned-pinned *vs*. quasi-clamped-pinned). Since the objective of the test was to measure damping of a single principal mode under well-defined conditions, a straight sample of SG tubing was used for all subsequent tests. The properties of the tube and stabilizer are listed in Table 1.

Table 1 Properties of Steam Generator Tube and Stabilizer Samples

	Tube Sample	Stabilizer	Comments
Material	I600[2]	304SS	
Length (m ±0.002m)	1.437	2.438	1.35-m span for tests
OD (mm ±0.05 mm)	13.02	8.15 ±0.10	SG Tube Nominal 0.51 in. (13.0 mm)
Wall thickness (mm ±0.05mm)	1.16	N/A	Nominal 0.044 in. (1.12 mm) min.
ID (mm ±0.05 mm.)	10.70	N/A	
Elastic Modulus (MPa)	30	N/A (flexible)	

Based on the specified principal frequency, a 1.44-m long section of tubing (1.35 m between supports) was used for the measurements. Vibration frequencies for the first three modes are listed in Table 2. The frequencies and frequency ratios show that the tube is essentially vibrating as a single single-span beam with support conditions that are very close to the ideal pinned-pinned configuration.

Table 2 Frequencies and Frequency Ratios of Vibration Modes for Tube Alone in Air

Mode	Measured Freq. f_n (Hz)	Predicted Frequency		Measured Frequency Ratio f_n/f_1	Predicted Ratio f_n/f_1	
		Pinned-Pinned	Clamped-Clamped		Pinned-Pinned	Clamped-Clamped
1st	17.2	18.0	40.9	≡ 1	≡ 1	≡ 1
2nd	74.0	72.1	112.6	4.30	4.00	2.76
3rd	150.8	162.3	220.9	8.77	9.00	5.40

The stabilizer consisted of a wound wire cable with one end beveled/rounded off and the other end fitted with four metal tabs angled out to provide a spring-load against the tube inner wall in a real SG. For the damping tests, these spring-loaded tabs were not in contact with the tube, since the tube section was meant to represent a span some distance away from that feature of the stabilizer.

[2] Inconel-600, a tubing alloy used in some CANDU SGs.

During preliminary tests, the tube was excited at or near midspan, either by a gentle tap with a soft-tipped impact hammer (or other suitable blunt instrument), or by displacing the tube by hand or with a string and then letting it go ("snapback" testing). Displacing the tube by hand at midspan produced the clearest principal-mode vibration and was used for the subsequent damping measurements.

For each of the four test series listed in Tables 3 to 5, five individual tests were carried out, each consisting of a series of tube excitations at midspan. After each excitation "event", the vibration was allowed to decay for at least 30 cycles for the unstabilized tube (at least 2 sec), and at least 15 cycles (at least 1 sec) for the stabilized (more highly damped) tube. Approximately 30 "events" were initiated during 100 seconds for tests with the unstabilized tube, and 15 events during 20 seconds with the stabilized tube. The two different time periods correspond to two different frequency resolutions required to fit narrow (light damping) *versus* wider (higher damping) peaks in the FFT spectra. Data sample size and acquisition rate were chosen to give reasonable accuracy (10 FFT averages, 1000 Hz acquisition rate) in the frequency domain. Time histories and frequency-domain acceleration spectra were recorded.

Damping ratios were obtained with the following three methods:

1. Log-decrement analysis: measuring the rate of decay of free-oscillation vibration from successive peak amplitudes in the time histories obtained following excitation of the tube,
2. Time-history analysis: fitting the general equation for damped vibration to the same time histories, and
3. Frequency-spectral analysis: fitting peaks in the frequency-domain spectra obtained from the entire 100-second (unstabilized tube) or 20-second (stabilized tube) duration of each test.

ANALYSIS

Frequency-Spectral Analysis

Fourier-transformed acceleration spectra for all tests were double-integrated in the frequency domain to produce displacement FFT spectra. Vibration frequencies and damping ratios were extracted from least-squares fits of the usual damped-resonance function to the peaks corresponding to vibration in the first pinned-pinned mode, with the program TableCurve2D®. Sample fits are shown in Figure 3 and averaged results from the five tests under each of the four test conditions are listed in Table 3.

Table 3 Damping Values Obtained by Fitting Peaks in FFT Spectra (Lowest Vibration Mode)

Test	Average Peak Frequency (Hz)	+/- [3]	Average (Minimum) Damping Ratio (%)	+/- [3]
Tube Alone – Water	15.66	*0.05*	2.28 (2.13)	*0.22*
Stabilized – Water	13.87	*0.18*	6.04 (4.06)	*1.74*
Tube Alone - Air	17.25	*0.03*	1.73 (1.54)	*0.15*
Stabilized - Air	17.17	*0.28*	5.26 (3.35)	*2.50*

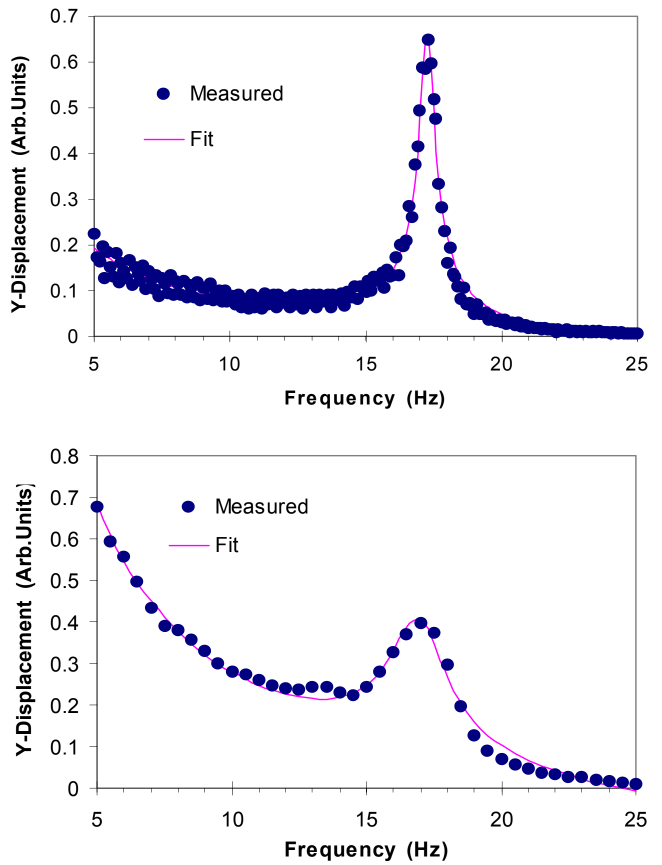

Figure 3 Peak Fits to FFT Spectra for Tube Alone (top) and Stabilized Tube (bottom)

Log-Decrement Analysis

Three "events" from each test (*i.e.*, a total of 15 events for each of the four test series) were selected for analysis and the corresponding time slices were extracted from the data stream. Examples are shown in Figure 4. After filtering out high-frequency components (> 55 Hz), damping values were obtained from the positive and negative peak amplitudes for the first 10 (or more) cycles in the vibration decay with the usual equation [5]

$$\delta_n = \frac{1}{2n\pi}\ln(y_1 / y_n) \tag{1}$$

where δ_n is the "cumulative" damping ratio corresponding to the decay up to and including the nth cycle, and y_n is the peak amplitude for the nth cycle in the vibration decay. Constant offsets in the signal levels due to imperfect signal conditioning can affect the results and were taken into account.

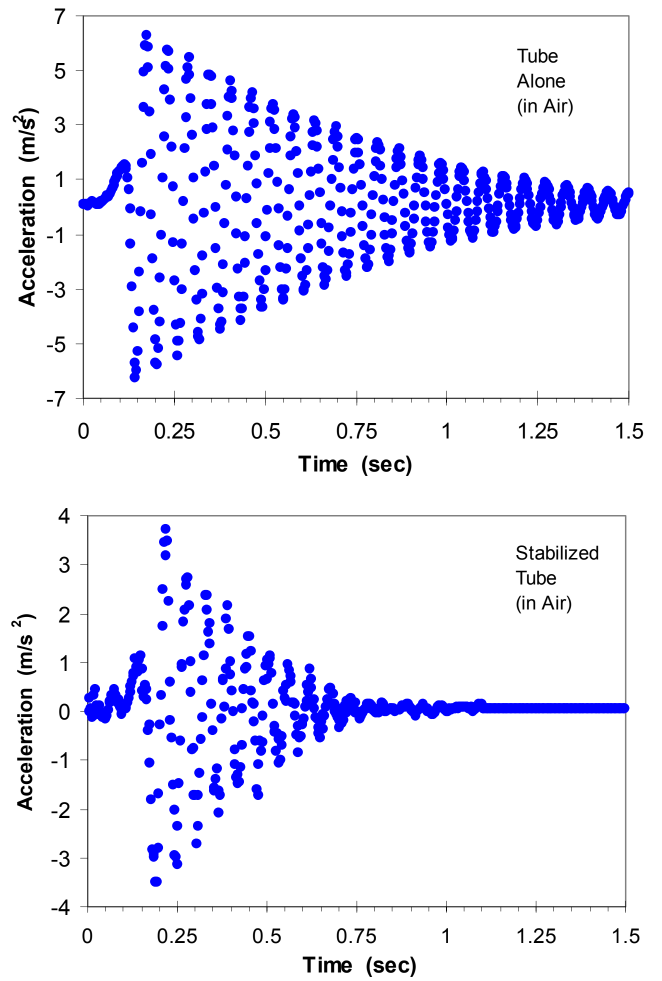

Figure 4 Time Histories for Sample Events with the Tube Alone (top) and Stabilized Tube (bottom).

Figure 5 shows sample results from this analysis in terms of cycle-to-cycle and cumulative damping values. The cycle-to-cycle values are calculated from peak amplitudes corresponding to consecutive vibration cycles while the latter are calculated for increasing number of cycles. These results represent the baseline case in which the empty tube appears to be very close to a linear vibrational system with purely viscous damping.

[3] The maximum of (i) the average uncertainty due to fitting and (ii) the standard deviation in the individual test results making up the average.

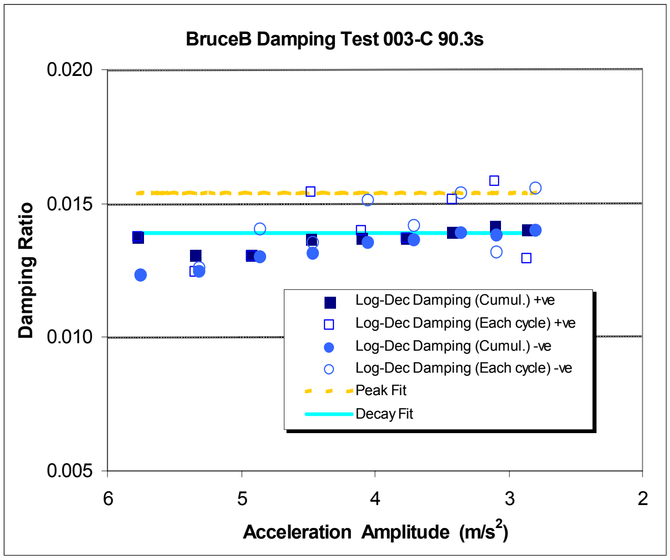

Figure 5 Damping Values Obtained From Log-Decrement Analysis for a Single "Event"

For a non-linear system, which is more likely the case for all of the present tests except the simplest, the tube alone in air, the cycle-to-cycle peak amplitudes will not decay purely exponentially with constant damping and a single constant frequency of vibration. The intent is to provide an equivalent viscous damping ratio as the best means of parametrizing the energy dissipation process associated with the tube-support combination. In this case, a decision must be made as to the number of cycles to be used in extracting a cumulative damping ratio. Therefore, for selected events, the peak amplitudes were extracted for the 1st through the 10th (or more) cycles, so that trends in the log-decrement damping per cycle could be obtained and correlated with vibration amplitude. Based on the results such as these, 10 cycles was chosen as a reasonable number. The results are listed in Table 4.

Table 4 Damping Values Obtained with the Log-Decrement Method

Test	Average Damping Ratio (%)	+/- [4]	Minimum Damping Ratio (%)
Tube Alone - Water	1.73	*0.18*	1.52
Stabilized - Water	4.27	*0.20*	3.96
Tube Alone - Air	1.50	*0.13*	1.32
Stabilized - Air	4.64	*0.23*	4.22

Note that the data appear non-linear even after filtering and so the cycle-to-cycle log-decrement values are relatively inaccurate (even in Figure 5, which is one of the cases showing nearly linear behaviour). This is particularly a problem for tests with the stabilizer and/or in water, making it difficult to assess trends such as the variation in damping as a function of vibration amplitude.

[4] The maximum of (i) the standard deviation for results from individual "events", and (ii) the average uncertainty for overall test averages.

Time-History Analysis

The log-decrement analysis described above is a simplified approach to parametrizing the exponential time decay of a freely vibrating system. A more rigorous method is to fit the data with the complete response function as a function of time. Therefore, for the same three events from each test selected for log-decrement analysis, the time spectra for the 1st to 10th cycles were fitted to the standard expression for vibration of subcritically damped systems with an exponential time decay [5]

$$y(t) = e^{-\delta 2\pi f (t-t_0)} A_0 \cos 2\pi f (t - t_0) + C_{offset} \tag{2}$$

where f is the frequency of vibration in Hz, A_0 is the amplitude at time $t{=}t_0$ and C_{offset} allows for a time-independent offset in the signal. Note that this equation is written in terms of displacement; however, it can be shown that the functional form and resulting damping and frequency parameters are the same for the acceleration signals (second derivative) measured in these tests. Sample fits are shown in Figure 6, with the results listed in Table 5.

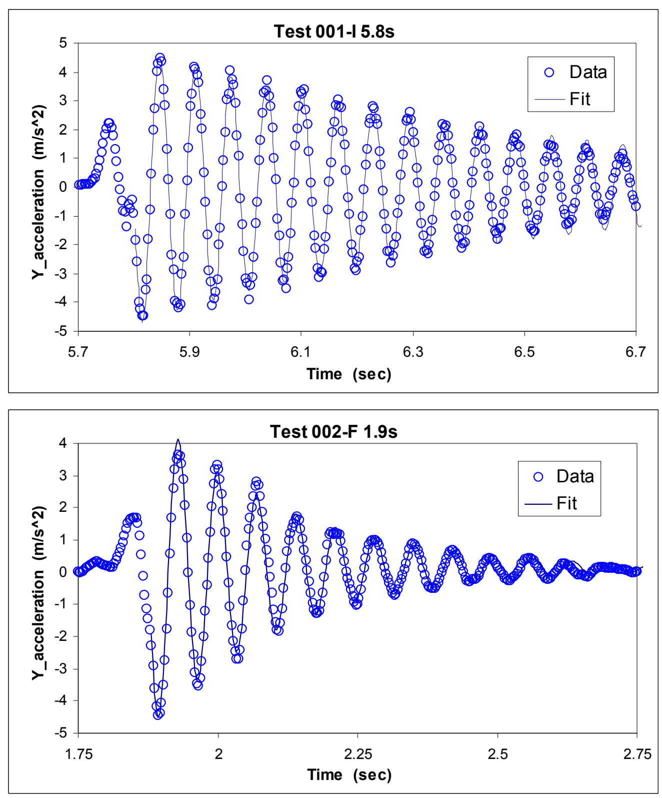

Figure 6 Least-Squares Fits to Vibration Decay Spectra for Tube Alone w/Water (top) and Stabilized Tube w/Water (bottom)

Table 5 Damping Values Obtained by Fitting Vibration Decay Time Histories

Test	Frequency (Hz)	+/- [3]	Average (Minimum) Damping Ratio (%)	+/- [3]
Tube Alone - Water	15.73	*0.04*	1.61 (1.33)	*0.20*
Stabilized - Water	14.20	*0.06*	4.26 (3.87)	*0.26*
Tube Alone - Air	17.29	*0.03*	1.49 (1.31)	*0.13*
Stabilized - Air	17.40	*0.05*	3.97 (3.73)	*0.53*

DISCUSSION & CONCLUSIONS

Results for the damping ratios from all three analysis methods are compiled and shown in Figure 7. The following comments can be made:

1. The frequency-spectral (half-power) analysis was attempted because it is fast and straightforward. However, damping values for different "events" obtained with this method are much less consistent than values obtained with either the log-decrement or decay fitting procedure, as shown by the large uncertainties quoted in
2. Table 3 for the stabilized tube. The half-power method assumes that the (linear) system is excited by input forces which are the same for all frequencies and are steady-state. The loading in this case is transient and, particularly for the stabilized tube, the system is non-linear, so it may be understandable that the frequency spectra do not reflect the true damping properties [3]. Note that in these tests, the *minimum* damping values measured with this method are similar to the average values obtained using the preferred method (fitting the vibration decay as a function of time). However, without more data this cannot be used as a reliable method.
3. The log-decrement method and vibration decay-curve fitting for the first 10 cycles resulted in damping values within the experimental uncertainty of each other. A high-frequency filter (f_{cutoff} = 55 Hz) was necessary to obtain consistent results for tests with the stabilized tube, which showed higher damping values and non-linear behaviour.
4. Of the three methods used, the decay-curve fitting procedure resulted in values that were more consistent within each test sequence and were slightly conservative relative to values obtained with the log-decrement and the (average) frequency-spectral methods. The most conservative approach would be to use the minimum damping values obtained from each test series since that would result in slightly higher vibration amplitudes than average values. However, given the degree of conservatism already built into guidelines for SG tube vibration, it is reasonable to use the averaged values from the decay curves as "conservative average" values (*c.f.,* Ref. [4]). For the stabilized tube these values are 4.3% (filled with water) and 4.0% (filled with air), compared with 1.6% (filled with water) and 1.5% (filled with air) for the unstabilized tube. Therefore, for the effective structural damping ratios required for calculating tube vibration response, the effect of adding the stabilizer is an increase in the damping ratio of approximately 2.6%.
5. No tests or "events" were found consistent with damping ratios as high as those recently reported for OTSG stabilized tubes, between 8.6% and 12.7% [4]. Such high values are likely due to differences in the support conditions and/or stabilizer designs and/or contact conditions between stabilizer and tube. If the stabilizer is somehow attached to or pressed against the tube in the vicinity of the span being tested, for example, higher damping values might be expected, due to added mass and the possibility of increased energy dissipation via the interaction between tube and stabilizer. In the field, the stabilizer may well be installed so that it extends through the U-bend section. This configuration would maximize contact between stabilizer and tube – and thus maximize damping - in the U-bend section, which is usually a region of concern with respect to flow-induced vibration.
6. The experimental uncertainties in the present tests are most likely much less than the uncertainties associated with the variation in tube response due to non-linear interactions between tube and stabilizer, depending on whether the tube span is vertical or in the U-bend, for example. These tests may be conservative for spans approaching or in the U-bend because in a vertical section the stabilizer is presumably not resting against the tube to the same degree as it would be in a non-vertical section.

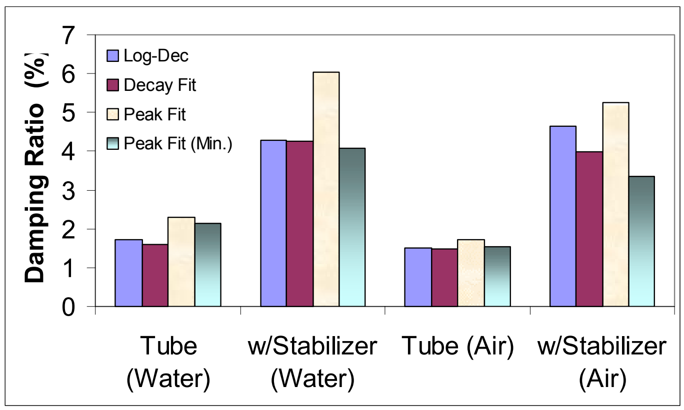

Figure 7 Combined Damping Results for all Three Methods

ACKNOWLEDGMENTS

The assistance of C. Lade in setting up and performing the measurements is greatly appreciated.

REFERENCES

[1] Vibration analysis of shell-and-tube heat exchangers: an overview—Part 1: flow, damping, fluidelastic instability, M.J. Pettigrew and C.E. Taylor, J. Fluids and Structures 18 (2003) p.469; --Part 2: vibration response, fretting-wear, guidelines, M.J. Pettigrew and C.E. Taylor, J. Fluids and Structures 18 (2003) p.485.

[2] Flow-Induced Vibration of Power and Process Plant Components, M.K. Au-Yang (ASME Press, New York, 2001).

[3] Piping System Damping Evaluation, A.H. Hadjian, EPRI Report EPRI-NP-6035, 1988 October.

[4] Damping of Steam Generator Tubes, C.K. Chandler, Proceedings of the ASME-PVP Symposium on Flow-Induced Vibration, Cleveland, OH, July 2003, Paper# PVP2003-2078, ASME PVP-Vol. 465 p.91.

[5] Theory of Vibration with Applications, 3rd ed., W.T. Thomson (Prentice Hall, Englewood Cliffs, NJ, 1988).

