DAMPING MEASUREMENT FOR A STEAM GENERATOR TUBE WITH GAP SUPPORT IN AIR AND WATER

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ABSTRACT

This paper presents the damping characteristics of a clamped-Simply Supported (SS) Steam Generator (SG) tube vibrating in air and water environment. For the damping measurement, a forced vibration test was performed on the tube having a length of 2.5 m with single gap support at the mid-length of the tube. Fluid effects to the tube damping were identified by measuring the damping from air and water environments, and then, comparing with other researchers results. To see an effect of the water inside of the SG tubes, two water environment tests were carried out; water outside of the tube only and water inside and outside of the tube at the same time. The water test results compared with a semi-analytical formulation that is composed of a viscous damping, a friction damping and a squeeze film damping occurring between the tube and the gap support. Measured damping values shows higher damping at low frequency, and then, the value decreasing with a nonlinear manner as frequency increase. In air tests, 0.7% critical damping was obtained at the first mode as lowest value while in water, 2.5% at the first mode as the lowest value. When the inside of the SG tube fills water with water environment, 3.4% was obtained as the lowest damping values at the first mode. Present test results correspond well with the predictions by the empirical correlation proposed by Pettigrew.

INTRODUCTION

It is well understood that vibration phenomenon such as fluidelastic instability, vortex shedding, and random turbulence excitation due to axial and cross-flow in SG tube bundle should be considered for SG design. Damping known as energy dissipation mechanism that reduces the amplitude of the flow-induced vibration of SG tubes should be determined from a vibration test.

Not only vibration analyses of CANDU SGs but basic flow-induced vibration mechanisms were reported by Pettigrew et al.(1978, 1980, 1986) while fluidelastic instability studies in-depth for Japan SGs by Nakamura et al.(1995, 2002). Pettigrew (2003) discussed three important energy dissipation mechanism that contribute to damping of multi-span SG tubes with liquids; these are viscous damping, squeeze film damping in the relatively small gap between the tube and the support and friction damping at the support. In accordance with the empirical correlation proposed by Pettigrew (2003), the most dominant dissipation mechanism is the squeeze film damping when it comes to the multi-span tube in water

The purpose of this study is to obtain total damping, to identify each of three damping mechanisms and to make comparison with previous studies and the empirical correlation of Pettigrew.

Since steam generator tubes are working under the mostly water environment in the inside as well as the outside of it at the lower straight parts of the tube, in order to identify fluid damping, three different water conditions are utilized for the test such as the outside water only, inside only, and the both. We may report the total damping of a straight tube consisting of the tube structural damping, impacting damping between the tube and the supports, and three different fluid damping.

DAMPING MEASUREMENT

Specimen and test setup

In this tset, a fixed-simply supported single tube of 2.2 m length with one tube support are used. The inner diameter and the outer diameter of the tube are 17.0cm and 19.1 cm, respectively. Figure 1 shows our experiment setup. Gap between the tube and the support is 0.33 mm. A force-controlled random signal vibration test was precisely carried out using electromagnetic shaker. 0.2N, 0.5N and 1N were used as controlled-forces to see if any nonlinear characteristics with force; we expect that no. of impacting and impacting strength may increase as shaking force goes up. Three accelerometers were evenly attached on

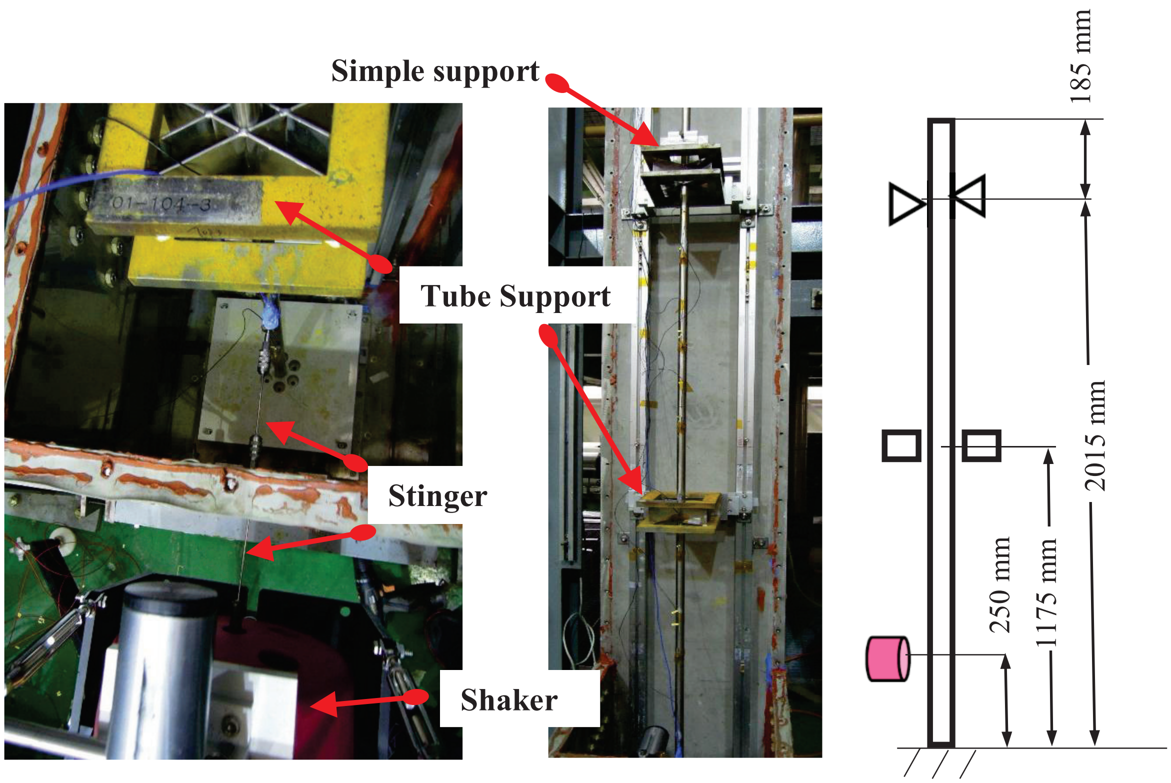


Figure 1 Test setup

the surface of tube in single span. Therefore, 6 acceleration signals were recorded as responses of the tube to shaking force.

For water environment test, detachable ducts were attached around tube and supports which is shown in Figure2.

Figure 2 Water environment test

Finite element analysis

Our test setup is very simple to make a Finite Element (FE) model so that it is very convenient to prediction the vibration characteristics of it prior to performing test. Once we know target natural frequencies and mode shapes, we may easily select shaking point, sensors and cut-off frequency. ANSYS commercial code (R 15.0, 2013) was utilized for FE analysis. It is well known that natural frequency of a structure submerged in water is lower than that of it in air because of adding water inertia to the structure. It is also known that the mode shape, however, does not change. In this reason, FE analysis was done for the structure in air and for the structure that contains water inside. Since there is a gap between tube and the mid-support, basically two calculations were made for an inactive mode and active mode of the mid-support; the former means a fixed-Simply Supported (SS) tube in single span of 2.2m, the later means a fixed-SS-SS tube in two spans of 2.2m. A few lower mode shapes are shown in Figure 3 for the inactive modes, and Figure 4 for the active modes, respectively.

Figure 3 Inactive mode shapes of a Fixed- SS tube of 2.2 m in air

Figure 4 active mode shapes of a fixed-SS-SS tube of 2.2 m in air

As shown in two figures above, typical sinusoidal waves were obtained as expected. As no. of mode goes up, the no. of half wave increases. Material properties for this calculations are summarized in Table 1, calculated natural frequencies in Table 2, respectively.

Table 1: Material Properties

Property	Value
Tube Density (kg/m^3)	8470
Tube Young's Modulus (GPa)	203
Tube Poison Ratio	0.3
Water Density (kg/m^3)	1000

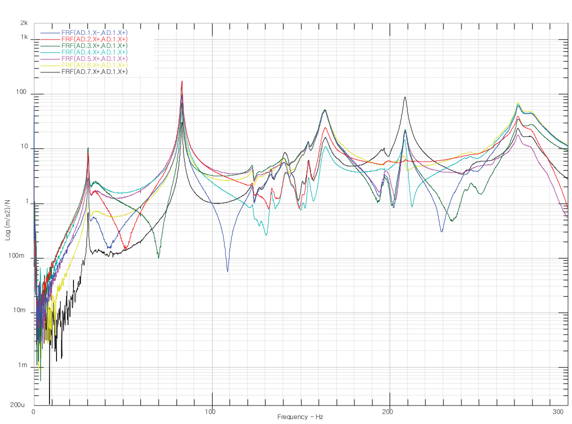
Table 2: Natural frequency according to support condition and test environment

Mode no.	Active Mode		Inactive Mode	
	In air (Hz)	Inside water (Hz)	In air (Hz)	Inside water (Hz)
1	112	106	36.9	35.1
2	153	147	112.	107
3	278	267	194	187
4	309	309	308	293

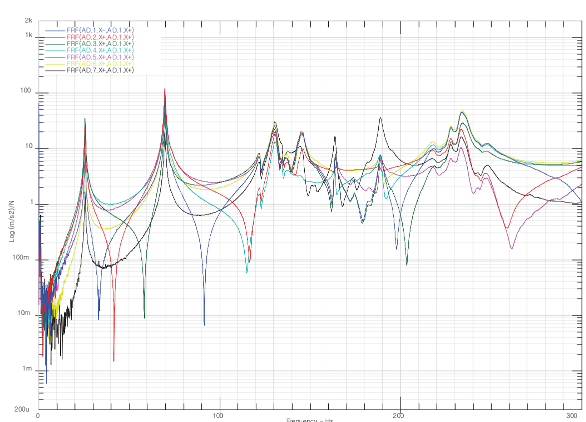
Vibration test results

Frequency Response Function (FRF) of a test under air environment was shown in Figure 5 (a), a test with water inside of tube shown in Figure 5 (b), a test under water environment shown in Figure. 5 (c), and a test with water inside of tube submerged in water shown in Figure 5 (d).

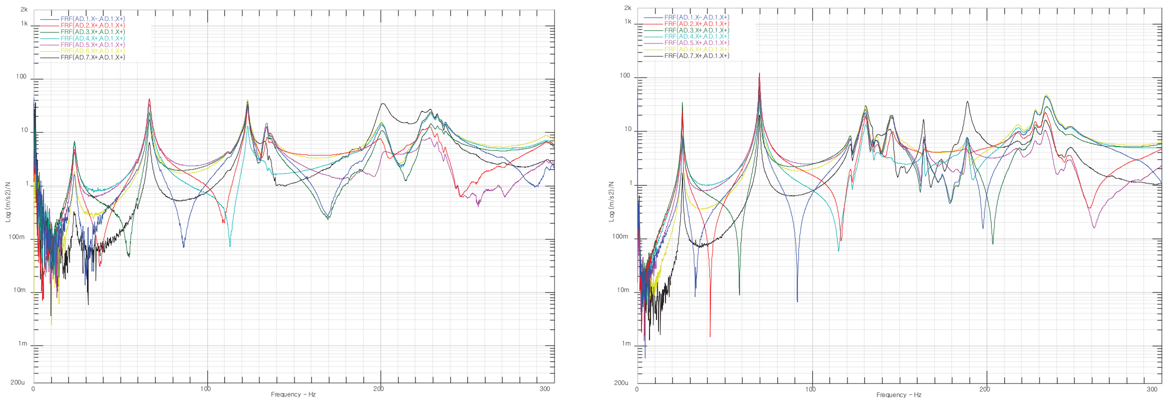
FRF in Figure 5 were obtained when shaking force of random signal was 0.2N. Although there is a gap support at the mid-length of tube, the shaking force was not enough to generate impacting between the tube and support, which means the vibration displacement was bound in the gap of 0.33 mm. That is the reason why sharp peaks of FRFs are clearly seen in Figure 5.



(a) Air environment



(b) Water inside of tube



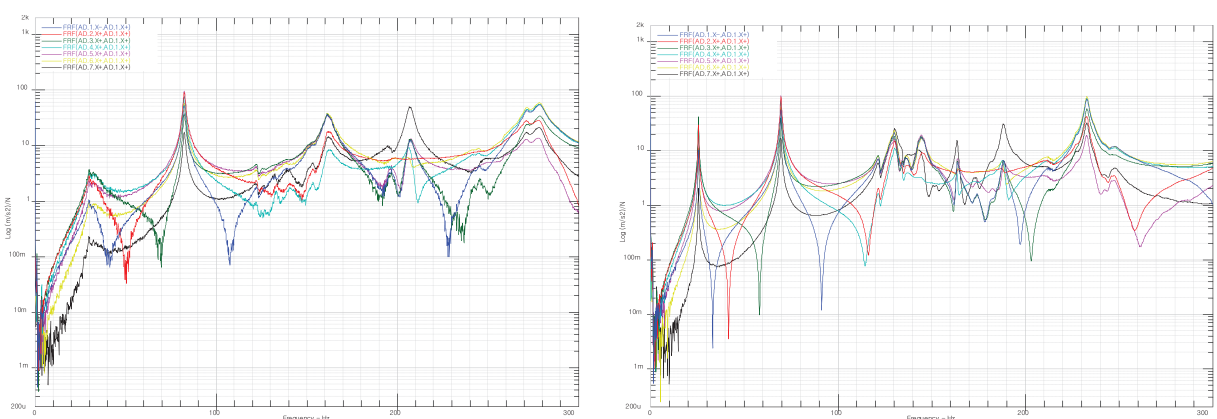
(c) Water environment (d) water inside of tube under water environment

Figure 5. Frequency Response Function of a fixed-SS tube with gap support at the mid-length of it when shaking force was 0.2N.

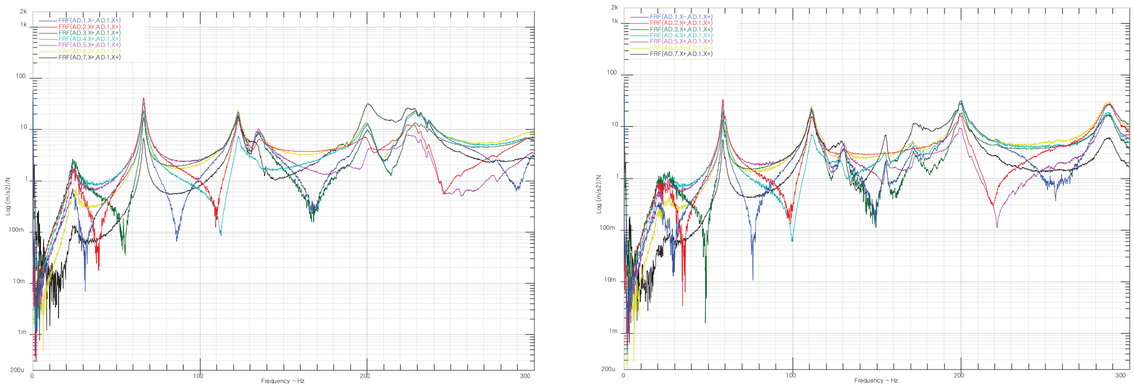
Figure 6 shows FRFs when shaking force was 1N. By the broadness of the first peaks, we may judge that vibration amplitude of the tube are enough to make impacting at the first mode except one test case of the tube containing water, which is shown in (b) of Figure 6. We know the first beam mode of a Fixed-SS tube as a half sine wave. There is a gap support at the mid-length where the displacement of the tube due to vibration is the maximum point while the first beam mode. As shaking force increases up to a certain force level, therefore, the first peak of FRFs may be broaden and shorten. When the tube contains water, tube mass increases so that the inertia mass of tube increase also. In this test case, shaking force of 1N is not enough to make the tube impact to the gap support, so that the FRF in (b) of Figure 6 is almost the same as that in (b) of Figure 5, which was obtained from the shaking force of 0.2N.

It is well known that structure in water environment shows lower natural frequency and higher damping as compared to that in air. In this test, we can find the same results. The first natural frequency of the tube in air at inactive mode is approximately 31 Hz while 24 Hz in water environment. Damping factor of the first mode increases approximately from 0.007, or 0.7% in air to 0.009 or 0.9% in water. In case of 2nd mode, the damping factors are 0.003 ~ 0.006, or 0.3 ~0.4 % in air, and approximately 0.009, or 0.9%. The 2nd natural frequency decreases approximately from 83 Hz to 67 Hz.

All test data are depicted in Figure7.



(a) Air environment (b) Water inside of tube



(c) Water environment (d) water inside of tube under water environment

Figure 6. Frequency Response Function of a fixed-SS tube with gap support at the mid-length of it when shaking force was 1N.

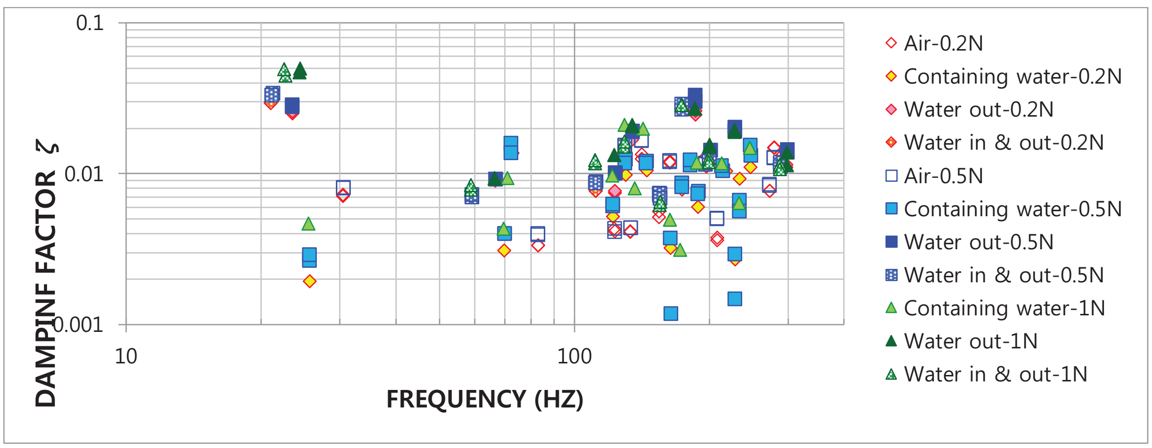


Figure 7. Measured damping of the tube in air, containing water, water environment, and containing water with water environment

One interesting observation is that the tube containing water seems to be very weak damping, which is in the range of 0.2% to 0.5 % that is the lowest value; even lower than the test in air environment. However, as shown in (a) of Figure 5, the first peak does not show a sharp and clear peak. We believe that the first peak is not one but two; one is for the first mode in z direction, the other is for the first mode in y direction. Since two peak is not exactly the same frequency, calculated damping believed to be a little overestimated when band-width method was used to calculate damping. Measured natural frequency are summarized in Table 3.

Table 3: Natural frequencies in terms of shaking force and test environment

Mode	In air (Hz)			Containing water (Hz)			Under water (Hz)			Water in and out (Hz)		
	0.2N	0.5N	1N	0.2N	0.5N	1N	0.2N	0.5N	1N	0.2N	0.5N	1N
1	31.0	30.7	31.6	25.7	25.6	25.5	23.5	23.4	23.4	21.0	21.2	22.6
2	83.1	82.8	82.5	69.8	69.6	69.5	66.7	66.6	66.4	59.0	58.9	58.9
3	123.4	123.4	122.8	121.9	121.6	121.4	123.3	123.2	122.9	111.6	111.4	111.4
4	140.8	139.8	137.4	130.1	129.6	129.3	134.3	134.6	135.2	129.4	129.4	129.1

REVIEW ON DAMPING THEORY FOR MULTI-SPAN TUBES

There are four energy dissipation mechanisms that one should consider for the damping of multi-span SG tubes with liquids; these are viscous damping, friction damping at the support, squeeze film damping in the relatively small gap between the tube and the support, and material damping of the tube. Therefore, the total damping is expressed by

$$\xi_{Total} = \xi_v + \xi_{Fric} + \xi_{Sq} + \xi_{matl}. \tag{1}$$

It is known that the material damping of SG tube is less than 0.2%, the smallest one among the four damping mechanisms.

Friction and Squeeze film damping

Dampings arisen by the interaction between the SG tube and tube support are friction damping, ξ_{Fric}, and squeeze film damping, ξ_{Sq}. As discussed by Pettigrew (2003), the friction damping is formulated by

$$\xi_{Fric} = \left(\frac{N-1}{N}\right)\left[0.5\left(\frac{L}{l_m}\right)^{0.5}\right] \tag{2}$$

and squeeze film damping by

$$\xi_{Sq} = \left(\frac{N-1}{N}\right)\left[\frac{1460}{f}\,\frac{\rho\, D^2}{m}\left(\frac{L}{l_m}\right)^{0.5}\right] \tag{3}$$

where f is frequency in Hz, N is number of spanρ is density of fluid, D is tube diameter, m is mass per unit length, , L is height of support, and l_m is span length. The span length is, originally, defined as the average of the three longest spans when the lowest modes and the longest spans dominate the vibration response. However, higher modes and shorter spans govern the vibration response, then, the span length should be these shorter spans.

Viscous damping

Viscous damping was derived for a marine structure in an oscillating flow such as ocean tide. The derived viscous damping is a function of Keulegan-Carpenter number and Reynolds number. Pettigrew used a simplified formula such as

$$\xi_v = 100\left(\frac{\pi}{\sqrt{8}}\right)\left(\frac{\rho\, D^2}{m}\right)\left(\frac{2\,\upsilon}{\pi\, f\, D^2}\right) \tag{4}$$

RESULTS AND DISCUSSION

We compare present test data with Pettigrew's for the test in air environment, which is shown in Figure 8, and for the test in water environment, which is shown in Figure 9 (Blevins 1990). It is obvious that present data fall well into the range of previous data. However, the first damping value seems to be higher than Pettigrew's data. We believe that two peaks is not exactly the same frequency but almost the same, thus the first peak seems to be broader than the real single peak. We believe that is the reason why the damping at the first mode was estimated to be high.

Damping factors from air test are significantly scattered so that one cannot tell if there is any trend according to frequency. Present test data shows that damping factor increases as shaking force goes up no matter what the modes, or natural frequencies, or test environments are; for instance, in air environment damping factor at the first mode increases from 0.007 (or 0.7 %) at 0.2 N to 0.0085 (or 0.85%) at 0.5 N while in water environment from 0.025 (or 2.5%) at 0.2 N to 0.05 (or 5%) at 1N.

Present test data from water environment seems to be well agreed with the previous Pettigrew's data that is shown in Figure 9. Measured damping from water environment is important considering that the steam generator tubes are operating in water and in steam-water mixture. It is well known that energy dissipation is generally high at low frequency, and then, the dissipation decrease almost linearly as frequency increases. Not only present data but also Pettigrew's shows such declining trend. One thing we should report is that damping at the second mode is relatively low. One possible explanation is that squeeze film damping may not be dominant at the second mode, at which tube does not move ideally because nodal point formulate at the mid-length. If squeeze film damping is not dominant, then, the total damping becomes lower.

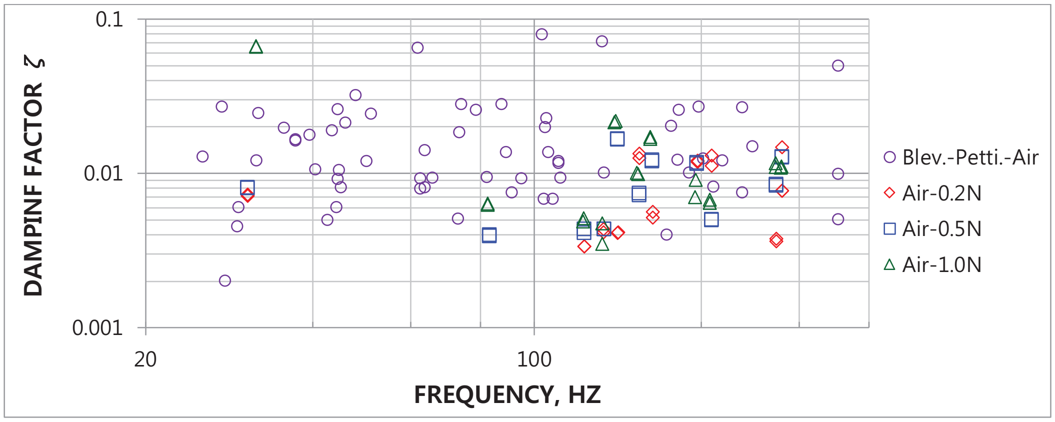


Figure 8. Measured damping of the tube in air, and Pettigrew's test data (Blevins, 1990)

Analytical models in equation 1 through 4 may be drawn by reflecting material properties and geometry data of specimen. Figure 10 shows our test data, Pettigrew's data and prediction line by analytical models. Whole test data are reasonably well agreed with the prediction except damping at the second mode. We believe that once tube vibrates in an inactive mode, a certain vibration mode that formulate a nodal point at the gap support may yield relatively small damping because squeeze film damping is not dominant at all. Prediction does not work well approximately over 150 Hz. One may say that a certain minimum value independent to frequency may exist over 150 Hz.

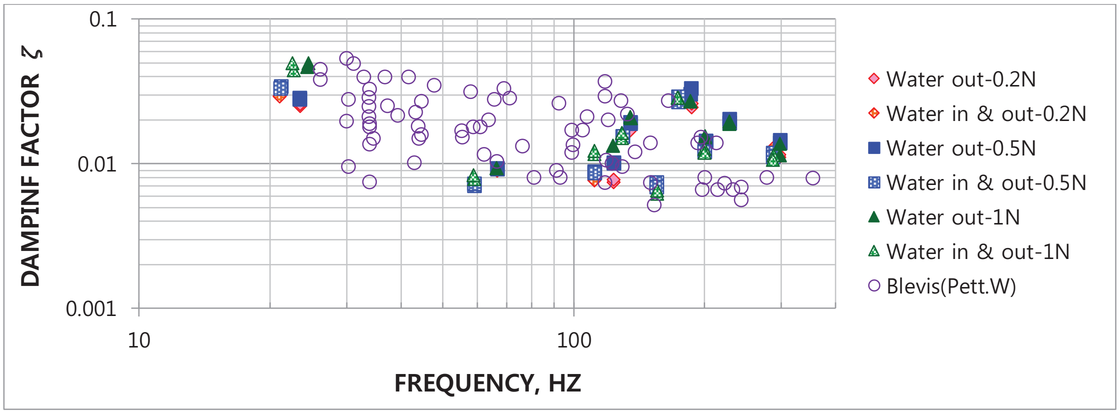


Figure 9. Measured damping of the tube in water environment, and containing water with water environment (Blevins, 1990)

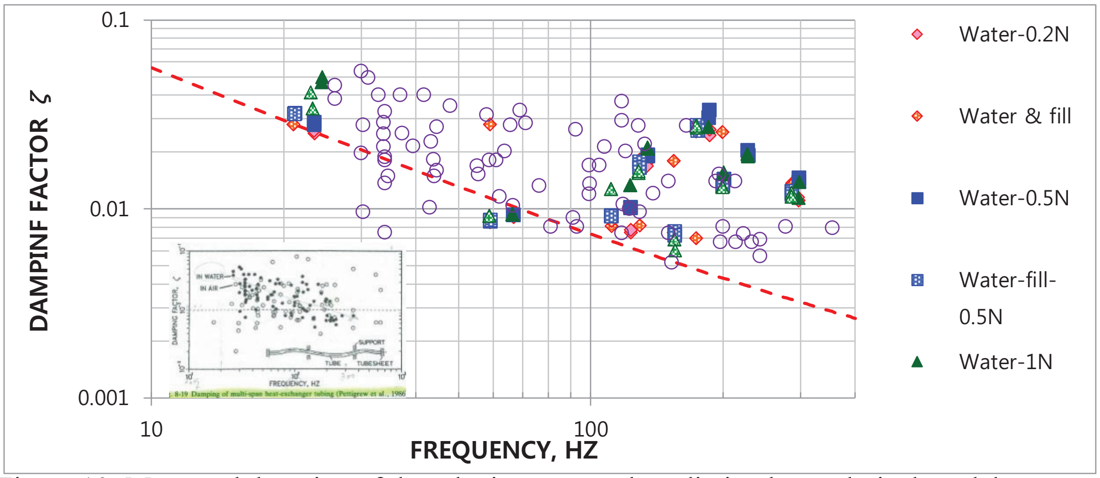


Figure 10. Measured damping of the tube in water and prediction by analytical model proposed by Pettigrew

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea grant funded by Korea government (MSIP) (No.2012M2A8A5025825). Authors thank Doosan Heavy Industries and Construction Company for providing tubes and supports of steam generate.

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