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Field measurement of damping in industrial chimneys and towers

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Abstract. In the design of industrial chimneys and towers, structural engineers must assume a level of the inherent damping in the structures. In order to better estimate the dynamic response of those structures, actual damping was measured from wind-induced vibration signals of chimneys and towers and its characteristics with respect to the response levels, the structural systems, and the wind direction were discussed. Damping ratio and natural frequency for three chimneys and two towers were calculated using random decrement technique.

Key words: damping; frequency; field measurement; random decrement technique; chimneys and towers; wind-induced vibration.

1. Introduction

In Japan, many slender structures such as skyscrapers, chimneys, and towers are exposed to relatively frequent earthquake and typhoon events. In order to properly resist these dynamic loads, the structures should be designed with accurate information of structural properties as well as external loadings. The response of a structure to dynamic loadings is strongly dependent on such dynamic properties as the fundamental frequency and the damping of the structure. The fundamental frequency can be calculated with information of mass and stiffness distributions, while the damping of the structure is a difficult quantity to estimate at the structural design stage. Also the damping varies with response levels, type of structural system, partitioning systems, soil and foundation

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systems, and materials used for construction. In the design of structures, structural engineers must "assume" a level of the inherent damping in the structure. With the large uncertainty associated with the inherent damping present in a structure, a corresponding large uncertainty is introduced in predicting the dynamic response of that structure from wind or seismic effects.

Actual damping of tall structures was reported by Haviland (1986), Taoka (1981), Jeary (1986), Davenport and Hill-Carroll (1986), Tamura *et al.* (1994), and Galsworthy and El Naggar (2000). In particular, Galsworthy and El Naggar stressed the damping contribution from the foundation type and the flexibility of the supporting soil. Nevertheless, we need to collect more data on damping of chimneys and towers without floors and/or exterior walls. Authors believed that actual damping needs to be measured in deed in order to better estimate the dynamic response of those structures. The objective of this study is to measure and analyze actual inherent damping of chimneys and towers and to provide that information to structural engineers. The dynamic response of chimneys and towers due to strong winds has been observed from the year 1981. Three chimneys and two towers were investigated.

Chimneys and towers are more vulnerable to frequent wind storms than earthquakes. Wind-induced acceleration signals were used to estimate inherent damping in the structures. The characteristics of damping with respect to the response levels, structural systems, and wind direction were discussed. The technique that was used to calculate damping is the Random Decrement Technique proposed by Cole (1971) where the signals to be analyzed should be random.

2. Structural details and record data

In total 5 structures as shown in Fig. 1 were investigated. The S Tower is a triangular-shaped space frame and the T Tower a circular-shaped steel tower. At the top of the T tower, however, a passive tuned mass damper is installed. Both of these towers are positioned at the top of the main building structures. The K Chimney is a double-warren-typed frame structure, the H Chimney is a circular-shaped reinforced concrete structure, and the Y Chimney is a bundled deformed-square-shaped reinforced concrete structure. The details of those structures are listed in Table 1.

The anemometers were installed at the top of the structures or at a location elevated from the ground. The accelerometers were placed at several different heights of the structures including the top of the structures. The accelerations to be analyzed for damping evaluation were those measured at the top of the structures. The acceleration signals were sampled at the rate of 10 Hz. Some of S Tower data had 5.0 Hz sampling frequency. The record length per data file for the S Tower was 14 minutes and 10 seconds. For the T Tower, H Chimney, and K Chimney, it was 6 minutes 49 seconds and for the Y Chimney, 5 minutes 59 seconds.

3. Analytical procedure and random decrement technique (RDT)

Along-wind and across-wind direction data with respect to X and Y axes were selected for damping analysis to evaluate aerodynamic damping effects. For the case of the K Chimney, wind direction was not taken into account because information on wind direction was not available. For the response signals to be analyzed, they are all first passed through Chebyshev bandpass filter. Center frequencies of the filter for the first mode were chosen after analyzing power

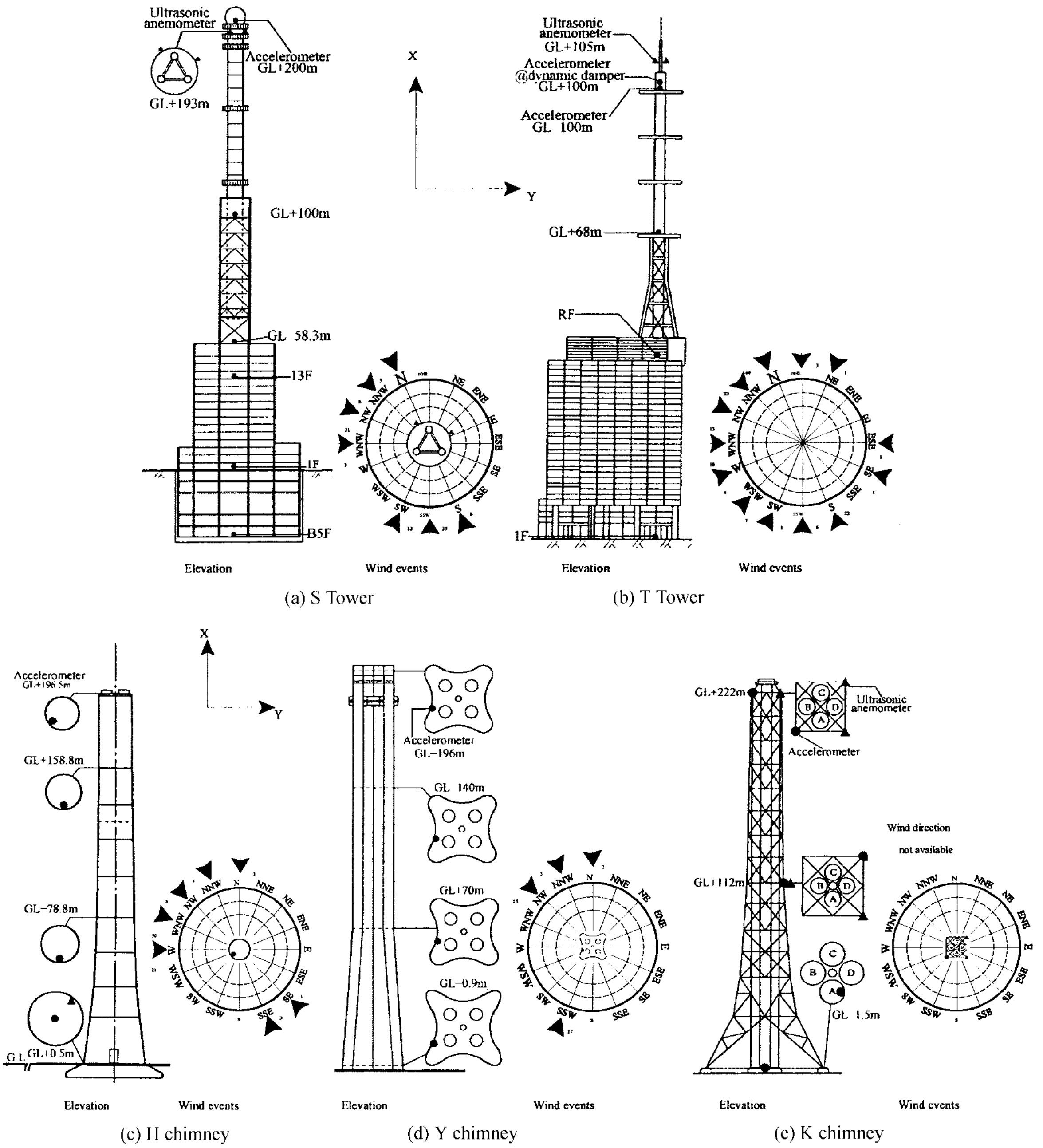
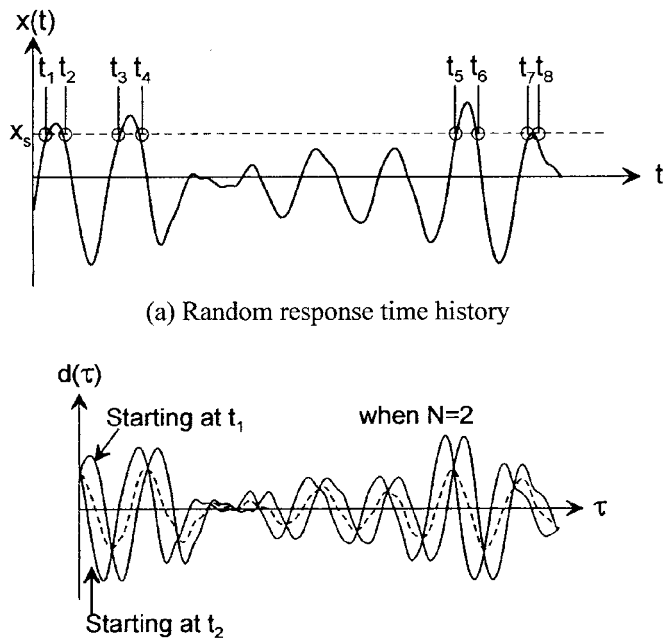


Fig. 1 Industrial chimneys and towers investigated

spectrum. The bandpass-filtered signal was interpolated by higher-ordered polynomial to 200-400 Hz. The signals were then analyzed by the random decrement technique. The first 3-4 cycles of the random decrement signature was fitted to the ideal decaying curve of a linear single degree-of-freedom system. Damping ratio and natural frequency were then calculated by using the fitted signature.

Table 1 Details of chimneys and towers in vestigated

Structures	S_{Tower}	T_{Tower}	$H_{Chimney}$	$Y_{Chimney}$	$K_{Chimney}$
Record period	Oct. '87~ June '97	Sept. '91~ Oct. '97	Aug. '81~ Aug. '97	Sept. '96~ Aug. '97	April '94~ Sept. '97
Main structure/ tower or chimney structure	Steel/triangular frame	Steel/circular cylindrical steel	RC	RC	Bundled circular cylinder steel with frame
Dimension	h = 200 m	h = 100 m	h = 200 m, d = 14 m, Bottom d = 27 m	h = 200 m, d = 25.5 m, Bottom d = 37.5 m	h = 230 m, 4 cylinders
# of data files/ record length	92/14 min 10 sec	146/6 min 49 sec	80/6 min 49 sec	49/5 min 59 sec	35/6 min 49 sec



(a) Random response time history

(b) Random decrement signature (N=2)

Fig. 2 Extraction of random decrement signature

In general, dynamic response of a structure depends on its initial conditions and the excitation. The concept of RDT is that the response can be decomposed into three parts: the response due to initial displacement, the response due to initial velocity, and finally the response due to the random excitation. The random decrement signature $\delta(\tau)$ consists of averaging N segments of the length τ_1 of the system response in the following manner:

$$\delta(\tau) = \frac{1}{N}\sum_{i=1}^{N} x_i(t_i+\tau), \qquad 0 \le \tau \le \tau_1$$

where $x_i(t_i) = x_s(i = 1, 2, 3, \ldots)$, $\dot{x}_i(t_i) \ge 0(i = 1, 3, 5, \ldots)$, and $\dot{x}_i(t_i) \le 0(i = 2, 4, 6, \ldots)$. The

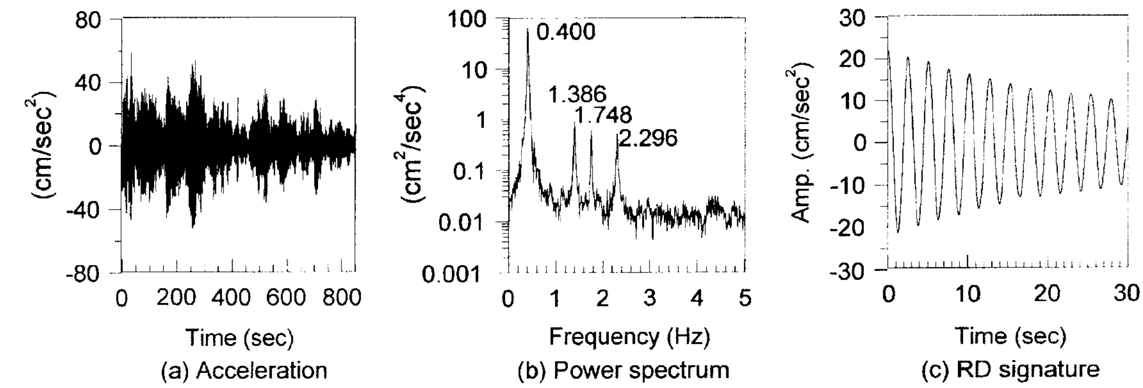


Fig. 3 An example of procedure of RDT of the S Tower data

parts due to initial velocity vanish because the slopes are alternating positive and negative and their distribution is random. Also vanish the parts due to the excitation because, by definition, the excitation is random. The procedure is well illustrated in Fig. 2. As the number of segments increase the more smooth curve can be obtained.

Fig. 3(a) shows the along-wind acceleration time history of the S Tower when the maximum wind was in the direction of X-axis. The corresponding power spectrum is shown in Fig. 3(b). The first mode is distinct from the other modes. Fig. 3(c) shows the corresponding random decrement signature.

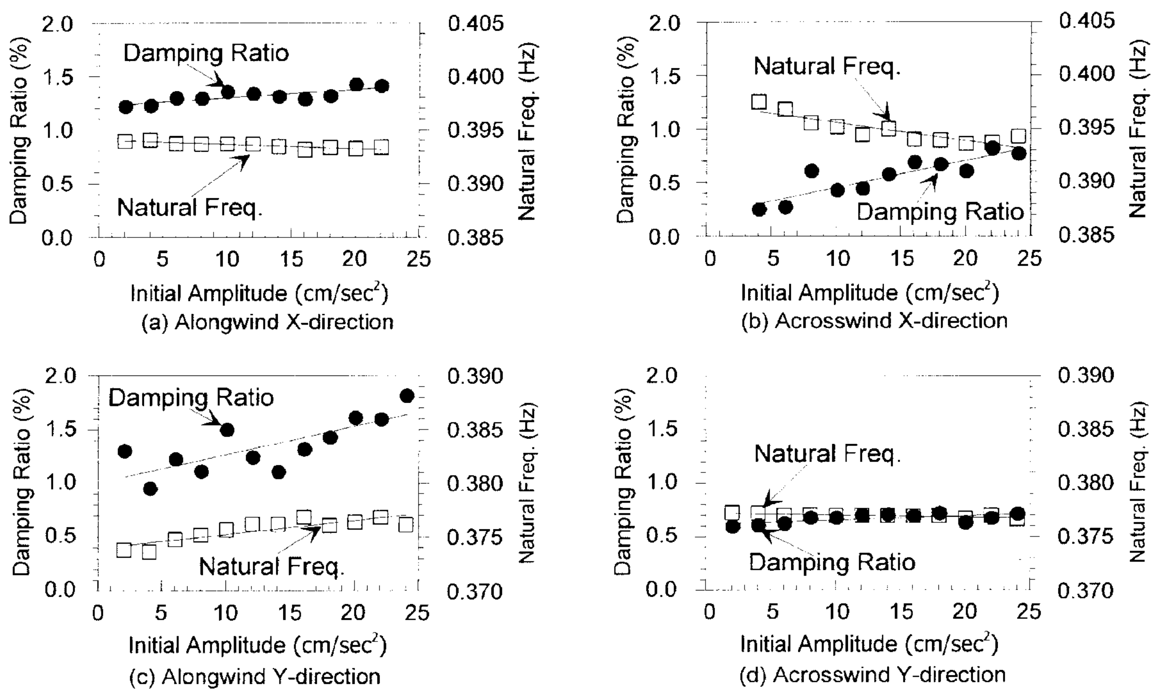


Fig. 4 Variation of damping and frequency with amplitude of S Tower

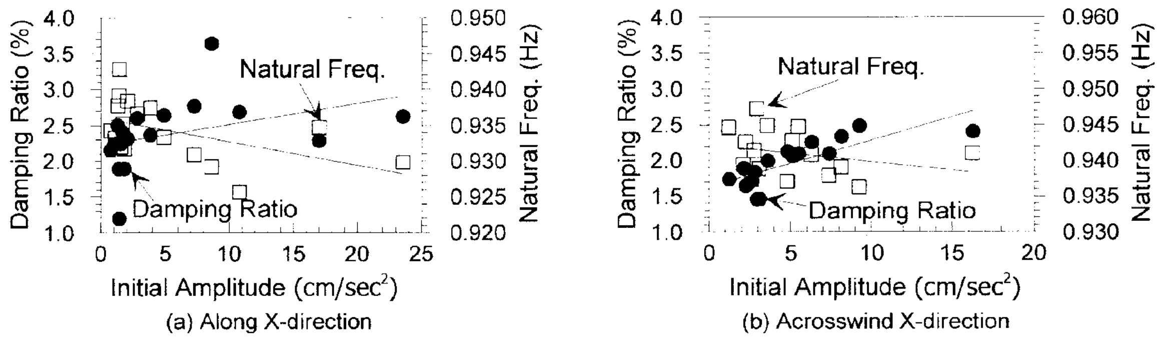


Fig. 5 Variation of damping and frequency with amplitude of T Tower

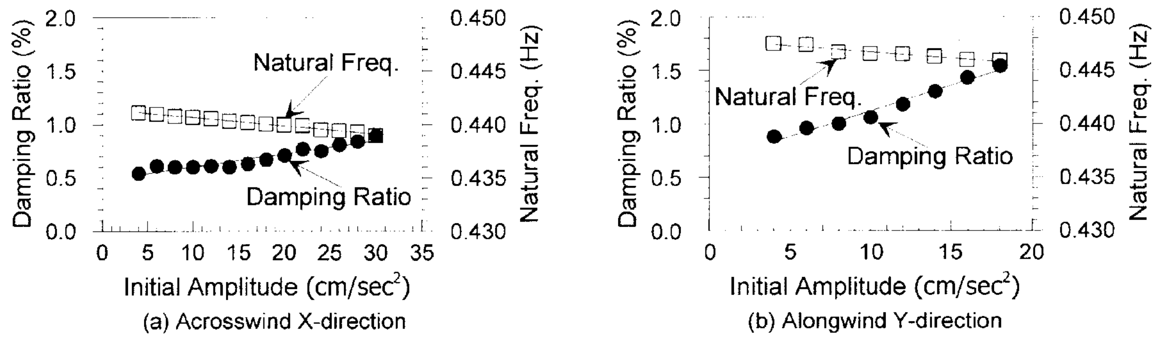


Fig. 6 Variation of damping and frequency with amplitdue of H Chimney

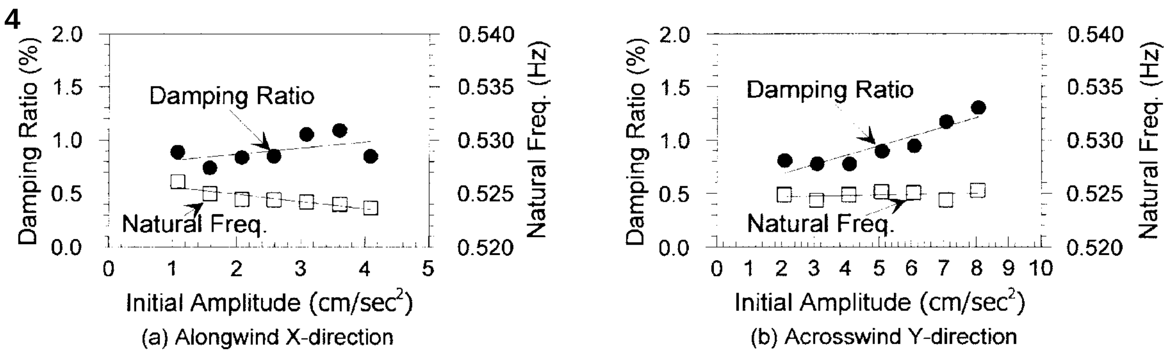


Fig. 7 Variation of damping and frequency with amplitude of Y Chimney

4. Results of measured damping and frequency

The damping ratio and the natural frequency with respect to the response level of the structures are shown in Fig. 4 through Fig. 8. The damping increases with the response level while the natural frequency decreases with it except for the along-wind Y-direction of the S Tower. It is observed from the figures that the damping in the along-wind direction is bigger than that in the cross-wind direction. This seems to be due to the aerodynamic damping and the mean deflection of the structures.

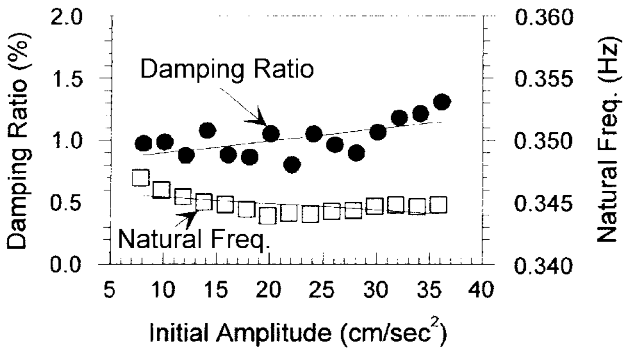


Fig. 8 Variation of damping and fre-quency with amplitude of K Chimney

The difference in natural frequency between X-direction and Y-direction represents different the stiffness of the structures in both directions. The damping in the T Tower is relatively high (about 2% critical damping) because a TMD was installed at the top of the tower. The dynamic characteristics in the Y-direction of the T Tower could not be evaluated because the first mode of power spectrum was not distinct, probably due to the TMD.

The damping and natural frequency of the H Chimney are presented only in the across-wind X-direction and in the along-wind Y-direction because the cross-section of the H Chimney is

Table 2 Measured damping and frequency

	Damping ratio (%)				Natural Freq. (Hz)				Ref.
	X_a	X_c	Y_a	Y_c	X_a	X_c	Y_a	Y_c	
S	1.31	0.55	1.35	0.67	0.39	0.39	0.38	0.38	Steel
T	2.38	1.98	–	–	0.93	0.94	–	–	TMD
H	–	0.69	1.17	–	–	0.44	0.45	–	RC
Y	0.90	–	–	0.95	0.52	–	–	0.52	RC
K	–		1.01		–		0.34		Steel

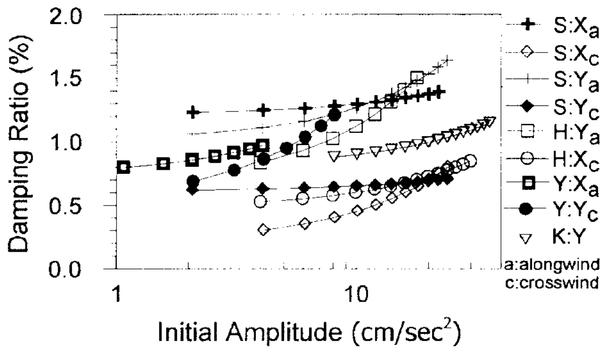


Fig. 9 Fitting curves of damping ratio

Table 3 Measured and design values

	Damping ratio (%)		Natural freq. (Hz)	
	Measured	Designed	Measured	Designed
S	0.55-1.35	1	0.38-0.39	0.38
H	0.69-1.17	2	0.44-0.45	0.39
Y	0.90-0.95	2	0.52	0.45
K	1.01	–	0.34	–

circular, that is, no directionality. In case of the Y Chimney, winds from the Y-direction were not available, so the damping and frequency were given only in the along-wind X-direction and in the across-wind Y-direction. Fig. 8 shows the variation of damping and frequency of the K Chimney in the Y-direction. These values were calculated using six data files whose mode characteristics in the power spectra were the same because there was no available wind direction information.

The averaged value of measured damping in each tower and chimney is listed in Table 2. Fig. 9 shows the fitting curves of damping in each tower and chimney except for the T Tower (TMD installed). In Table 3, the measured and design values of damping in all investigated tower and chimneys are compared. It is seen from the table that the measured damping values are lower than the design values, probably because the design values are evaluated considering large amplitude regime. This is expected to be reasonable because the damping is dependent upon the response amplitude of the structure, as it is seen from the figures.

5. Conclusions

The actual damping of some chimneys and towers in Japan was measured. The damping information may be helpful to structural designers at the design stage. It is interesting to note that the damping in the along-wind direction is higher than that in the across-wind direction. It seems to be due to the aerodynamic damping and the mean deflection of the structures. As well known, it was seen that the damping increases as the response amplitude increases while the natural frequency decreases as the response decreases. Damping is a difficult quantity to estimate at the design stage, as it is seen that the measured values of damping are lower than the designed ones. It is also seen that the damping of triangular-framed steel structure was higher than that of circular reinforced concrete structure. In general, however, damping can not be measured under the design dynamic load.

Acknowledgement

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