World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:10, No:8, 2016

Tuned Mass Damper Effects of Stationary People on Structural Damping of Footbridge Due to Dynamic Interaction in Vertical Motion

M. Yoneda

Open Science Index, Civil and Environmental Engineering Vol:10, No:8, 2016 publications.waset.org/10005183.pdf

***Abstract*—**It is known that stationary human occupants act as dynamic mass-spring-damper systems and can change the modal properties of civil engineering structures. This paper describes the full scale measurement to explain the tuned mass damper effects of stationary people on structural damping of footbridge with center span length of 33 m. A human body can be represented by a lumped system consisting of masses, springs, and dashpots. Complex eigenvalue calculation is also conducted by using ISO5982:1981 human model (two degree of freedom system). Based on experimental and analytical results for the footbridge with the stationary people in the standing position, it is demonstrated that stationary people behave as a tuned mass damper and that ISO5982:1981 human model can explain the structural damping characteristics measured in the field.

***Keywords*—**Dynamic interaction, footbridge, stationary people, structural damping.

I. INTRODUCTION

THE phenomenon of synchronous lateral excitation caused by pedestrians walking on footbridges such as the London Millennium Bridge has increasingly attracted public attention [1], [2]. This synchronization phenomenon is assumed to be caused by dynamic interaction between the bridge and human body in the lateral direction [3].

The dynamic interaction between the bridge and human body may be occurred in the vertical direction. In practice, human occupants reportedly led to the changes of natural frequencies and significant increases in the structural damping [4], [5].

Many researchers [1], [3] have measured the structural damping of the footbridge through full scale measurements because the structural damping plays an important role in the bridge serviceability.

Generally, it is attempted to excite the footbridge by human jumping on the deck with a natural frequency of the bridge, by human walking and so on. If the tuned mass damper effects of stationary people are true, then the structural damping must be estimated definitely considering the tuned mass damper (TMD) effects of stationary people on the bridge deck due to dynamic interaction in vertical motion.

In Japan, the effects of stationary people on the bridge deck (human-bridge interaction) have not been considered. According to the dynamic response of the human body exposed to vertical whole-body vibration, the apparent mass showed a principal resonance at a frequency around 5 and 6 Hz for standing and seated subjects. Therefore, TMD effects of stationary people on the bridge deck (people who let a bridge vibrate) resulting from human-bridge interaction may occur depending on the scale of the bridge. However, there is a lack of information on the properties of civil engineering structures occupied by stationary people. The purpose of this study is to extend the limited knowledge available. A full scale measurement is carried out to investigate the influence of stationary people on a slender and lightly footbridge with center span length of 33 m. Modal properties (frequency and damping) were estimated from the damped free vibration. Complex eigenvalue calculation is also conducted by using two degree of freedom ISO5982: 1981 human model [6]. Based on experimental and analytical results, it is revealed that the structural damping of the footbridge increases according to the increase of number of stationary people on the center span of the bridge due to the dynamic interaction.

II. FOOTBRIDGE BEING TESTED

Fig. 1 shows the footbridge being tested. This footbridge with the span length of about 33 m and the effective width of 1.5 m is located in Osaka prefecture. It is appended that this footbridge is simply supported bridge because it has a hinge connection at middle bridge pier as shown in Fig. 2.

The weight per unit length of this bridge is assumed to be 7.35 kN/m/Br. with reference to the almost same-size footbridge which is designed as standard type. The measured fundamental frequency of this bridge is about 2.84 Hz in condition that stationary 1-2 occupants are at the center point of the bridge. By calculating the moment of inertia I from this measured value of 2.84 Hz and by the use of frequency equation as simple supports, the moment of inertia I=0.0141 m4/Br. is obtained. Therefore, the weight per unit length for the footbridge being tested is 7.35 kN/m/Br. and the moment of inertia I is assumed to be I=0.0141 m^4/Br.

III. EXPERIMENTAL RESULTS ON STANDING POSITION

A. Measuring Method

The test is conducted under the stationary load of 1-14 subjects (author and 13 university students) participated in an experiment. The total weight is 8,742 N as shown in Table I. The modal weight corresponding to the fundamental mode (1st vertical symmetrical mode) is estimated to be 7,35 N/m/Br.×33 m×1/2=121,275 N on the assumption that the maximum

---

M. Yoneda is a Professor at the Department of Civil and Environmental Engineering, Kindai University, Higashiosaka, Osaka 577-8502 Japan (phone: +81-6-4307-3546; fax: +81-6-6730-1320; e-mail: yoneda@civileng.kindai.ac.jp).

amplitude of the first vertical symmetrical mode is 1.0 at the center. The weight ratio between the stationary load of 14 subjects and the modal weight corresponding to the fundamental mode is evaluated to be 7.21%.

Fig. 1 Footbridge being tested

Fig. 2 Hinge connection at middle bridge pier

One accelerometer is installed in the vertical direction of the bridge center point in order to measure the damped free vibration excited by bending and stretching movement of one person according to the increase of the subject on the stationary standing position one by one in the state of being windless to decrease the aerodynamic damping effect. In principle, measurements were performed three times to obtain the damped free acceleration response which was sampled by Δt=0.005 s. These obtained data are filtered with the frequency range of between 2.3-3.3 Hz to estimate the structural logarithmic decrement of the bridge. FFT analysis is also performed for the time history data in order to obtain the fundamental frequency of the bridge from the maximum value of the power spectrum density.

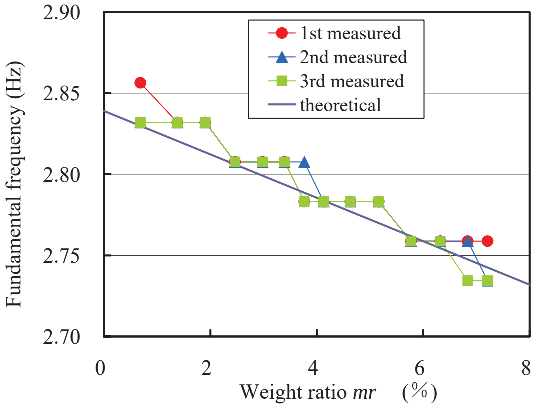

Fig. 3 Relationship between the fundamental frequency and the weight ratio (stationary state of the standing position at the center span of the bridge)

TABLE I
MAIN SPECIFICATIONS OF THE 14 SUBJECTS

Subject	Gender	Height	Weight(N)	Total weight(N)
1	Male	175cm	833	833
2	Male	174cm	843	1,676
3	Male	166cm	637	2,313
4	Male	173cm	676	2,989
5	Male	161cm	627	3,616
6	Female	162cm	500	4,116
7	Female	160cm	451	4,567
8	Female	150cm	441	5,008
9	Male	167cm	608	5,616
10	Male	171cm	647	6,263
11	Male	172cm	735	6,998
12	Male	177cm	666	7,664
13	Male	180cm	627	8,291
14	Female	156cm	451	8,742

B. Fundamental Frequency

In case of full scale measurements, the number of people standing at the center point of the bridge is increased according to the order shown on Table I. Fig. 3 shows the relationship between the fundamental frequency and the weight ratio in case that people is in the stationary state of the standing position at the center span of the bridge. It is appended that theoretical value in this Fig. 3 is evaluated by:

$$f = \frac{1}{2\pi}\sqrt{(1.008)^2 \times \frac{48EI}{m\ell^3}} \tag{1}$$

where, EI is the flexural rigidity, ℓ is the span length of the bridge at simple supports, m is the mass exchanged as single-degree-of-freedom (SDOF) system. The value of 1.008 is the coefficient to correct deviation between basic SDOF system and beam theory shown in (2) and (3), respectively:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{48EI}{m\ell^3}} \tag{2}$$

$$f = \frac{1}{2\pi}\left(\frac{\pi}{\ell}\right)^2 \sqrt{\frac{EI}{w/g}} \tag{3}$$

where k is the spring constant, g is the gravity acceleration.

It can be seen from Fig. 3 that the deviation between theoretical values and actual measurements is relatively small and that the assumed values of the weight and the moment of inertia of the bridge being tested are appropriate.

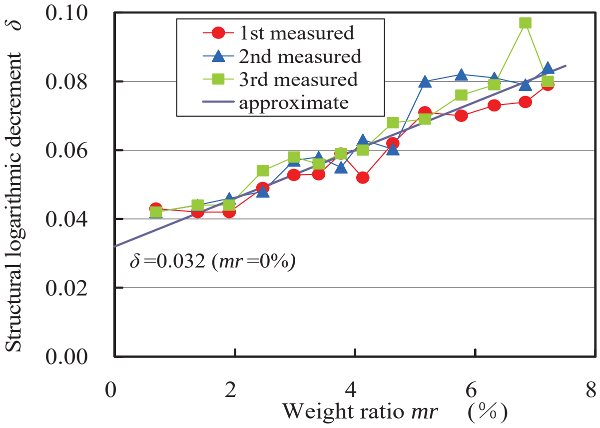

Fig. 4 Relationship between the structural logarithmic decrement and the weight ratio (stationary state of the standing position at the center span of the bridge)

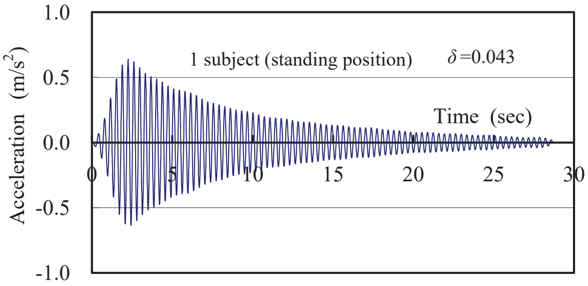

Fig. 5 Time history acceleration when one subject occupied (stationary state of the standing position; first measurement)

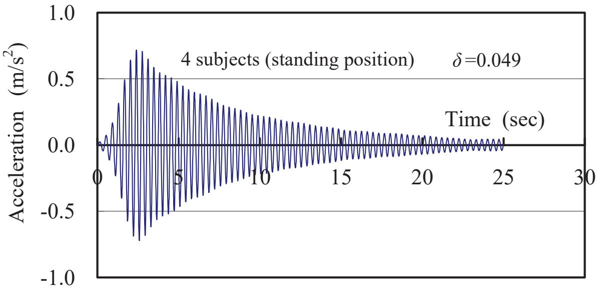

Fig. 6 Time history acceleration when 4 subjects occupied (stationary state of the standing position;1st measurement)

C. Structural Damping

Fig. 4 shows the relationship between the structural logarithmic decrement and the weight ratio in case that people is in the stationary state of the standing position at the center span of the bridge. Based on this figure, it can be seen that the structural logarithmic decrement definitely increases according to the increase of the weight ratio although the slight difference is recognized. It is also confirmed that the true value of structural logarithmic decrement of this bridge is δ=0.032 when nobody assumed to be on the bridge.

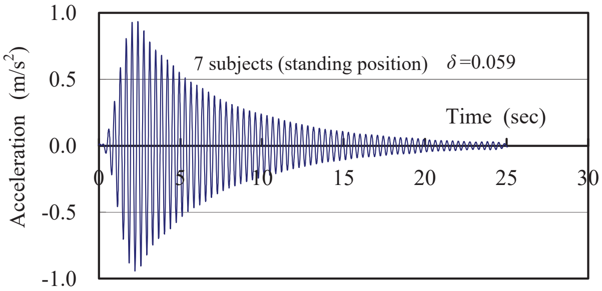

Fig. 7 Time history acceleration when 7 subjects occupied (stationary state of the standing position; 1st measurement)

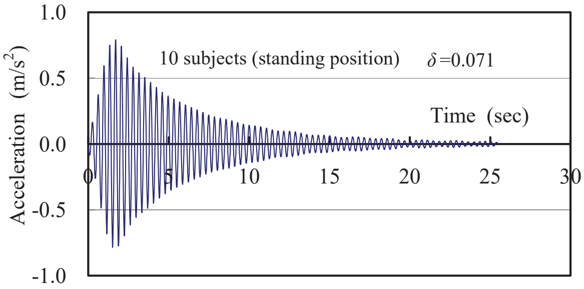

Fig. 8 Time history acceleration when 10 subjects occupied (stationary state of the standing position; 1st measurement)

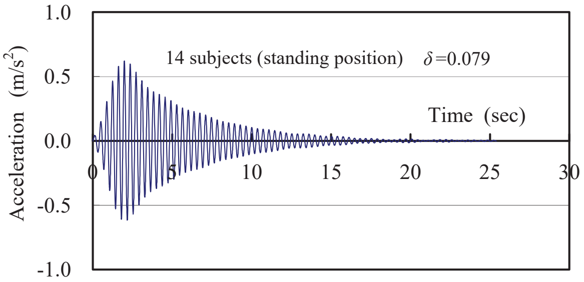

Fig. 9 Time history acceleration when 14 subjects occupied (stationary state of the standing position; 1st measurement)

As a reference, Figs. 5-9 show the time histories in case of 1, 4, 7, 10, 14 subjects at the center span in the stationary state of the standing position, respectively. These figures clearly demonstrate that the structural damping increases according to the increase of the number of people on the standing position. For instance, Fig. 10 shows the relationship between the wave number and the acceleration amplitude in case of 14 subjects at the center span in the stationary state of the standing position. It is confirmed from Fig. 10 that the distinct beat phenomenon does not occur and that the structural damping of the bridge does not almost depend on dynamic response amplitude in case of 14 subjects at the center span in the stationary state of the standing position.

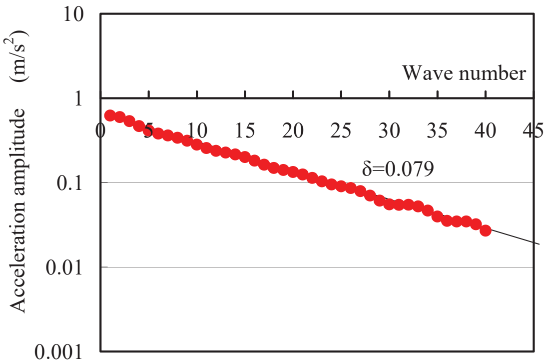

Fig. 10 Relationship between the wave number and the acceleration amplitude when 14 subjects occupied (stationary state of the standing position; 1st measurement)

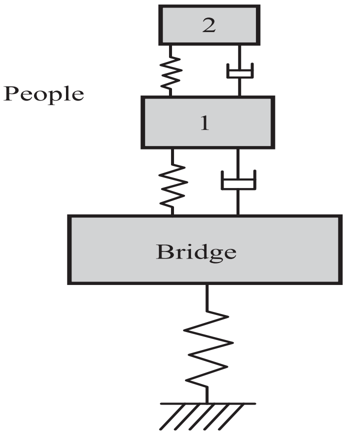

Fig. 11 Interaction model to investigate the dynamic behavior between people and footbridge

IV. COMPARISON OF COMPLEX EIGENVALUE CALCULATIONS AND MEASUREMENTS

A. Two Degree of Freedom Human Model (ISO5982: 1981)

A human body can be represented by a lumped system consisting of masses, springs and dashpots. The international Standard, ISO5982:1981 provided a two degree-of-freedom system, although it is really two single-degree-of-freedoms, with the model parameters being determined by experiments. In this paper, ISO5982:1981 human model is adopted for the vertical vibration of the human body in a standing position. It is appended that the vertical vibration of the human body in a standing position is not described in ISO5982:2001 which was revised in 2001. The parameters of ISO5982:1981 human model are given in Table II. The data in Table II indicates that the Weight 2 consists of the masses of the head and the upper torso, and the Weight 1 represents the rest of the body.

TABLE II
PARAMETERS OF THE 2 DOF ISO MODEL FOR STANDING PEOPLE

Element	Weight (N)	Stiffness (kN/m)	Damping (kN.s/m)	Frequency (Hz)
1	607.6	62.0	1.46	5.03
2	127.4	80.0	0.93	12.49

B. Comparison of Complex Eigenvalue Calculations and Measurements

The interaction model to investigate the dynamic behavior between people and footbridge is expressed as shown in Fig. 11 when ISO5982:1981 human model is adopted. Natural frequency and structural damping of the bridge can be estimated by carrying out complex eigenvalue calculations for this model. Damped circular frequency ω_n and damping constant h_n can be expressed as:

$$\omega_n = \xi_n \tag{4}$$

$$h_n = \frac{-\varsigma_n}{\sqrt{\varsigma_n{}^2 + \xi_n{}^2}}\xi_n \tag{5}$$

when *n*-th conjugated complex eigenvalues are defined as:

$$p_n = \varsigma_n \pm i\xi_n \tag{6}$$

where i is the imaginary unit. Therefore, damped natural frequency f_n and structural logarithmic decrement δ_n of the bridge taken into account the interaction between people and footbridge can be expressed in:

$$f_n = \frac{\omega_n}{2\pi} \tag{7}$$

$$\delta_n = h_n \frac{2\pi}{\sqrt{1-h_n{}^2}} \tag{8}$$

Although it may be thought that the vertical vibration characteristics of the human body differs slightly in individuals, the parameters of ISO5982:1981 human model shown in Table II is adopt for all of the test subjects when the complex eigenvalue calculation is performed.

Fig. 12 shows the relationship between the weight ratio and logarithmic decrement in the standing position, comparing the analytical value with the measured value obtained by full scale measurements. It is appended that the analytical value in this figure represents the value that added up the computed value and 0.032 which is corresponding to those when nobody is on the bridge. It can be seen from Fig. 12 that the analytical values based on complex eigenvalue calculations are fairly in good agreement with those measured in the field. On the other hand, Fig. 13 shows the relationship between the weight ratio and fundamental natural frequency in the standing position, comparing the analytical value with the measured value based on full scale measurements. It can be seen from Fig. 13 that the difference of both results is relatively small, although the analytical values based on complex eigenvalue calculations are slightly on the small side in comparison with the measured values.

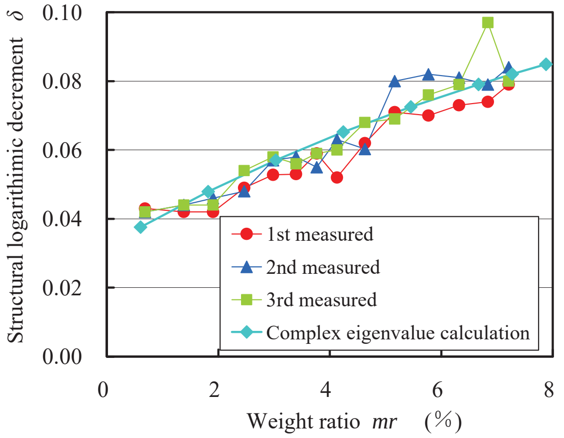

Fig. 12 Relationship between the weight ratio and logarithmic decrement in the standing position, comparing the analytical value with the measured value obtained by full scale measurements

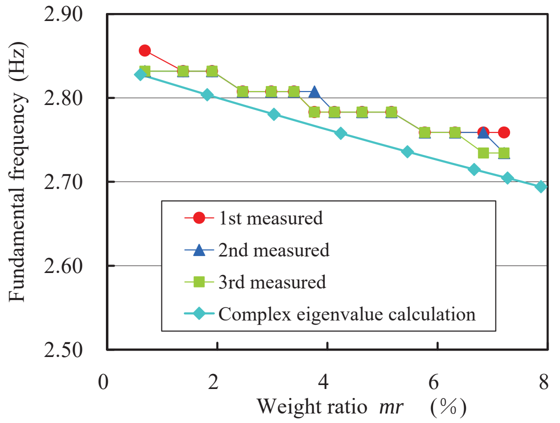

Fig. 13 Relationship between the weight ratio and fundamental natural frequency in the standing position, comparing the analytical value with the measured value based on full scale measurements

V. MEASUREMENT RESULTS IN A SQUATTING POSITION

Based on the measurements of vertical whole-body vibration, in both standing and seated subjects the principal and second resonance in the apparent mass occurs in the 5-6 Hz and 10-13 Hz frequency, respectively. Therefore, it may be thought that there are no significant differences in damping characteristics due to both postures of standing and seated subjects.

As far as it is known, the effect of a squatting position on the structural damping of the existing bridge has not been reported until now. Accordingly, additional experiments were carried out to investigate the structural damping characteristics due to the squatting subjects occupied at the center of the bridge. It is appended that many subjects crouched down on tiptoe without touching their heel in the ground. This posture is unstable compared with the standing posture. The experiments were carried out on another day when full scale measurements in the standing position were investigated. However, same subjects as shown in Table I took part in the experiment and the turn to appear on the bridge is the same, too.

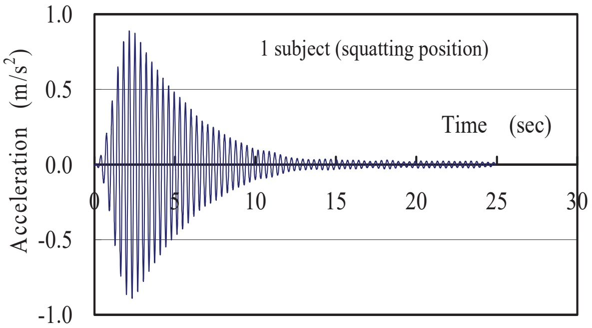

Fig. 14 Time history when one subject squatted at the center span in the stationary state

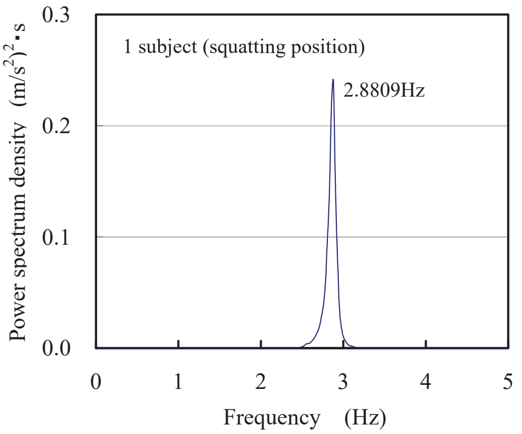

Fig. 15 Power spectrum density obtained by FFT analysis for the time history data shown in Fig.14

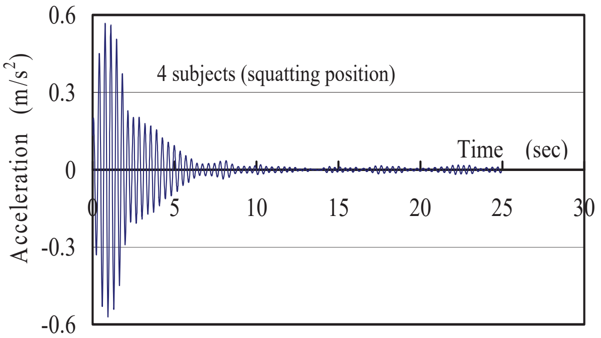

Fig. 16 Time history when 4 subjects squatted at the center span in the stationary state

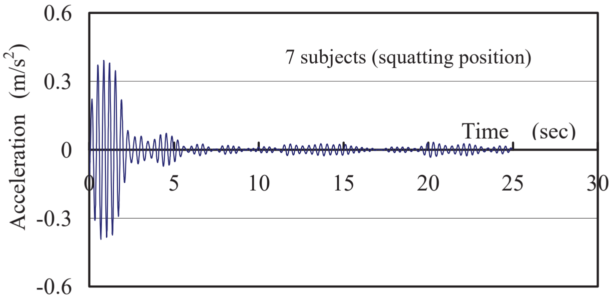

Fig. 17 Time history when 7 subjects squatted at the center span in the stationary state

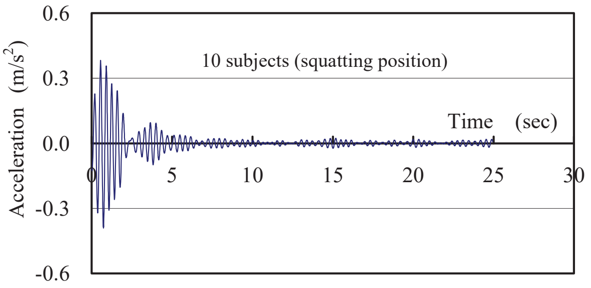

Fig. 18 Time history when 10 subjects squatted at the center span in the stationary state

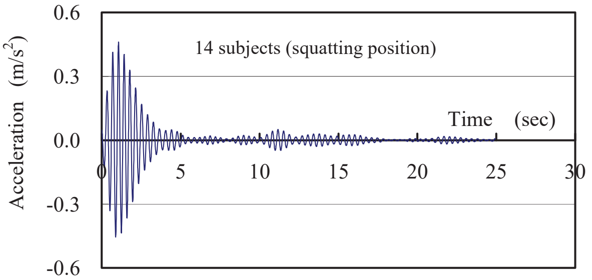

Fig. 19 Time history when 14 subjects squatted at the center span in the stationary state

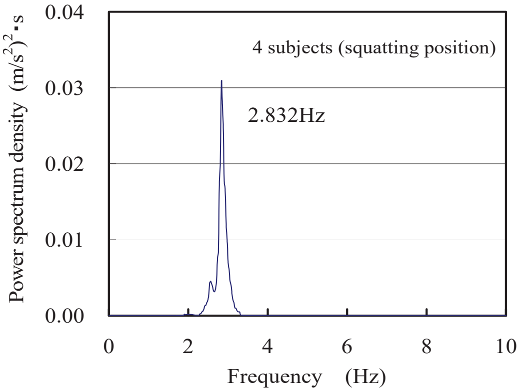

Fig. 20 Power spectrum density obtained by FFT analysis for the time history data shown in Fig. 16

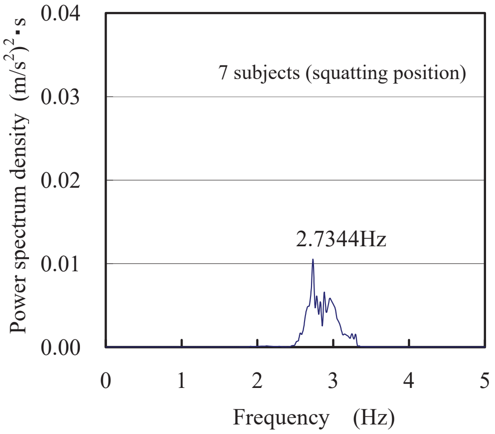

Fig. 21 Power spectrum density obtained by FFT analysis for the time history data shown in Fig. 17

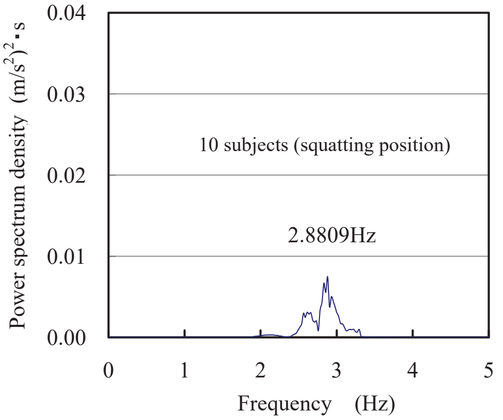

Fig. 22 Power spectrum density obtained by FFT analysis for the time history data shown in Fig. 18

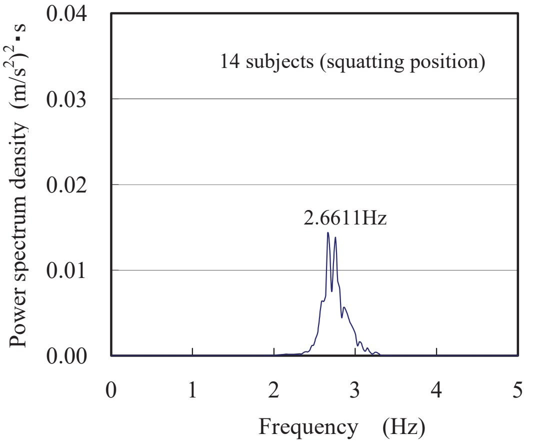

Fig. 23 Power spectrum density obtained by FFT analysis for the time history data shown in Fig. 19

The procedure of the experiment is about the same as described below. One accelerometer is installed in the vertical direction of the bridge center point in order to measure the damped free vibration excited by bending and stretching movement of a certain person according to the increase of the subject on the stationary squatting position one by one in the state of being windless to decrease the aerodynamic damping effect. The certain person squatted from the standing posture after exciting the bridge. In principle, measurements were performed three times to obtain damped free acceleration response which was sampled by Δt=0.005 s. These obtained data are filtered with the frequency range of between 1.9-3.3 Hz to estimate the structural logarithmic decrement of the bridge. FFT analysis is also performed for the time history data in order to obtain the fundamental frequency of the bridge from the maximum value of the power spectrum density.

The field experiments in a squatting position were carried out three times and each result was the almost same. Therefore, the results obtained by third experiment are summarized in this Chapter.

Fig. 14 shows the time history when one subject squatted at the center span in the stationary state. Fig. 15 shows the power spectrum density obtained by FFT analysis for the time history data shown in Fig. 14. The logarithmic decrement of δ=0.0947 is obtained for the time history data when one subject squatted at the center span. This value of δ=0.0947 is nearly equal to that when 14 subjects occupied on the bridge in the standing position. Therefore, it can be said from this result for the bridge being tested that the added structural damping in a squatting position is greater comparing with that in a standing position.

Figs. 16-19 shows the time histories when 4, 7, 10, and 14 subjects occupied at the center span in the stationary state of the squatting position, respectively. Figs. 20-23 show the power spectrum density corresponding to the history data shown in Figs. 16-19.

It can be seen from Figs. 16-19 that the beat phenomenon becomes to occur distinctly in proportion to the increase of the number of people in the squatting position. Although it is difficult to estimate the structural damping for the beating wave, based on these results, it can be confirmed that the subjects in the squatting posture increase the structural damping of the bridge than those in the standing posture. This might be because the principal frequency of the squatting position become smaller from 5.03 Hz and come close the value of 2.84 Hz which is associated with the natural frequency of the bridge. The beat phenomenon observed in the squatting position clearly demonstrates that the increase of the structural damping may be caused by the TMD effect due to the pedestrian on the bridge.

There is a possibility that the beat phenomenon might be observed for the bridge with the fundamental frequency of about 5 Hz even if the subjects occupy on the bridge in the standing position. A couple of peaks like ripples appeared referring to the power spectrum density shown in Figs. 20-23. Each peak might be caused by each subject in the squatting position with a bit lower frequency of 5 Hz. These aspects would be the object of future studies.

VI. CONCLUSIONS

This paper deals with the TMD effects of stationary people on structural damping of footbridge due to dynamic interaction in vertical motion. A full scale measurement is carried out to investigate the influence of stationary people on a slender and lightly footbridge with center span length of 33 m. The results are summarized below:

1) Based on the experiment results in the standing position, it was found that the structural logarithmic decrement definitely increases according to the increase of the weight ratio between the total weight on the bridge and the modal weight corresponding to the fundamental mode although the slight difference is recognized. It is also confirmed that the true value of structural logarithmic decrement of this bridge is δ=0.032 when nobody assumed to be on the bridge.
2) The complex eigenvalue calculation is performed using ISO5982:1981 human model. It is found that the structural damping based on complex eigenvalue calculations are fairly in good agreement with those measured in the field. It was also seen that the difference of both results is relatively small, although the analytical values based on complex eigenvalue calculations are slightly on the small side in comparison with the measured values.
3) Additional experiments were carried out to investigate the structural damping characteristics due to the squatting subjects occupied at the center of the bridge. The logarithmic decrement of δ=0.0947 is obtained for the time history data when one subject squatted at the center span. This value of δ=0.0947 is nearly equal to that when 14 subjects occupied on the bridge in the standing position. Therefore, it can be said from this result for the bridge being tested that the added structural damping in a squatting position is greater comparing with that in a standing position.
4) The beat phenomenon becomes to occur distinctly in proportion to the increase of the number of people in the squatting position. Although it is difficult to estimate the structural damping for the beating wave, based on these results, it can be confirmed that the subjects in the squatting posture increase the structural damping of the bridge than those in the squatting posture.
5) This might be because the principal frequency of the squatting position become smaller from 5.03 Hz and come close the value of 2.84 Hz which is associated with the natural frequency of the bridge. The beat phenomenon observed in the squatting position clearly demonstrates that the increase of the structural damping may be caused by the TMD effect due to the stationary people on the bridge.

Needless to say, a lot of further study might be necessary to investigate the TMD effect on the structural damping paying attention to many bridges with various fundamental natural frequencies. It is hoped that this study will provide useful information for bridge engineers in investigating the dynamic behavior of pedestrian bridges.

REFERENCES

[1] Dallard, P., Fitzpatrick, A. J., Flint, A., Le Bourva, S., Low, A., Ridsdill Smith, R. M. and Willford, M., "The London Millennium Footbridge", *The Structural Engineer,* vol.79, no.22, 2001, pp.17-33.
[2] Dallard, P., Fitzpatrick, A. J., Flint, A., Low, A., Smith, R. R., Willford, M. and Roche, M., "London Millennium Bridge: Pedestrian-Induced Lateral Vibration", *Journal of Bridge Engineering*, vol.6, no.6, 2001, pp.412-417.
[3] Fujino, Y., Pacheco, M. B., Nakamura, S. and Pennung, W., "Synchronization of Human Walking Observed during Lateral Vibration of a Congested Pedestrian Bridge", *Earthquake Engineering and Structural Dynamics*, vol.22, 1993, pp.741-758.
[4] Sachse, R., Pavic, A. and Reynolds, P., "The influence of a group of humans on modal properties of a structure", *Proceedings of the Fourth International Conference on Structural Dynamics*, 2002, pp.1241-1246.
[5] Tianjian, J., "On the combination of structural dynamics and biodynamics methods in the study of human-structure interaction", *The 35th UK Group Meeting on Human Response to Vibration*, pp.183-194, 2000, pp.183-194.
[6] International Organization for Standardization, "Vibration and shock-Mechanical driving point impedance of the human body", *ISO 5982*, 1981.