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52. *Period and Damping of Vibration in Actual Buildings during Earthquakes.*

By Teiji Tanaka, Shizuyo Yoshizawa, Yutaka Osawa
and
Toshizo Morishita,

Earthquake Research Institute.

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Abstract

Period and damping values of actual buildings at rather high amplitude levels are estimated from the strong-motion seismograph records using the method based on the power spectral density analysis. Also, these structural parameters of the buildings at minute amplitudes are evaluated by the same procedure from the response records in ordinary times. Both results are then compared, and it is shown that an increase in vibration amplitude of about 1000 times produces approximately a 20% increase in the period on an average. A similar trend is also found for the damping values of the buildings.

1. Introduction

The natural period and damping of vibration of a structure are the very important and basic parameters which control the dynamic response of the structure during an earthquake. In the present situation, the methods for calculating these structural parameters with a satisfactory accuracy have not yet been established, because of the complexity of actual structures in the mechanism of lateral rigidity and damping, direct experimental determinations of these values in actual structures being the only way to obtain the reliable values of such quantities. For this reason, a large number of vibration tests in actual structures have so far been carried out and also much effort has been made to improve the methods as well as equipment to be employed in the tests.

Since the amplitudes of vibrations induced in actual structures during these tests are, in most cases, limited to rather low levels, mainly because of insufficient power of a vibration generator, an alternative approach is required to determine the period and damping values of the structures at high amplitude levels. One approach is to estimate such values through the analysis of the response records of the structures during earthquakes.

An earthquake with magnitude 6.1 occurred on July 1, 1968 in the middle of Saitama Prefecture, about 45 km northwest of Tokyo. The reported intensity in Tokyo was IV in the Japanese scale. During this earthquake, the response records of some forty modern buildings were obtained in Tokyo and its vicinity by the strong-motion seismographs.[1)]

It is, therefore, intended in this paper to estimate the values of the period and damping of the buildings from these earthquake response records and then to compare the results with those obtained from the records of microtremors in the same buildings to provide information on the amplitude dependency of the structural parameters in actual buildings.

2. Method of determining the period and damping

2.1 *Method*

As is well known the autocorrelation function $\varphi(\tau)$ of the output of a linear single degree of freedom system to a stationary random input with a constant power spectral density S_0 is given by

$$\varphi(\tau)=\frac{\pi S_0}{2h\omega_0^3}\left[\cos\left(\sqrt{1-h^2}\omega_0|\tau|\right)+\frac{h}{\sqrt{1-h^2}}\sin\left(\sqrt{1-h^2}\omega_0|\tau|\right)\right]e^{-h\omega_0|\tau|}, \quad (1)$$

and the corresponding power spectral density function $S(\omega)$ is expressed as

$$S(\omega)=\frac{S_0}{(\omega_0^2-\omega^2)^2+4h^2\omega_0^2\omega^2}, \quad (2)$$

where, $\omega_0=2\pi f_0$ and h are the natural circular frequency and damping coefficient of the system, respectively, and $\omega=2\pi f$ is the circular frequency of the input.

In the application of this random vibration theory to actual problems of estimating the values of the period and damping of structures, two different methods have been developed. One is the method based on the output autocorrelation function. As can be seen in Eq. (1), the output autocorrelation function of the single degree system is proportional to the response function of the system to an impulse. Therefore, the values of f_0 and h can easily be determined from a $\varphi(\tau)$ versus τ curve by the well-known logarithmic decrement method.

The application of this concept to scientific problems was proposed more than 30 years ago by Takahashi and Husimi.[2)] Similar studies

1) Strong-motion Earthq. Obs. Comm., *Strong Motion Earthquake Records in Japan, Volume* 7, Published by Earthq. Res. Inst., Univ. of Tokyo, (1969).

2) K. TAKAHASHI and K. HUSIMI, "Vibrating System Exposed to Irregular Forces," *Geophy. Mag.*, **9** (1935), 29.

were later carried out on the actual structures such as dams, towers, buildings and so on.[3),4),5)] Lately, Matsushita, et al.[6)] have reported the result of application of this method to the same accelerograms as treated here. The suitability of the autocorrelation technique as a method for deducing these structural parameters has been discussed by Cherry and Brady.[7)]

The other method is based on the power spectral density function. In the output power spectrum, the spectral density becomes maximum at a frequency $\omega\sqrt{1-2h^2}$, and the damping coefficient h can be calculated as follows,[8)] knowing the frequencies f_1 and f_2 where the spectral densities become $1/\lambda$ of its maximum.

$$h \doteqdot \frac{A}{2}\left(1-\frac{3}{8}A^2\right), \tag{3}$$

where,

$$A=\frac{f_2^2-f_1^2}{f_2^2+f_1^2}\cdot\frac{1}{\sqrt{\lambda-1}}\,. \tag{4}$$

In practice, $\lambda=2$ is usually used for simplicity.

Although the power spectral analyses for the microtremor records in actual buildings have often been conducted recently, only a few examples of damping estimates of the buildings have been reported.[9)]

Needless to say, since the vibrations observed at a point in a building represent a resultant of vibrations of various modes which develop in the building, it is expected that the derived autocorrelation diagram does not, in general, show the typical form as its envelope decays exponentially with lag time. Therefore, it seems to be difficult to determine the reliable values of the period and damping directly from the

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3) T. Hatano and T. Takahashi, "Stability of an Arch Dam against Earthquakes," *Jour. Tech. Res. Lab. of Elec. Power.*, **5** (1955), no. 5, 18, (in Japanese).

4) E. Shima, T. Tanaka and N. Den, "Some New Instruments Used in Earthquake Engineering in Japan," *Proc. 2nd World Conf. Earthq. Engg.*, (1960), 761.

5) H. S. Ward and R. Crawford, "Wind-induced Vibrations and Building Modes," *Bull. Seism. Soc. Amer.*, **56** (1966), 793.

6) K. Matsushita, M. Izumi and I. Sakamoto, "Some Analyses of Strong-motion Accelerometer Data during the Higashimatsuyama Earthquake of July 1, 1968," *Report Annual Meeting Arch. Inst. Japan*, (1969), 585, (in Japanese).

7) S. Cherry and A. G. Brady, "Determination of Structural Dynamic Properties by Statistical Analysis of Random Vibrations," *Proc. 3rd World Conf. Earthq. Engg.*, **2** (1965), 50.

8) H. Kawasumi and E. Shima, "Some Applications of a Correlator to Engineering Problems," *Proc. 3rd World Conf. Earthq. Engg.*, **2** (1965), 298.

9) *loc. cit.*, 5), 8).

autocorrelation diagram without the aid of some filtering techniques. On the contrary, the latter method based on the power spectral analysis has an obvious advantage in that the parametric values for the different modes can be obtained separately and, therefore, is employed in the present investigation after making a slight improvement on the method for convenience in the practical application.

The power spectral density function is defined as the Fourier transform of the *true* autocorrelation function derived from a vibration record of infinite length of time. When the length of the record is finite, we cannot estimate the true autocorrelation function for arbitrarily long lags. Furthermore, it is said that the use of lags longer than a moderate fraction, say 10 per cent, of the length of the record is usually not desirable. In the practical cases, therefore, we can only compute so called the *apparent* autocorrelation function from a record of considerably short length. However, a good estimation of smoothed values of the true power spectrum can be obtained from the Fourier transform of a *modified apparent* autocorrelation function, which is the product of the apparent autocorrelation and a suitable even function called the lag window.[10] It is apparent that when this process of analysis is adopted for determining the damping value of a structure, a much larger value than the true one would be obtained. However, if the effect of smoothing in the process could be known and the corrections for this influence could be made on the apparent damping value, the true value of damping could be obtained. With the above expectations in mind, we examined the effect of smoothing and searched for the way of correction.

In the present investigation, the so called 'hamming' type lag window expressed by Eq. (5) was used.[11]

$$w(\tau)=0.54+0.46\cos\frac{\pi\tau}{T_m} \qquad \text{for } |\tau|<T_m\,, \qquad\qquad (5)$$
$$=0 \qquad \text{for } |\tau|>T_m\,,$$

where, τ is a time lag and T_m is the maximum lag which we desire to use.

The corresponding frequency function is

$$W(\omega)=0.54\,W_0(\omega)+0.23\left[W_0\left(\omega+\frac{\pi}{T_m}\right)+W_0\left(\omega-\frac{\pi}{T_m}\right)\right], \qquad (6)$$

where,

10) R. B. BLACKMAN and J. W. TUKEY, *The Measurement of Power Spectra*, Dover Publications, Inc., 1958.

11) *loc. cit.*, 10).

$$W_0(\omega)=2T_m\frac{\sin\omega T_m}{\omega T_m}\,. \tag{7}$$

The modified autocorrelation function is the product of $\varphi(\tau)$ and $w(\tau)$, and its Fourier transform is represented by the convolution integral of the power spectrum for each time function. This operation implies smoothing of the response power spectrum $S(\omega)$ with the *spectral window* $W(\omega)$ as a weighting function. The smoothed spectral function is then expressed by

$$P(u)=K\int_{-\infty}^{\infty}\frac{1}{(1-u'^2)^2+4h^2u'^2}\Big[Y_0(u-u') + \frac{23}{54}\Big\{Y_0\Big(u-u'+\frac{1}{2f_0T_m}\Big)+Y_0\Big(u-u'-\frac{1}{2f_0T_m}\Big)\Big\}\Big]du' \tag{8}$$

where,

$$K=\frac{1.08T_mS_0}{\omega_0^4}\,,\qquad Y_0(u-u')=\frac{\sin\omega_0T_m(u-u')}{\omega_0T_m(u-u')}\,,\qquad u=\frac{\omega}{\omega_0}\,,\qquad u'=\frac{\omega'}{\omega_0}\,. \tag{10}$$

As an illustrative example, the power spectra computed numerically from Eq. (8) in the case of $h=0.02$ are shown in Fig. 1, taking f_0T_m as a parameter. As can be seen in Fig. 1, the degree of smoothing effect depends largely on the f_0T_m-value, in other words, the smaller the f_0T_m-value, the larger the apparent damping becomes. Fig. 2 shows the apparent damping coefficient h' as a function of f_0T_m, for various values of the true damping h. Fig. 2 indicates that the smaller the value of damping, the greater the effect of smoothing on the value becomes. It is also evident that the value of h' becomes equal to h at $f_0T_m\to\infty$, and takes $0.45/f_0T_m$ at $h=0$ when 'hamming' type lag window is used. Fig. 3 is another expression of the relation among h, h' and f_0T_m, and

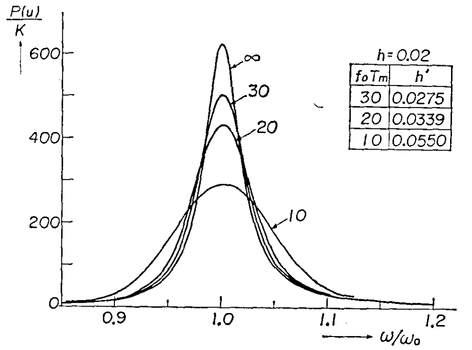

Fig. 1. The effect of smoothing on the power spectrum.

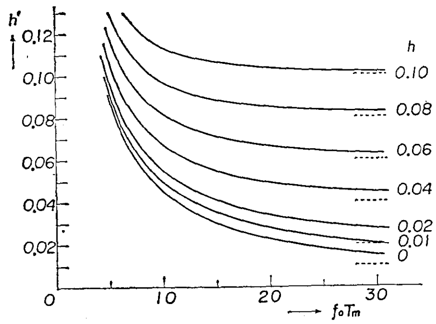

Fig. 2. Apparent damping coefficient h' as a function of f_0T_m.

it is used as a chart for evaluating the true value of damping h from the h' knowing the f_0T_m-value in the computed autocorrelation diagram. f_0T_m is nearly equal to the number of waves contained in the autocorrelation function of length T_m, because the frequency of free vibration of a single degree system with a low value of damping is almost identical with the natural frequency of the system.

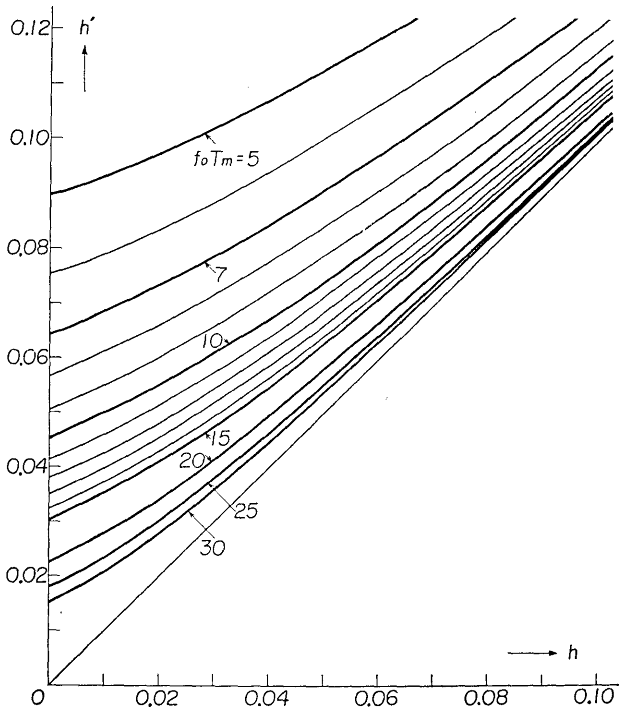

Fig. 3. A chart for obtaining the true damping coefficient h from the apparent value h'.

2.2 *Tests for accuracy of the method*

In order to check for accuracy in practical use of the chart shown in Fig. 3, a computational test was carried out by the following procedure. Firstly, the autocorrelations of the random response of a single degree of freedom system with given constants of the period and damping are calculated by Eq. (1). Next, the correlation function thus obtained is multiplied by the window functions having the different lengths of duration, and the Fourier transformation are performed on them. The apparent values of the damping and period are then evaluated from each of the spectra. Finally, the corrected values of damping are obtained by using the chart, and is compared with the true one which was previously given. The result of the test is shown in Fig. 4. It may be seen in

Fig. 4 that for the system with a period of 0.5 sec and a damping of $h=0.02$, the estimated values were 0.50 sec and $h=0.020$ for all the cases. It can be said that the chart has a sufficient accuracy for practical use.

Another test was conducted to examine the applicability of the present method to actual problems by analyzing the records of a simple model structure in response to microtremors. A moving coil type electromagnetic seismometer with an inverted pendulum was used for the model. The output voltage from the seismometer was directly fed to a high-speed A-D converter and digitization of the signal for two minutes was done at equal intervals of 0.04 sec. The results of the tests for the two seismometers with different constants are shown in Fig. 5. The values of damping estimated by the power spectral method agreed well with those determined from logarithmic decrement measurements of free vibration records of the pendulums. From these test results, it may be said that the present method can provide a reliable estimate of the period as well as the damping of a simple structure to random disturbances.

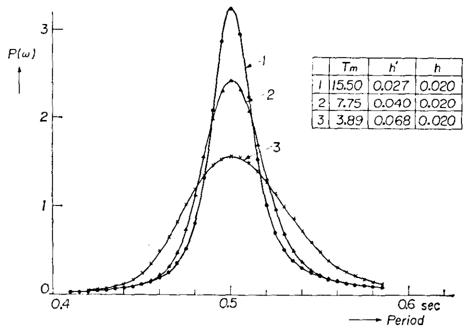

Fig. 4. The results of the tests for accuracy of the chart. (for system with $T_0=0.5$ sec and $h=0.02$)

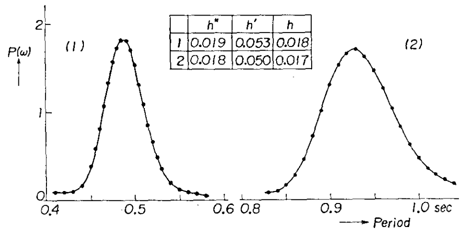

Fig. 5. Power spectra of the vibrations of seismometer pendulums in response to microtremors and the estimated damping values. h^*: Damping value obtained from free vibration record by logarithmic decrement method.

3. Application to vibration records of actual buildings

It is needless to say that the vibrational characteristics of a building measured by the ordinary vibration tests are considered to be those of the coupled system of the ground and the structure. Therefore, as far as the period and damping of the building in this sense are concerned, the present method may be applicable to the response records of actual buildings to earthquake motions as well as to microtremor excitation, if the input at a certain depth of the ground, for instance, at the bedrock satisfies the *white noise* assumption in the vicinity of the resonant frequency of the coupled system.

From this point of view, the microtremors at the bedrock may be considered as stationary random disturbances with uniform spectral density over a wide range of frequency. While the earthquake motions are not stationary in the strict sense, but when considering the observational fact that the velocity spectrum at the bedrock is characterized by a constant pattern,[12] it may be permissible to apply the foregoing method to earthquake records of buildings.

3.1 *Application to the strong-motion seismograph records*

The strong-motion seismograph records obtained in seventeen buildings during the earthquake of July 1, 1968 were selected to provide the data for the period and damping of actual buildings at high amplitude levels. In the analysis, the record on the upper-most floor of each building was used.

To investigate the effects of record length, the following computational tests were carried out preceding the analyses of the records. Fig. 6 shows a reproduction of the record (NS component) on the roof floor of the 8-storied steel reinforced concrete (SRC) building which is numbered 105-1. One initial point and three final points are identified as O, A, B and C, the corresponding record lengths are 25.0, 37.5 and 75.0 sec, respectively. The correlogram and the power spectrum for each of three different lengths of the record are illustrated respectively in Figs. 7a and 7b. In Fig. 7a, the effect of the record length is clear on the appearance of the original correlograms. However, no significant difference is seen between the power spectra as well as the damping values derived from them when the length of the record is chosen to be longer than about 5 times the maximum lag of the autocorrelation function. With this result in mind, in the following analysis the $f_0 T_m$-value was chosen as about 10, and the length of the sample record was taken to be at least 5 times, 10 times in most cases, that of the correlogram. The record length used in the analyses was 30 to 100 sec depending on the fundamental period of the building.

Digitization of the records was carried out on a direct photographic copy of the original record with the aid of the SMAC Digitizer from which the punched data cards are obtained as the output.

The station number, the name, the type of construction and the number of stories for each building together with the maximum acceleration and the approximate value of the maximum displacement obtained from the seismogram are listed in Table 1.

12) K. KANAI, S. YOSHIZAWA and T. SUZUKI, "An Empirical Formula for the Spectrum of Strong Earthquake Motions. II," *Bull. Earthq. Res. Inst.*, **41** (1963), 261.

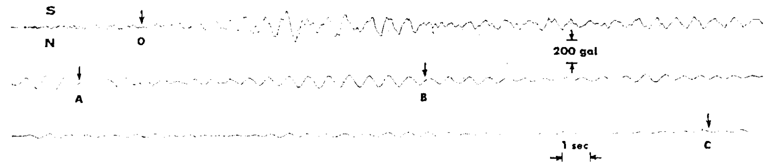

Fig. 6. Strong-motion seismograph record obtained at the station No. 105-1 (P1F, NS) during the earthquake of July 1, 1968. Arrows indicate the initial and final points.

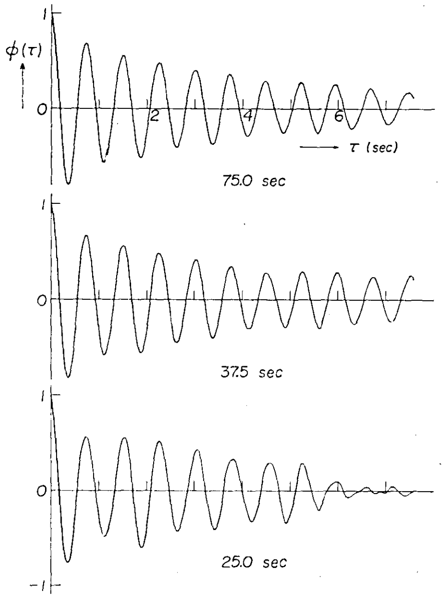

Fig. 7a. Correlograms for three different lengths of records.

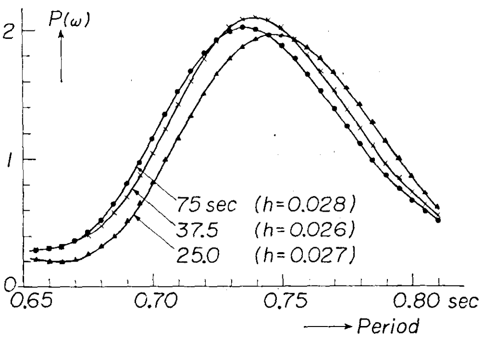

Fig. 7b. Power spectra and the estimated damping values.

In Figs. 8a and 8b are shown the reproduced record and the result of analysis, respectively, of a high-rise building, 21 stories high with 2 basements. In Fig. 8b, although the correlograms do not show a simple waveform due to the presence of short period vibrations, probably for the 2nd higher mode, superimposed on a base vibration of long period, the good separation of the base vibration is seen on the spectrum. This example also exhibits the general tendency of high-rise buildings to have long periods and low values of damping. Another example is shown in Fig. 9. The building is a SRC construction, 8 stories high with 1 basement. In this figure, the effect of interference between the two vibrations whose periods are very close to each other is evidently seen, and a satisfactory estimate of the damping cannot be secured from a spectrum showing this trend.

The power spectra for the other 15 buildings are illustrated in Figs. 13 and 14. The spectra have been normalized so that the maximum value of the spectral densities is equal to unity. The estimated values of the

Table 1. Period and damping values estimated from the analyses of the strong-motion seismograph records.

Station No.	Building	Types	No. of Stories (above/below) the G.L.	Orientation	Max. Accel. (gal)	Max.* Displ. (cm)	Period (sec)	Damping h
105-1	Metropolitan Municipal Office, No. 1 Bldg.	SRC	8/2	NS	141	2.0	0.75	0.028
				EW	183	1.3	0.54	0.040
105-2	Metropolitan Municipal Office, No. 2 Bldg.	SRC	9/1	NS	62	1.0	0.80	0.043
				EW	107	1.9	0.85	0.042
110	Daini Sennari Bldg.	SRC	9/1	NS	114	1.7	0.77	0.024
				EW	83	0.25	0.35	0.056?
111	Tokyo Tatemono Bldg.	SRC	8/2	NS	116	0.56	0.44	0.081
				EW	190	0.89	0.43	—
112	Uyeno Matsuzakaya Depart. Store	RC	7/3	NS	94	1.3	0.73	0.012?
				EW	106	1.5	0.75	0.026
113	Marubutsu Depart. Store	SRC	8/3	NS	173	1.2	0.53	0.027
				EW	220	2.8	0.71	0.024
117	Shimizu Construction Co., Main Office	SRC	9/1	NS	114	0.75	0.51	0.047?
				EW	210	1.5	0.52	—
123	Ohbayashi-gumi Bldg.	SRC	9/2	NS	84	1.0	0.70	0.038
				EW	81	1.3	0.79	0.018
126	Engineering Bldg. No. 5, Tokyo Univ.	RC	7/1	NS	152	0.60	0.39	0.031
				EW	141	0.58	0.40	0.038
130	San-ai Dream Center	SRC	9/3	NS	62	1.0	0.80	0.045?
				EW	77	1.4	0.86	0.033
131	Higashi-Shinjuku Den-Den Bldg.	SRC	8/2	NS	127	0.69	0.46	0.049
				EW	66	0.26	0.40	—
132	Shin-Tokyo Bldg.	SRC	9/4	NS	88	0.60	0.52	0.022
				EW	99	0.81	0.57	0·065
133	Mitsui No. 3 Detached Bldg.	SRC	10/3	NS	86	1.1	0.73	0.028
				EW	101	1.2	0.64?	—
134	Hotel New-Otani	SRC	17/3	NS	107	4.6	1.30	0.013
				EW	80	3.4	1.31	0.014
141	Keio Bldg.	SRC	8/2	NS	94	0.69	0.54	0.058
				EW	116	1.5	0.72	0.019
145	Fuji Bank, Head Office	SRC	16/4	NS	130	5.3	1.27	0.014
				EW	108	4.4	1.26	0.022
609	Hotel Empire	SRC	21/2	NS	93	4.6	1.39	0.020
				EW	154	7.7	1.40	0.022

* Approximate value. SRC: Steel reinforced concrete. RC: Reinforced concrete.

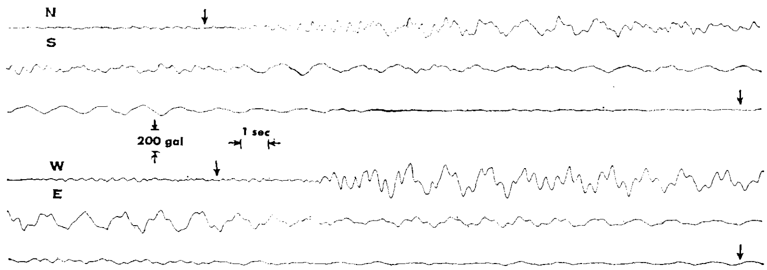

Fig. 8a. Strong-motion seismograph records obtained at the station No. 609 (22F) during the earthquake of July 1, 1968.

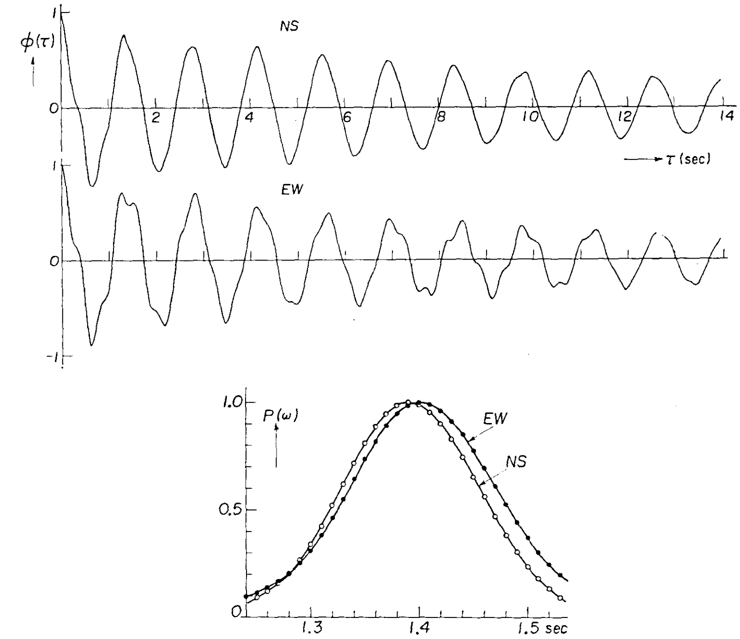

Fig. 8b. Correlograms and power spectra. (Station No. 609)

periods and damping coefficients for the fundamental translational mode of vibration of the buildings are summarized in Table 1.

3.2 *Application to the microtremor records in ordinary times*

Observations of microtremors at the strong-motion seismograph stations in Japan was projected by Prof. K. Kanai and were carried out in 1967 by the special research group represented by him. Part of the results of frequency analyses of the records have been reported to provide the fundamental data of the site characteristics as well as the dynamic properties of the buildings in which the seismographs are installed.[13]

13) The Research Group for Earthquake Response to Subsoil and Structure, *The Results of Microtremors Observations at the Strong-motion Seismograph Sites in Japan*. I-X, (1967), (in Japanese).

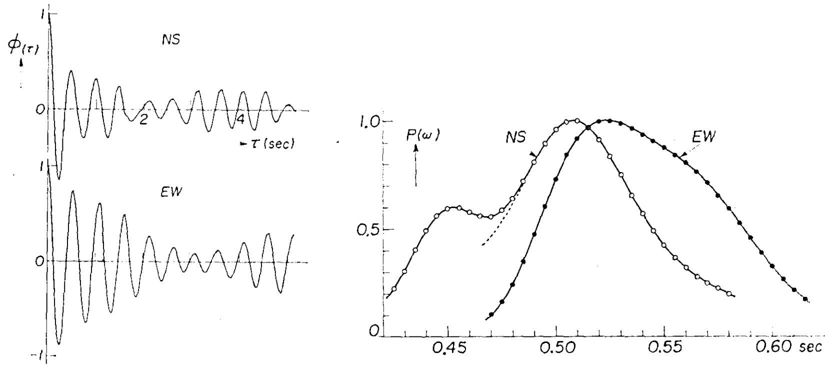

Fig. 9. Correlograms and power spectra. (Station No. 117)

Therefore, it is also intended in the present investigation to determine the period and damping of the buildings at very small amplitude levels from the analysis of the microtremor records in the buildings mentioned above.

In most observations, the record of the microtremors was taken at a place beside the base of the strong-motion seismograph. A magnetic recording microtremometer was used in the observation, so the digitization of the records was done efficiently with the A-D converter, DATAC-1000. The autocorrelation function was computed from the sample record of 60 to 200 sec length which was selected out from the original record for five minutes. Figs. 15 and 16 show the power spectra obtained for 30 components of 17 buildings. The values of the period and damping estimated are shown in Table 2, with the approximate amplitudes of vibrations at the time of the observations.

The vibration tests by means of a vibration generator have been conducted on some of these buildings, and the results are presented in the last two columns in Table 2 for the sake of comparison.

4. Comparison of results

Not many experimental results have been reported to date with regard to amplitude dependency of the vibrational properties of actual full-scale buildings.[14),15),16)] According to the results, the values of period and damping increase gradually with increasing amplitude of vibration.

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14) J. L. ALFORD and G. W. HOUSNER, "A Dynamic Test of a Reinforced Concrete Building," *Bull. Seism. Soc. Amer.*, **43** (1953), 7.

15) N. N. NIELSEN, "Vibration Tests of a Nine-Story Steel Frame Building," *Jour. Engg. Mech. Div.*, ASCE, **92** No. EM1, (1966), 81.

16) N. N. NIELSEN, "Dynamic Response of a 90-ft Steel Frame Tower," *Proc. 4th World Conf. Earthq. Engg.*, (1969), (in press).

Table 2. Period and damping values estimated from the analyses of the records of microtremors in the buildings.

Station No.	Orientation	Max. Displ. (μ)	Period (sec)	Damping h	Vibration Test	
					Period (sec)	Damping h
105-1	NS	12.7	0.63	0.019	0.59	0.031
	EW	10.1	0.46	0.028	0.41	0.034
105-2	NS	4.2	0.61	0.013?		
	EW	4.0	0.63	0.032		
110	NS	13.8	0.66	0.024	0.575	0.019
	EW	7.9	0.32	0.027	0.295	0.031
111	NS	6.3	0.40	0.061		
	EW	6.3	0.39	0.032		
112	NS	2.5	0.54	0.016		
	EW	2.4	0.54	0.020		
113	NS	2.5	0.42	0.038		
	EW	4.0	0.58	0.025		
117	NS	7.0	0.46	0.051		
	EW	6.5	0.44	—		
123	NS	10.0	0.59	0.020		
	EW	14.0	0.65	0.020		
126	NS	10.0	0.36	—		
	EW	9.0	0.37	—		
130	NS	17.4	0.65	0.020	0.57	0.07
	EW	25.0	0.76	0.022		
131	NS	7.5	0.42	0.026		
	EW	5.6	0.36	0.028		
132	NS	8.7	0.46	0.047		
	EW	8.7	0.49	0.035		
133	NS	9.5	0.60	0.022		
	EW	11.1	0.54	0.037		
134	NS	10.0	1.06	0.018	0.89	0.013-0.026
	EW	10.0	1.05	0.020	0.89	
141	NS	2.8	0.45	0.042		
	EW	2.5	0.62	0.016		
145	NS	7.5	0.96	0.011		
	EW	7.5	0.98	0.019		
609	NS	17.4	1.27	—	1.07	0.026
	EW	11.0	1.24	0.021		

In these experiments the magnitude of vibration of the structures was rather small, and change in amplitude level was not so large as 10 times or so.

On the other hand, as is seen in Tables 1 and 2, the maximum response amplitudes of buildings due to the earthquake are 0.3 to 8 cm, while those for microtremors are 3 to 25 microns. The ratio of vibration amplitudes between both cases attains to about 1000 times. Therefore, it is of interest to compare both results in getting information on amplitude dependency of the period and damping values of actual buildings for such a large difference in amplitude.

The seventeen buildings investigated have different heights from 7 to 21 stories, so that their fundamental periods are widely distributed from 0.35 to 1.4 sec. Fig. 10 shows the relation between the periods of the buildings estimated from the strong-motion seismograph records and those from the microtremor records. Fig. 11 shows the relation of the damping values for both cases. In Fig. 10 it can be seen that the periods of the buildings at the time of the earthquake are apparently larger compared with those in ordinary times. The rate of increase is about 20% on the average and there is no significant difference with respect to the periods of buildings as well as the types of construction.

As regards the damping values, the relation is not so simple as for the periods. In Fig. 11, however, a tendency for the damping to increase

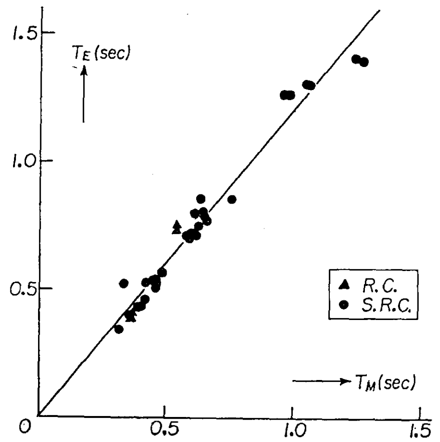

Fig. 10

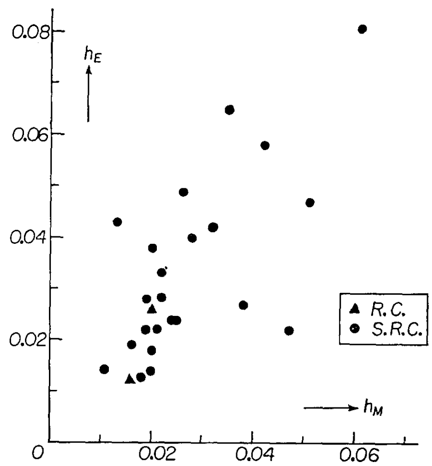

Fig. 11

Fig. 10. Relation between the fundamental periods of the buildings estimated from the strong-motion seismograph records (T_E) and those from the records of microtremors in the buildings (T_M).

Fig. 11. Relation between the damping values estimated from the strong-motion seismograph records (h_E) and those from the records of microtremors in the buildings (h_M).

with vibration amplitude may be seen for most buildings (the average value of the h_E: h_M ratios is about 1.3). Some pairs of the damping values show an opposite tendency to the above. This may be due to the erroneous estimate of the damping value of either of a pair.

Fig. 12 illustrates the relation of the damping coefficients to the periods of vibrations for the fundamental translational mode of the buildings estimated from the strong-motion seismograph records together with the results from vibration tests which have hitherto been carried out in Japan[17),18)]. The solid and hollow marks are the results from

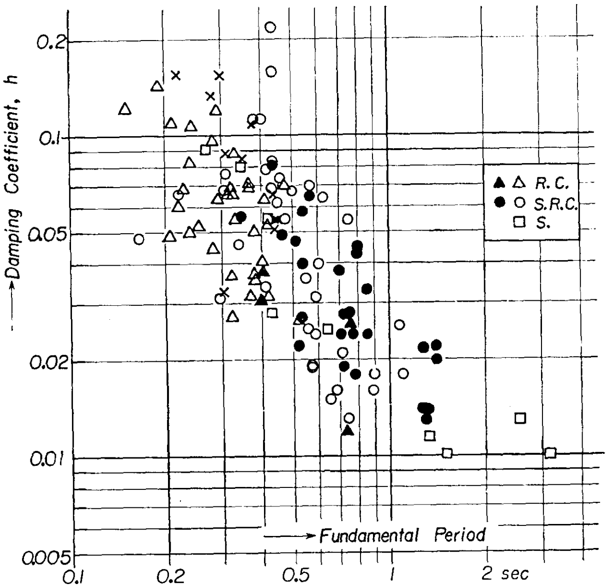

Fig. 12. Relation between the damping coefficients and the fundamental periods of the buildings. Solid and hollow marks are the results obtained from the strong-motion seismograph records and those from the vibration tests, respectively.

the present investigation and those from the vibration tests, respectively. The present results are consistent with the general trend that the damping is nearly inversely proportional to the period.

As can be seen in Table 2, the results from the microtremors data are 10–20% larger in period and comparably smaller in damping as compared with those obtained from vibration tests. This discrepancy is reasonable when considering the fact that most of these vibration tests were carried out before the completion of the buildings.

17) Japanese National Comm. of Int. Assoc. for Earthq. Engg., *Some Recent Earthquake Engineering Research and Practice in Japan*, (1968), 41.

18) Group for Dynamic Tests of High-rised Buildings, *Results of Dynamic Tests of High-rised Buildings*, (1969).

5. Concluding remarks

The suitability of the power spectrum method for determining the period and damping of a structure was examined, and the method has been improved slightly to make practical applications easier. In order to estimate these structural parameters of actual buildings at high amplitude levels of vibrations, the method was applied to the strong-motion seismograph records obtained in the buildings during an earthquake of moderate intensity. The results were then compared with those obtained from the analysis of the microtremor records observed in the same buildings. As a result, it has been found that the periods of actual buildings at the time of the earthquake showed approximately 20% larger values than those in ordinary times. A similar result has been obtained concerning the damping coefficients, although the accuracy for the values is insufficient to derive any quantitative conclusions about the amplitude dependency of the damping. Errors may be caused by inadequacy of the assumptions of white noise type input and a single degree of freedom system, or by unsuitable selection of the sample record. Therefore, the damping values presented in this paper should be regarded as tentative, and further investigation is needed to make it possible to estimate more precise values of damping. However, the present method is still useful for obtaining the approximate values of the structural parameters especially of large, heavy structures for which the usual methods of vibration test are often ineffective. It should also be pointed out that estimation of the period and damping values for some of the higher modes is also possible by the present method.

6. Acknowledgements

The authors wish to express their sincere thanks to Professor K. Kanai for permission in making use of the microtremor data at the strong-motion seismograph stations. Their thanks are also due to Miss K. Meguro for cooperation in digitizing the SMAC records. Computation in this study was done through the courtesy of the members of the Earthquake Prediction Observation Center of the Earthquake Research Institute, University of Tokyo.

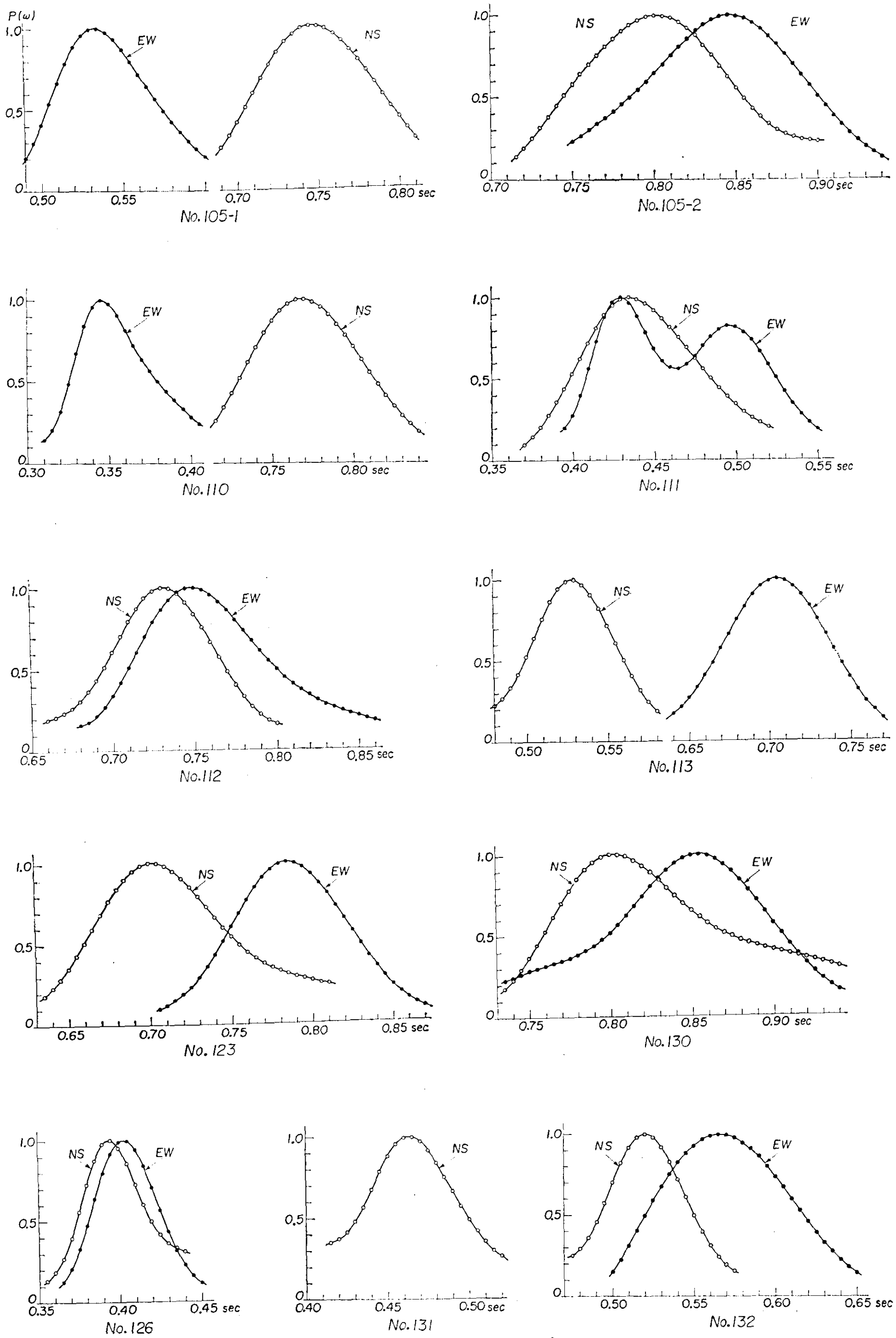

Fig. 13. Power spectra computed from the strong-motion seismograph records.

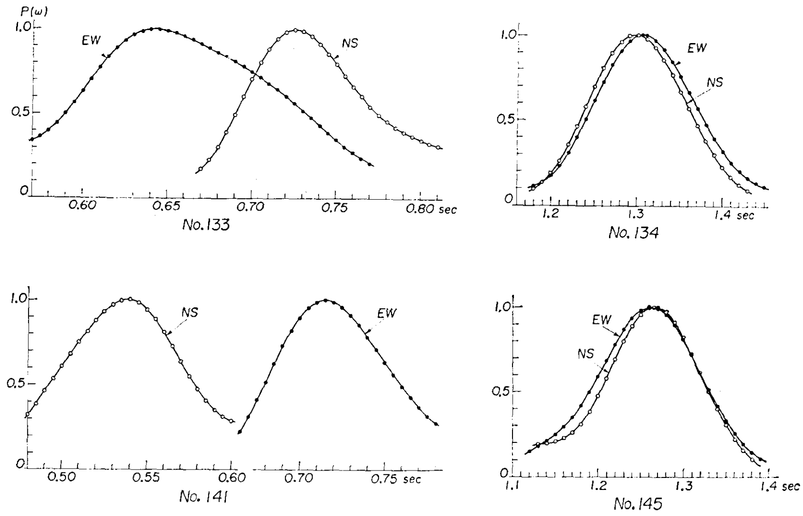

Fig. 14. Power spectra computed from the strong-motion seismograph records.

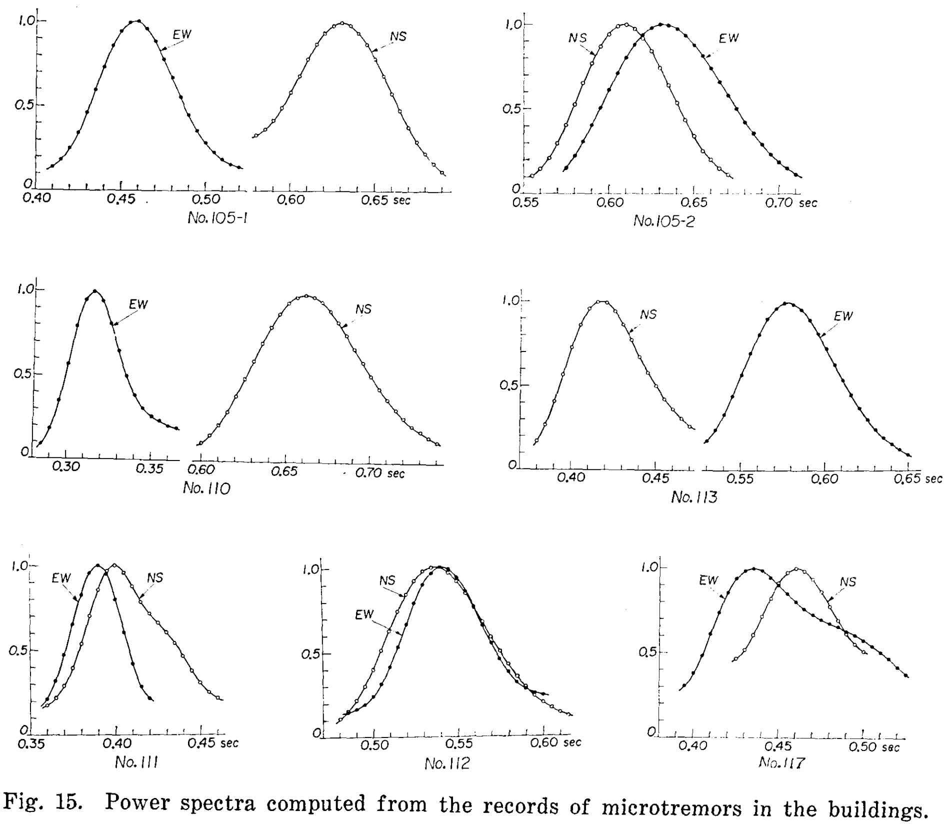

Fig. 15. Power spectra computed from the records of microtremors in the buildings.

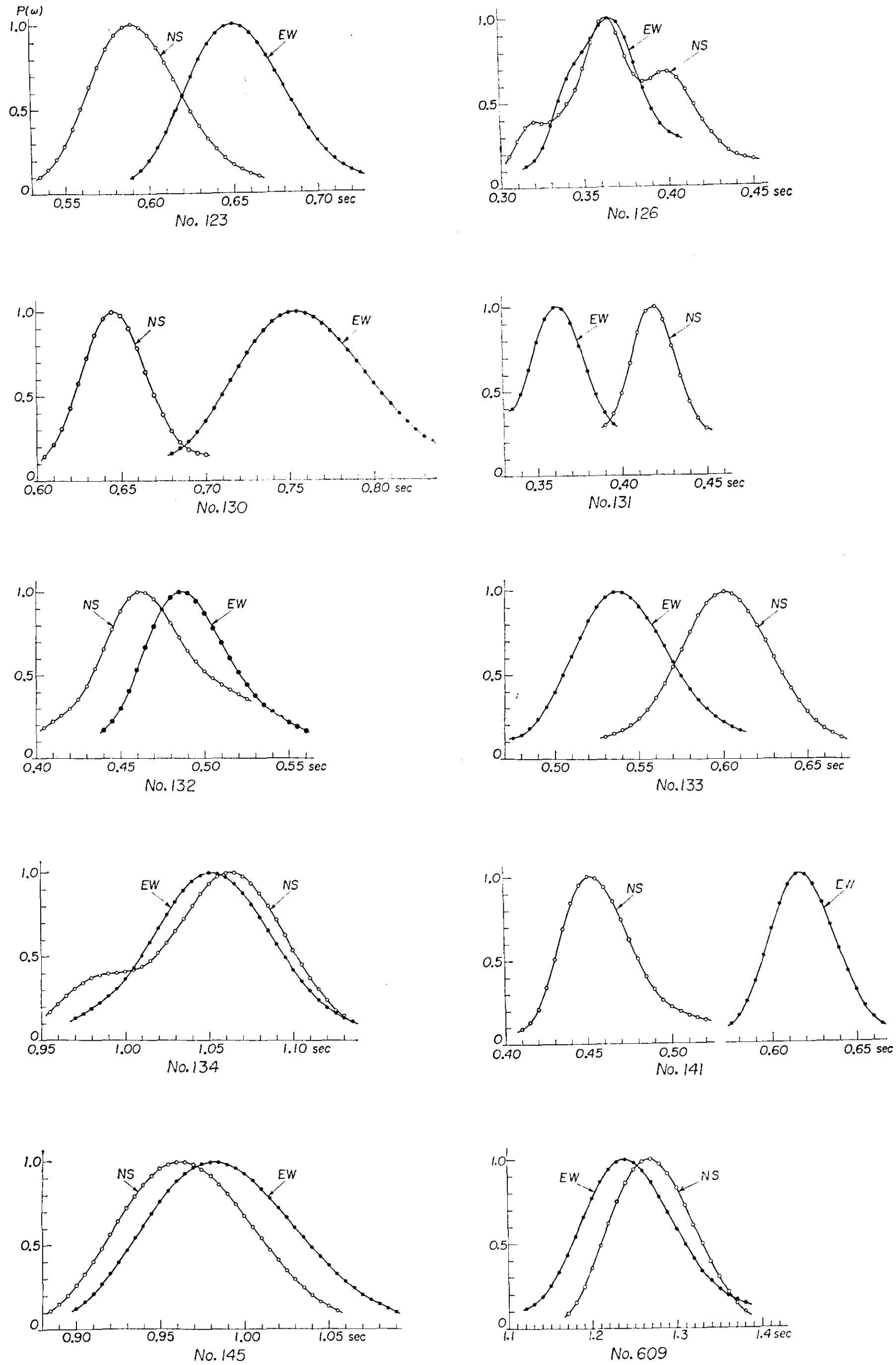

Fig. 16. Power spectra computed from the records of microtremors in the buildings.

52. 地震時における実在建物の周期と減衰

地震研究所 田中貞二 吉沢静代 大沢胖 森下利三

比較的大きい振幅レベルにおける実在構造物の固有周期および減衰定数を求める一つの方法として，地震時における構造物の応答記録を利用することが考えられる．

構造物と地盤を一つの連成系と考え，また基盤における入射波に白色雑音の仮定をおくことにより，応答記録のパワースペクトル解析から系の周期，減衰の値が求められる．

ここではまず，応答記録から計算された自己相関関数が有限の長さをもつ場合に，パワースペクトルに与える平滑化の影響をしらべ，得られる見かけの減衰値に対する補正用の chart を作つた．

この方法を 1968 年 7 月 1 日の埼玉県中部の地震 ($M=6.1$) の際に得られた 17 建物の強震計記録に適用し，その周期および減衰定数の値を推定した．また，これらの建物における平常時の微動記録から同様な方法を使つて微小振幅レベルに対する値を求め，地震時のそれとの比較を行なつた．

その結果，平常時 (振幅 3～25μ) の約 1000 倍の振幅レベルをもつ地震時 (振幅 0.3～8 cm) におけるこれら建物の一次周期は平常時に比べて約 20% 増加することがわかつた．減衰定数については推定値の精度がかなり低いけれども，ほぼ同様な傾向が見出された．