Summarized Report on Dynamic Tests of High-rised Buildings and Cooperative Plan for Large-scale Vibration Tests in Japan

The Group for Dynamic Tests of High-rised Buildings(I)

Abstruct

In the present paper, vibration test methods common in Japan are briefly introduced and their results are summarized.

BCS type vibration generator which makes a cooperative plan in performing large-scale vibration tests possible is introduced briefly.

1. Introduction

Since the removal of height limit for buildings, many tall buildings have been constructed in and around Tokyo. In order to establish rational and comprehensive design standards for such buildings, actual behaviors of those buildings during an earthquake must be made clear. However, an earthquake seldom comes on expected or desired time. Shall we, then, just remain satisfied by installing seismographs on those buildings and simply wait? The present day engineers are armed with the art of analyses, though it may be far from being satisfactory, and only if the vibrational nature of those buildings becomes known, it will not be very difficult to make fair enough guesses on behaviors during an earthquake with help of recent computer technique.

Therefore, compilation of such data as natural frequencies, modes of vibration and damping characteristics is considered important, and it has become one of the routine procedures to measure those items when a tall building is newly constructed.

2. Methods of Vibration Tests

There are several methods which have hitherto been employed in the measurements of the natural periods, modes and damping of buildings.

(1) Semi-static method; Horizontal force is applied statically by means of wire cable with quick release mechanism, and the sudden release of the force put the structure into free vibration. With the appropriate instrumentation, the vibrational characteristics can be measured. This method is simple and quick for comparatively small scale structures.

(I): Member list will be found in Appendix 1 of this paper.
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(2) Man Power; When the damping of a structure is small and its natural period is moderately long, the repeated application of man power sometimes proves effective for vibration excitation.

(3) Application of propulsive agent; The progress in astronautical sciences makes it available to apply rocket propellant for the purpose of vibration tests. The preliminary test was conducted at the B. R. I. on its open house day, 1966.[1] The test was successful as shown in Fig. 1. This method seems to be promising for the test of tall buildings by intermittent application of the thrust of properly controlled duration each.

(4) Vibration generator; The use of vibration generators is the most popular in our country. One of this type of large capacity was already introduced at 1 WCEE by Drs. Hisada and Nakagawa.[2] This model could produce 10 tons of centrifugal force, but a little too large and heavy to be portable. For routine tests as mentioned previously, it is preferrable to be portable while the capacity is considered satisfactory if it produces an amplitude distinctly distinguishable from the background noise.

To run the test, there are two alternates. One is so called "run-down" test in which the rotor speed is continuously increased beyond the resonant frequency, and then decreased in the similar manner, during which the amplitudes are recorded. From thus obtained resonance curves, the natural period and damping are determined. But, it is considered that thus obtained curve does not represent a resonance curve in strict sense.[3],[4] The other method is to increase the speed discretely in step-by-step manner, and at each speed level the amplitude is recorded. The latter method generally gives a sharper resonant peak than the former provided that the speed stability is sufficiently good and speed level interval near the peak is sufficiently small.

Application of quick brake makes it possible to observe the rate of decay of the free vibration amplitude, which contributes to more precise determination of damping characteristics.

(5) Use of pendulum; In order to apply exciting force to a structure the natural period of which is comparatively long, at a frequency at or close to the resonant frequency, it is sometimes difficult to achieve the aim by means of a vibration generator because of the smallness of speed. A genius idea of pendulum application was proposed by one of the authors, Dr. K. Nakagawa on a certain occasion which proved effective. 3 meter long pendulum has its natural period of about 3.5 seconds. Such a pendulum can be hung from the ceiling structure with four parallel wires, the mass of which consists of such as reinforcing steel bars or concrete blocks. 10 ton weight will be sufficient to shake a building of 20,000 tons with an amplitude of 1 mm at the pendulum amplitude around 1 meter. The pendulum is suddenly released from initially displaced position of several tens of centimeter from the neutral point. Man power of pendulum excitation is also practicable for testing.

(6) Micro tremor observation; Micro tremor observation atop of a building to determine the natural frequency is often carried out together

with or as an alternate of the aforementioned vibration generator tests. Usually, the power spectral curve is constructed from which the natural period of a structure are determined. It is to be noted, field observation curves contain various frequency components, and in many cases, those modes of small damping are predominant.

3. Results of Recent Vibration Tests

Summarized results of vibration tests conducted recently are given in Table 1. It is to be noted that all results given in Table are the results obtained under small amplitudes, the order of which are indicated in Column 19 of the Table.

Building designation given in Column 1 may be identified from Appendix 2 at the end of this paper.

In Column 2, SRC and S mean steel frame encased in reinforced concrete and pure steel frame with fire coating, respectively, while * means precast concrete slab units.

In Column 11 to 18, suffices 1 and 2 indicate the first and second modes respectively.

In Column 9, vibration generator is abbreviated as V, man power as M, free vibration or semi-static as F, pendulum as P, and micro tremor observation as T. Types of vibration generators are designated by a, b and c, and unbalance moment at the test is given by 4 digit numbers, the unit of which is kg-cm. For example, Va 1260 means manually driven vibrator with the unbalance moment of 1260 kg-cm, run-down. Vb is AC driven without feedback speed control, and Vc,DC driven with feed-back system. P-11.3 indicates 11.3 ton weight pendulum. Most of the tests were conducted when the buildings were almost completed, except Bldg D before the finishing work started and Bldg I about 1/3 of finishing work advanced.

Type Vc vibration generator is the prototype of BCS type about which details will be given in the following chapter. A Vc set consists of two identical units, each weighs about 600 kgs and powered with 1.1 kw DC motor. Two counter rotating units generate unidirectional force which can be varied in 6 steps. The maximum unbalance moment is 6,840 kg-cm. The speed range is 0-6 rps. These two units can be operated both in phase and by 180 degrees out of phase. Electronic control system takes care of speed and phase within the error of 0.5 %.

As an example, the test results on Bldg L are described below with some details. Bldg L is a steel encased reinforced concrete building with precast concrete finish exterior, 18 story high with 2 basements. The broad idea about this building may be acquired from Fig. 3.

The vibration tests were conducted in 3 phases. First, when the steel skeleton frame was completed. In this stage, both semi-static and vibration generator tests were conducted. Because of the poor holding of speed level of the vibration generator, the semi-static test played an important role in determing damping. The second test was carried out about one month after the final placement of concrete, and the third shortly before completion. Some improvements of speed controlling system applied after the first test proved to be effective and accuracy in speed control was satisfactory. The results are summarized in Table 2 and also given in Figs. 2-7.

It is interesting to see that the vibrational periods of bare steel frame is very close to the final periods while the bare concrete structure gives shorter periods. The damping of the steel frame is extremely small as compared with other hitherto observed RC or SRC cases. This is probably due to the relative stiffness of superstructure to the soil. Fig. 2 shows the vertical component distribution in the transverse direction of the building and indicates the contribution of the soil deformation and hence the energy dissipation into the soil cannot be overlooked. Another example as in Table 1, Bldg I also indicates the steel frame exhibits equally as small damping.

As shown in Table 2, the damping in torsional mode is much smaller than translational modes in this building. In order to excite the torsional mode, two units of vibration generator were used. They were positioned a certain distance apart from each other on the same floor level and driven with 180° phase difference, which resulted in pure couple. It was found, however, that a single unit which was positioned eccentrically with respect to the gravity centroid was sufficient to identify both translational and torsional modes in most cases. The micro tremor observation was also carried out in the final tests. It is interesting to note that the predominant period thus obtained is in coincidence with that of the torsional mode which has the least damping. It is highly probable that this building will vibrate predominantly in torsional mode during an earthquake.

In order to determine the damping constant, $h = c/c_c$, two methods are commonly used; one is to determine through the decay rate of the free vibration. The free vibration can be excited either by semi-static method or quick braking of the vibration generator. The other method is to calculate the damping constant from the resonance curve obtained by the vibration generator tests by the following formula;

$$h = \frac{1}{2} \cdot \frac{\Delta f}{f_n} ,$$

where f_n = resonant frequency, and
Δf = width of the resonance curve at the amplitude level equal to $1/\sqrt{2}$ of the peak amplitude.

Comparison is given in Table 3, and shows good agreement between two methods, which means the accuracy of speed control of the vibration generator herein used is sufficient for the purpose. Typical results of the tests are shown in Figs. 4, 5, 6 and 7.

Another interesting finding is that thus measured frequency or period may be amplitude dependent. A series of tests was conducted on a single storied prefabricated RC building, and the results are given in Fig. 8.

4. Development of BCS Vibration Generator

Even though many test results have been hitherto compiled as shown in Table 1, the variety of test methods and apparatus makes it difficult to make direct comparison. If all vibration generators are of the same degree of accuracy and capable of performing precision discrete speed running, thus obtained data would be far more valuable.

About the time when all members of the group inclined to such a mood, Building Research Institute of Construction Ministry was thinking about having a large scale precision vibration generator which was capable of testing a moderate size building up to failure. The timely success of the control system of Vc type vibration generator at comparatively low cost gave a chance to all members get together. Though there existed quite opposite requirements; big capacity and high frequency versus portably light with moderate capacity and speed, aforementioned success of the dual units generator had lead the group members to an idea of having a multi-unit set something like CIT type[5], which may be separately owned by member organizations. Each unit thus separately owned shall be capable of performing routine tests with sufficient accuracy, but when necessary, any number of units can be simultaneously operated under a single pilot unit. Such a set may have one central control unit with precision pilot rotor accompanied by many son units.

Finally compromised plan was to have two types of son units - deluxe and standard. The deluxe model is a type identical to the standard type in performances in a certain range, but capable of increasing both unbalance moment and speed beyond the allowable limits for the standard model. For certain specialized experiments for civil engineering structures or 4 or 5 storied concrete panel type prefabricated apartment houses, sufficiently high speed is necessary. General specifications are given in Table 4. In both types accuracy of speed is aimed to be kept within 0.1 %.

BRI takes a mother and 3 deluxe sons while most of other organizations are going to have one or two standard sons with or without a mother unit. It is expected that when several sons get together, an exciting force over 30 tons can easily be available. This type of vibration generator was named "BCS" type after the sponsoring organization, Building Contractors' Society of Japan.

The control system of BCS vibration generator consists of 3 blocks; pilot panel (mother), individual control panel and service panel as diagrammatically shown in Fig. 9. The individual control panel takes care of selection of individual or simultaneous operation as well as in or out phase selection. Speed prescriptor is also contained in this panel.

The service panel contains a silicon controlled rectifier through which the power is supplied to individual motor. Indicators and necessary safety devices are provided.

The voltage differences between tachometric generators on the pilot rotor and the individual rotors are detected and thus the speed of individual motors are controlled by means of synchronous governer to diminish those voltage differences. In order to detect number of revolutions of individual rotors with precision, a pulse generator is installed on each son rotor shaft. The wiring diagram is shown in Fig. 10.

A set of BCS type vibration generator was jointly manufactured by Itoh Seiki Co., Ltd. and Toyo Electric Manufacturing Co., Ltd., and handed over to BRI in March, 1968. The performances were proved to be satisfactory.

5. Closing Remarks

Vibration test methods of actual buildings, now more or less routinized in Japan are described, and their results are summarized in Table 1. In order to explain procedures of routin tests sample records on a particular building are presented in Figs. 4-7.

Through those tests, the accuracy of speed control and stability was proved important, and further, 0.5 % accuracy seems to be sufficient for the purposes of our concern.

A multi-units type vibration generator of BCS type has been developed which makes a cooperative plan in performing a large scale vibration test possible. The plan consists of a mother control unit and separately owned son units by various organizations, all of which can be simultaneously operated under a single mother unit and produce a huge exciting force.

Authors acknowledge to all members of the Group sponsored by the Building Contractors Society of Japan for their contribution in carrying out laborious tests. Names listed in Appendix 1 are only those who have submitted summarized data as given in Table 1 for the present report. Authors also acknowledge Mr. M. Hirose of the Shimizu Construction Co. for his devotion in preparing illustrations.

References

(1) Ohsaki, Y.; The Use of Jet Reaction for Dynamic Tests of Buildings Trans. AIJ, No.142, December, 1967.

(2) Hisada, T. and Nakagawa, K.; Vibration Tests on Various Types of Building Structures up to Failure, Proc. of WCEE, June, 1956.

(3) Doring, A.; Transients in Simple Undamped Oscillators under Inertial Disturbances, Journal of Appl. Mech., June, 1959.

(4) Nielsen, N.N.; Dynamic Response of Multistory Buildings, EERL, CIT, June, 1964.

(5) Hudson, D.E.; Synchronized Vibration Generators for Dynamic Tests of Full Scale Structures, EERL, CIT, November, 1962.

APPENDIX 1. Members of the Group for Dynamic Tests of High-rised Buildings

Chairman	OTSUKI, Yukio, The Shimizu Construction Co., Ltd.
Secretary	NAKAGAWA, Kyoji, Building Research Institute, Construction Ministry.
Members	FUNAHASHI, Issao, Takenaka Komuten Co., Ltd.
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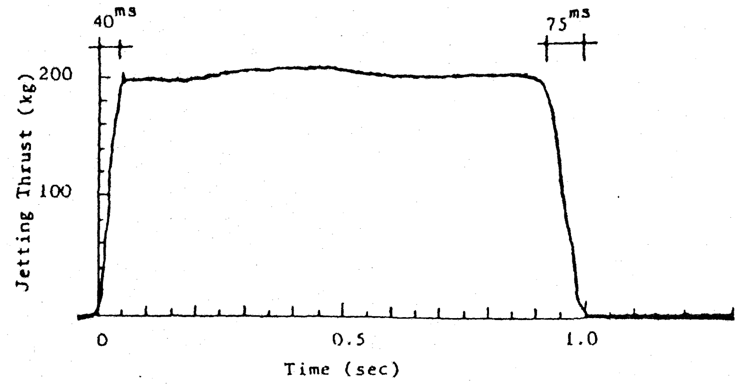
	KAZAMA, Satoru, Waseda University, Tokyo.
	KINOSHITA, Katsuhiro, Takenaka Komuten Co., Ltd.
	OHTA, Tasuku, Taisei Construction Co., Ltd.
	OSAWA, Yutaka, Earthquake Research Institute, University of Tokyo.
	OTA, Tokiharu, Kajima Construction Co., Ltd.
	TSUNODA, Tomohiko, Ohbayashi Gumi Co., Ltd.
	YAMAHARA, Hiroshi, The Shimizu Construction Co., Ltd.

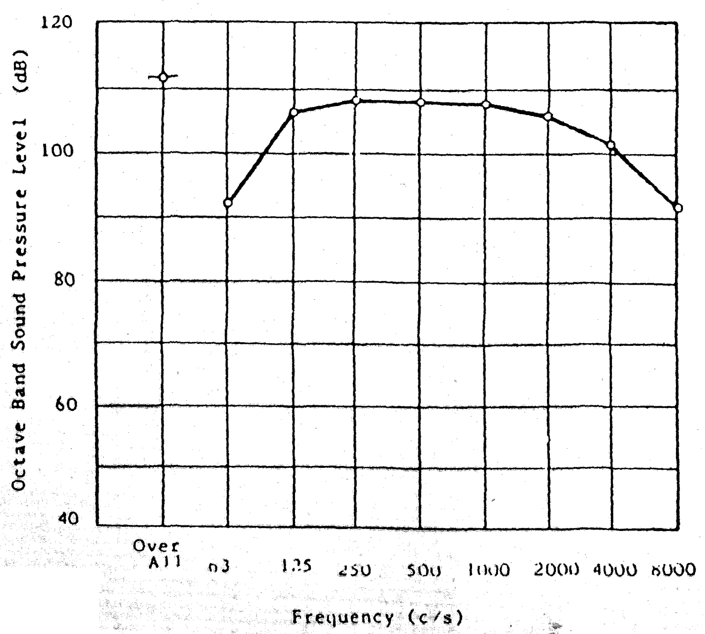
APPENDIX 2. Identification List of Buildings in Table 1

Designation of Buildings	Name of Building	Name of Organization where the original data are held
A	New Building of Science and Engineering Department, Waseda University	Science and Engineering Dept. Waseda University
B	Main Office Building of Fuji Bank, Ltd., Tokyo	Building Research Institute, Construction Ministry
C	Meitetsu Bus Terminal Building, Nagoya	Waseda University
D	Hotel Empire, Yokohama	Ohbayashi Gumi Co.
E	DIC Building, Tokyo	Takenaka Komuten Co.
F	Hotel New Otani, Tokyo	Earthquake Research Inst., University of Tokyo
G	Dentsu Main Office Building, Tokyo	Ohbayashi Gumi Co.

H	No.114 Bank Building, Takamatsu	ERI, University of Tokyo
I	Kasumigaseki Building, Tokyo	Kajima Construction Co.
J	Nissan Motor Car Building, Tokyo	Shimizu Construction Co.
K	Nihon Fudosan Bank, Main Office Bldg., Tokyo	Shimizu Construction Co.
L	First Life Insurance Co., Oimachi Building, Oimachi, Kanagawa	Shimizu Construction Co. & Takenaka Komuten Co.



(a) A Typical Thrust of Propellant



(b) Noise Level during Combustion of Propellant

Fig. 1. Thrust and Noise Pattern of Rocket Propellant

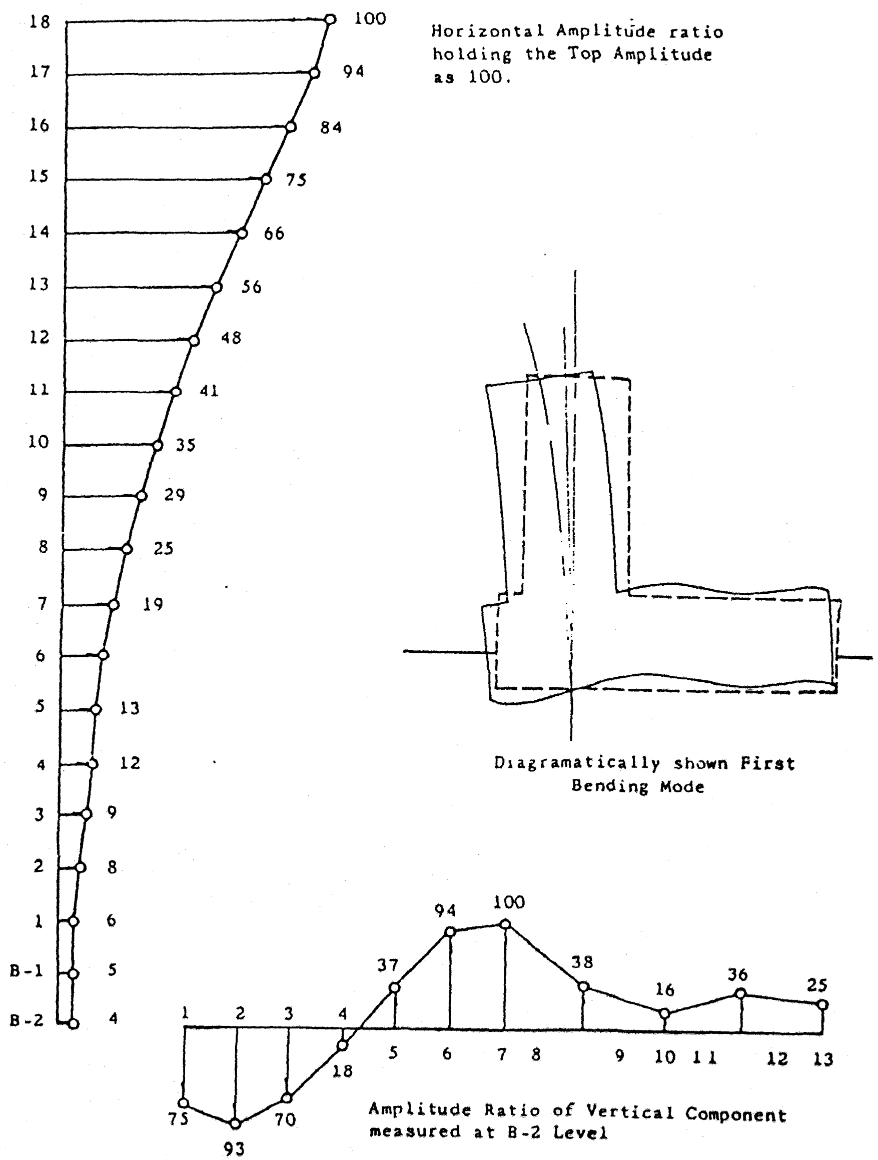


Fig. 2. Ground Deformation Observed during Vibration Tests

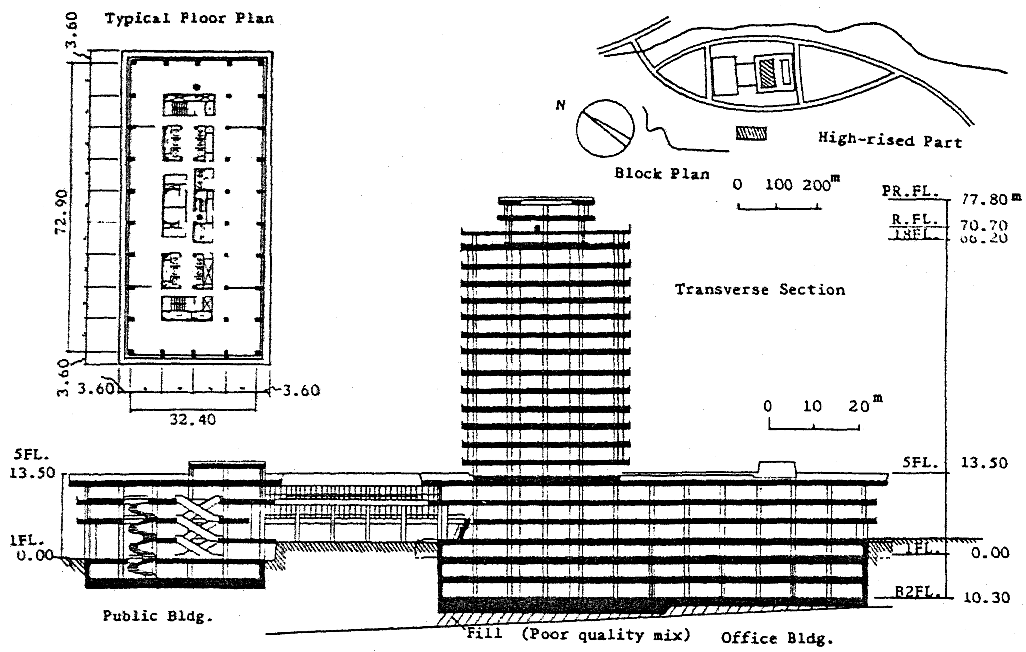


Fig. 3. General Drawing (Transverse Direction) of Bldg. L
• indicates vibration generator position.

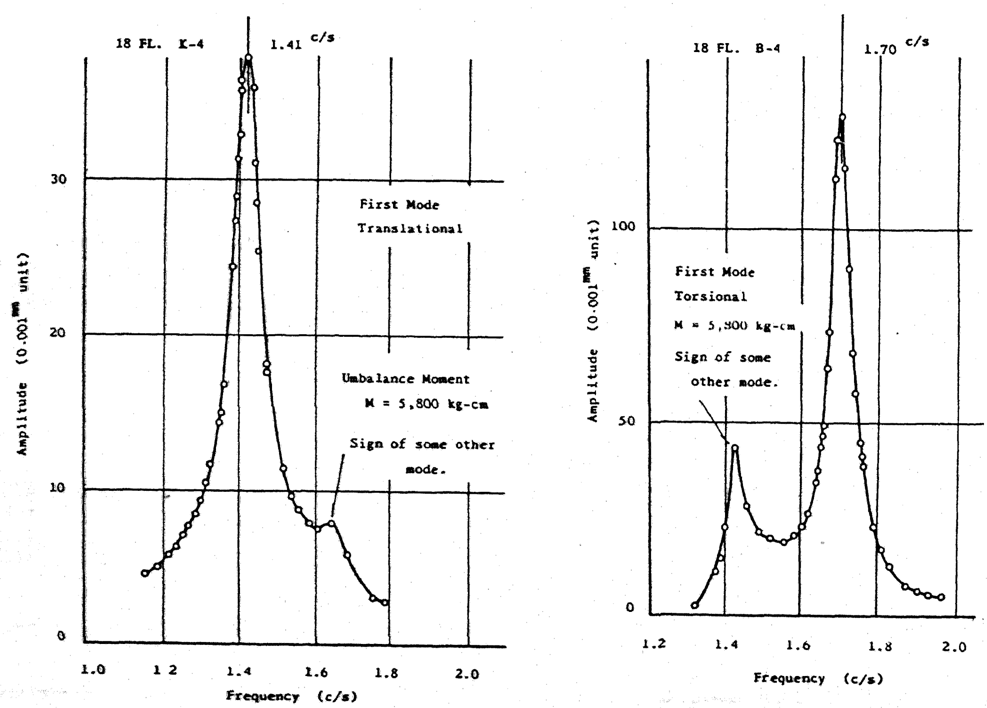


Fig. 4. Typical Resonance Curve obtained from Vibration Tests

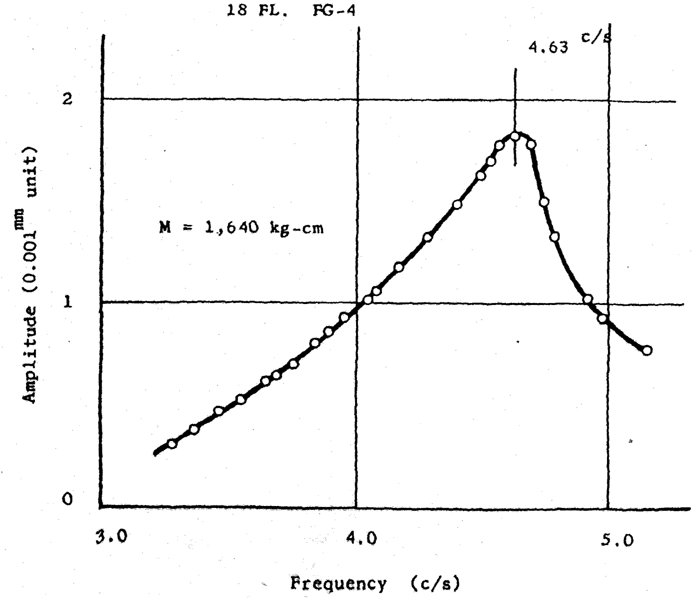


Fig. 5. A Typical Second Mode Resonance Curve

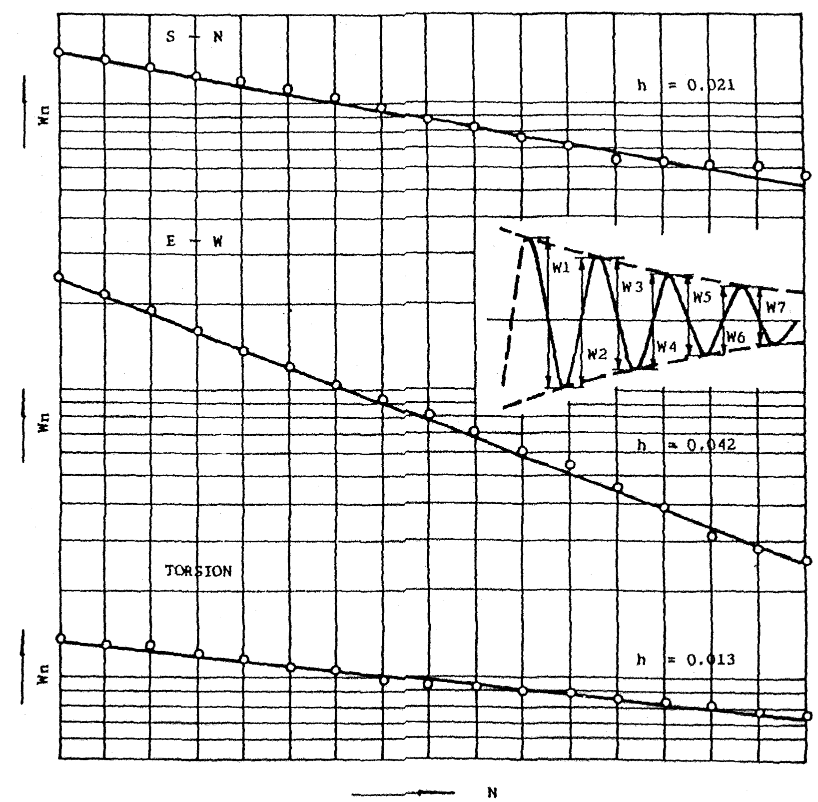


Fig. 6. Typical Decay Curves of Free Vibrations

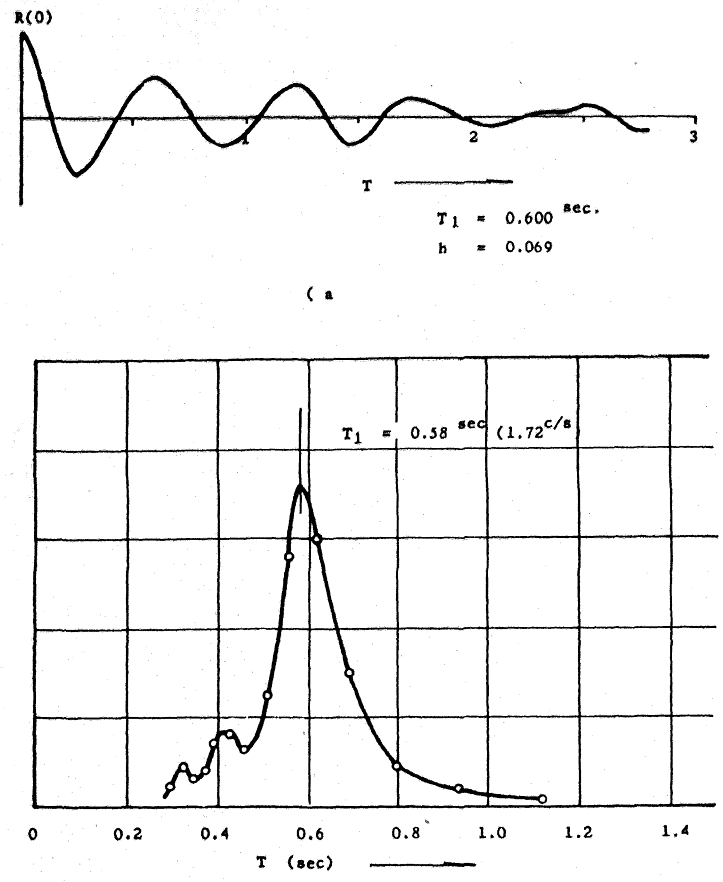


Fig. 7 A Typical Autocorrelation Curve (a) and A Power Spectral Curve obtained from Micro Tremor Observation Data.

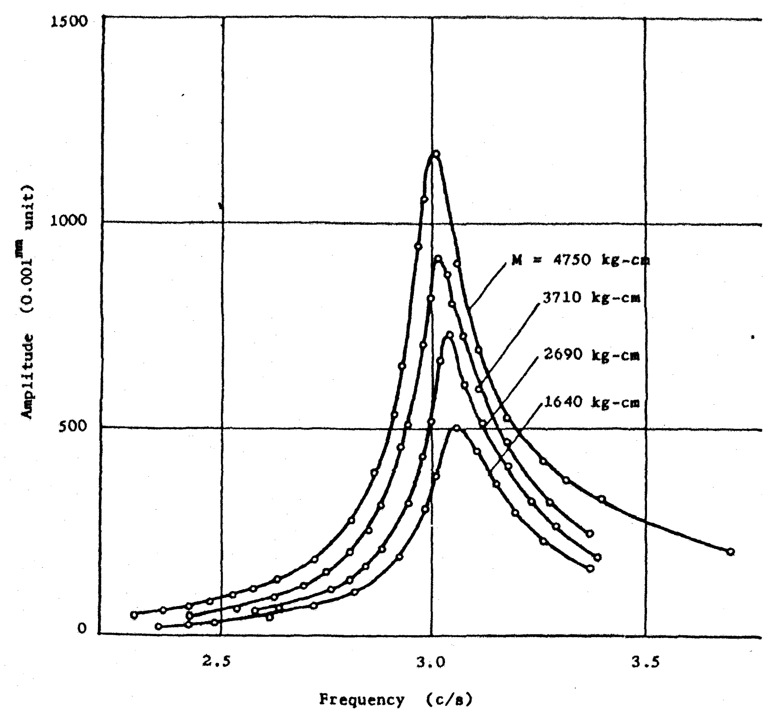
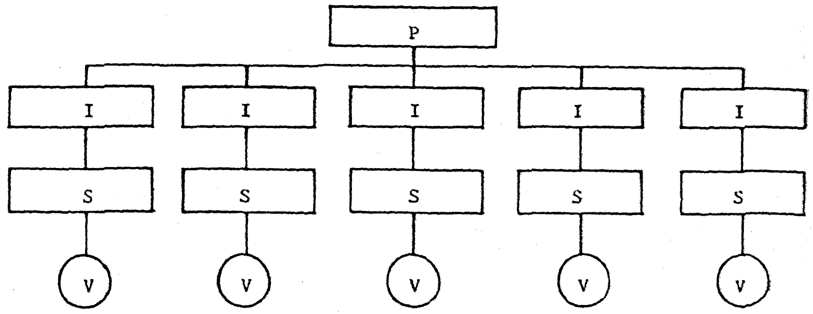


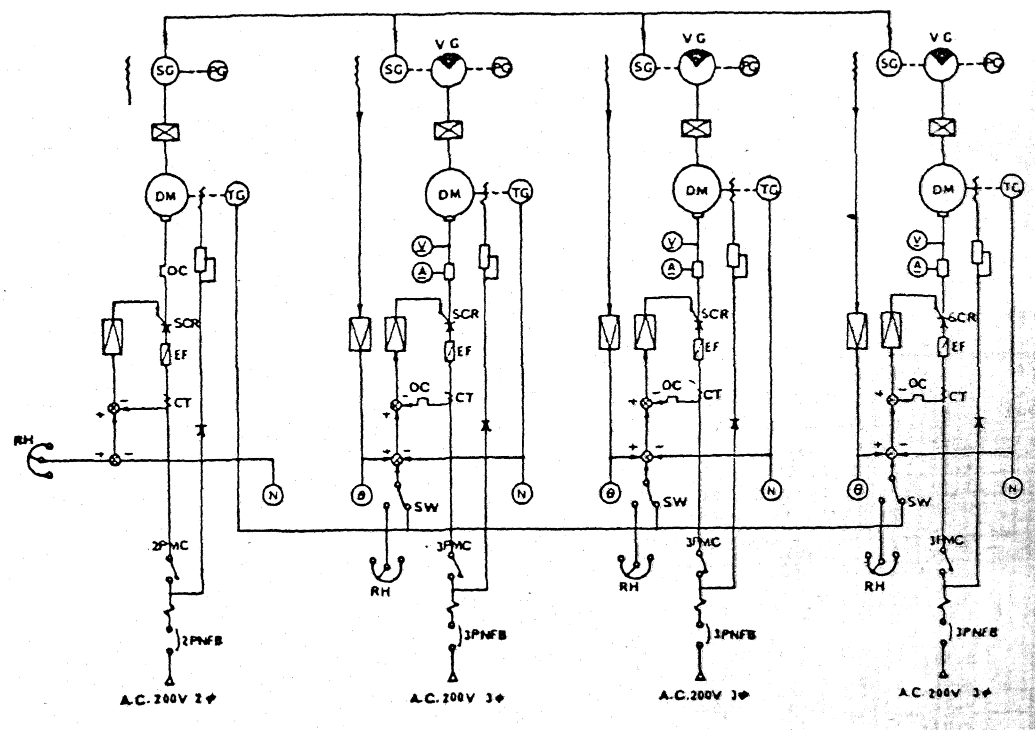
Fig. 8. Curves showing the Shift of Resonant Frequency with Amplitude Level or Force Level.



P : Pilot Panel   I : Individual Panel

S : Servise Panel   V : Vibration Generator

Fig. 9. Block Diagram of BCS Vibration Generator



VG	: Vibration Generator	OC	: Over Current Relay	RH	: Rheostat
SG	: Synchronous Generator	SCR	: Silicon Controlled Rectifier	TG	: Tachometric Generator
PG	: Pulse Generator	EF	: Expulsion Fuse	2PNFB	: 2 Pole No-fuse Braker
DC	: D.C. Motor	CT	: Current Transformer	3PMC	: 3 Pole Magnetic Conta

Fig. 10. Wiring Diagram of Control System of BCS Vibration Generator

Table 1. General Descriptions and Test Results of Buildings

1	2	3	4	5	6	7	8	9	10
Building Desig-nation	Types	No. of Stories Above GL. Basements	Height Depth (m)	Typical Floor Plan Dimentions(m) Long.	x Trans.	FL. Area (m^2)	Shape of Plan	Test Method	Bldg. Status when tested
A	SRC	18	59.2	45	x 19	920	Rectangle	Va 1260	Complete
		2	8.5						
B	SRC	16	66.7	57	x 57	3,230	Square	T	Complete
		4	21.3						
C	SRC	18	62.3	52	x 31	1,610	Rectangle	Vb 3300	Complete
		2	13.2						
D	SRC	21	67.7	18	x 18	320	Square	Vb 0660	Structure only
		2	14.8					F	
E	S *	18	69.5	54	x 16	840	Rectangle	Vc 3710	Complete
		5	23.8					1640	
F	SRC	17	61.2			3,110	3 Wing	T	Complete
		3	14.5				asteroid		
G	SRC	14	51.4	59	x 27	1,690	Rectangle	Vb 5900	Complete
		3	16.5						
H	SRC	16	54.0	35	x 24	840	Rectangle	M	Complete
		2	13.4						
I	S	36	147.0	80	x 42	3,530	Rectangle	Vb 1800	Structure with
		3	17.4					P 11.3t	finish 1/3
J	SRC	16	59.6	56	x 42	2,340	H - longer	Vc 5800	Complete
		4	17.3				legs		
K	SRC	14	58.5	61	x 20	1,220	Rectangle	Vc 5800	Complete
		4	16.4						
L	SRC	18	75.3	73	x 33	2,370	Rectangle	Vc 5800	Complete
		2	12.7						

Table 1. General Descriptions and Test Results of Buildings (continued)

1	11	12	13	14	15	16	17	18	19	20
Building Desig-nation	Calculated Results Periods(sec) T_1	T_2	Damping h_1	Observed Results Periods(sec) T_1	T_2	Damping h_1	h_2	Torsion T_1	Maximum Amp(μ)	Name of Tested Organization
A	1.43	0.49	0.03	1.10	0.33	0.018	0.020		30	Waseda University
	1.22		0.03	0.89	0.29	0.016	0.025		50	
B	1.89	0.70	0.05	1.05	0.33					Building Research Institute
C	0.88	0.54	0.05	0.55	0.24	0.040	0.070		15	Waseda University
				0.59	0.24	0.045	0.070		15	
D	2.14	1.15	0.05	1.07	0.35	0.026			80	Ohbayashi Gumi Co.
E	1.64	0.55	0.03	1.40	0.50	0.010	0.023	1.25	440	Jointly Nihon University &
	1.53	0.56	0.03	1.32	0.45	0.012	0.025			Takenaka Komuten Co.
F	1.69	0.73		Extremely Complicated						Earthquake Research Institute,
				T_{max} = 0.89						University of Tokyo
G	1.30	0.52	0.05	0.93	0.30				200	Ohbayashi Gumi Co.
	1.21	0.49	0.05	0.65		0.050			90	
H	0.69	0.32	0.05	0.56	0.20	0.020				ERI, University of Tokyo * by F
I	3.03	0.82	0.01	3.14	0.93	0.010			4,000	Kajima Construction Co. Computed
	2.30	0.76	0.01	2.56	0.89	0.013				periods adjusted to actual load.
J	1.37	0.58	0.075	0.65		0.015		0.55	50	Shimizu Construction Co.
				0.68		0.016		(h_1 = 0.011)	85	
K	1.35	0.54	0.065	0.74	0.26	0.013		0.68	190	Shimizu Construction Co.
	1.27	0.51	0.065	0.57	0.21	0.019		(0.011)	100	
L	0.83	0.35	0.065	0.78	0.24	0.022	0.059	0.59	35	Jointly Takenaka Komuten Co. &
	1.02	0.45	0.065	0.66	0.22	0.043	0.067	(0.011)	20	Shimizu Construction Co.

Table 2. Vibration Tests under Various Stages during Construction of Building L in Table 1

Building Stata		Bare Steel Frame Complete, Concrete up to 5 FL.	One Month after Concrete Work Finished	Near Completion All Exterior & Interior Finished
Transverse Direction				
T_1	Computed	0.78	0.70	0.83
	Observed	0.79	0.66	0.78
T_2	Computed	0.31	0.32	0.35
	Observed	0.23	0.21	0.24
h_1	Assumed	0.02	-	0.065
	Observed	0.008 F	0.030	0.022
h_2	Observed	-	0.097	0.059
Longitudinal Direction				
T_1	Computed	0.71	0.90	1.02
	Observed	0.72	0.57	0.66
T_2	Computed	0.28	0.41	0.45
	Observed	0.21	0.19	0.22
h_1	Assumed	0.02	-	0.065
	Observed	-	0.035	0.043
h_2	Observed	-	0.052	0.067
Torsion				
T_1	Observed	0.70	0.53	0.59
h_1	Observed	-	0.019	0.011

Table 3. Comparison of Two Methods for Damping Estimation

Methods	Modes of Vibration (First mode only)		
	Transverse	Longitudinal	Torsion
$h = \dfrac{\Delta f}{2f_n}$	0.021	0.042	0.014
Decay rate of free vibration	0.021	0.042	0.013

Table 4. General Specifications for BCS Type Vibration Generator

Types		Deluxe	Standard
Directions of exciting force		2 perpendicular directions in a horizontal plane	Same as Deluxe
Unbalance moment range		20 to 150 kg-m	0 to 75 kg-m
Maximum obtainable excitation		10 tons	3 tons
Speed range of operation		0.2 - 15 cps	0.2 - 8.0 cps
Control stage division	I.	0.2 - 2.0 cps	Same as Deluxe
	II.	0.8 - 8.0 cps	Same as Deluxe
	III.	1.5 - 15.0 cps	None
Capacity of driving motor		7.5 or 11.0 kw	3.7 or 7.5 kw
Total weight, not heavier than		1,500 kg	850 kg
Accuracy of revolutional velocity shall be within		0.5 %	Same as Deluxe