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ASEISMIC SURVEYS OF EXISTING TALL CONCRETE CHIMNEYS

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Abstract.

Two of the tallest reinforced concrete chimneys are still in use at two smeltry plants in Hitachi and Saganoseki, Japan. Their construction periods were between 1914 and 1916. One of them, the Saganoseki

Chimney, was attackd by a local earthquake in 1968 and this caused the top 10 meters in length fell down. Surveys were carried out in connection with their future lives as well as aseimic capacities. Besides of material tests, vibrational observations were carried out on the foot of chimneys using a new developed methodology based on statistical analysis. The vibration data were processed by a computer and graphically displayed on a sheet aided by an automated plotting device. A running spectrum presentation has been developed by the author for precise estimation of natural frequencies. It is found that the chimneys will be safe for 30 years or more in future unless a strong earthquake directly his them.

Keywords ;

Reinforced concrete, chimney, earthquakes, wind, vibration, spectrum, data processing.

Chapter 1. Historical Background

Hitachi was a name of a small town about a hundred kilo-meters north of Tokyo, facing on the Pacific Ocean. The name is also familiar as the city where the big Hitachi Company founded there. Hitachi is also famous as one of Japannese mines of copper ores since 16th century. Modern minig industry has been developed in this century with the aids of national ploicy. Before the tall chimney was constructed there in 1914, air pollution had been serious environmental problems for some ten years by smoke with sulfer oxide which gave strong damages on both human health and agricultural products. After several unsuccessful efforts, a tall chimney was proposed as an only remained method to avoid the pollution by jetting out smoke up to high sky over the height of misty clouds.

The planning had received some fears that it might fail on pollution control as experienced in the past in low stacks. The project of construction was the first experience about 70 years ago and concrete engineering was in the beginning era in Japan. A young civil engineer H. Miyanaga, who graduated from the University of Tokyo 1909 and later became the vice president of the mining company, had devoted his efforts to the design and construction of 510 feet (155.4 m), high chimney. Concrete placing were carried out by false works outside of the shell and the chimney was comleted succesfully in 1914.

The next year, the Saganoseki Chimney was immediately projected in Kyushu for the new smeltry plant in needs of imported non-ferrous ores. The Japanese engineers intended to construct the world tallest concrete chimney, 550 feet (167.6 m), by themselves, however, the Weber Chimney Company in Chicago was very earnest for the project on using the inside false work execution of chimneys, which the company patented. An agency having the licence finally contracted the works under the design of the company. Special cautions were taken into consideration on seasonal attacks of typhoon and on seismic forces. The chimney was completed in December, 1916.

Both chimneys are running through half the century without any maintenace on the vertcal shells except several camouflage painting in order to escape from aerial target during the World War II. Good durability is proved on those structures, however, the Saganoseki Chimney have been affected by more unfavourable circumsances of typhoons and of earthquakes than the Hitachi Chimney. Leakage of smoke had been observed since 1960 near the top of chimney shell and in August 6, 1968, about 10 m length of the top shell was broken down by a local earthquake.

The Japan Mining Company, the owner since 1929, is much afraid of chimney failures if they are attacked to cause fatal damages by any future earthquakes. Surveys on the safety of chimneys were carried out by the author in 1970 at Saganoseki, and in 1974 at Hitachi, respectively, for consideration of their future lives. The sites where the chimneys stand are off the plants, at the summit of hills, and observation has been therefore never carried out on both meteorological and geophysical aspects. No inspection stairs are remained after their completion.

Engineering tests were then projected by one of nondestructive testings, a sort of sounding inspection on ground vibration. Testing methods and analysing technique have been developed by the author these years for vibration measurements of bridges and buildings under usual conditions[1]. Materials were tested on cocretes and steel bars obtained from the damaged top shell. Theoretical estimations on vibrational characteristics are carried out using an electronic computer and they are concluded that the Saganoseki Chimney has less capacity against future earthquakes. On the contrary, the Hitachi Chimney appears to have enough lives due to mild circumstances. The Japan Mining Company decided to construct another concrete chimney 200 meters high (656 feet) at Saganoseki on accunt of future security. The works were contracted by the Kajima Construction Company, Japan and the shell concretes were executed in only 50 days using sliding formworks. The new chimney was completed in January, 1974.

Chapter 2. Surveys on Design and Materials of the Chimneys

2. 1. *Structural Properties*

Detailed dimensions of the chimneys are shown in Table 1. Fig. 1 is one of the design drawings of the Saganoseki Chimney reproduced for the author's research, showing general view. Figs. 2 and 3 show the photographs of the two chimneys taken on measurements. The lack of top capping is observed on the Saganoseki Chimney. Specifications on the design and execution of chimneys are not clear except on wind loadings and seismic forces because no written engineering reports are left. Blue prints that show general dimensions are remained for the maintenance purposes of chimneys, from which material properties can be estimated. For sake of international contract, a stress table is found on the drawing of the Saganoseki Chimney and the maximum concrete stresses are found not to exceed 50 kg/cm^2. Deformed bars are specified as Johnson bars with square cross section and round bars of mild steels are found from the crashed shell instead of deformed bars.

The design of the two chimneys were carried out by nearly the same engineering consideration based on American technology using foot-pound system. Wind loads are considered as 30 lb/ft^2 against the stack, however, seismic acceleration is specified in metric systemas 1200 mm/sec^2 after the recommendation of Japannese earthquake engineers. Construction works were accompanied by the smoke shafts

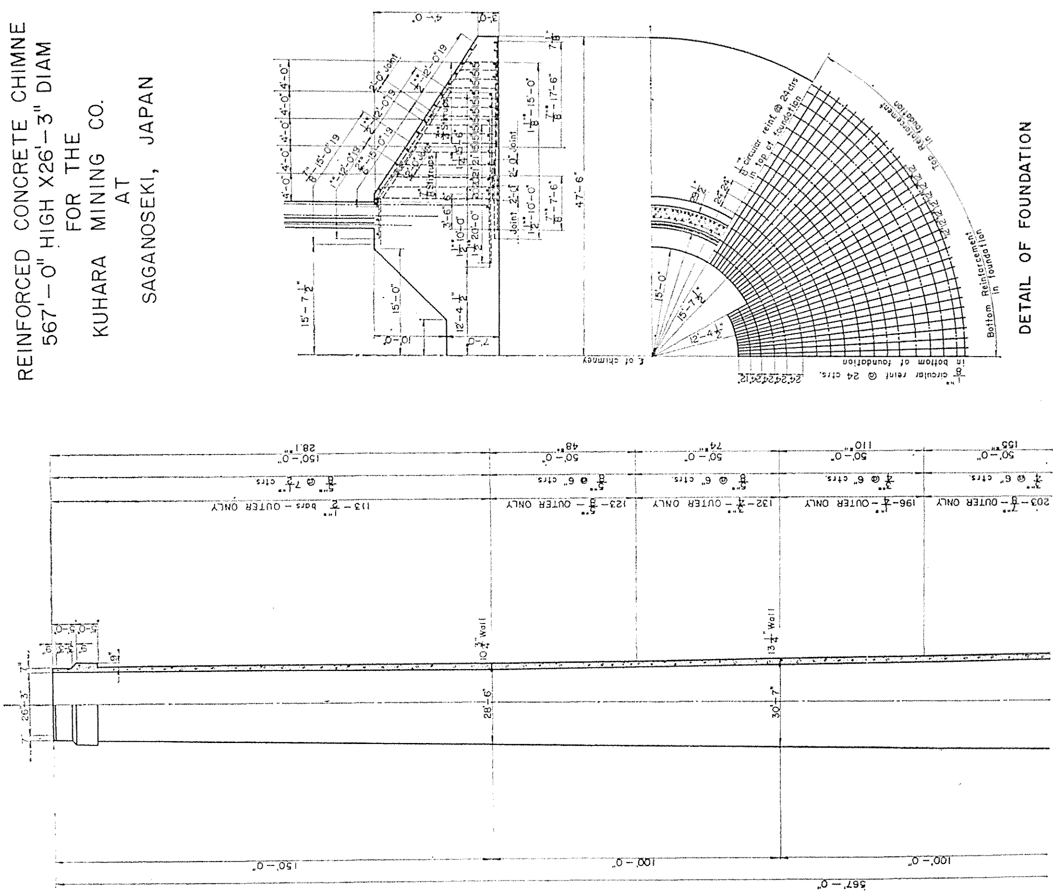
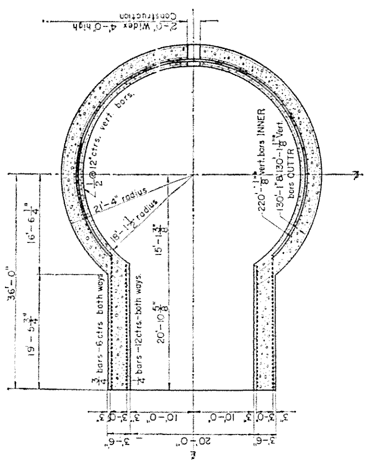


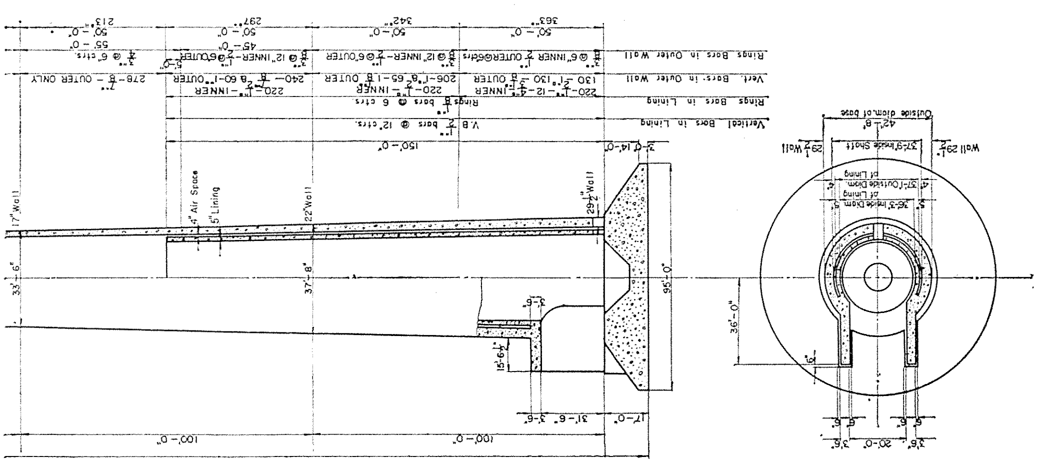
Fig. 1. One of the Design Drawings of



DETAIL OF OPENING BASE OF SHAFT

	AREA OR SQUARE BARS						
SIZE	1 1/8"	1"	1 1/8"	3/4"	5/8"	1/2"	3/8"
AREA	1.26"	1.00"	163"	563"	391"	25"	141"
BOMD LENGTH	45"	40"	35"	30"	25"	20"	15"

NOTE :
ALL BARS TO BE CORRUGATEU JOHNSON BARS



the Saganoseki Chimney, redrawn and duplicated.

Table 1. Chimney Dimensions and Design Criteria.

Location,	Saganoseki	Hitachi
Year completed,	1916	1914
Height of shell (m),	167.6	155.4
Height of top above sealevel (m),	294.	467.
Outside diameter on top (m),	8.4	7.8
Outside diameter on base (m),	13.0	12.0
Thickness of shell on top (m),	0.18	0.20
Thickness of shell on base (m),	0.75	0.51
Height of inside cooling shell (m),	45.7	45.7
Basemeter diameter (m),	29.0	25.9
Basement depth (m),	5.2	4.0
Weight of shell (ton),	5200	3300
Weight of basement (ton),	5000	3000
Design concrete stress (kg/cm^2),	c. a. 50	—
Design wind load (kg/m^2)	146	—
Design seismic acceleration (cm/sec^2),	120	—

which connect the chimneys to the smeltry plants creeping over the slope of hills. It took costs as much as the chimneys because the chimneys stand rather far from the plants. It is supposed that the cooling shell which is constructed inside the chimney is not always necessary for the purpose.

2. 2. Concrete Testing of the Saganoseki Chimney

Testing specimens of concretes and steel bars were taken from the crashed shell of the Saganoseki Chimney. Strength of concretes was tested by four cubic specimens sliced into about 12 cm in height. The maximum strength is 324 kg/cm^2 on the core of shell width. Two samples of outside shell surface showed 206 and 221 kg/cm^2, respectively. Only 147 kg/cm^2 was found on the sample of inside wall that must be suffered by smoke. Modulus of elasticity varies from 3.5 to 1.9×10^5 kg/cm^2, proportional to the strength, and they correspond to n values, the ratio of elastic modulus of steel by that of concrete, from 6 to 11.

Cncretes seemed to have been finely executed during construction. Weathering and chemical reaction with smoke, however, must have penetrated from both surfaces of the shell for 70 years to weaken the concretes. Depth of suffering can be visually observed by alkaline tests using phenol-phthalen solution on concrete sections. It turns red on good quality of concretes and vanishes on suffered depth. It became clear that the neutralized depth reached about 2.0 to 2.5 cm from the surface of the shell and about 4.0 cm from the inner surface. Strong chemical reactions were partly observed around cracks, from which leakage of smke occurred. Accounting on the concrete technolegy level of 70 years ago, good execution could not be expected on the horzontal joints of concrete placing and the weak materials would be spoiled faster than the remained concretes. The reason is visually attested over the chimney surface that has chalked stain drawn from each joint.

Covering depth of steel reinforcement is specified as 6 cm and maximum size of coarse aggregates seemes to be 2.0 cm. Chemical reactions have penetrated inside

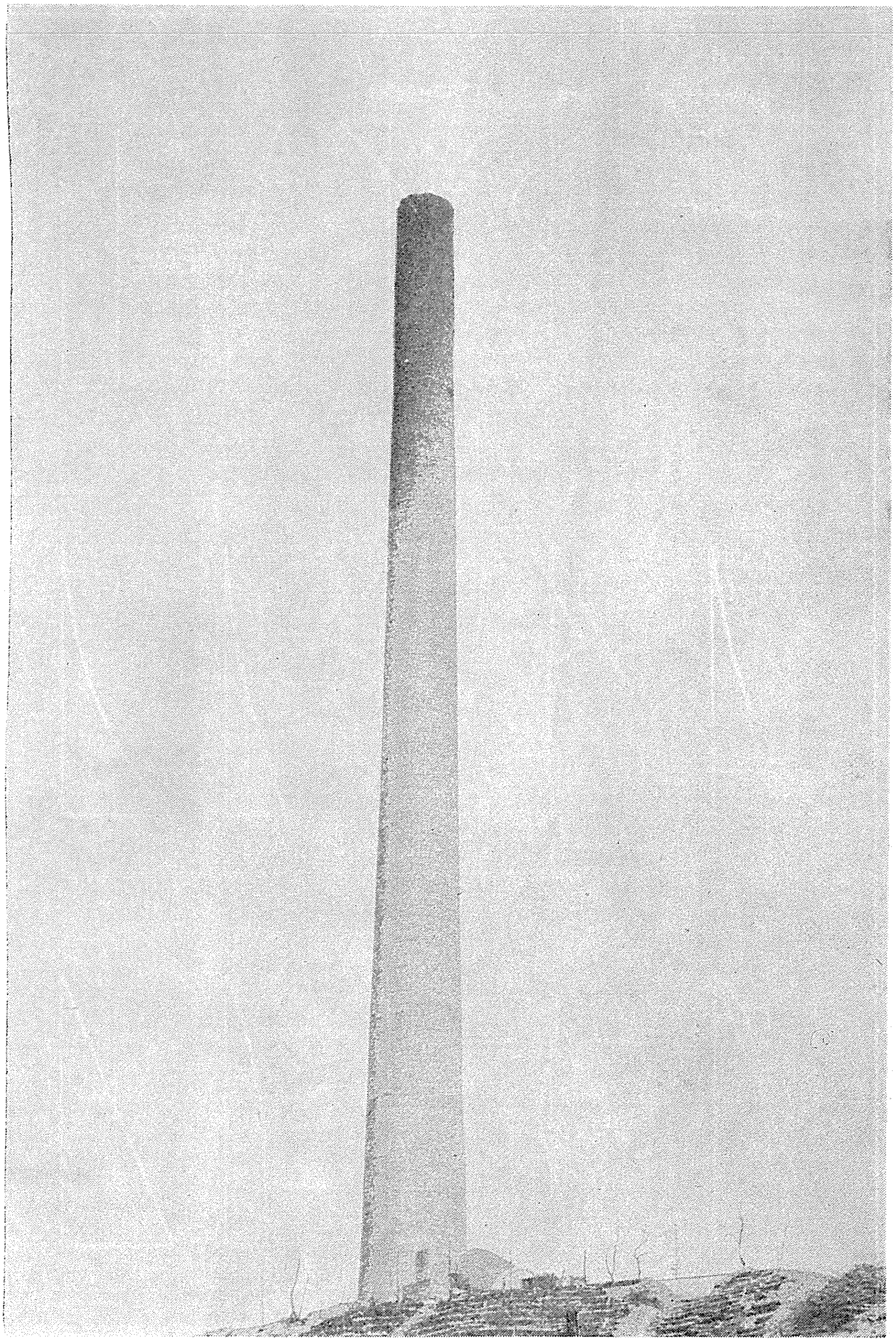


Fig. 2. View of the Saganoseki Chimney after top failure.

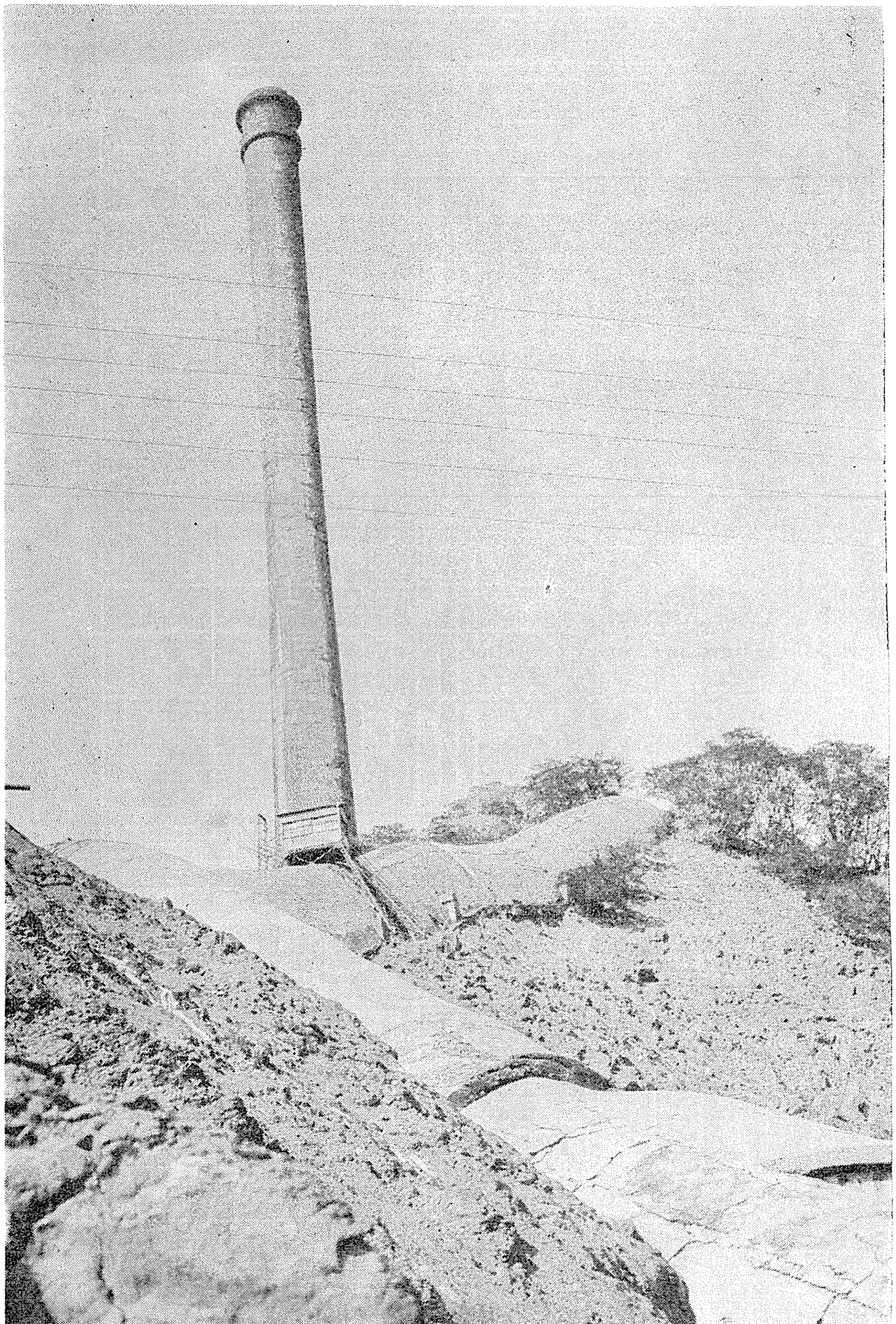


Fig. 3. View of the Hitachi Chimney.

of shell concrete about the rate 1 cm depth by 15 years, so it would take more 30 year before the steel reinforcement get stained without alkalin circumstances if the facts are simply extrapolated.

Concrete material tests on the Hitachi Chimney were also conducted by the pieces which were picked up around the basement. The specimens are supposed as a part of the top capping ring. Strength tests by drilled cores showed no remarkable disadvantages.

2. 3. Steel Bars of the Saganoseki Chimney

Johnoson's steel square bars are of high carbon steels with strength of about 6200 kg/cm^2 and of less ductility. Several round bars are of mild steels with 4100 kg/cm^2 strength. There appear no mild steels specified in the drawings, and it is supposed that the mild steels are replaced by the deformed bars during execution by the unexpected shortage of the imported materials.

Chapter 3. Measurements of Chimney Vibrations

3. 1. Introduction

Generally, structures play more or less vibrational phenomena. Even on rigid foundations, ground shows small amplitudes if high sensitive sensors are used. Tall stacks are very easily excited by winds so as to occure vibrations which are well known as von Kármán's vortex excitation (see Appendix B). As the chimneys stand on hilly open places, wind velocity is enough to excite chimneys even on a calm day so that vibration sensors may take the motion on the foot of chimneys.

The first observation on chimney vibrations was carried out in December 1916 at Saganoseki by Professor Ohmori,[4] who was a famous earthquake reseacher of the University of Tokyo. Before false works were taken off on comletion, he waited vibrations by a seismograph at the top of chimney about a week. On December 26th, at 3 p.m., a high gale reached to 35 meter per second and the maximum double amplitudes were recorded as 7.7 inches (19.56 cm) transversely to the wind direction with periods of 2.35 seconds. No measurements were recorded on the chimneys since that year before 1970 when the author took a chance by a new developed methodology which is based on the statistical analysis of vibration due to electronic devices.

It seems useful information for structural safety to obtain static and dynamic characteristics of the existing structures by various non-destructive testing, because theoretical estimations will not always agree with the expected theoretical properties. Several facts are found to be less safe than the estimated values based on the unknown contitions. There arise, however, some difficulties to test real structures. Besides of costs, which are anyhow basic ones, the tests are restricted not to disturb usual services which the structures are subjected to. For instances, tests on highway bridges must be carried out not to disturd traffic flows, building tests need special cautions for their tenants not feel uncomfortable vibrations. Moreover, the tests must be so simple, low in costs, and easy enough to be operated any sites where the structures stand. Data must be gathered as much as possible from the view point of statistical analysis under consideration of standardized procedures.

The tests are not always possible on real structures, for instances, against wind loadings and seismic acceleration. The author's aims for the study have at first started in order to analyse the structural behavior under seismic acceleration and to contribute aseismic design criterion for flexible structures. Design seismic forces must be evaluated from the statistically expected values based on the earthquake observations that can be rarely measured on the sites where the object structures stand. Vibrational characteristics of seismic forces against strucures are the most uncertain phenomena to be considered as design parameters. Provided earhpuakes are assumed as random processes having some typical properties of spectra, on which several researchers noticed the plateau velocity specra of earthquake motion[2]), sturctures are affected indirectly through the interaction of ground motion and structures including their basements. Theoretical estimations are possible for the calculation of vibrational response if the physical properties of structures are given. Few measurements were, however, carried out in the physical properties of structural vibration including basements and ground properties on account of difficulty, because large structures are excited only by earthquakes so that measurements may succeed.

Usual testing methods are favorable for small structures by loading tests or by a shaking machine, and it is important to record the stresses by the aids of various strain meters. Vibrational mesurements of existing structres are desirable in order to know the behavior with a more convenient methodology under the control of the researchers without waiting any seismic attacks through years day and night. It seemed, however, to be unrealistic before years until the electronic equipments were developed as recent days and electronic computers played for a great deal of statistical calculations. Instead of heavy mechanical seismographs, sensors that generate electric signals can catch small motion of structures as well as ground motion, and the vibrational data are able to be magnified through amplifiers so as to be observed as useful values. Thanks to a data-recorder which records voltage signals on a magnetic tape, the data can be played back anytime when the researchers wish to use for analysis.

When the vibration measurements are carried out on field works, quality of data is not always expected as refined manner, but the data usually show random waves which are seemed less useful. Recent developments of statistical analysis have changed the situation of random data as most valuable, because the randomness occures as the results of fruitful properties mixed in a single datum. If those properties could be separated indivisually, or transformed into some visual patterns from which we can ignore some information on the phenomena, the random data are said to be analysed effectively. The processes how to judge the analysed results are alike the work of human brain in which various data are compared with the past experienced stores.

The author has been gathering vibration data as could as possible chances that might be allowed for bridges, buildings, dams, machinery and towers including the chimneys[1]). Standardizing of measurement has been specified through various author's experiences on relatively large amount of vibrational data. The next article shows the concepts of measuring systems that are applied to the chimney surveys.

3. 2. Measuring Instruments and their Systems Design

There are many sorts of vibrographs which are the instruments used for recording vibrations of structures and for measuring frequencies and amplitudes. The vibrograms, the records taken by the instruments, are the data to be analysed in order to know the dynamic behavior of structures. They are, however, inconvenient for more precise discussions on the properties of phenomena except frequeney and amplitude. Before a data-recorder has not been developed as recent days, a curve-tracer produces voltage signal reversely from given vibrograms and electric instruments simultaniously compute correlation and spectrum.

The system, including from vibrographs to analysing instruments, has not worked effectively to meet the needs of large amount of data analysis, because engineering testing must be compared among the numerous data which are obtained by the standardized procedures. One of the important purposes of the study is laid on the systems design how it will be the ideal composition from measurement to analysis. As to an electronic instrument, for instance, the requirements for the specifications are often differnt between users and instrument makers, who the latter wish to make them with precision under the assumptions of laboratory uses without accounting of field operation. The sy stems composition that the author insists is schematically drawn in Fig. 4, in which vibrographs are replaced by sensors cabled from a measuring station.

Field measuring system has to be projected for easy operation under the unfavorable field circumstances and for works in safety on sites of the object structures. All the equipments are battery operative or driven by car batteries without the AC supplies, because the AC power supplies are not always expected on fields and, moreover, alternating cycles are different in east and west zones in Japan. A light wagon truck specially equipped with extra batteries carries a data-recorder and several instruments and tools. Standardized setup for field measurments is consisted from three sensors in a unit. Vibrations of vertically and two hrizontally perpendicular directions are recorded directly or through amplifiers into a magnetic tape of a data-recorder that has four recording trucks and one of which is used for announcing or timing signals.

The sensors may be choosen in any sort of principles if they generate voltage signals due to vibration. A velocity sensor generates voltage signals without any power supply by swinging a coil through a magnetic field. Accelerometers may also be used, but they are not always favorable for structural vibration because of their sensitiveness up to noisy high cycles. Periods of structural vibration to be noticed are ranging from slow cycles of about ten seconds to about 0.01 seconds; i. e. 100 cycles per second. It is the most important and difficult problems to detect slow phenomena.

Extension cables are considered carefully on practice from both costs and accuracy. Cables are often extended to more than 500 meters between a sensor and a data-recorder. If specially designed cables are needed, field works will be limited within the length of cables. A self working amplifier is designed for relaying voltage signals between several terminals of intermediate cables of low cost wiring. A wireless transmitter is occasionally used for remote obsevations, and a more favorable method is found in a handy system consisted from a sensor and a cassette recorder with two trucks, one of which records announcing or timing signals through a transmitter. A popular stereo cassette tape recorder is applied with a special mixing amplifier for the purpose.

Measurements using more than three sensors in a unit are found that the sensors need excess labour on account of field workability and that the costs of instrument grow expensive. Magnetic tapes, dry batteries, cables, transceivers and other materials must be of popular products which can easily be purchased on a record

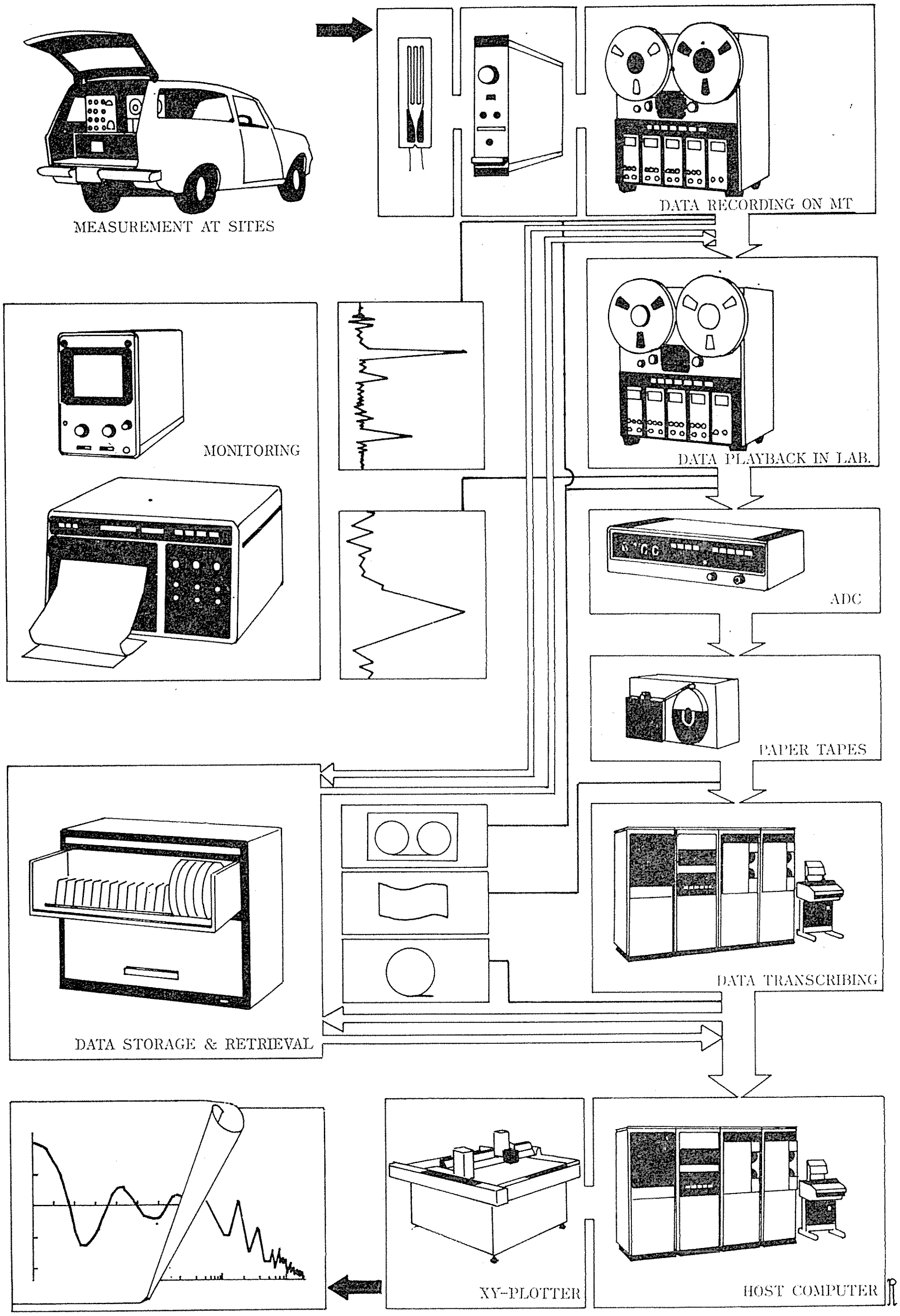


Fig. 4. Systems flow on Data processing of Vibration Data.

shop. The author once failed on a test by lack of tapes of special sizes. There occure, however, needs of sychronized testing on several sites covering wide areas with many sensors together. This problem has been studied from the point of reproducing technique in a laboratory referring timing signals on a tape after synchronized recording of radio receivers.

Field mesurement works are carried out merely on data recoding without any analytical calculations except looking over CRT-scopes or indicators whether the data are successful or not. A real-time spectrum and correlation analyzer is useful on a site if it is operative, and this instrument is considered as one of the monitoring devices through field works. Vibrograms are also useful as the monitoring aids during works or after tests. (see Table 5 in Appendix E)

3. 3. *Measurements at the Chimney*

It was our first experience among the many cases of the field tests that no stares were allowed directly to reach to the object structures. The chimneys had no inspection stairs and, if there be some stairs, it would be very dangerous for measuring works. In order to obtain the vibrational properties of tall stacks, it is the best way to settle the sensors along vertical stack up to some height where bending oscillation may occure, but it was almost impossible for the tall chimneys. The author did not certainly believe that the sensors could catch the bending phenomena of chimneys at the foot of chimneys, but it was worth to try measurements what might happen. Because the chimneys are tall enough and large in weight, minute vibrations would be detected even on the basements owing to elastic properties of ground materials. Excitation against chimneys were expected by wind and, von Kármán's vortex excitation would be also expected even on slow wind speed against a ronnd cylinder.

Measurements were carried out at Saganoseki in April, 1970, unfortunately on a calm clear day with a gentle breeze of about 5 m/sec. Three sensors were settled on the horizontal shaft attached to the chimney shell for three movements of relatively perpendicular directions, vertically, horizontally along the smoke shaft and transversly. Beyoud the social noisy effects, the vibrations showed random manner that was certainly included by those of the chimney and occasionaly grew their amplitudes when wind breathed. The data were recorded on a magnetic tape through amplifiers about half an hour. Fig. 5 shows such records reproduced from a data-recorder aided by computer graphics.

The same procedures were carried out on the measurement of the Hitachi Chimney in April, 1974, also on a clear calm day. There was no hesitation by that time because the random data were proved for the effective analysis. Fig. 7 is the results of the obtained vibrations. Reproduced vibrogramms are a part of cataloged records stored on a computer readable tape in which the various vibration data are sequentially recorded. Three components of movements are followed one by another on a tape. Starting position of a record on a tape is operated by the computer software accounting byte numbers on a tape. In order to understand the general properties of vibration, visual vibrogramms are useful for relative comparison among the data. Three movements are obviously different each other and the vertical movement is the smallest in amplitudes. As the wind direction was parallel to the horizontal smoke shaft on both chimneys, the record of channel No. 2 shows breathing phenomena that run perpendicularly to the wind direction, with the amplitudes being small enough not to exceed 0. 2 cm/sec in the velocity sensors.

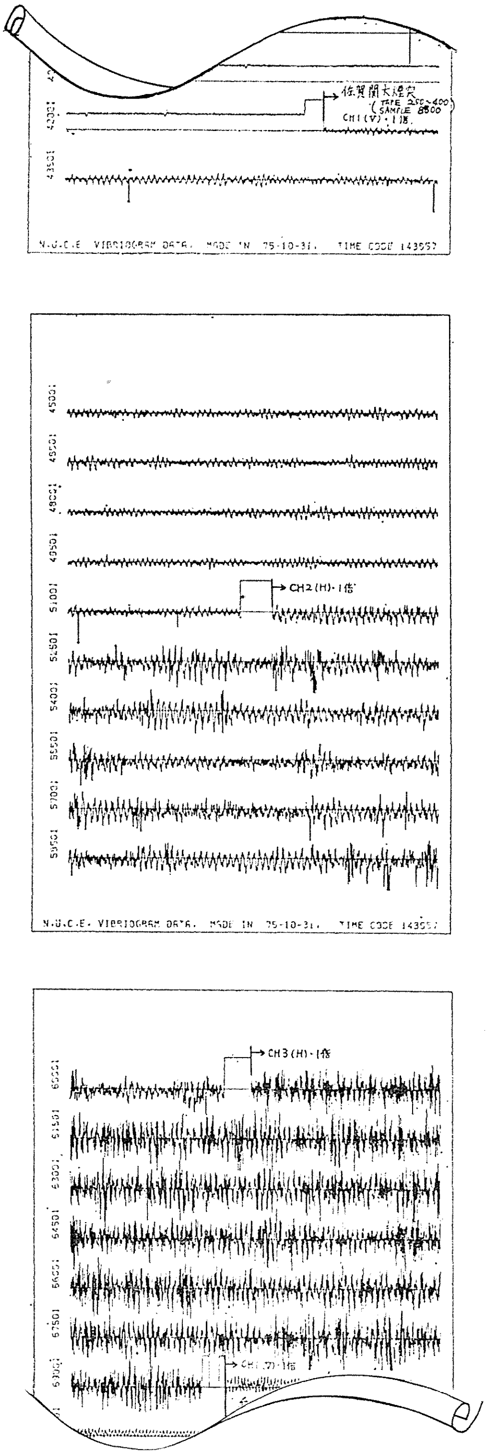


Fig. 5. Vibrogramms of the Saganoseki Chimney.

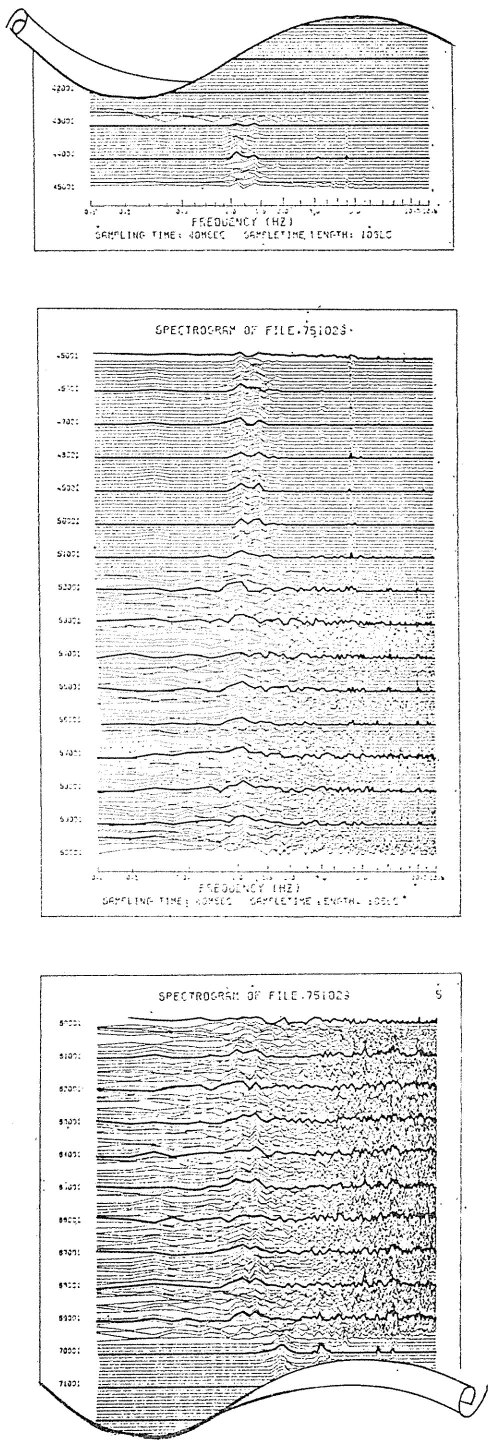


Fig. 6. Running Spectra of the Saganoseki Chimney Vibrations.

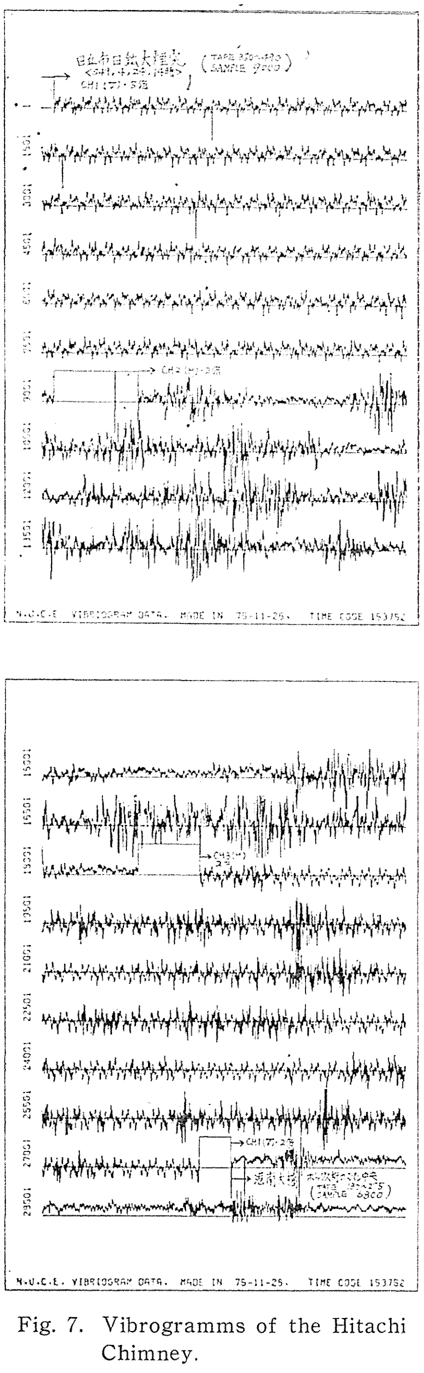


Fig. 7. Vibrogramms of the Hitachi Chimney.

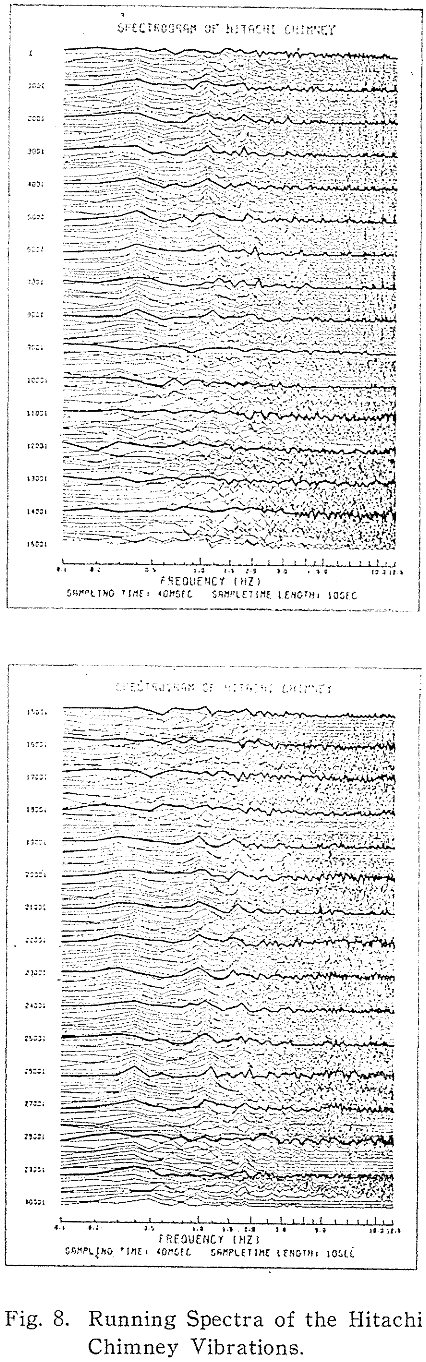


Fig. 8. Running Spectra of the Hitachi Chimney Vibrations.

Chapter 4. Electronics Data Processing of Vibration Data

4. 1. Introduction

Owing to the recent development of communication technology, electronic instruments have been applied for measuring techniques of structural vibrations instead of electric or mechanical apparatuses. Most of the vibrational phenomena are replaced by the electric signal which can be modulated for the analysis. Correlation and spectrum are those which frequently appear in the communication technology and they also became familiar these years in the vibration analysis. Mathematical methods of the correlation and spectrum, on which the latter Appendix A shall be shared, are based on the statistical consideration that need a large amount of calculus.

Elementary analyses of vibration data are taken over by manual works on vibrogramms measuring frequencies and amplitudes aided with measurs or scales. It is not an efficient labor for such works and, consequently, an automated apparatus is necessary for large amount of vibration data. The author formerly tried to set up a curve tracer which produces voltage signal tracing automatically after a cuved line and computes simultaniously by an analog computer, and it worked however with less efficiency. On the other hand, theoretical treatment of random process has been developed in recent years using digital computers that can calculate those values if they are given into computers as an acceptable format, i. e., digital values.

An ADC that stands for Analog to Digital Converter, is the apparatus needed for such purposes to obtain digitalized values incrementally at the desired interval and to punch out on paper tapes. Several instruments named as some data-logger work for calculus of correlation and spectrum within reading directly from sensors or reproducing from a data-recorder. These instruments are of useful aids in order to obtain fast information where the most valuable properties appear. The processes by such instruments must be carried out during vibration tests or when played back from a data recorder. It needs some concentration on viewing the phenomena throughout the processes. It is desirable for more precise treatment of the observed data to accumulate in a huge storage device and to compare with the past experienced data which are obtained by the information retrieval processes. So-called data storage and retrieval processes must be carried out on even vibration data as found on the documentation processes after standardized consideration. Data-storage design is then projected by the author for such purposes using an ADC by which the vibration data are accumlated into a computer readable magnetic tape.

In order to practice by the appropriete devices, the analog records are put into an ADC and punched out on paper tapes after reproducing from a data-recorder with tape speed shifted down at 5 to 10 times slowly. The digitalized values are converted into every 8 bit binary number covering +127 and −127. The analog tapes are continuously punched out on paper tapes with interval of 0.02 second without taking any cares on the quality of measured data. Between logical records, there are some noisy signals that occurred by starting or stopping of tapes, but it works as a record terminater for retrieval purposes. The records of paper tapes are then transmitted into a computer-readable magnetic tape(MT) at the Nagoya University Computation Center. The MT is specified to meet a standard record FORMAT that can be operated by IBM 360 and/or equivalent systems.

The record FORMAT on the MT is set up with the standard volume and file labels for fixed-length records of each 80-bytes, blocked to 2400 bytes, and at recording density of 800 bits per inch of tape length. Several files are recorded on the one volume of the MT and they can be respectively referred after their file names. Each file has also several vibration data continuously following on a tape. The terminaters between data groups are not given by any of speclal character bytes but by the software which counts the record length in bytes. Besides of the MT, a reference directory is made showing vlolume number, file name, starting counter, length of data records of each group as well as descriptions on the measured structures.

Data storage processes on the MT are expected to be more convenient if a system is proposed so that paper tape processes are replaced by directly recording to the MT. Such system depends on the future development at reasonable costs. (See Table 5 in Appendix E)

4. 2. Cataloged Vibrogramms

It is basically useful for vibration analysis to know the phenomena as images of vibrogramms directly or indirectly reproduced from the original measuremets. Some of those vibrogramms show effective information such as on frequencies and damping properties without any statistical procedures. Moreover, the vibrogramms are never mathmatically equal to each other and they have different figures that can be identified respectively. Comparative study is of useful aids to know the general properties of measurements among the data. The vibration data accumulated in the MT are no visible records, and wave patterns are therefore occasionary needed for precise observation on such records. Vibrogramms are also able to be reproduced from the original analog tapes, and a DAC will be used for writing records on a sheet reversely Converting from Digital tapes to Analog signals. Computer-aided plotting devices are much convenient for such purposes.

Before getting the desired records from the MT, reference sheets are also prepared showing all the wave patterns of records stored in the MT. The author named them as cataloged vibrogramms. Figs. 5 and 7 are made from such sheets showing the records of chimney vibration of Hitachi and of Saganoseki, respectively. One sheet of the cataloged vibrogramms are included by 10 lines of wave figures that logically continues from top left to bottom right. Each line has every one minute length of original records, therefore, 10 minutes phenomena are shown on a 210 × 300 mm sheet of a plotting device. Numerals on the left column are counters of bytes showing accumulated counts of each starting line address. The data of the MT are continuously drawn on such sheets after programmed page writing and titles. As mentioned in the above article, the records on the MT have no physical terminator between the logical groups of measured values. However, overscaled square signals are followed before and after a logical record as the results of tape interruption during tests. Starting position of a logical record can be strictly determined by the programming software after coarse searching on the byte counter of the MT.

Figs. 5 and 7 are showing the three vibrogramms of velocity sensors from top to bottom; vertical and two horizontal movements of the chimney basement. The waves are of random manner but clearly of different properties. Each second group of waves corresponds to the horizontal movements of chimney perpendicularly to the wind direction, and the wind gust can be observed from the results.

4. 3. Running Spectrum Presentation

When the vibration measurements are carried out without any previous knowledge on the properties of existing structures, the vibration data are obtained through some black boxes as random manner. If vibration tests are taken over under the controlled circumstances based on purely theoretical assumptions, the results can be thoretically testified even on such randon data using analytical procedures. When the vibration data are given as shown in Figs. 5 or 7, precise discussions of some finite length of records scarcely afford true facts throughout the whole phenomena. Statistical consideretions are, therefore, necessary through astandardized process so that some typical properties may be emphasized among random data. A spectrum is one of such processes which emphasize frequency characteristics out of the random data. Practical calculus of a spectrum usually takes a deal of statistical processes so that few spectra are obtained from the finite length of data records. Decision where to be noticed and how long to be evaluated on the given records is based on non analytical foundation, but depends merely on researchers' consideration about the phenomena concerned.

Since the vibration phenomena never occure strictly at the same interval, spectra show different patterns according to such decision and also to the methods of calculus, in other words, there are no strictly true theoretical patterns that might be found by pure analysis. This is no other than statistical properties. Then the spectra must be compared among those estimated by the standardized procedures. Figs. 6 and 8 are showing the numerous spectra arranged from top to bottom of a sheet for comparison of the phenomena varing sample boundary against time. Every 10-th spectrum is drawn by a thick pen for visual aids. The figures are named as the running spectra in this paper.

Every 256 byte digitalized record is sequentially read from the MT into a computer and plotted out graphycally on a sheet after spectrum calculation. Beginnig of the 256 bytes is continuously dislocated at some number of bytes on the MT and automatical paging and titling are carried out on the plotting sheet by a programm. Numerals on the left column of the sheet identify the reference counter of bytes at every 10-th spectrum showing the beginning counter of records. No special cares are taken into consideration on the quality of the MT records, so that noises or some data terminators are also drawn on the sheet. However, aided by the counters and compared with the cataloged vibrogramms in which also appear the same counters, effective spectra are clearly noticed out of illegal figures. These running spectra are filed in a book, left pages of which appear the vibrogramms, and right side of pages, the running spectra corresponding to the same samples.

4. 4. Results of Chimneys Vibrations

Visual observation over such two sorts of figures provide much interesting information on the properties of the vibration data. On the results of chimney vibration, it is firstly noticed that several remakable peaks must be belonged to the natural frequencies of chimney vibration, and that the periods are justified within comparing those peaks appeared along the same coordinates on the spectra. The peaks that appear only on one spectrum line would occure by some noisy effects and they never reappear on the same positions. Some of the peaks are so small as if they might be of noisy ones, but they occasionay reappear at the same positions after they diminish on the preceding spectra. These are assumed as the true facts.

Secondly, a very slow period can be estimated on the results of the Hitachi Chimney. The period is about 3.3 seconds that corresponds to the natural frequency of the first order when the chimney makes bending vibration as a beam clamped at the basement. On the contrary, it is impossible to find out such slow phenomena out of the running spectra of the Saganoseki data. The facts are much suggestive on the states of chimney structure. Provided the chimneys are of full strength along their height, the most probable vibration would be of the first order, and high frequencies would diminish rapidly. On the other hand, if the chimney has weak joints at some height, the small bending moment would remain around them so that the chimney vibrates after more higher mode of natural frequencies. The author could conclude from these results that the Saganoseki Chimney has less rigidity on the shell at some height than the Hitachi Chimney.

An intersting fact must be thirdly noticed on the results that seem in the running spectra of the Hitachi measurements. The frequencies corresponding to about 0.8 and 2.0 Hz are obviously those of the natural frequencies, and they correspond to the second and third modes of beam bending vibration. These frequencies are not strictly fixed values, but show somewhat waving toward left or right when the peaks of spectra are traced from top to donwards on the sheet. The author never found such waving results on several running spectra obtained from the vibration measurements of bridges. The peaks on those cases strictly lie along vertical lines on a sheet except few cases on which a heavy-duty track drived on through a small bridge. The author had assumed an assumption that the waving phenomena as the results of interaction of chimney and its inelastic foundation. However, more possible assumption may be considered on the phenomena that the Hitachi Chimney has a little difference on flexibility about the two directions, and that the chimney moves after one or another dominated frequency. Two frequency peaks closed each other are found on the running spectra of the Saganoseki Chimney, and these would be of the same mode of vibration corresponding to the two directions. (See Table 3).

4. 5. Softwares

FORTRAN is basically used for programming language for data processing of vibration data, and COBOL is partly applied for some utilities of sorting and merging of punched card data, because recording FORMAT on the MT is the same as card image, i. e., every 80 byte record length. Moreover, an access program is rather convenient for such MT with standard labels and with multiple filed recording. READ/WRITE programs of the MT which are called from FORTRAN written programs are specially prepared as sub-routines by machine oriented language of the object computer, FACOM 230-60, Nagoya University Computation Center (NUCC).

Data transcribing processes are taking over by a medium system, FACOM 230-35(NUCC), where paper tapes are transmitted into the MT. Utilities programs are also prepared for such purposes. CALCOMP Type-1136 plotting device is applied for the graphical output of computed results by the off-line and closed services of the NUCC. Several plotting routines such as PLOT, NUMBER, and SYMBOL are owing to the NUCC resources.

A large amount of spectrum calculus is carried out by the aids of a subroutine FFT(Fast Fourier Transform) and related programs of the resources on which the author is much indebted to Professor Ninomiya, the NUCC. If the data processing is carried out by a usual spectrum analysis, trigonometric functions SIN and COS are frequently referred so that the accumulated operating times may not remain in reasonable limit for more than a million data.

The author has developed several set of subroutines related to the structural analysis and graphical display in connection with an automated structural analysis. Some of them are applied for estimating natural frequencies of the chimney vibration in this paper. (See Appendix E).

Chapter 5. Aseismatic Properties of the Chimneys

5. 1. Earthquakes that hit the Saganosehi Chimney

There are numerous theoretical studies in connection with aseismic desigh of tall structures. Few cases are found on failures of concrete chimneys under real earthquakes. The Saganoseki Chimney gave us the interesting information on the safety of structures. A very important fact is that the chimney remained safely by the past several strong earthquakes including the one of April 1 st. 1968. A local earthquake which broke the chimney on its top 10 meters occurred on August 6, 1968. Critical strength of the chimney must be laid between the effects of those two earthquakes depending on magnitude and distance. The shake of the April 1 st. caused strong damages covering wide districts of Kyushu and Shikoku in spite of far distances of its epicenter in the sea, showing in Fig. 9. On the contrary, the local earthquake of the Aug. 6 hits less damages and few surveys were carried out by structural researchers.

Basically, an earthquake affects stronger movements on a structure if relative distance, between an epicenter and an object structure, is getting shorter. Statistical relations of such ground movements are presented by Professor Kanai from his various observations of earthquakes as summarized below[2);

$$V=10^{(0.61M-1.73\log_{10}X-0.67)} \tag{1}$$

where V is the maximum velocity (cm/sec) in a spectrum of ground movements by a given eqrthquake with a magnitude scale M and with distance X(km) between its epicenter and an observatory. The magnitude scale of earthquake is based on the standard of the Japanese Meteorological Bureau, and equivalent to Richter's scale. Calculated results are shown in Table 2 on the two earthquakes that hit the chimney. Two separate locations of Saganoseki and Ohita, are compared in Table 2. Ohita is a medium city of Kyushu and severely damaged by the bigger earthquake, against which the chimney stood safely.

5. 2. Dynamic Response of Chimneys

When flexible structures are affected by the random shaking of earthquakes, stresses and deformations are not able to be strictly estimated as those manner in statical loadings that are evaluated from accelerations of earthquakes. Stochastical estimations are necessary under the assumptions of dynamic properties of structures. Besides of dynamic response analysis, however, simple consideration is useful for easily understanding of chimney behavior that the chimney vibrates only after one of its natural frequencies. Povided Fn be natural frequency of the n-th mode, vibration is accelerated by choosing the same periodical intensity included in seismic

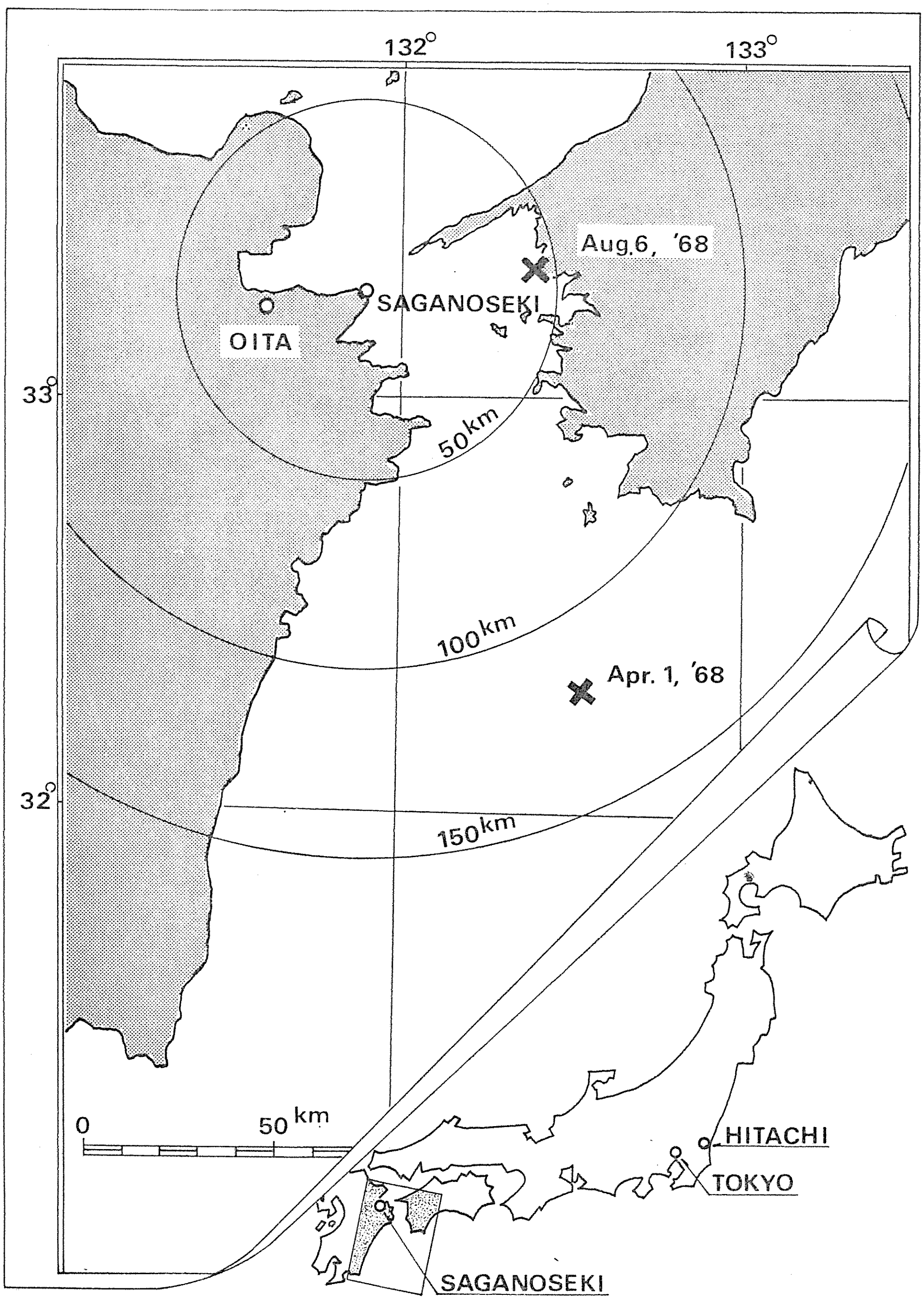


Fig. 9. Location map showing epicenters and Chimneys.

Table 2. Estimated Earthquake Velocities.

Date of Earthquakes	Magnitude M	Ohita		Saganoseki	
		X	V	X	V
Apr. 1, 1968	7.5	136	1.64	120	2.04
Aug. 6, 1968	6.6	71	1.42	45	3.16

* X in kilo meters, V in cm/sec.

Table 3. Chimneys Frequencies Measured and Estimated.

Mode	Saganoseki		Hitachi	
	Meas.	Estim.	Meas.	Estim.
1 st.	(0.4)	0.38	0.3	0.23
2 nd.	1.2/1.4	1.54	0.8/1.0	1.06
3 rd.	3.7/4.4	3.76	1.8/2.6	2.67
4 th.	7.0	6.97	3.5/4.0	5.05
5 th.	10.0	11.76	—	8.27
6 th.	—	17.90	—	12.20

* Frequencies in Hz.
** 1.2/1.4 means two observed values corresponding to the same mode.
*** Estimated values are theoretically calculated using the chimney dimensions.

spectra. Without considering resonance magnification, distribution of acceleration along chimney height is proportional to the corresponding vibration mode, and the maximum accerelation A is assumed as;

$$A=2.\pi.Fn.V \tag{2}$$

Since a conventional design assumes the uniformly distributed seismic forces along the chimney height, real earthquake shaking gives somewhat different effects on chimneys, especially on taller shells, because vibrations have several different modes and the maximum acceleration appears at the top of chimney. Accumulated shearing forces and bending moments show some different patterns along the height.

The results of the vibration measurements are then applied for the evaluation of Equation (2). Peaks of measured spectra are found at (0.4), 1.3, 4.1, 7.0 and 10.0 Hz, respectively, and these cycles would belong to the chimney natural frequencies. The first mode frequency 0.4 Hz is assumed from Ohmori's observation, because such slow phenomena are not found out of the running spectra. Accelerations are then calculated as 8, 30, 81, 139 and 199 cm/sec^2, respectively for each mode considering the seismic velocity of 3.16 cm/sec. The last two values exceed the design seismic acceleration 120 cm/sec^2 at about 16 and 66 %.

It is more clearly noticed when comparing shearing forces and bending moments of the chimney in these modes how they contribute to the accumulated maximum stresses. Fig. 10 schematically shows the procedures of superposition on each mode obtained theoretically from beam models (see Appendix C). The top figures show vibration modes of a cantilever up to the third mode. Each maximum amplitude at

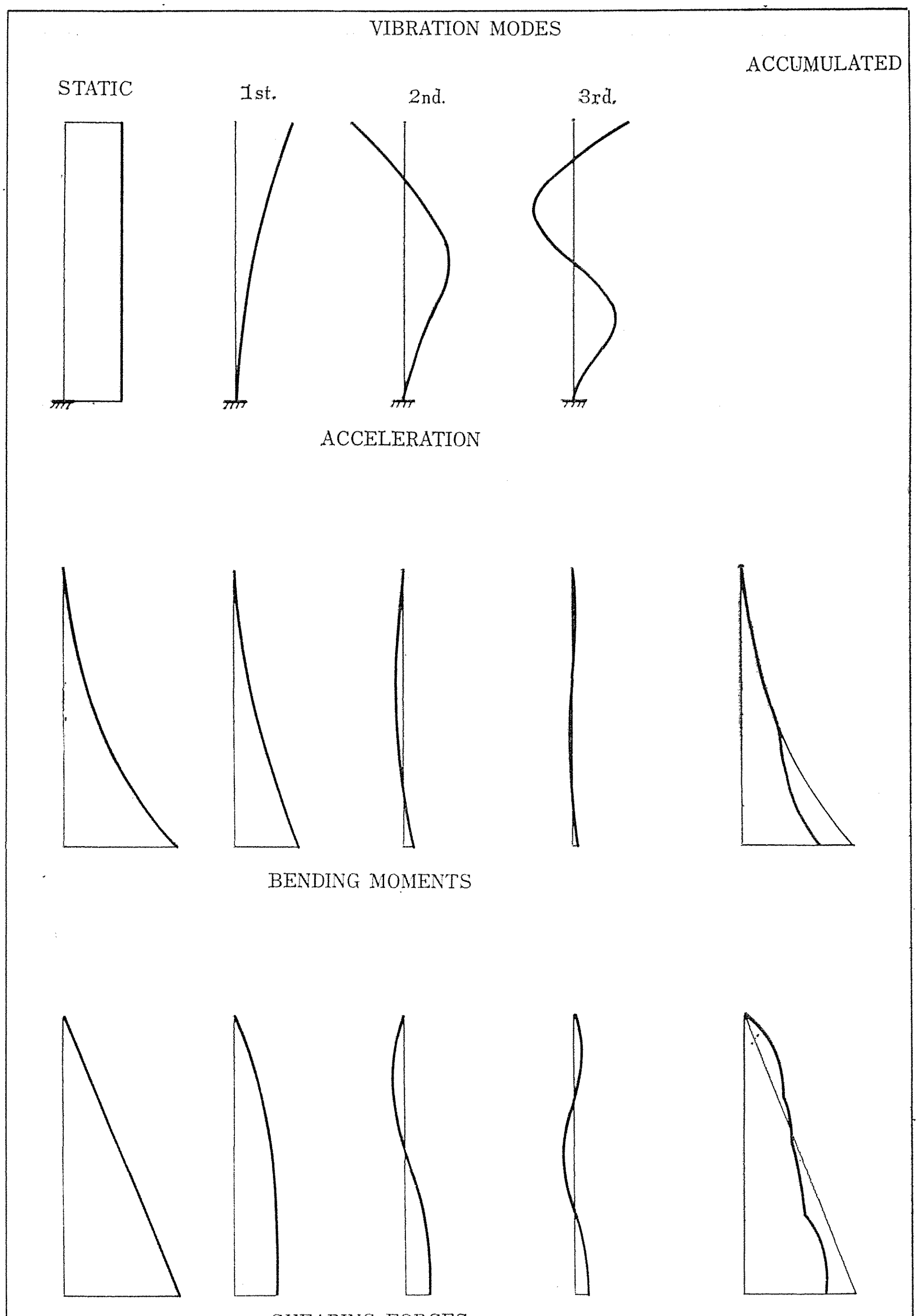


Fig. 10. Procedures of Superposition of Vibration Modes.

the free end is equalized to the unity of the left scale, which means a simple assumption of design seismic acceleration that distributes uniformely along height. When a statical loading is applied against the chimney, acceleration of earthquakes equally distrbutes on a beam. On the other hand, a modal analysis assumes that the acceleration distributes proportionally to each vibration mode. Bending moment distributions are shown in the middle row of Fig. 10 in which the left curve is statically determined distribution under uniform loadings. The following three figures toward right are those of the corresponding modes. The right figure is made from such three figures accumulated by their absolute values, also comparing with the left curve in it. The bottom figures are made for the shearing force distribution similarly drawn as for bending moments.

Estimated bending moments and shearing forces are found that the accumulated values are beyond the simple assumptions on a beam from its middle to the free end. If the chimney could strictly resist against the design assumption, higher part of shells are of dangerous by strong earthquakes. Conclusively speaking, the cause of failure on top of the Saganoseki Chimney may be by excess acceleration due to resonance vibration of higher mode natural frequency.

There are many reports in which chimneys of medium height are broken by earthquakes at about one third of their height. The reason of such failures are probably by the second mode of natural vibration which has the node at about one third of their height. It is important for the safety of chimneys to know their vibrational characteristics by the vibration measurements. Theoretical analysis of a clamped beam generally induces a series of natural frequencies up to indefinitively high cycles. However, real structures will not play such high cycle phenomena because of cohesive and non elastic properties of materials. The spectrum analysis using the measured data will afford practical values to be applied in the theoretical analyses.

The results of the spectrum analysis of the Saganoseki Chimney did not clearly show the first mode oscillation of about 0.4 Hz. On the other hand, the Hitachi Chimney has such cycle from the data analysis. It is necessary to discuss precisely on this property. As mentioned in the introductory part of this paper, the Saganoseki Chimney had oscillated with the slow cycle when tested in 1914. The chimney had probably lost its bending stiffness at some height where the bending moment remains in the least value and most possible oscillation mode have its node around there. The Saganoseki Chimney is therfore expected to be less safe on future earthquakes and will be broken at some height. The chimney remained safely against the recent earthquake in January 1975, therefore, it will be safe before an earthquake hits the chimney as strong as that of August 1968.

The Hitachi Chimney is expected to be in full strength along its whole height because the first mode of oscillation can be clearly found on the spectrum. The conclusions on the states of chimneys are deduced from relative comparison of measurements on two chimneys. The author had hesitated to report the results just after the first measurements on the Saganoseki Chimney were carried out, because no experiences of measurements had been obtained on such structures. If any chances are allowed to test those chimneys after several decades, the data will be more effective to the safety of chimneys.

Chapter 6. Conclusions

Vibration measurements were carried out on the foot of tall chimneys without disturbing any usual works of smeltry plants. The works on measurements were needed no special procedures except for the recoding of the random vibration for half an hour. Measuring conditions at the chimney were never finely prepared for the purpose, but it was the author's aim to propose the new developed methodology in order to obtain the succesful results of the study.

Natural frequencies could be precisely detected up to 4th or 5th mode using the running spectra presentations. Comparative study among data clarified a pair of frequencies closed together. The chimneys seemed to behave as elastic beams but slightly different stiffness in the two horizontal directions. The Hitachi Chimney seemed to be in full strength along its height because the vibrations included by the first mode of natural frequencies. On the contrary, the Saganoseki Chimney showed no such slow phenomena, but it seemed to be much flexible so as to ocure higher mode of oscillation up to 5th mode. These facts teached us the Saganoseki Chimney is losing its stiffness.

Material tests on the Saganoseki Chimney showed that the concretes were affected by weathring and smoke as a rate of 1 centi meters by 15 years from the surface of the shells. When the suffered depth reaches to the steel reinforcement or penetrated through the shell, strength of the shell would be lost. By extraporating the facts, the chimney would be chemically safe more than thirty years for the remained concretes.

Dangerous earthquakes against the chimney are depending on the magnitude scale and on the relative distance between the chimney and its epicenter. Critical limit is to be considered by the velocity spectrum of an earthqnake. Failures of the Saganoseki Chimney showed this limit lying between 2.04 and 3.06 cm/sec.

Comparative studies are of useful tools to know the states of structures under the usual conditions. Author's investigation needs the measurements of vibrations before and after the structural failures. However, few chances are expected such as on these chimney cases. Measurements of vibration must be stored with the aids of information retrieval systems on any cases when the measurements are allowed on existing structures.

Acknowlebgements

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References

1) S. Shimada; An Application of Correlation Techniques to the Dynamic Measurements of Structures, Trans. of Jap. Soc. of Civil Eng. Vol. 174, pp 11-23, Feb. 1970 (in Japanese).
2) K. Kanai et al.; Eathquakes and Vibration Theory, Series of Architecture Engineering Vol. 11, pp 137-144, Shohkokusha, 1963, (in Japanese).
3) The Japan Seismological Agency; The Seismological Bulletin, April and August, 1968.
4) The Japan Mining Company; Publication on Memoir of the Company' History. (in Japanese).

Appendix A. Correlation and Spectrum Calculation

Let us consider two functions $f(t)$ and $g(t)$ depending on a variable t, which usually means time. Correlation is calculated within getting a mean value after products of two functions. Sample length is choosen as T, where t is varied from t_1 to t_1+T. Two sample functions are considered either at the same coordinates of t or relaively dislocated by some time lag τ, that is, from $t_1+\tau$ to $t_1+\tau+T$ for another function. Correlation C is depending on τ;

$$C(\tau)=\int_{t_1}^{t_1+T} f(t).g(t+\tau).\,dt \tag{i}$$

Practically, a function is sequentially evaluated at a finite sampling period and a set of N numbers are taken over into digital calculus corresponding to the same interval T. Each N values of the two functions are choosen out of sequential data and starting positions are either at the same numerals or dislocated by an integer counting τ by the sampling period. Fourier's analysis of a given function is carried out similarly as Equation (i), in which the function $g(t+\tau)$ is replaced by a trigonometric function Sin ωt or Cos ωt. Digital computation is carried out on such N numbers of data, and the trigonometric function is evaluated at N-dividened coordinates of k-round circles. FFT (Fast Fourier Transform) works the fastest calculation in a computer when N is selected to some n-power of 2, such as 128 and 256.

Two values estimated by k-th Sin and Cos transform are then composed into a power,

$$S(k)=A_k{}^2+B_k{}^2 \tag{ii}$$

where, A_k and B_k are k-th Fourier transformed values. $S(k)$ is proportional to the frequency intensity of the given data at

$$F=(k/N).\ \text{(sampling period)} \tag{iii}$$

The runnig spectrum is drawn against logarithmic scale of F in row direction.

Appendix B. Kármán's Vortex Excitation on a Cylinder

When a round cylinder is transversely laid in a wind strem, eddies appear behind the cylinder and shed out into downstream periodically. Th. von Kármán had studied the stadility problems of these eddies theoretically, and so they are called as Kármán's vortices after his name. Mechanism of shedding eddies behind an obstacle has never been clarified theoretically but strong periodicity is found experimentally in the random wake and on the obstacle itself. The shedding frequencies are known to be proportional to the wind speed, and a reduced frequency remains at some value, that is;

$$S=F.\ D/V$$

Where, F is frequency in Hz, D is depth of an obstacle and V is wind velocity. S is known about 0.2 for a round cylinder. Wind gives a drag force against a cylinder along the wind direction, and a periodical force occures normal to the wind direction so as to excite vibration. If the shedding frequency reaches to one of natural frequencies of a cylinder, resonant vibration will make growth its amplitude.

Considering the chimney diameter as 9 m and the first one of natural frequencies of the chimney as 0.4 Hz, the wind velocity for resonance vibration is obtained as about 18 m/sec (65 Km/h), which may be frequently expected on high places.

Appendix C. Dynamic Structural Analysis of Chimneys

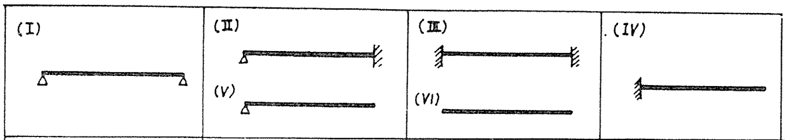
A structural model of the chimney may be assumed as an elastic beam fixed at a basement. Acceleration of an earthquake shakes the basement in the horizontal direction, so that the beam begins to vibrate. Theoretical treatment is convenient and similar on beam bending to consider that the basement will not move but accelerations work along the beam. Vibration mode, or a mode, means a state of beam bending under its stationary vibration and displacement by the beam bending is given as;

$$Y(x,\ t)=A.\ f(x).\ \exp(i\omega t+b) \tag{i}$$

which is a solution of the following differential equation;

$$EI\frac{d^4Y}{dx^4}=m\omega_2 Y \tag{ii}$$

Where EI is stiffness of a beam, m is consistent mass and ω is angular velocity under one of the beam natural frequencies, A is an indefinte constant decided by the other conditions. The function $f(x)$ plays an important role in the vibration problems as well as the angular velocity ω. When a beam is of uniform section along its length, $f(x)$ and ω are given by a set of infinitively many solutions. Practically, the first 3 or more set are in uses for calculus. The solutions are shown in Table I with the various beam conditions. Angular velocity ω is calculated as;



$\sin\beta_i l = 0$		$\tanh\beta_i l = \tan\beta_i l$		$\cosh\beta_i l \cos\beta_i l = 1$		$\cosh\beta_i l \cos\beta_i l = -1$	
i	$\beta_i l$	i	$\beta_i l$	i	$\beta_i l$	i	$\beta_i l$
1	3.14159	1	3.92660	1	4.73004	1	1.87510
2	6.28319	2	7.06858	2	7.85320	2	4.69410
3	9.42478	3	10.21017	3	10.99561	3	7.85476
..	....	..	....	4	14.13716	4	10.99554
				5	17.27876	5	14.13717
				..	....	6	17.27876
						..	....
	$i\pi$		$(i+\frac{1}{4})\pi$		$(i+\frac{1}{2})\pi$		$(i-\frac{1}{2})\pi$

(I) SIMPLE BEAM

$$f_i(x) = \sqrt{2}\ \sin\beta_i x$$

(II) HALF CLAMPED BEAM

$$f_i(x) = \sqrt{\frac{2}{\sinh^2\beta_i l - \sin^2\beta_i l}}\left(\sinh\beta_i l \sin\beta_i x - \sin\beta_i l \sinh\beta_i x\right)$$

(III) CLAMPED BEAM

$$f_i(x) = \left(\cosh\beta_i x - \cos\beta_i x\right) - \frac{\cosh\beta_i l - \cos\beta_i l}{\sinh\beta_i l - \sin\beta_i l}\left(\sinh\beta_i x - \sin\beta_i x\right)$$

(IV) CANTILEVER

$$f_i(x) = \left(\cosh\beta_i x - \cos\beta_i x\right) - \frac{\cosh\beta_i l + \cos\beta_i l}{\sinh\beta_i l + \sin\beta_i l}\left(\sinh\beta_i x - \sin\beta_i x\right)$$

(V) PENDULUM

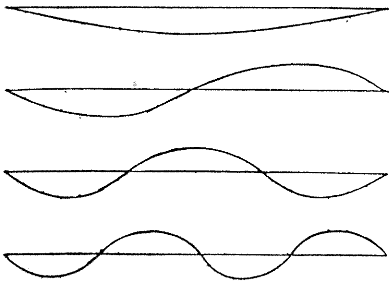
$$f_i(x) = \sqrt{\frac{2}{\sinh^2\beta_i l - \sin^2\beta_i l}}\left(\sin\beta_i l \sinh\beta_i x + \sinh\beta_i l \sin\beta_i x\right)$$

(VI) FREE BEAM

$$f_i(x) = \left(\cosh\beta_i x + \cos\beta_i x\right) - \frac{\cosh\beta_i l + \cos\beta_i l}{\sinh\beta_i l - \sin\beta_i l}\left(\sinh\beta_i x + \sin\beta_i x\right)$$

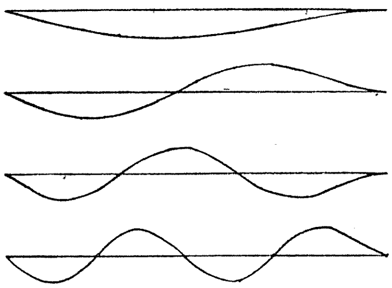
Fig. 11-1

(I) SIMPLE BEAM



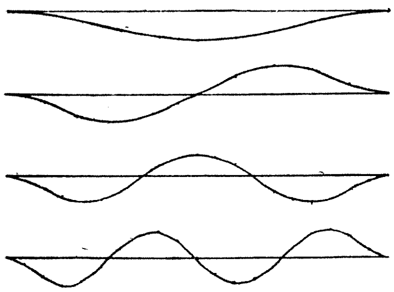
x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	0	0	0	0	0
0.05	0.22123	0.43702	0.64204	0.83125	1.00000
0.1	0.43702	0.83125	1.14412	1.34500	1.41421
0.15	0.64204	1.14412	1.39680	1.34500	1.00000
0.2	0.83125	1.34500	1.34500	0.83125	-0.0
0.25	1.00000	1.41421	1.00000	0.0	-1.00000
0.3	1.14412	1.34500	0.43702	-0.83125	-1.41421
0.35	1.26007	1.14412	-0.22123	-1.34500	-1.00000
0.4	1.34500	0.83125	-0.83125	-1.34500	0.0
0.45	1.39680	0.43702	-1.26007	-0.83125	1.00000
0.5	1.41421	0.0	-1.41421	0.0	1.41421
	symmetry	anti-symmetry	symmetry	anti-symmetry	symmetry

(II) HALF CLAMPED BEAM



x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	0	0	0	0	0
0.05	0.28377	0.48887	0.69106	0.87553	1.03849
0.1	0.55724	0.91715	1.20591	1.37513	1.40985
0.15	0.81053	1.23173	1.41329	1.28430	0.87553
0.2	1.03456	1.39351	1.26035	0.64202	-0.22123
0.25	1.22149	1.38220	0.78616	-0.27594	-1.17587
0.3	1.36498	1.19882	0.11174	-1.07546	-1.37513
0.35	1.46049	0.86550	-0.59077	-1.41329	-0.69099
0.4	1.50550	0.42267	-1.14194	-1.14446	0.43706
0.45	1.49967	-0.07598	-1.40077	-0.38452	1.28442
0.5	1.44486	-0.57035	-1.30049	0.53993	1.30683
0.55	1.34514	-1.00150	-0.86541	1.23144	0.49008
0.6	1.20675	-1.31923	-0.20438	1.39201	-0.64067
0.65	1.03787	-1.48865	0.51756	0.95063	-1.35800
0.7	0.84852	-1.49510	1.12213	0.09275	-1.19872
0.75	0.65021	-1.34669	1.46493	-0.82120	-0.25971
0.8	0.45574	-1.07449	1.47476	-1.41422	0.86818
0.85	0.27886	-0.73023	1.17616	-1.46177	1.48866
0.9	0.13400	-0.38223	0.69035	-1.00204	1.26756
0.95	0.03602	-0.11020	0.21630	-0.34672	0.49391
1	0	0	0	0	0

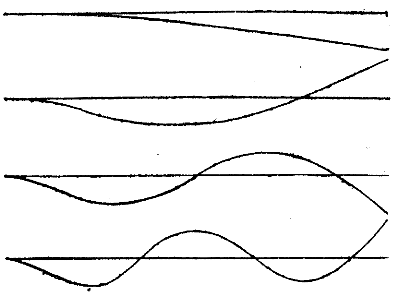
(III) CLAMPED BEAM



x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	0	0	0	0	0
0.05	0.05160	0.13400	0.24694	0.38223	0.53246
0.1	0.18910	0.45574	0.77005	1.07449	1.32178
0.15	0.38675	0.84852	1.26761	1.49510	1.45002
0.2	0.61939	1.20675	1.50783	1.31923	0.67360
0.25	0.86313	1.44486	1.37080	0.57035	-0.52789
0.3	1.09600	1.50550	0.86863	-0.42268	-1.33938
0.35	1.29873	1.36498	0.13306	-1.19882	-1.20344
0.4	1.45545	1.03457	-0.62836	-1.39351	-0.22020
0.45	1.55436	0.55724	-1.19633	-0.91715	0.91895
0.5	1.58815	0	-1.40600	0	1.41457
	symmetry	anti-symmetry	symmetry	anti-symmetry	symmetry

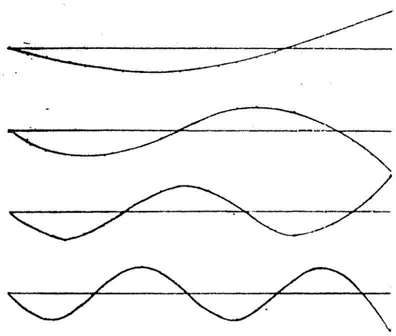
Fig. 11-2

(IV) CANTILEVER



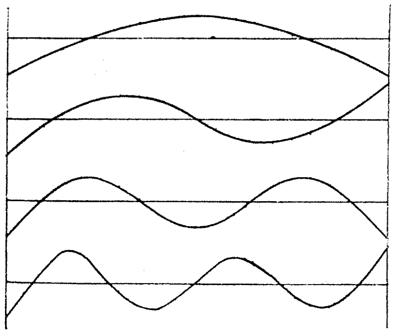
x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	0	0	0	0	0
0.05	0.00859	0.05070	0.13408	0.24693	0.38223
0.1	0.03355	0.18526	0.45614	0.77002	1.07449
0.15	0.07367	0.37757	0.84860	1.26750	1.49511
0.2	0.12774	0.60211	1.20901	1.50758	1.31925
0.25	0.19457	0.83452	1.44900	1.37032	0.57040
0.3	0.27296	1.05227	1.51248	0.86774	-0.42257
0.35	0.36175	1.23535	1.37614	0.13148	-1.19862
0.4	0.45977	1.36694	1.05185	-0.63112	-1.39309
0.45	0.56590	1.43393	0.58349	-1.20110	-0.91631
0.5	0.67904	1.42733	0.03937	-1.41424	0.00170
0.55	0.79817	1.34247	-0.49859	-1.21057	0.92060
0.6	0.92227	1.17895	-0.94753	-0.65299	1.40051
0.65	1.05041	0.94043	-1.23610	0.09043	1.21301
0.7	1.18175	0.63409	-1.31485	0.79478	0.45146
0.75	1.31549	0.26996	-1.16290	1.24284	-0.51199
0.8	1.45095	-0.14008	-0.78974	1.28608	-1.20090
0.85	1.58754	-0.58333	-0.23166	0.88331	-1.25517
0.9	1.72479	-1.04752	0.45702	0.10407	-0.58801
0.95	1.86235	-1.52218	1.21697	-0.90718	0.60415
1	2.00000	-2.00000	2.00000	-2.00000	2.00000

(V) PENDULUM



x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	0	0	0	0	0
0.05	0.26819	0.49010	0.69098	0.87553	1.03849
0.1	0.52547	0.91977	1.20573	1.37514	1.40985
0.15	0.76134	1.23606	1.41296	1.28432	0.87553
0.2	0.96606	1.40010	1.25979	0.64206	-0.22123
0.25	1.13102	1.39188	0.78522	0.27585	-1.17515
0.3	1.24904	1.21281	0.11016	1.07529	-1.37515
0.35	1.31460	0.88557	-0.59339	1.41295	-0.69104
0.4	1.32402	0.45136	-1.14631	1.14379	0.43696
0.45	1.27558	-0.03507	-1.40805	0.38323	1.28419
0.5	1.16950	-0.51204	-1.31262	0.54246	1.30630
0.55	1.00786	-0.91844	-0.88563	1.23635	0.48888
0.6	0.79450	-1.20092	-0.23805	1.40160	-0.64340
0.65	0.53472	-1.32017	0.46144	0.96931	-1.36423
0.7	0.23501	-1.25518	1.02864	0.12918	-1.21291
0.75	-0.09739	-1.00506	1.30916	0.75018	-0.29209
0.8	-0.45486	-0.58802	1.21522	1.27577	0.79432
0.85	-0.82995	-0.03752	0.74374	1.19184	1.32016
0.9	-1.21589	0.60415	-0.03012	0.47582	0.88320
0.95	-1.60715	1.29435	-0.98410	0.67916	-0.38285
1	-2.00000	2.00000	-2.00000	1.99999	-1.99999

(VI) FREE BEAM



x/L	$f_1(x)$	$f_2(x)$	$f_3(x)$	$f_4(x)$	$f_5(x)$
0	2.0	2.0	2.0	2.0	2.0
0.05	1.53523	1.21589	0.90725	0.60415	0.31054
0.1	1.07375	0.45486	-0.10393	-0.58802	-0.96646
0.15	0.62312	-0.23501	-0.88309	-1.25518	-1.30025
0.2	0.19429	-0.79450	-1.28573	-1.20092	-0.61047
0.25	-0.19986	-1.16950	-1.24229	-0.51204	0.55450
0.3	-0.54581	-1.32403	-0.79386	0.45136	1.35061
0.35	-0.83062	-1.24905	-0.08886	1.21281	1.20819
0.4	-1.04306	-0.96607	0.65569	1.40010	0.22226
0.45	-1.17444	-0.52549	1.21526	0.91976	-0.91796
0.5	-1.21930	0	1.42238	0	-1.41386
	symmetry	anti-symmetry	symmetry	anti-symmetry	symmetry

Fig. 11-3

Fig. 11. Beam Constants under various Support Conditions.

$$\omega=\beta^2\sqrt{gEI/m} \tag{iii}$$

When a beam is excited at its basement by an acceleration, amplitude of which being A, the beam statistically has some chances to vibrate after one of its modes and the maximum acceleration A occures at the free end of beam unless resonance be accounted. The accelration at the basement is a random phenomenon, stresses on the beam would randomly accumulated by each of modes. Intensity of acceleration may be taken proportionally to the intensity of a spectrum density, on which seismic spectra are applied. Response analyses simultaneously traces these phenomena aided by a computer. Discussions on them are not included in this paper. Since the chimneys have varing dimensions along those height, modes and natural frequencies are evaluated numerically by means of FEM(Finite Element Method).

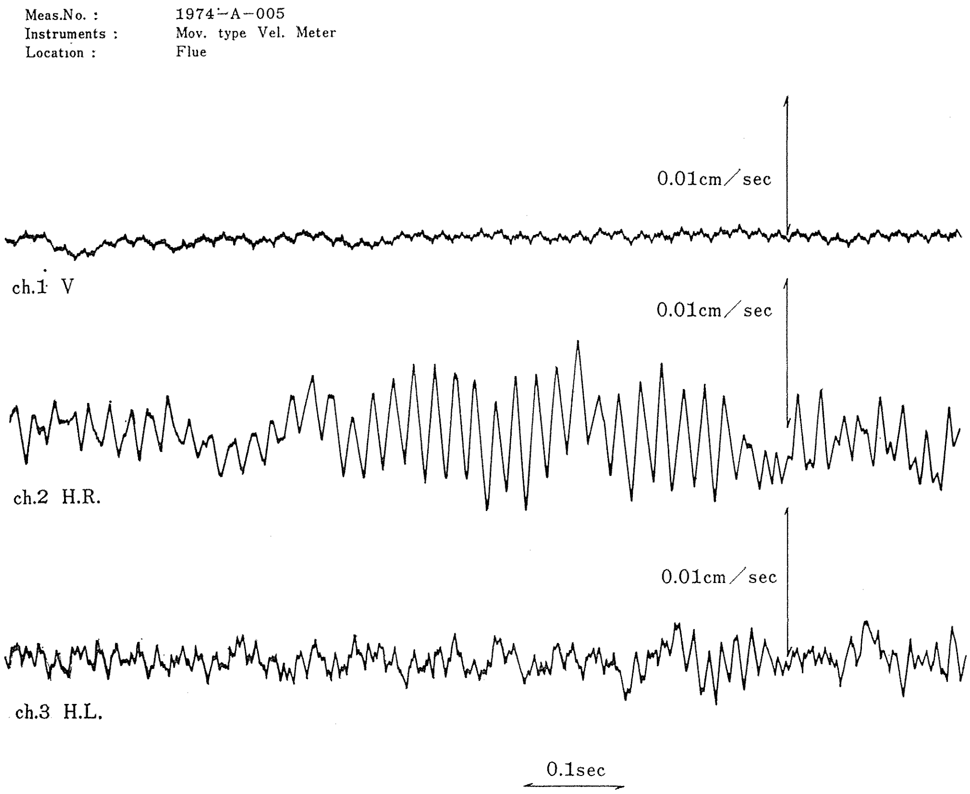
Appendix D. Several Graphical Presentations of Vibration Data

In order to understand the general properties of vibration data, several graphical figures are drawn by aids of laboratory instruments. Fig. 12 shows an oscillogramm of the Hitachi Chimney vibration, comparatively showing three phenomena on a sheet. Such oscillogramm is of useful aids for comparing the phenomena at the same coordinates of time, however, the sheet is generally going to a long roll for random data and there appear no remakable properties between some finite sampling periods.

On playing back the measured data from a data-recorder in a laboratory, a real time working correlator and spectrum analyzer is used for the analysis. The analyser takes the data at a given sampling period into 3 bit digital values and calculates the correlation and spectrum. The results are displayed on a CRT and can be duplicated on a sheet by an operator's control. Fig. 13 is an example of an auto-correlation figure and Fig. 14 shows a spectrum corresponding to the correlation. The analyzer works for obtaining the fast knowledge on the periodicity of data, however, it affords less information on several periodical phenomena included in a datum.

The same procedures are carried out using a digital computer and plotted out on a sheet. The auto-correlation and spectrum are shown in Figs. 15 and 16, respetively. It seems more precisely than real time analysis. Several peaks are found and these are testified by the results in Table 3 of this paper. The comparative study which the author insists is carried out on these auto-correlation and spectrum figures. Firstly, the auto-correlaton figures are compared with the theoretical patterns, previously prepared as the reference figures, an example of which showing in Fig. 17. The reference figures are showing free oscillation waves of a system composed from a mass, a spring and a dash-pot with various damping constant. Comparing the auto-correlation figure with the theoretical groups where the most alike pattern appear, the fit figure gives that the measured data will be simultaniously occured by such theoretical model with the given damping constant. On chimney vibration, the demping constant is found as about 0.05 which means that the chimney is fairly elastic.

Secondly, the spectrum calculated is compared to the theoretical spectrum which is evaluated by the response characteristics of a one mass vibration system. Fig. 18 is one of the theoretical response curves and this is prepared for the vibration sensors



Meas. No. : 1974-A-005 Location : Flue
Instruments : Correlator C-100 Ch. 3
Site : Hitaehi-Chimney
Auto. Correlation $\Delta t=40$ msec
Meas, No. : 1974-A-005 Location : Flue
Instruments : Spectrum Analyzer F-100 Ch. 3
Site : Hitachi-Chimney
Power Spectrum $\Delta f=0.133$ Hz

Fig. 12. A part of Oscillograms of the Hitachi Chimney.

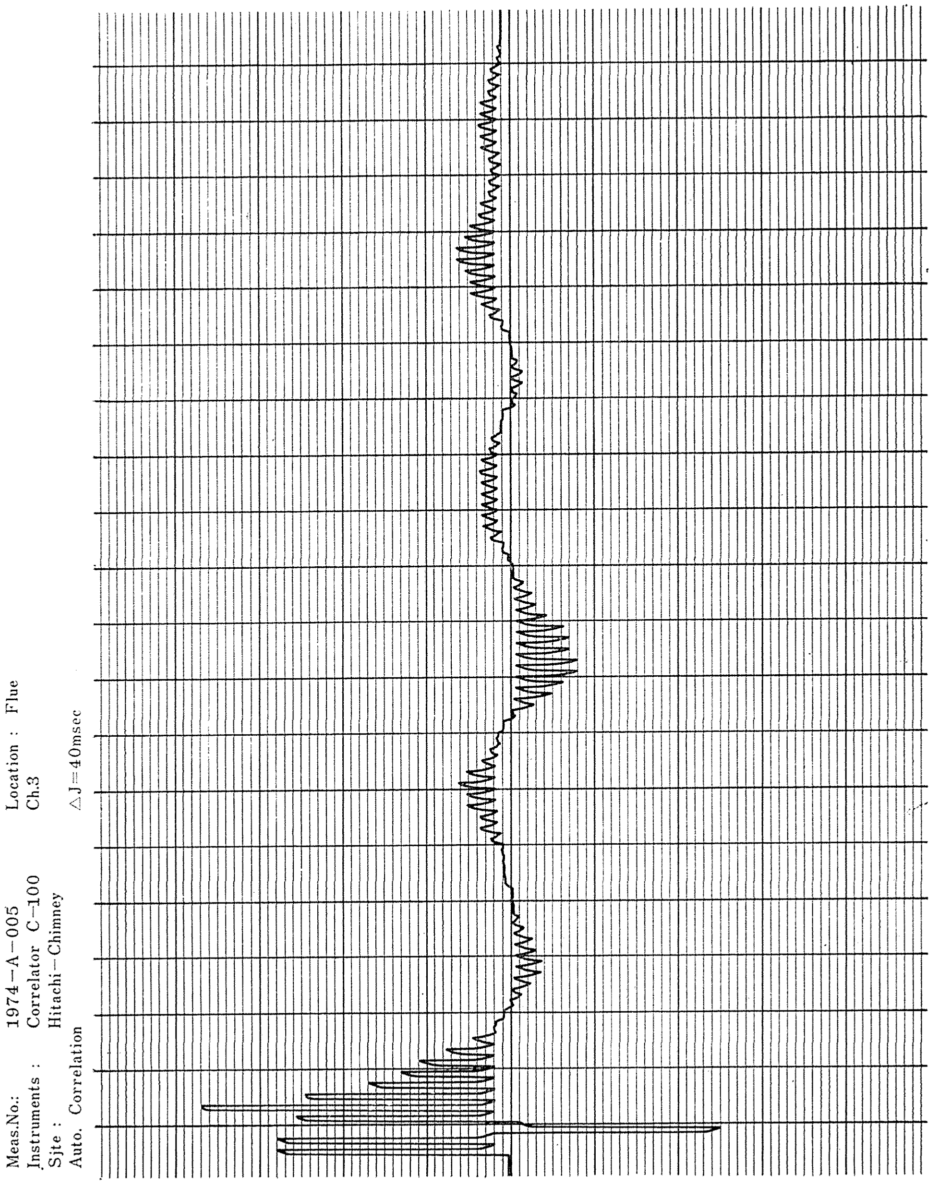


Fig. 13, Real time operated Auto-correlation Result.

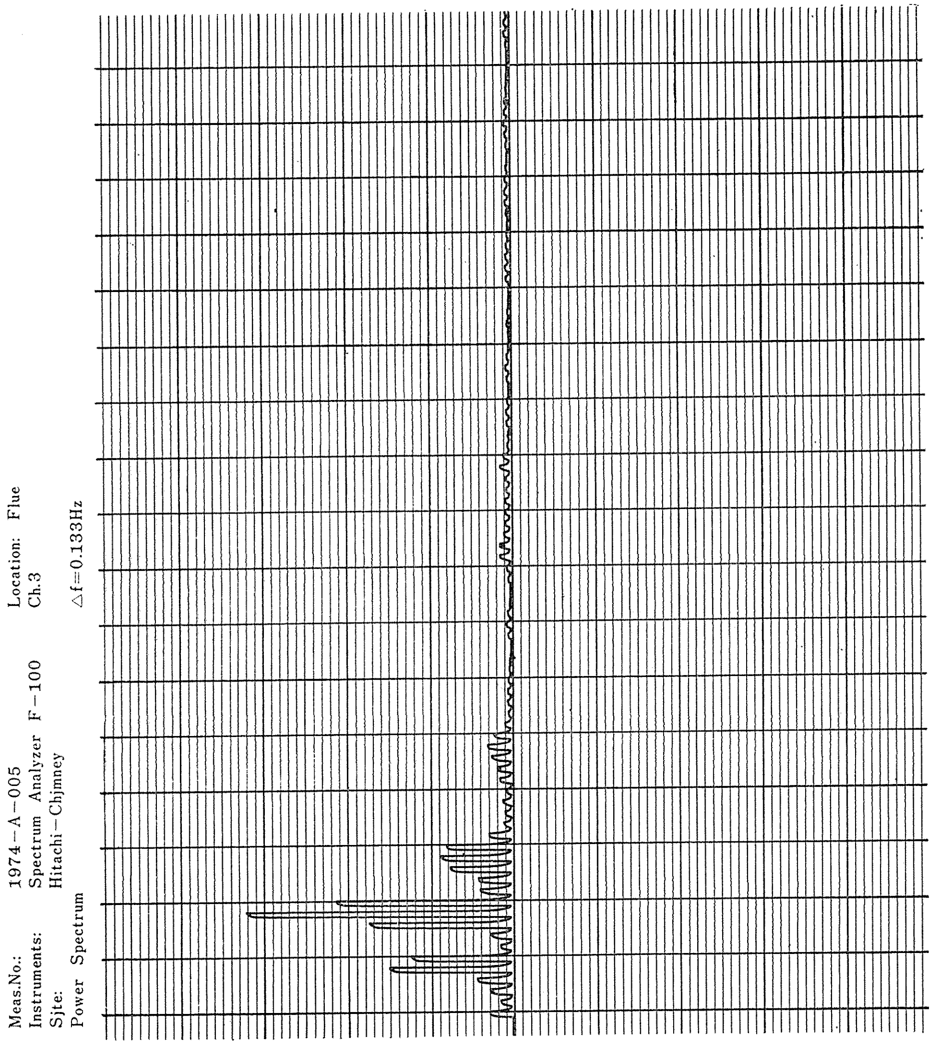


Fig. 14, Real time operated Power Spectrum Result.

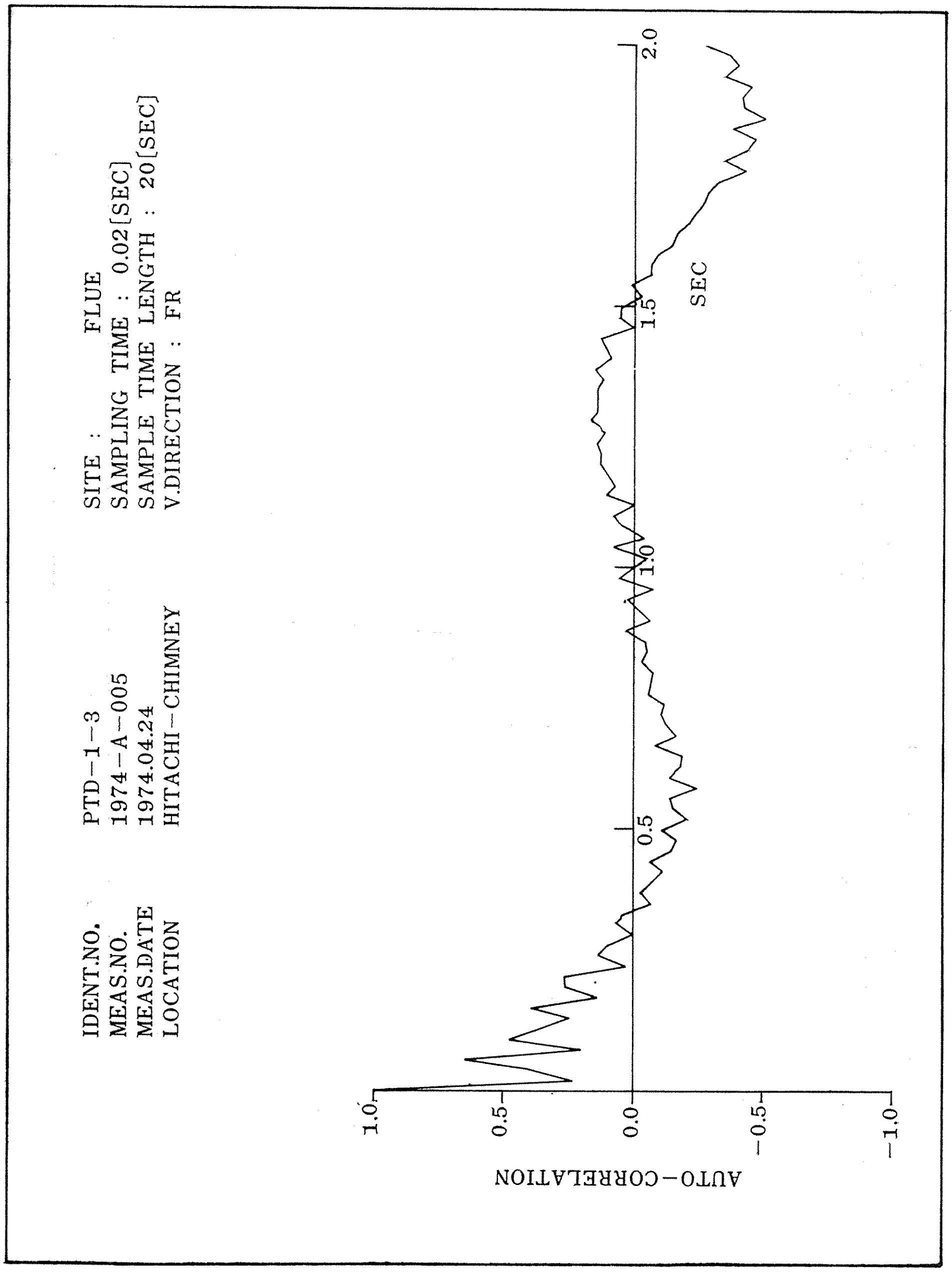


Fig. 15, Digital Computed Auto-correlation Result.

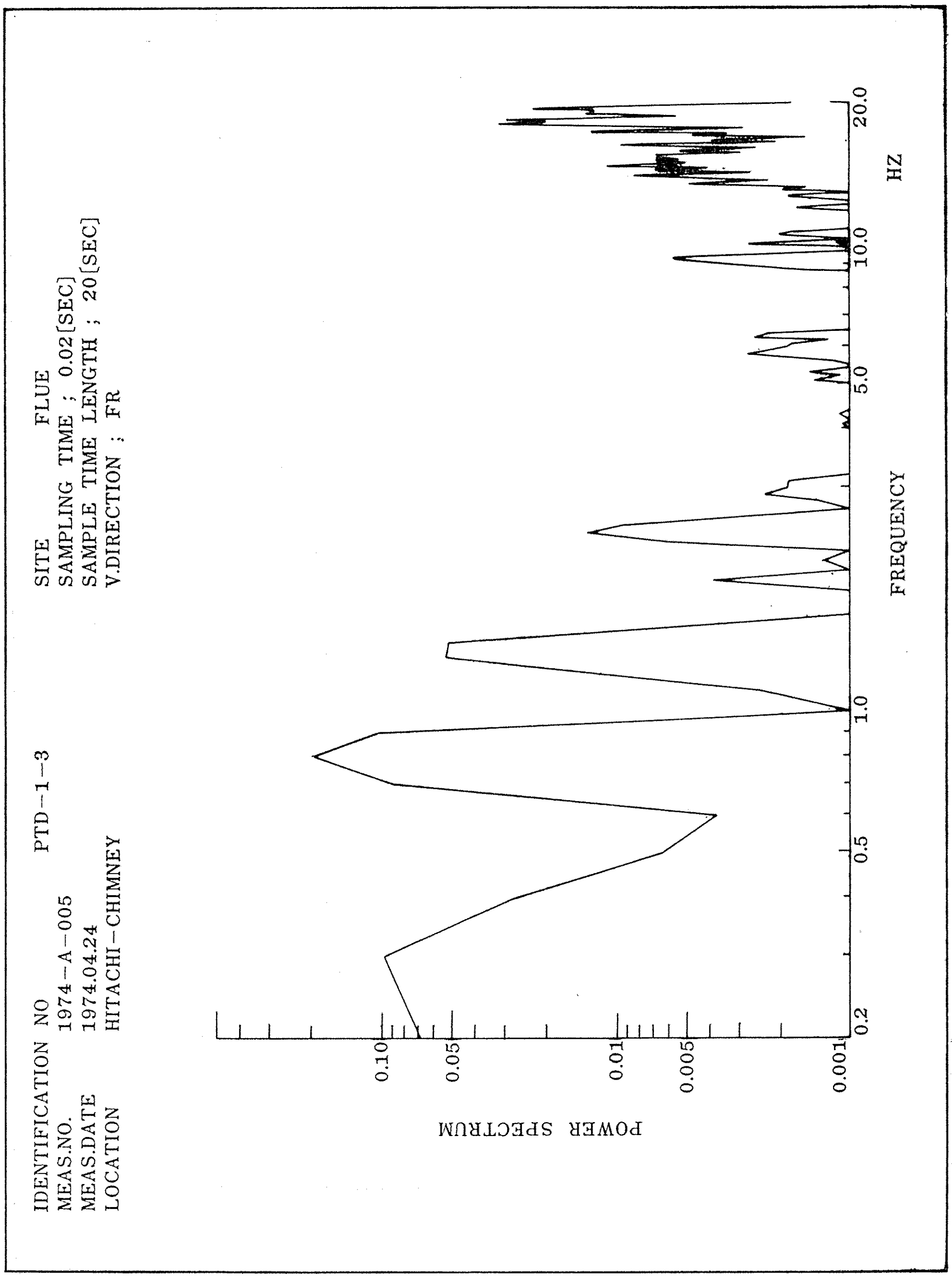


Fig. 16, Digital Computed Power Spectrum Result.

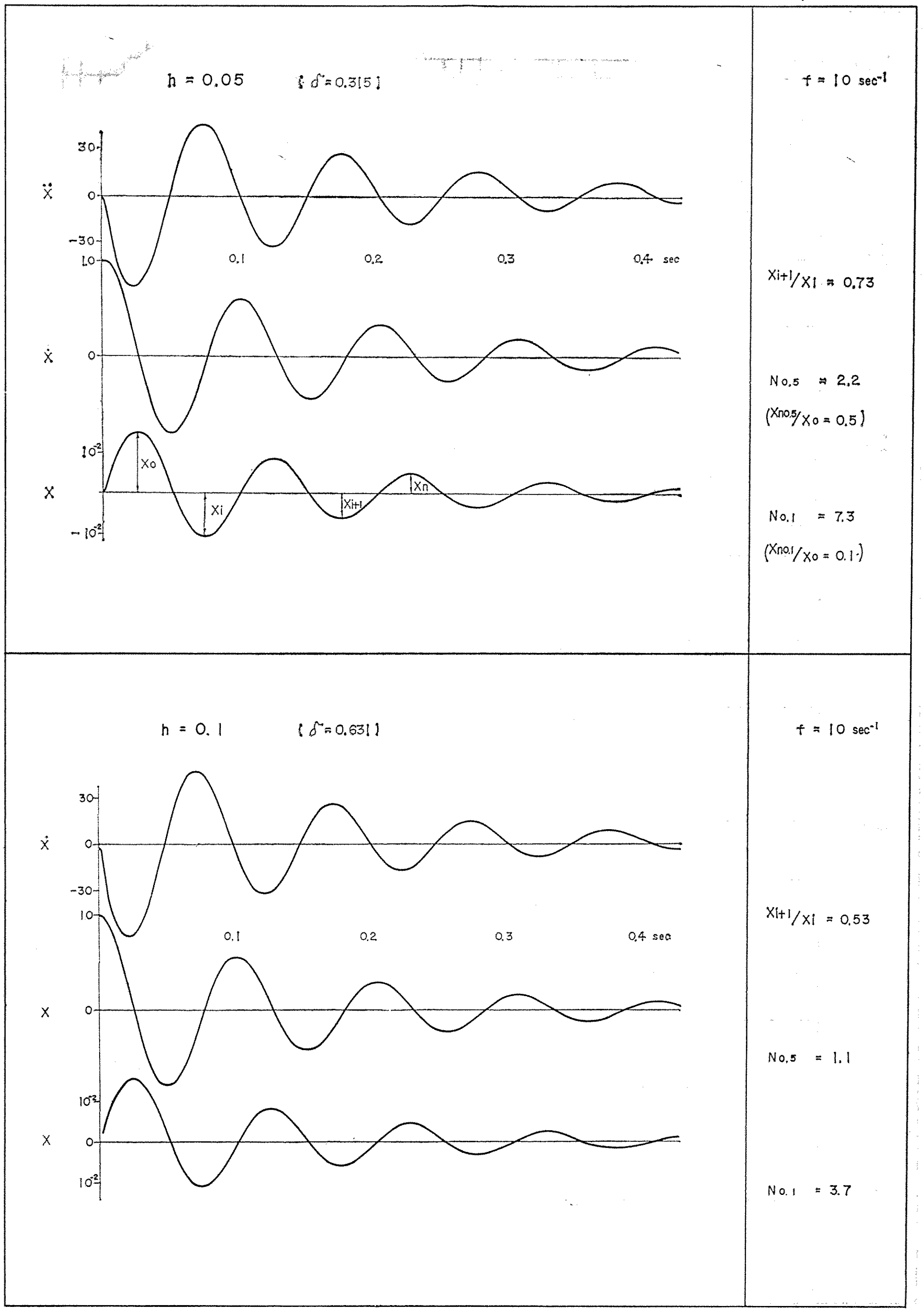


Fig. 17. Reference Patterns showing Damping Oscillation.

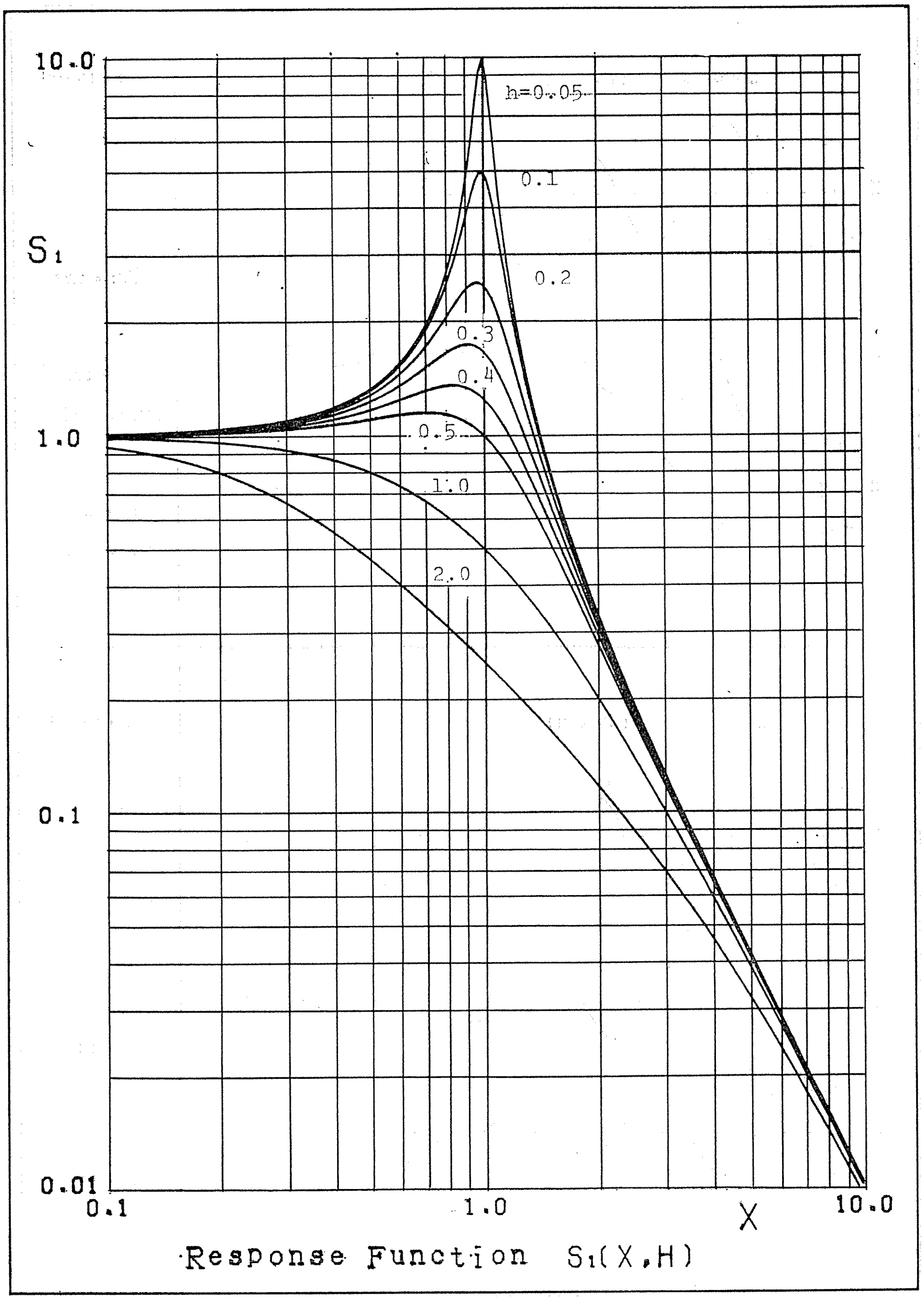


Fig. 18, Reference Patterns showing Response Characteristics.

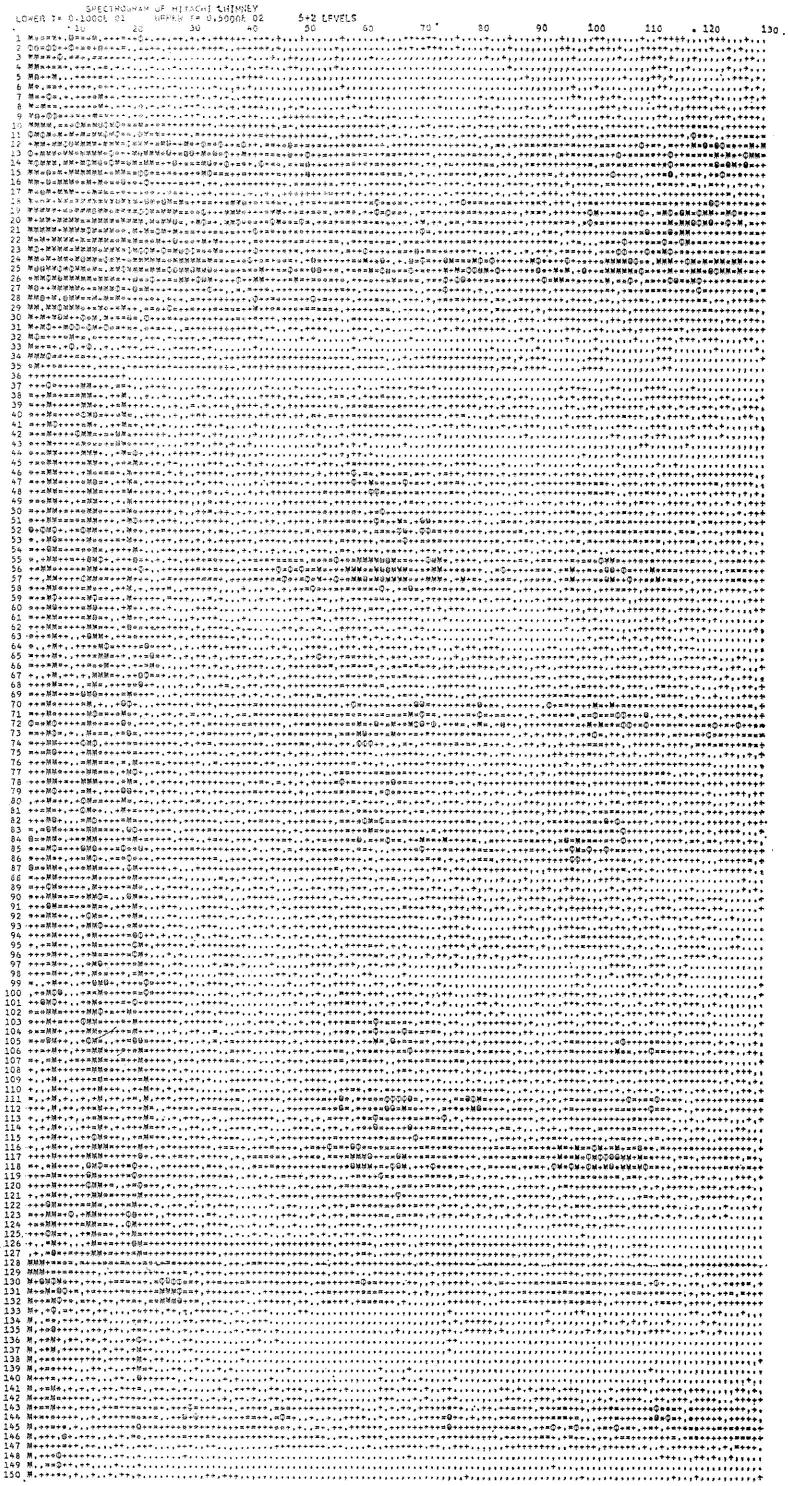


Fig. 19, Dot-matrix presentation of Running Spectra, Page 1.

Fig. 20. Dot-matrix presentation of Running Spectra, Page 2.

used in measurements. The theoretical response curves are drawn against logarithmic scales on both axes. Comparative procedures are carried out on the calculated spectrum searching where the most similar patterns appear within sliding the theoretical figures on the measured curves. Fig. 16 is included by several peaks which can be assumed to have the damping constant as about 0.05. A very slow cycle is found in Fig. 16 as about 0.3 Hz. This is estimated about 0.4 or 0.5 as the damping constant, which is rather cohesive response on the structure.

More detailed properties can not be detected by such a single spectrum, therefore, many spectra must be relatively compared on whole data. The running spectrum is then introduced in this paper. Before displaying on graphical sheets, a dot-matrix presentation is used for monitoring purposes. Figs. 19 and 20 are showing the running spectra of the Hitachi Chimney vibration at the same pages corresponding to the vibrogramms in Fig. 7. Waving frequencies can be clearly noticed out as dotted columns.

Appendix E. Computer Programs

It is necessary for comparative study of existing structures to estimate static and dynamic properties of theoretical models by aids of a computer calculus. Some of problem oriented programs are of useful aids, but never suitable for general purposes. The author has prepared many computer programs for structural analyses considering the graphical output and random process analysis. These programs do not aim the analysis of high statically indeterminate structures, but afford the minimum core sizes in a computer to save for user's program area.

Variable length common areas are served for common data storages. Data read and listing operations are composed of several different subroutines which are not always loaded unless necessary. Graphical output is carried out by some of the listing programs. Data read-in programms are carefully prepared to meet the data storage and retrieval processes. As the input conditions of structural calculus have various values such as structural dimensions and material properties, each logical group of values is identified by a label showing what sort of data they belong to. The label is served as a keyword in retrieval operation.

When input data are read into computer calculus by punched cards, several label cards are inserted among logical records to identify the records and to control the processes. If these cards are stored in other storage devices, the keywords can afford sufficient information on the records. The retrieval processes are also carried out on the vibration data stored on a magnetic tape. Some of these tapes are included by the structural dimensions and other values as well as vibrtion data merged into a same tape. If a special case study is carried out besides the standardized processes, the program cards are recorded on the same tape as the reference data.

A set of structural analysis programs is consisted of more than 30 SUBROUTINEs for various purposes. Each program is prepared as having the least arguments on data reference and the labeled common areas serve for the purposes. The most basic operation is carried out by only four processes; initialization, data read, structurai analysis, and results listing. The random process analysis are carried out by the other set of SUBROUTINEs consisted of about 20 basic routines. Graphical processing programs are prepared for the automated engineering drawings and geometric drawings. Some of these programms are applied for the perspective drawings of the object structures as a visible aid. When a trussed structure is affected under vehicle loading, emphasized deformation of structure can be drawn perspectively on a sheet using these graphics subroutines. On chimney drawing, the structural model is a straight line, not an interesting object for perspective drawings.

Dynamic response of chimney vibration was carried out by random shaking of simultanious earthruakes using the above subroutines. The deflection of the chimney model was graphically drawn on a 16 mm cine-film at a sampling period, and a motion picture was produced for moving images of the chimney bending. The animation technique will be frequently applied in future structural analysis. Fig. 21 is showing a part of the film. The running spectrum was also reproduced in a moving pictures on a 16 mm film, however, the moving images are found less effective for precise discussions.

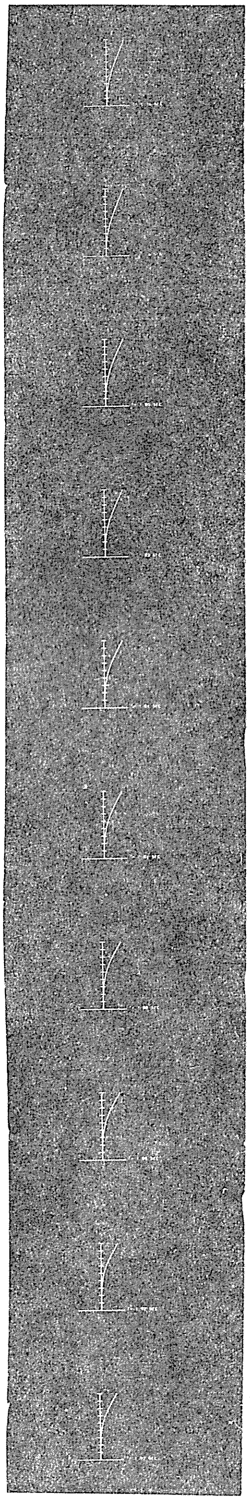


Fig. 21. A part of Motion Pictures of Chimney Vibration.

Table 4. Basic Subroutine Name List.

Ⅰ. Structural Analysis.

1.	WORK 1	Data area reservation.
2.	CDREAD	Puched card input.
3.	MREAD	MT-Data input.
4.	MWRIT	MT-Data output.
5.	DREAD	Read data from disque.
6.	DRITE	Save data into disque.
7.	MTDATA	Data search from MT.
8.	STABLE	Stability calculus.
9.	ELENG	Element length calulus.
10.	FLEXMX	Flexibility matrix generation.
11.	TGRAH	Topological maps.
12.	TRUSS	Truss calculation.
13.	DEFORM	Displacement calculus.
14.	STRESS	Stress calculus.
15.	MAXDEF	Max. or Min. Displacement.
16.	MAXSTR	Max. or Min. stress.
17.	MAXRES	Max. or Min. response.
18.	EIGEN	Eigen values and modes.
19.	PRINTD	Input data service list.
20.	PRINTF	Loading condition list.
21.	PRINTU	Displacement list.
22.	PRINTS	Stress list.
23.	PRTUMX	Max. or Min. displacement list.
24.	PRTSMX	Max. or Min. stress list.
25.	RNGN	Response trace on time.
26.	WEIGHT	Accumulated weight.
27.	INFLIN	Influence lines.
28.	BM	Function on bending moment.
29.	BD	Function on deflection of beam.
30.	RESP	Function on unit response.
31.	IXIYIZ	Moment inertia of closed section.
32.	GRAVTY	Area, gravity point, etc.
33.	MOHREN	Stress circle analysis.
34.	GRAPHU	Graphical display of skelton.

Ⅱ. Set of Random Process Analysis.

1.	MEANS	Mean value calculus.
2.	RMSQR	Root mean square calculus.
3.	SHIFTC	Circular shift of array.
4.	ARROT	Rotation on XY plain.
5.	ARMOVE	Parallel move on XY plain.
6.	DRIFT	Eliminate DC drift.
7.	INVERT	Array rearrange bottom top.
8.	ORDERL	Array rearrange from big.
9.	ORDERS	Array rearrange from small.
10.	CONVLT	Convolution integral,
11.	FTRANS	Fourier transform.
12.	FFTS	Fast Fourier transform.
13.	COSTW	Fast generation of cosine.
14.	RNWAV 1	Generation of random wave.
15.	RNWAV 2	Generation of random wave.

16.	MAXMIN	Max. or Min. value in array.
17.	POWER 1	Power spectrum.
18.	CROSS 1	Cross correlation.

Ⅲ. Graphical presentation set.

1.	INTPT	Linear inter/extrapolate.
2.	SPLIN 1	Spline smoothing of array.
3.	SPLIN 2	Spline smoothing in plain.
4.	BCURV	Bezier smoothing.
5.	TCURV	Smoothing by second degree.
6.	KOTEN	Crossing point of two lines.
7.	RYOIK 1	Logical condition left or right.
8.	RYOIK 2	Logical condition inside or out.
9.	DOVERT	Distance between two points.
10.	OUTLIN	More outside tracing.
11.	PROJCT	Projection.
12.	PERSO	Perspective projection.
13.	PERS 1	Perspective Projection.
14.	HATCH	Hatching lines.
15.	VGRAM	Vibrogram presentation.
16.	CORGRAM	Correlation presentation.
17.	LPDOT	Dot matrix presentaion.
18.	VFRAM 1	Variable frame projection.
19.	SOLMOR	Display of solid figure.
20.	CTLKTL	Display of contour line.
21.	LOGAX	Logarithmic scaling.
22.	KANJI	Japanese letter presentation.

Table 5. Instrumentation.

Real-Time Analyzing System, an Example Set-up.

1. A 4-channel reproducing data recorder with variable tape speed (SONY).
2. 3-channel DC-Amplifiers.
3. A band-pass filter.
4. CRTs covering 3 channel observation on scopes with lasting imapge tubes.
5. A Real-Time Correlator (TEAC) with monitoring CRT and a listing recorder.
6. A Real-time Spectrum Analyzer with monitoring CRT and a listing recorder.
7. An analog-Digital-Converter (ADC) including tape output.
8. An oscillograph for monitoring purpose.

Data Transcriber Set-up.

1. A micro digital computing system with 16 K. words core, operated by stored programs.
2. A console typewriter or an operating keyboard.
3. A cassette tape reader for digital values.
4. A paper tape reader.
5. A magnetic tape controler with two tape decks for read/write purpose of IBM 360 series compatible tapes.
6. An analog tape reproducing player for open reel tapes.
7. An analog tape reproducing player for cassette tapes.
8. A Multi channel ADC.
9. Graphycal monitor using CRTs, which may produce hard-copies, if possible.
10. A magnetic disque for buffer storages.

Instrumentation Examples for Vibrational Set-up

1. 4-channel data recorder (SONY).
2. 3-sensors of a vertical and of two horizontal directions (AKASHI).
3. 3-channel DC-Amplifiers.
4. 3-CRTs for monitoring (IWATSU lasting image tubes).
5. 3 set of extension cables with connecting terminals.
6. Some connecting cables between instruments with BNC connectors and others.
7. An engine generator for AC tools and AC cables with terminals.
8. Transceivers.
9. Timing clock generator and signal switches for synchronized tests.
10. An Oscillograph with 4 channels for monitoring purpose.
11. Cameras, movie pictures, telescopes, repairing tools, circuit testers, etc.
12. Magnetic tapes for the recorder, oscillogram papers for the oscillograph, films, dry batteries, etc.
13. DC power supplies are built in a car. AC/DC voltage regulator is occasionally necessary.