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Safety Inspection System of Existing Structures

Système d'inspection pour la sécurité des structures

Inspektionssystem für die Sicherheit von Bauwerken

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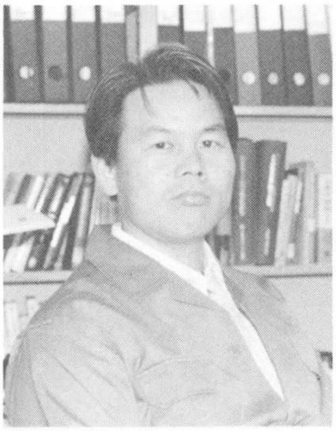
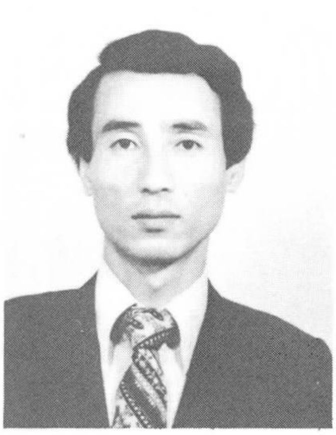


Tadaaki Tanabe, born in 1940, got his Dr. of Eng. at the University of Tokyo, worked with Reese Consult. Eng. in USA and then at the Central Research Institute of Electric Power Industry, Japan. He joined the Nagoya University in 1981 for the research of concrete structures.



Masafumi Kato, born in 1947, got M.Sc. at Nagoya University. He worked at the Technical Research Laboratory, Takenaka Co., Ltd., Japan. He the joined Nagoya University in 1978. He is now working on structural measurement systems.

SUMMARY
Over the past 18 years, the authors have been involved with the analysis of vibration data obtained from existing structures. Recently some comparison have been carried out on data measured twice within ten year period on the same structures. The method of statistical analysis is established into an inspection system which makes graphical representations with the aid of standardized computer programs.

RESUME
Forts d'une expérience de dix-huit ans dans l'auscultation des ouvrages soumis à des vibrations, les auteurs ont entrepris récemment la comparaison systématique de séries de mesures effectuées sur un même ouvrage pendant une période de dix ans. La méthode d'analyse statistique utilisée a été généralisée pour être introduite dans un système d'auscultation qui fournit des résultats graphiques à l'aide de programmes standardisés.

ZUSAMMENFASSUNG
Seit 18 Jahren befassen sich die Autoren mit der Vibrationsanalyse von Bauwerken. In den letzten Jahren wurde eine Methode ausgearbeitet, welche die am gleichen Bauwerk gemessenen Daten von zwei 10-Jahresintervallen vergleicht. Mit der Methode der statistischen Analyse wird ein Überprüfungssystem festgelegt, das die Resultate graphisch mit Hilfe des Computers darstellt.

1. INTRODUCTION

It is usually a problem of man's sensibility to comprehend the safety of something. One says it is safe and another insists it is dangerous. As to the existing structures of civil engineering, no practical reasons could be found for repairing or reconstructing until some unfavourable failures would occure. For an instance of aseismic design of structures, the theory will be proved when an earthquake fortunately attacks a structure as an expected magnitude, but our interests are laid how existing structures are safe or not at present before an earthquake attacks them. Therefore, real vibrational characteristics are needed to evaluate the theoretical assumption.

Formerly, the measurement of natural frequencies is beyond of practical procedures because structures are too large to be excited by a shaking apparatus. Thanks to the recent development of electronic techniques, faint vibration is able to amplify for data recording. Random vibration, which is ever ignored as nonsense, has become fruitful data for the statistical analysis. This is possible only by the use of an electronic computer.

Our first systematic test was carried out in 1968 along with a load capacity test of an old bridge. Strain measurement was carried out under traffic control in midnight. However, our measurement of the bridge vibration was carried out in daytime under usual traffics. The method aimed not only the safety of field works, but also to develop a new non-destructive testing of existing structures. It was found that our procedures are easy and safe for field works, reasonable on costs and of good accuracy for estimating natural frequencies of the bridge.

The Jpapn Expressway Corporation is ever earnest to test bridge vibration in order to take the data for a loading design. On occasions of new bridge construction, a huge shaking apparatus is set for measurement. It is, however, more expensive than our method, but the authorities are not allowed to abandon the machine instantly. So that we have had several occasions to cooperate the tests, and which proved precise agreement between two results.

Since 1969, the corporation constructed an expressway for Nagoya from Tokyo with many bridges of various shapes. From the point of view of our research interests, we were allowed to test them before public uses. Random excitation on bridges was done by a heavy duty truck under construction work. In 1981 after eleven years, We tested the same bridges by the same method at the same positions and under usual traffics.

Experienced by a lot of tests these years on many structures, we have become a counsellor of structural safety how they are. Most of requests are concerned, more or less, with the interaction of structures against foundations, because structures are never built under standardized earth condition. For the sake of mutual understanding among clients, a standardized method is required to show them the facts clearly, and to compare relatively how it differs or meets. We named the method as a safety inspection system.

The system is consisted of a measuring system, a data management system aided by computer graphics, and some knowhows to make engineering decision. The first two systems are able to standardize physically as hardwares and softwares. The last article depends on many examples ever experienced.

Recently some comparison has been carried out between the data of structures that measured twice with ten years interval; bridges as mentioned above and a tall concrete chimney, respectively. We will explain several interesting topics obtained by our measurements in the following two chapters.

2. CHARACTERISTICS OF BRIDGE VIBRATION

2.1 General properties

No structures vibrate more analogically to the theoretical assumption than bridges. There is a relationship between the natural frequency and the length of span due to the design specification that limits the maximum deflection against bridge span.

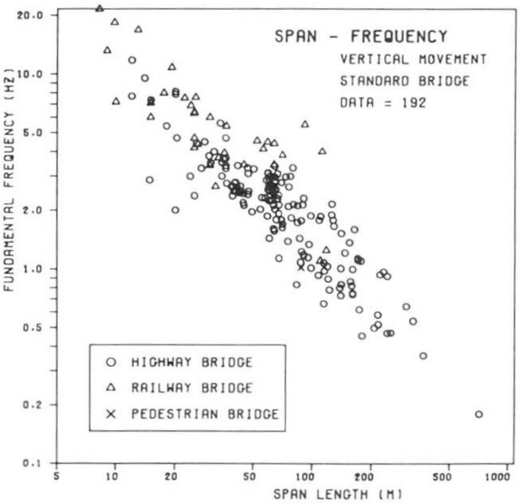


Fig.1 Relationship of fundamental frequency to span.

Fig.1 shows statistical distribution of natural frequency along bridge spans summarized from many reports. As a matter of theoretical facts, a maximum value of static deflection due to its own weight is proportional to the square of period of its natural oscillation. That is 25 cm to 1 second, 1 metre to 2 seconds, and so on. The fact meets approximately with any kind of vibration even in horizontal direction, where the static deflection should be calculated by loading of its weight horizontally. This is the reason why a natural frequency is an important parameter to know the structural stiffness.

2.2 An arch span with less horizontal stiffness

Unexpected low frequencies are often detected in horizontal direction on a long girder, because a bridge is basically designed to bear the vertical loading. Stresses are checked in design against horizontal as well as longitudinal loadings, but nothing is specified for those movement.

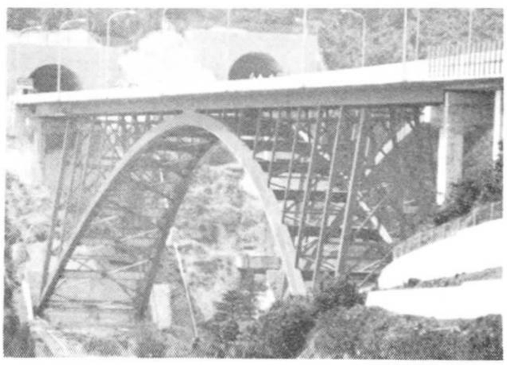


Fig.2 An arch bridge that caused lateral vibration.

An expressway(Fig.2) was constructed over a valley with a 160 metres arch rib. Gentle breeze is enough to excite the horizontal vibration with a period of 1.3 second. Moreover, longitudinal movements were eminent at both bridge ends. Because of 2.4% down slope of roadway, the lower end moved greater than the upper. An erection engineer confessed us that the bridge should have been designed to be more strengthened for the sake of concrete casting. The joint with a bearing system was damaged soon after public uses by the twisting of the floor system in a horizontal plain.

2.3 A failure test of a prestressed concrete span

When a bridge is losing its bearing capacity, natural frequencies will decrease relatively. An interseting failure test was carried out in 1980 on a small prestressed bridge over an expressway. It was removed for the sake of a new bypath construction afterwards.

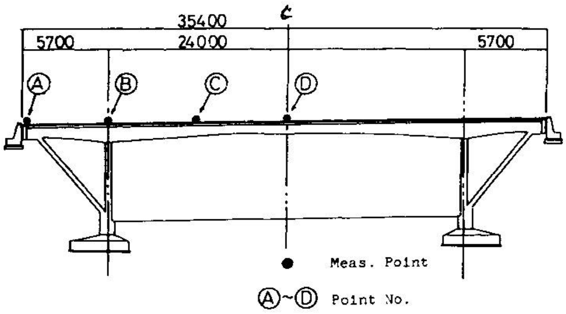


Fig.3 An over-bridge for load capacity and vibration tests.

An oil jack supressed a girder with anchored rods. After every release of loading, the natural frequency was measured. It decreases as 5% at 60% loading of the maximum capacity and it reached to 17% at 95% loads. The lateral vibration decreased as about 8% at final stage.

Usually, a structure has several number of frequency modes. The lowest cycle is much concerned with the bearing capacity of a structure. The higher modes are little affected relatively to the first mode. A spectrum analysis is, therefore, worth to know the decrement of a principal frequency among others.

2.4 Long term surveys of expressway bridges

As introduced in the previous chapter, the data of the expressway bridges were taken twice with eleven years interval. The data were compared carefully from the point of view on frequency decrement. Steel bridges showed no remarkable difference, but the second test was unfortunately carried out after strengthening works of floor systems which damaged by about eightyeight million traffic vehicles during ten years, where heavy trucks increased as about 30% to 48%. The concrete slabs were strengthened by intermediate stringers.

On the contrary, a prestressed long bridge showed about 5% loss of value on a principal frequency. The bridge is consisted of three each two spaned continuous girders. A pier with 31 metres height is fixed to a girder forming a T-shape with each 90 metres span. The bridge took any mending but asphalt pavement. The test results do not seem serious on accounting other properties, but it is recommended to test again after more ten years. We have several other concrete bridges for the second test.

2.5 Medium span bridges

A lot of short and medium span bridges are important to test their security by comparing natural frequencies and damping parameters. We have little for twice tests, but many of various ages. A simple prestressed girder bridge is so elastic at its completion that a truck driver of field works once asked us its security. Medium span highway bridges with about 50 metres are often notorious for public users because they feel uncomfortable vibration.

A man feels very sensitive when vibration ranges about 3 to 4Hz, which is the principal frequency of such bridges. As far as they are notorious, they seem to be safe at present because they have small values of damping parameter. Characteristics of vibration on small bridges are much affected by the composite system with piers, abutments, foundations and filling earth.

Many people think that abutments never move dynamically, however, it is natural to observe some degree of vibrations, in which we found rarely unreasonable movements. Generally speaking, a new structure seems to be laid softly on the earth. It becomes hard as if it is tightly connected with the earth. This is comparatively observed in the spectrum analysis as the increase of high frequency elements. An abutment, for an instance, showed lateral movement when measured at its completion, however, it was detected little after ten years.

Another abutment is situated at the foot of a hill as if it retains the landslide of the hill. The vibration was observed when a heavy duty truck ran around the active area ranging to about 200 metres distance. The bridge was reconstructed to escape from this area.

Japanese civil engineers are very often requested to construct a structure on the soft alluvial layer. Short span bridges are then designed for saving the large concentrated reaction against the earth. Hammer action on a pile gives good information to know the characteristics of earth and to decide whether or not the pile has sufficient bearing capacity during works.

3. A STUDY ON TALL CONCRETE CHIMNEYS

3.1 A breaf history

In 1914, a mining company constructed a tall concrete chimney with 155.4 metres near HITACHI city by the national technology. In 1916, another concrete chimney, 165.6 metres, was erected at a smeltry plant in KYUSHU by the international contract. The latter was the tallest in the far east. The chimneys are ever being in use more than a half century without any mending, or almost impossible to do something. The tallest chimney was attacked by twice earthquakes in 1968 and caused 12 metres loss of height by the second earthquake.

The mining company asked us in 1969 if there could be any method to test its safety by non-destructive inspection. We had no prospects at that time that vibrational measurements might be effective to sound chimney safety, however, it seemed worth to do something on picking up vibrational phenomena. Since the chimney is in dangerous state to climb up over the shaft, sensors were set at the basement. Shaking on a chimney was expected by the natural wind due to von Kármán's vortex excitation.

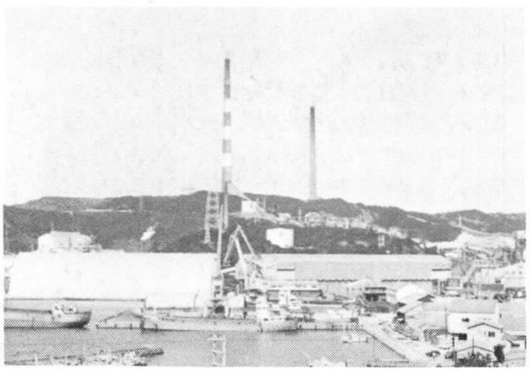


Fig.4 The broken old chimney and the new chimney, KYUSHU.

It was our first experience to take data on such a structure, but the data were in good quality for the statistical analysis. The same procedure was taken at the first chimney in 1974. Moreover, the second measurement was carried out in 1981 on that broken chimney after 12 years use. By that time the mining company erected a new chimney, 200 meters height, in 1974 in the same yard. It was also measured. A contractor of the new chimney had carried out a vibration test at its completion by a shaking apparatus, therefore we can make assess our method relatively.

3.2 Natural frequencies

We had feared that the sensors would not work at the bottom of chimney. Thanks to the calm environment, sensors catched faint random vibration that were breathing whenever the wind blew. The data were identified to have several eminent frequencies. The running spectra were displayed in the first time for our analyses, successfully. The data were random, however, we could find out possible frequencies on the graphical pattern. One of them is swaying to and fro along time axis. It is supposed that the chimney has a little different bending stiffness in two direction. Another one varies its intensity so as to appear and disappear.

The broken chimney had its principal frequency as 0.39 Hz when measured in 1916 by a seismogram. It showed 0.31 Hz in 1969 after the loss of height by earthquake, and 0.30 Hz after more twelve years in 1981. The second natural frequency, about 1.2 to 1.7 Hz, dropped as about 5% during 12 years, however the third and fourth increased a little.

In order to compare theoretically, an elastic model is assumed with respect to the rocking basement. The numerical results teaches us that the first mode of vibration is delicately affected by the condition of the earth. On the other hand, higher mode of frequency could be more concerned with the materials of chimney shaft.

The first natural frequency of the chimney vibration is not so important as that of a bridge. It gives a reference value for static stability standing on the earth. A series of natural frequencies are to be compared relatively where the first one is reduced into a unit. The series becomes as about 1, 4, 10, 18, 30, respectively. Such series are calculated by several theoretical models so as to demonstrate the measured values. The data of other two chimneys are reasonable. The broken chimney seemed to have less effective height because the third and fourth frequencies are relatively large.

3.3 Discussions on the safety

We were requested by the owner of the broken chimney how it be. Materials test was also carried out on the fallen specimens. The dynamic response was calculated by a theoretical model against the random excitation of earthquake. It teached us that the broken chimney should be assumed as not an elastic beam along the whole shaft, but as to be a stacked block with little strength over high shaft. We concluded in 1969 that the chimney would cause loss of height about ten or twenty metres by a next strong earthquake, but would remain safely along the sufficient height.

Comparative studies among three concrete chimneys have clarified the characteristics of vibration more practically. When a chimney is elastic, it has several frequency modes. The highest frequency which could be observed is about 10 Hz, and this plays an important roll for possible chimney failure against an earthquake. The first natural frequency should be considered as a parameter for static stability that cause a chimney turn over. A series of natural frequencies will teach the distribution of stiffness along the shaft.

Our studies have been supported by the powerful aid of an electronic computer. For instances, the running spectra are able to calculate practically by the FFT method. Unless shown graphically, we could not identify the higher frequency mode definitely. The FEM helps much for theoretical models.

4. MEASURING SYSTEM

4.1 Concepts for the system

Vibrational data of a structure are valuable only when they are measured at the structural site. Since we have students, field measurements should be safe and easy for their collaboration. Moreover, it is desirable not to disturb field works under construction or daily uses of a structure. A precise instrument designed for the laboratory use is not always suitable for rough circumstance in the field. Formerly, one of the most important tasks was to keep the reliable electric power supply for the instruments. Sensors, for an instance, apply a moving coil system which generates voltage output without any amplifiers.

Since 1960th, a battery driven instruments has appeared that suits for a movable laboratory in a motor car. Among several fabricators, we adopted a SONY data recorder by the following reasons. It uses a standard audio tape which is able to purchase at any place. The company will keep the same specification for a long period. It is expected to exchange a data tape among many researchers, and so on. We have about 200 original data tapes during these 15 years.

A measuring system is basically consisted of three sensors and a data recorder with 4 recording channels, the fourth of which is for voice recording. Two or more same but absolute systems are recommended to make a synchronized measurement at several positions for the sake of field workability.

4.2 Self-recording sensors

A portable sensor is sometimes required at a distant position from an equipped car. For an instance, at the work site of a long span bridge, a sensor is equipped with a cassette recorder. A fabricator of oceanographical instruments makes us good advices for our ideas, however, it costs a little expensive yet.

Accounting the recent development of a micro-processor with large memory chips, a satelite data accumulating system is becoming practical with reasonable costs which could enough to pay for extension cables. The vibration data are directly recorded into a cassette tape or a disquette as digital values. A personal computer makes intelligent procedures even in a field office. Such a system will become popular in near future.

4.3 Use of a vibration level meter

Standardized by ISO, a vibration level meter is able to use as a sensor. The meter indicates, however, mean magnitude of vibration that may make feel a man's sensibility. It is useful to know at a position instantly whether or not it vibrates. As a preliminary survey of the chimney, we had checked by a meter that the chimney basement was certainly vibrating.

For the inspection of structural stability, a natural frequency is reqired. A low frequency less than 1 Hz is difficult to feel physically, and this is more important when a structure or a structural member becomes dangerous. As mentioned in the article 2.1, possible maximum deflection of an elastic structure depends to its natural frequency, therefore a very simple frequency meter shall be fabricated along with a level meter.

5. SOFTWARES FOR DATA ANALYSIS

5.1 BASIC language interpretor as a manager of programs

Several number of libraries on computer programs are prepared for our researches, where usual structural analysis by FEM is included for estimating the dynamic behavior of a structure. The VIBDAP, vibration data processing, is a program package for data handling under the support of a graphic library. Storage and retrieval of vibrational data are of important works. It needs special peripherals for digitalizing the analog records into the computer readable formats.

In order to carry out the inspection reasonably, some standardized procedures are required so that various results are relatively compared or emphasized among a lot of data. On the other hand, special analysis is very often required on every case when a man is interested to look over the data from the different stand point. His demands could be impatient for waiting a new computer program. For instance, looking at a graphic screen, he may ask a figure instantly more enlarged, with different scales, or being transformed by functional relationship. For this purpose, we use a language interpretor 'NUCE-BASIC' as an interactive processor for the management of various procedures.

Considering on the explosive increase of computer users who learned BASIC language on a personal computer, any of problem oriented programs could become more convenient if they are controled under a BASIC language. A user is to learn only special commands which are prepared by an engineer for additional procedures. Such idea is possible whenever a BASIC language processor allows to refer other program units. NUCE-BASIC is composed by standardized FORTRAN and able to work alone interactively as like that of a personal computer. Its principal purpose is, however, to make other FORTRAN sub-programs easy to refer under BASIC statements.

Another processor 'COMMAND-EDITOR' is prepared for an engineer who composes a problem oriented BASIC lnaguage interpretor with additional FORTRAN sub-programs. This is a generator of a program which ensures to refer additonal sub-programs with necessary arguments. For instance of a SUBROUTINE SUBA(A,B,C), BASIC statements allows to say SUBA A,B,C. A function sub-program such as FUNCB(X,Y) is able to use in mathematical expressions. Well known libraries such as of the TEKTRONIX's graphics are useful whenever they are supplied as a set of sub-programs. Accounting of the user's manner of language, keywords could be referred by alias names.

As a supervisor of research activities on computer programming, we have been troubled many years for making better manuals so as to collaborate together among program developers. It is cumbersome to comprehend manuals which are supplied by a programmer with not always the kindest manners. The idea of NUCE-BASIC is helpful to share the duties among engineers, program developers, supervisors as well as users.

Common users are requested to have the knowledge of a BASIC language in the least sense, which could be trained by a personal computer without toil. They are informed by an engineer that the current processor is intelligent with additional commands, specification of which is only the manual to be referred.

A program developer is to compose several sub-program units independently for definite procedures. He may be asked to decompose sometimes a large program unit into a set of simple procedures. Rules for programming, as used in common software companies, become more understandable whenever he comprehends his shares to contribute one of BASIC commands. On the contrary, an engineer is to take care of syntactic design so that a user is easy to operate on his keyboard.

5.2 Usage of computer graphics

Our safety inspection system is basically supported by visualisation techniques aided by computer graphics. Since vibrational phenomena are invisible, nobody could exactly understand them unless he might be experienced again on a shaking bed. But his understanding is subjective to his personal experience. Several properties such as natural frequencies and damping parameters are decoded for the sake of mutual understanding among engineers who are trained how they mean.

Since graphical media are able to inform a lot of properties at a glance, various kind of graphical reports will help to inform the vibrational phenomena objectively. However, they seem alike the art of impressionism to a client who asks the safety of a structure. It is required, therefore, to show him a lot of examples how they meet together or differ relatively so that he is convinced on the facts measured.

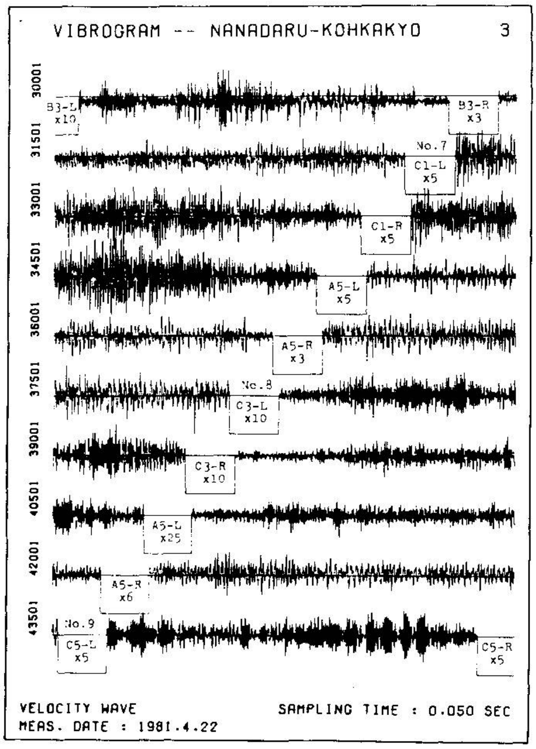


FIG.5 Catalogued oscillogram.

An oscillogram gives basical information on the vibrational data. All of digitalized waves are drawn graphically so as to edit a catalogue of measured data. An A4-sheet has length of ten minutes records with reference counters of digitalized values on a magnetic tape, by the aid of which any position of data groups may be extracted for another analyses(Fig.5).

The catalogued oscillogram is a long continuous record, physically. But it is consisted of many logical records which are terminated by DC signal clearly different against the wave data.

The tape has several files. At the beginning of each file, literal information is added on the measurement as well as the data format so as to help the file read from a program.

The first impression is very important as like looking at man's face to estimate the randomness on an oscillogram. Usually, a new elastic structure gives fine images. It becomes rougher and less active after years. Concrete structures seem to become older than steel structures.

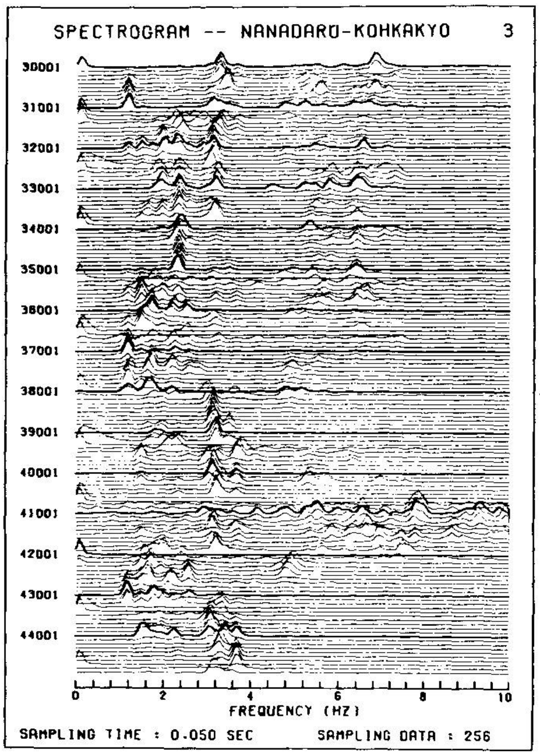
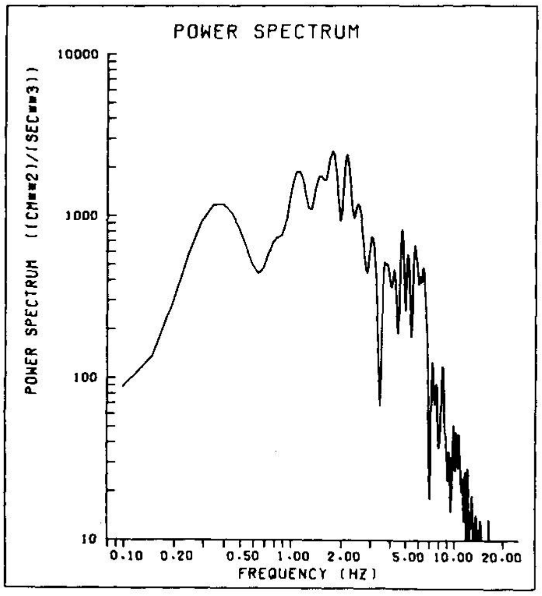


Fig. 6 Running spectra

EL CENTRO NS IMPERIAL VALLEY



SAMPLING TIME = 0.020 SEC SAMPLE DATA = 1024
SMOOTHED SPECTRA BY HAMMING WINDOW 5 CYCLES
START COUNTER NUMBER = 1

Fig. 7 A spectrum drawn with logarithmic scales.

The spectrum analysis is one of the powerful tool in order to extract the periodical properties that are hidden in randomness. However, it is delicate with respect to the numerical procedures. From the administrative point of view, running spectra are convenient along with the catalogued oscillogram.

Without accounting illogical boundaries between data, spectra are calculated at every 4 seconds using each 256 samples by the FFT method. The spectra are drawn sequentially from top to bottom on an A4-sheet so as to correspond to the oscillogram.

Each line of spectra is not so accurate as to determine the periodical properties, but it helps to say that this peak is true and the other may be false as error, because the true peaks are found at the same distance along the frequency axis(Fig.6).

More precise spectrum analyses are carried out on a series of records chosen from a catalogue. This is, so as to say, static against running spectra. There are many possible ways on the graphical presentation, because a result will make quite different impression if, for instance, scale axis is transformed logarithmically. Several methods are standardized for the sake of relative comparison among records as well as to the theoretical background.

For the aids of engineering decision making, various kinds of measures or scales are prepared graphically. A simple pendulum with a spring and a dashpot is assumed as a theoretical dynamic model in the first analogy of a measured structure. Fig.7 shows an example of a spectrum which has a pendulum system with a period of about 3 seconds and a damping parameter of about 0.2, because an overall shape of the spectrum seems to be overlaid on a small hill. Since the axes are drawn logarithmically, graphical calculation is able to extract the effect of such pendulum using the theoretical measure. In this example, we concluded that it is the properties of the ground on which a structure stays.

5.3 Interactive handling

Well educated knowledge is required for an analyst of structural safety. He must know some previous information on a respective structure how it may behave dynamically. There will appear many reasonable peaks on a spectrum, but he must decide them whether or not they correspond to those of theoretical prospects. One of natural frequencies could be found faintly in a record or be magnified in another record. He then extracts partial length of records from the catalogued file in order to carry out more precise investigation.

Looking at a graphic screen, a record created in an array V(N) is displayed by a command under the BASEC interpretor, Moreover, several commands are served for interactive procedures (Fig.8). Each procedure is so simply programmed that an analyst can choose any possible transformation on a record, while he can observe the record graphically at any moment. The characteristics of graphical shapes is more important than the numerical values during the procedures. He can enlarge or reduce the values instantly so that the record may become better graphical quality. He then tries to find out some typical graphical patterns which coincide with those of theoretical ones.

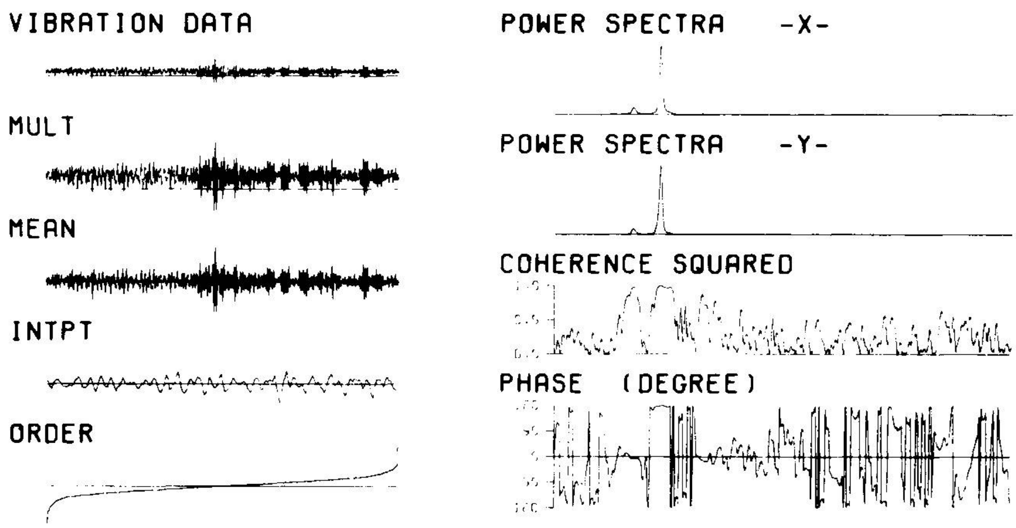


Fig.8 Examples of interactive procedures of vibrational data.

The above interactive procedures are usually carried out on the analog record by expensive electronics instruments while looking at a cathode ray tube. A phenomenon runs on a CRT dynamically. Therefore, it needs careful preset on the instruments throughout the measurement and the analysis. In order to avoid mishandling on an instrument, this is required to be automatic, clever and consequently of high costs. Whenever the analog records are digitalized, we need not hasten to catch up with the time dependent phenomena.

The original record should be taken correctly by measuremts, but a few instruments are enough to ensure the field works. A sensor, for an instance, may have non-linear response against forced vibration. An equalizing amplifier is required from the sense of analog procedure. But, it is unnecessary because the same procedure is carried out digitally. Prior to the digital procedures, however, the response properties of a sensor are given as the least information. This the reason why the field works are carried out by reasonable costs.

As found in common BASIC interpretor, the NUCE-BASIC allows to run after programmed statements. This is a local program which a user may compose. A user is not, however, obliged to do much on his keyboard as a programmer, because many preset commands are supplied by FORTRAN written sub-programs which are able to refer directly or indirectly in BASIC statements.

Practically, a user has at first little idea how a datum should be processed. He is allowed to try anything on his keyboard until he finds a reasonable result. A log makes a record, if necessary, of his keyboard input so that he can remind his jobs how he did. He can reuse the log as texts of BASIC statements by the least effort. Such procedure is applied to all other activities of computer aided design.

5.4 Methods to determine values

5.4.1 Natural frequencies

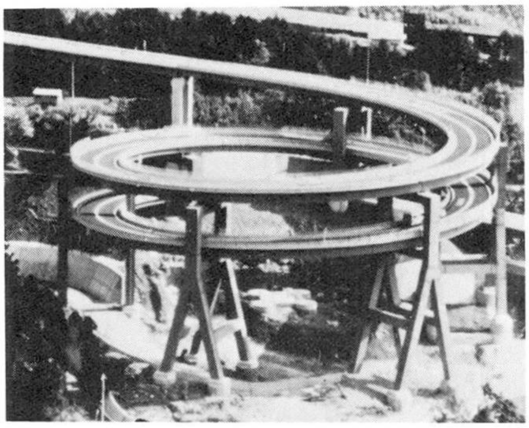


Fig.9 A spiral bridge.

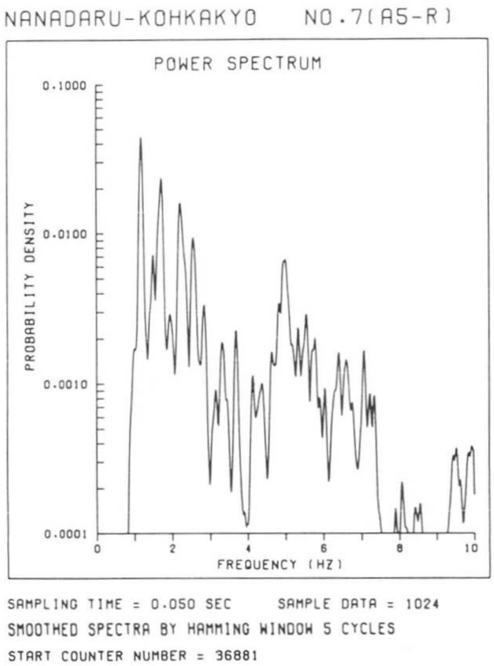


Fig.10 An example spectrum having many peaks.

It is easy to find a peak and to read its frequency on a spectrum if there exists only an eminent hill. It is also possible to point out several peaks by a program, however, unreasonable peaks due to noise are chosen out interactively only by visual aids looking at a graphic screen.

Many natural frequencies are found on a spatial structure. Two or more synchronized measurements are required at several positions where each vibrational mode could be emphasized. Fig.10 shows an example spectrum with many peaks obtained by the measurement of a spiral road bridge(Fig.9).

Correlation is then calculated between two data and compared graphically. In order to identify a value which is possibly subjected to a frequency mode, some discussions are necessary with taking account of amplitudes, phases as well as theoretical estimation.

We have identified six elements of spatial frequency mode where sway, twist and oval deformations of the spiral structure are included. Four other frequencies are identified to be subjected to local vibration of girders which are sustained by columns. Numerical calculation by FEM showed good agreement, therefore the structure is confirmed it is safely designed and constructed.

5.4.2 Damping parameters

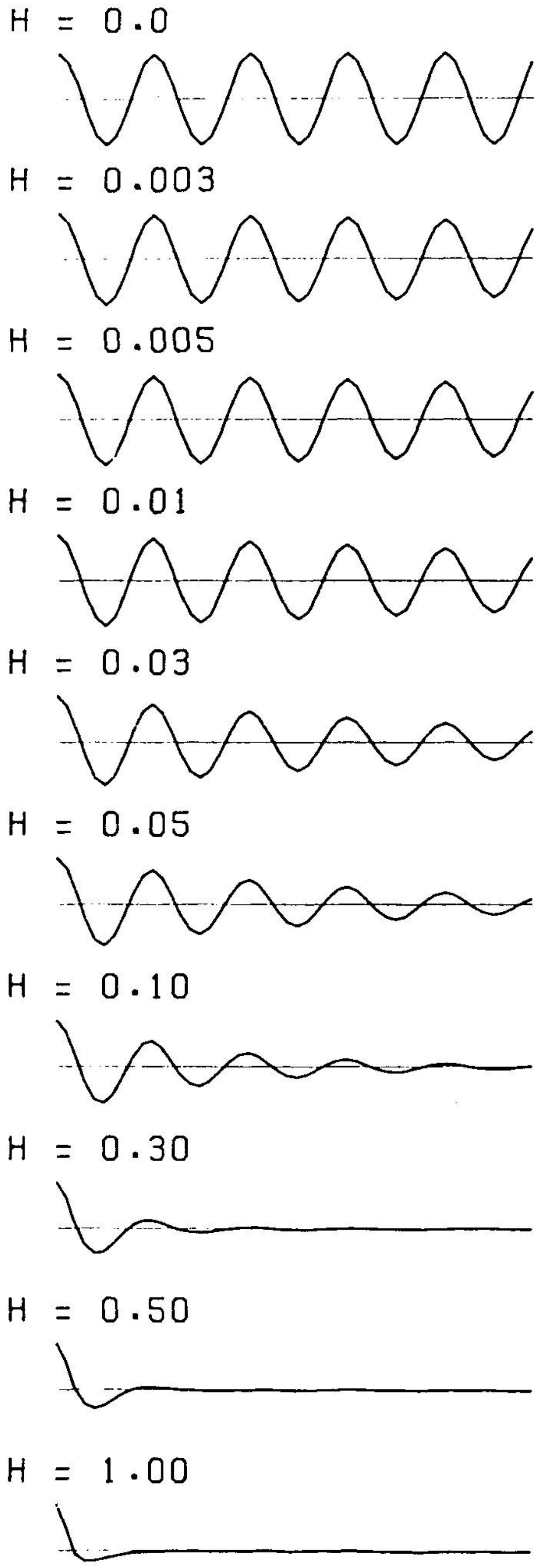


Fig.11 Response of a simple pendulum with a dashpot.

A damping parameter is one of the leading values to evaluate a structure whether cohesive or not against dynamic loading. As for practical procedures, three methods are used together or respectively. One is a half power method that evaluates a damping parameter from the width of a spectrum hill at a half of its height.

The second method is more graphical than the above. A spectrum should be drawn by the logarithmic scales both on power and frequency axes. Looking at a graph, we are going to find out several hills, the shapes of which may be proportional to those of theoretical patterns. An example is shown in Fig.7.

The third method is also graphical. An auto-correlation function is calculated from the vibration data. We use the properties of this function that it is nearly proportional to the free oscillation of a structure excited by an impulse. Compairing to the theoretical patterns, which are prepared graphically, a damping parameter is decided as of the most proportional pattern. This method is very practical to identify a high cohesive damping parameter(Fig.11).

An auto-correlation function is convenient practically to compare dynamic response among different structures or different occasions on the same structure. When a structure is new and elastic, a fine sinusoidal figure is obtained. Something spoiled after public uses, such as increase of cracks on concrete floor of a bridge, then becomes the shape of function more steep and less periodical.

The behavior of earth structures is interesting. Vibrations are measured under piling works or by artificial excitation of a heavy duty truck at the site. The soils seem to become more elastic and harder after years. We found an example case at a bridge foundation which seemed in good settlement during ten years.

5.4.3 Error correction

As far as the statistical analysis is concerned, a probable value may not true. It may emphasize unrealistic images. We must be so clever as to identify the facts out of ghost images. There occure many errors by the following causes;

a) non-linearlity of sensors,
b) inappropriate sampling,
c) inevitable noise,
d) numerical errors,
e) human errors, and so on.

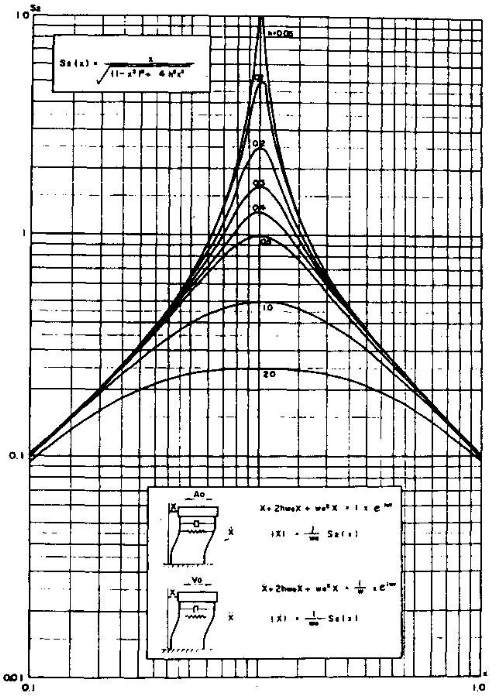


Fig.12 A monogram of response.

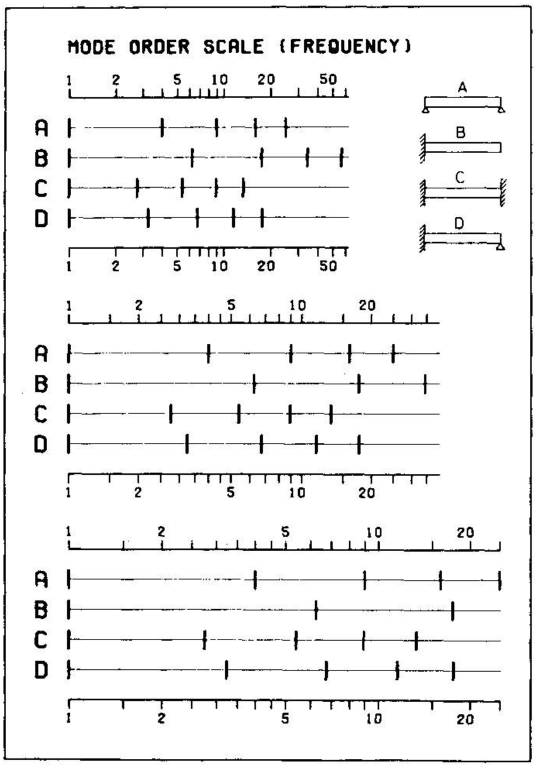


Fig.13 Frequency scales.

The first two items are carefully considered on the design of a measuring system to cut off the high frequency level. A velocity sensor prefers rather than an accelererometer. Some degree of non-linear properties are visually detected and corrected interactively as shown in Fig.8.

A figure of a response spectrum is important whenever it is drawn on logarithmic scales, because it is able to use as a sliding scale on a computed spectrum to subtract the effect of a sensor.

The same method is carried out by a transparent paper on which Fig.12 is drawn. Fig.13 is measures that graduates the natural frequencies of an elastic beam under several support conditions. This is used to find out some possible peaks on a spectrum.

The item c) is an important datum that should be recognized clearly in the analysis. A spectrum shows, for an instance, very sensitive peaks against partial amount of data, but it becomes not always correct even when a sufficient length of data are used for calculation. A graphical method suits therefore to tell us some possiblle property without a word. The use of colour graphics is under consideration in our research activities.

In order to avoid errors by mishandling of data or by misunderstanding, standardized procedures are recommended. In addition a lot of experience helps to correct misunderstanding. By our experience, the data measured in the past are often reviewed when nearly the same structures are tested. Theoretical analysis has become practical in recent years. The mode of frequency, for an instance, is often misunderstood as other.

6. CONCLUSIONS

In order to make administrative decision on the safty of a structure, there is no measures to compare the remainder of its life. If unexpected unhappy occures, man says 'it happens at its centenary'. A boy often puchases a tiny tortoise without living a few days. His father consoles him that it should have had a hundred years old.

Since structures are never mass produced as machinery parts, the statistical method of design criteria will not ensure the safety of a structure at its circumstance. Therefore, every structure should be inspected at its site. As like a medical doctor inspects a human body through a stechoscope, safety of structures could be assured by means of vibration tests and data processing. Same as the word 'medical electronics', systematic setup of structural electronics will be required in both hardwares and softwares.

A lot of information should be summarized for the inspection not only by the vibrational measurements, but also by other non-destructive methods. Comparative studies among the facts teach us only practical knowledge on the structures. Standardized methods are therefore necessary so that data may be relatively compared.

Vibrational phenomena are rather difficult for common people to understand the characteristics with respect to structural safety. We have introduced several examples in this paper how the measured data are analysed by the use of an electronic computer.

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