Measurement of the Fluctuation of Structures by Reflection of Laser Beam. I

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Measurement and analysis of fluctuations of structural objects are useful for monitoring the condition of these structures. In this paper, we propose a laser beam technique for studying these fluctuations, and report some results of our investigations, including an observation of forced vibration of a refrigerator, rotational frequency of an electric motor, and the appearance of a fluctuation in rotational speed due to fatigue. This technique has also been applied to real structural objects, a resonance of a automobile due to rotation of the engine, and intrinsic vibrations of buildings. Standard techniques used in fluctuation analysis are compared in a detection of an abnormal state of an electric motor. Data processing techniques of higher-orders are tested. Fluctuation analysis should be an important objective of analytical chemistry. The results obtained with this laser beam technique should form a useful collection of data regarding fluctuation analysis of various objects.

1 Introduction

The study of safety is indispensable for the healthy progress of human society. Thus far, this study has taken the form of safety engineering in chemical, mechanical and civil engineering. In today's large, complex technological society, a great deal of effort is required to establish effective safety guidelines and controls.[1] However, many fields still lack basic, comprehensive safety studies.[2] To promote the study of safety, we organized the Society for Safety Study in Japan, and have held several forums and workshops.[3]

Our safety studies are organized from three activities, measurement and analysis of the fluctuations in structural objects, construction of the databases from safety information in literatures, and invention of the software systems for the detection of abnormality and for the safety control and risk management. The interplay of these three activities is expected. The education for safety control and risk management is also important. The present report regards the first.

In the study of the safety of structural objects, such as buildings, bridges, airplanes and turbines in electric power plants, measurement and analysis of the fluctuations of these objects are fundamental. The fluctuation of a structure is defined as the natural change in the location of any point of the structure. The purposes of the present study are, first, to apply the techniques of advanced modern spectroscopy to the evaluation of the motion of bulk structures, and, second, to collect data regarding fluctuation, which should be considered a useful resource for the analytical sciences.

Fluctuation phenomena have attracted people's interest from old times for completely irregular and unpredictable motion. Early examples are the observation of Brownian movement in the late nineteenth century and the subsequent mathematical treatment by Einstein. In spite of their long history there are still new problems which have not been completely solved until now. The dissipative structures and oscillatory chemical reactions in the thermodynamics of open systems are much studied subjects in recent decades. The 1/f fluctuation has been known to appear in a number of phenomena in many fields. Mechanisms of the generation of the 1/f fluctuation have not been fully understood. Studies of fluctuations have shown some relations with studies of the chaos and the fractal phenomena. For fluctuation studies, classification of fluctuations of various types by the technique of the spectrum, for example, relations among such fluctuations, and mechanisms of the generation of fluctuations are important subjects. An application of fluctuations appeared more than thirty years ago. It was an estimation of the characteristic of a linear system by giving a fluctuation as an input. The characteristic of the system was estimated by calculating the cross-correlation function of the input and the output fluctuation.

In spectroscopy, frequencies of the intrinsic oscillation and the relaxation of oscillation are measured through the resonance phenomena. A great deal of effort has been directed towards improving the accuracy and efficiency of measurements in that field; for example, the stochastic excitation, or "correlation" technique.[4)] In this technique, a system is excited by a noise-like signal and the response of the system is analyzed. A very high sensitivity can be achieved using this method.

Fujiwara *et al* have shown that measuring the fluctuation in the refractive index is useful for detecting a critical phase of an aqueous sodium chloride solution.[5)] They used this technique to examine the significance of the salt concentration in human blood.

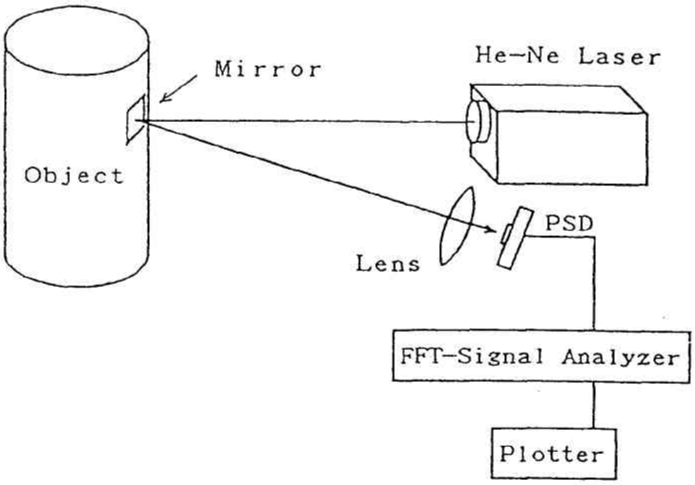

Fig.1 Laser beam system of the first type for measuring fluctuations in structural objects.

We eventually intend to measure the fluctuations of buildings, bridges, airplanes and turbines in power plants. However, before the fluctuations of these large objects could be measured, those of some smaller structures were measured to determine the feasibility of the proposed technique.

2 Experimental

We have constructed two types of measurement systems. The first type is shown in Fig.1. A beam from a He-Ne laser (NEC Model GLG5014, output power 4mW, beam diameter 0.7mm) had a nearly perpendicular incidence upon a mirror attached to the face of an object. The reflected beam was focused by a lens to a spot 1mm in diameter on a position sensitive detector (PSD, Hamamatsu Photonics Co. Model S3932, one-dimensional type, 12mm long). The PSD generated a voltage signal proportional to the distance between the light spot and the center of the PSD. Any movement of the structure changed the position of the light spot on the PSD, which produced a fluctuating time series signal. The time series was then fed to a signal analyzer (Advantest Co. Model R9211C), digitized by a 16-bit AD converter, and converted to a frequency spectrum. The number of sampling points was usually 800, which produced frequency resolutions of 1.25Hz (1kHz spectral range) and 2.5Hz (2kHz spectral range). The Hanning window was employed before applying a FFT. The spectrum was averaged within the frequency domain. In the measurement of an electric motor, a mirror was not used to reflect light. Instead, diffused reflection from a rotating shaft of the motor was focused on the PSD.

The second type is shown in Fig.2. It differs from the first type in no use of a reflection mirror but in use of a powerful telescope for gathering light. It was

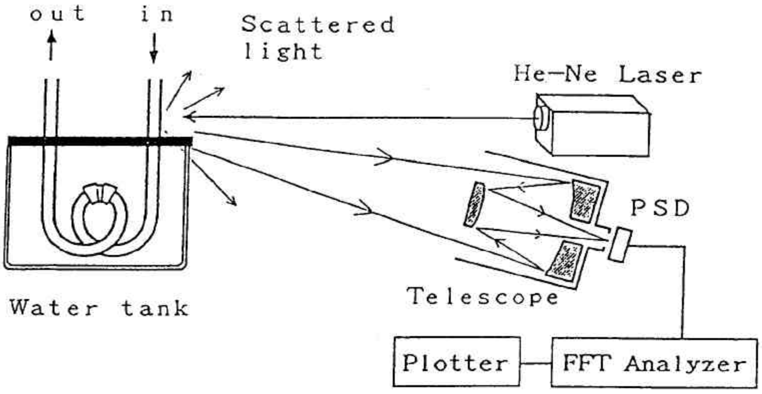

Fig.2 Laser beam system of the second type for measuring fluctuations in structural objects.

invented to measure fluctuations of structural objects in the distance.

In a one-dimensional measurement using only one laser beam, the component of a target fluctuation is measured along the path of a laser beam. To obtain more components, a two-dimensional measurement using two mutually perpendicular laser beams was examined. Our instrument based on the reflection of a laser beam described above seems natural. A scanning atomic force microscope, invented recently for the observation of surface structures of materials, employs a similar technique to ours for monitoring the motion of an observing tip over materials surfaces.

For fluctuations analysis three types of techniques are well known, the spectrum which is a Fourier transform of a time series of a fluctuation, the auto- and crosscorrelation function, and the probability density function which is a histogram of amplitudes of a fluctuation time series. These three techniques have their intrinsic characteristics. We compared them in a model experiment for detecting an abnormal state in an electric motor.

3 Results and discussion

3.1 Forced vibration of a refrigerator

The forced vibration of a refrigerator was measured by reflecting a laser beam from a mirror attached to one side of the refrigerator. The refrigerator's compressor a small vacuum pump on the roof of the refrigerator were used to the power spectra. In the quietest condition, where neither the compressor nor the pump was working, the spectrum consisted of a fundamental peak at 100Hz and its many overtones. Several weak overtone peaks of a fundamental peak at produce the forced vibration. Three distinct vibrational states were observed in

Fig.3

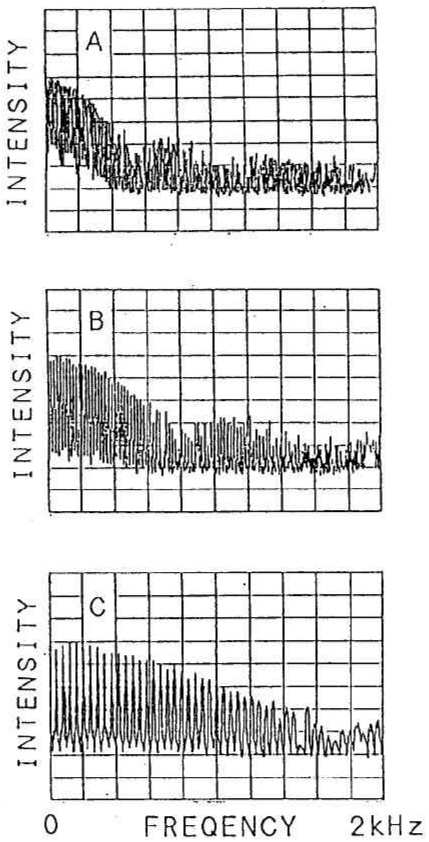

Fig.4

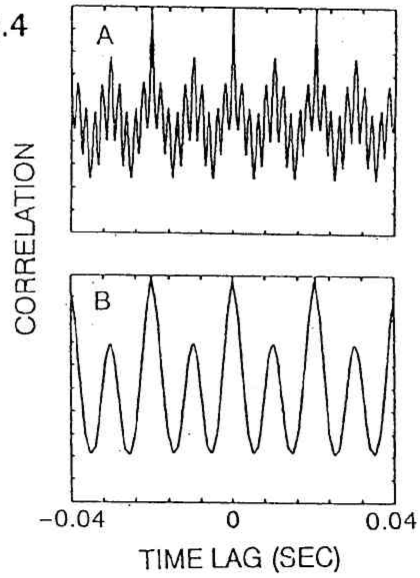

Fig.3 Detection of the rotational frequencies of an electric motor. A) slow, B) medium, C) fast.

Fig.4 Detection of an abnormal state of a motor by the auto-correlationfunction technique. A) a normal rotation, B) an abnormal rotation.

50Hz could also be observed. When only the compressor was working, the low frequency portion of the spectrum (100–300Hz) increased and several overtone peaks of the fundamental peak at 50Hz increased between 1.3 and 2.0kHz. Finally, when both the compressor and the pump were working, strong new peaks appeared at frequencies of 50, 150, 250, and 350Hz, which are forced vibration due to the vacuum pump, in addition to the peaks produced by the compressor which were observed earlier.

3.2 Rotational speed of an electric motor

We used a small electric motor (10W) with variable rotation speed as a model of a turbine in an electric power plant. Changes in the power spectrum were measured at different rotational speeds. The results showed that the rotational speed of the motor could be determined by this laser beam technique. Figures 3A–C show the power spectra measured at three different rotational

Fig.5

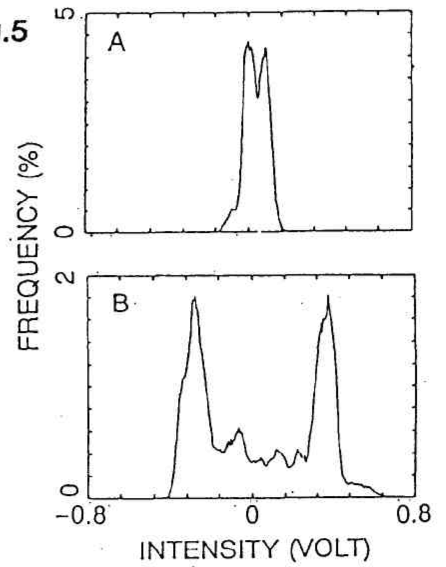

Fig.6

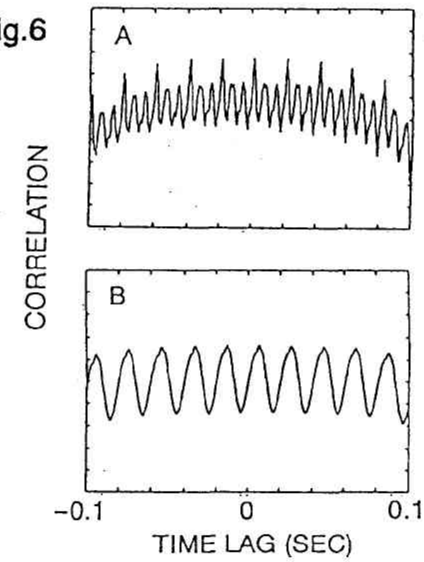

Fig.5 Detection of an abonomal state of a motor by the probability density function technique. A) a normal rotation, B) an abnormal rotation.
Fig.6 Detection of an abonomal state of a motor by the cross-correlation function technique in a two-dmimenional measurement. A) a normal rotation, B) an abnormal rotation.

speeds of the motor: slow, medium, and fast, respectively. Each spectrum consists of a fundamental peak, which indicates the rotational speed of the motor, and its many overtones. As the rotational speed increases, the separation between peaks also increases. The frequency of the oscillation of the envelopes of peaks also increases at higher rotational speed, which may suggest that the frequency of the oscillation of the envelope is given by the reciprocal of the length of time the light spot deviates appreciably from the center of the PSD.

3.3 Fluctuation of rotational speed of a motor

We found evidence of fatigue in a small electric motor (a few W) 6 weeks after the start of rotation. The fatigue appeared as fluctuation in the rotational speed. In the spectrum which was obtained immediately after the motor started running, a fundamental vibration at 50Hz was observed along with its many overtones. Six weeks later, the rotational speed of the motor had changed, as shown by a damping of the peaks of the averaged spectrum. This change is due to the fluctuation of rotational speed, which may represent a type of motor fatigue.

3.4 Detection of an abnormal state of a motor by fluctuation analysis techniques and a two-dimensional measurement

We studied a small electric motor as a model for the detection of an abnormal state in a rotating system. In this model an abnormal state is such that a rotational axis of a load does not coincide with a symmetry axis and that a rolling motion of the load may occur. A normal state is such that the rotational axis and the symmetry axis coincide. In time series data differences between two states were observed. The amplitudes were small of a time series in the normal state, due to a smooth rotation of the load. The amplitudes were large of a time series in the abnormal state, due to a rolling motion of the load. In spectra clear differences were not observed. Both spectra showed a peak for the fundamental periodicity and a number of its overtone peaks. However, auto-correlation functions showed clear differences. In Fig. 4A, which is an auto-correlation function for the normal state, shorter periodicities of 2ms and of 10ms are observed besides the fundamental periodicity of 20ms. In Fig. 4B, which is an auto-correlation function in the abnormal state, the peiodicity of 2ms is completely lost. We may associate this loss to masking the short periodicity of 2ms with small amplitudes by a rolling motion with large amplitudes. Finally, in probability density functions, functional shapes are similar in both states as shown in Figs. 5A and 5B. However, amplitudes are different by more than eight times. In the normal state the most probable amplitude is 80mV and 0mV, while in the abnormal state it is 400mV and -300mV. To summarize the results, the auto-correlation function and the probability density function were useful for detecting this type of an abnormal state, while in the technique of the spectrum the detection of an abnormal state was difficult.

Structural objects usually execute complex three-dimensional motion. For the analysis of such motion a multi-dimensional measurement may be required. In the above mentioned system we examined a two-dimensional measurement using two mutually perpendicular laser beams. The beams were also perpendicular to the rotating axis of the motor. In this measurement we obtained two components of the motion of the rotating object normal to the rotating axis. The cross-correlation functions calculated from two time series show marked difference between the normal and the abnormal states. In Fig. 6A, which is a cross-correlation function in the normal state, along with the fundamental periodicity of 20ms a correlation period of 1/3 of the fundamental one is clearly observed. In Fig. 6B, which is a cross-correlation function in the abnormal state, only the fundamental periodicity of 20ms is shown.

3.5 Model of a refrigeration system by water coolant: an example of higher-order data processing techniques

For the detection of a sign of a failure in a system, higher-order processing of data may be important. One of them is the technique of the difference

Fig.7

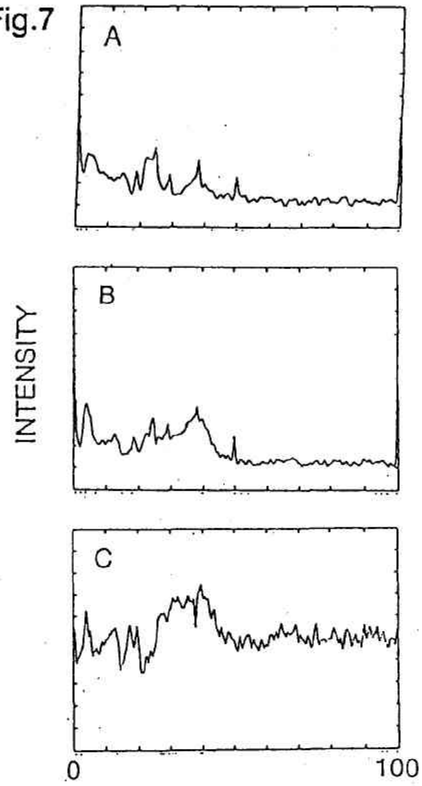

Fig.8

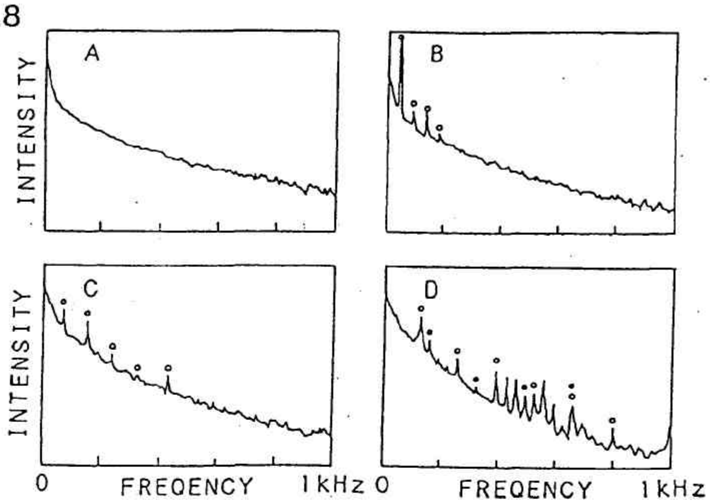

Fig.7 Detection of a sign of a failure in a model of a refrigeration system by water coolant: the difference spectrum as an example of higher-order data processing techniques. A) a spectrum in a normal state. B) a spectrum in an abnormal state. C) the difference spectrum.

Fig.8 Various resonances of an automobile due to the rotation of the engine. A) Spectrum when the engine is not running. No resonance. B) Resonance when the engine is rotating at 13.3Hz. C) Resonance when the engine is rotating at 21.7Hz. D) Resonance when the engine is rotating at 35.0Hz.

spectrum, which is the subtraction of a standard spectrum in a normal state from a spectrum in a possible abnormal state. We applied this technique to detect leak of water coolant in a model of a refrigeration system(Fig.2). Reflection of a laser beam from a metal pipe for water coolant was measured by use of the second type of our measurement instrument using a telescope. Fig. 7A shows a standard spectrum obtained in a normal state of the refrigeration system. Fig. 7B shows an abnormal spectrum obtained when water coolant leaked from a pipe in the refrigeration system. Fig. 7C shows the difference spectrum. Here the 0db horizontal line in the center of the figure indicates agreement of both spectra. A broad peak above the line in the range 25–45Hz may be considered as a sign of a failure of the system.

3.6 Resonance of an automobile

We also applied our technique to measuring the fluctuation of a parked automobile. One of the side-mirrors of the car was used to reflect the laser beam. The vibration of the mirror was measured at several different rotational speeds of the engine. We observed that, of the many vibration modes, the mode that resonated was one with a frequency of about twice the rotational speed of the engine. (We suppose that the frequency of the external force applied by an engine is twice the rotational speed of the engine.) Figures 8A–D show the power spectra obtained at four different rotational speeds of the engine. Figure 8A shows the spectrum measured when the engine was not running. None of the vibrational modes are excited. Figure 8B shows the spectrum when the engine was rotating at 13.3Hz. The vibration at 23.75Hz and its second to fifth overtones are excited. The even–odd rule that odd-numbered overtones are stronger than even-numbered overtones is evident. In Figure 8C another vibration at 41.25Hz and its several overtones are excited. The second, third, and fifth overtones are strongly excited. The spectrum was obtained at an engine rotation of 21.7Hz. Finally, another vibration, at a still higher frequency (66.25Hz), and its second to sixth overtones (o) can be observed in Figure 8D. This rotational speed also produced another series with a fundamental frequency of 83Hz (●), and a characteristic group with an interval of ca.17Hz between 200 and 400Hz.

Intrinsic vibrational frequency of a building

In this case, the laser beam was reflected from a mirror attached to the side of a opposite building outside of a window of our laboratory. Under these conditions, we measured the fluctuation of the building relative to our laboratory. A peak at 18.75Hz was clearly observed on a spectrum which slowly decreased as the frequency increased. Since buildings are known to vibrate at about 20Hz, this peak may represent the natural vibration of the building.

4 Conclusion

Using the laser spectroscopic technique proposed here, we observed intrinsic vibration of structures, forced vibration, and the resonance of the intrinsic vibration to an external force. The appearance of resonance depends upon the type of the external force applied. For the periodic excitation produced by a refrigerator compressor or a pump, or by an automobile engine, resonance occurred at an intrinsic vibration which had a frequency that was nearly equal to the excitation frequency. The frequency of rotational motion and the appearance of fatigue in a moving object were also observed. To our knowledge, this simple optical technique has not been applied to the diagnosis of large structures. By making our measuring system portable, we hope to be able to evaluate the safety of buildings, bridges, and turbines in power plants.

The traditional approach of analytical chemistry has been to measure signals. However, the technique which we have outlined here measures fluctuation. Unfortunately, not much data has been collected in this field. Therefore, we will continue to accumulate fluctuation data from various sources in the hope that they can be used to evaluate the dynamic characteristics of structures, which should assist in safety studies.

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プロジェクトＢ－１およびＢ－２の成果報告書は各々
原報：「ガマ毒bufadienolideの構造と人肝癌由来細胞PLC/PRF/5に対する殺細胞活性」
および
原報：「高等脊椎動物の胚葉分化を特徴づける分子マーカーの探索および細胞系譜追跡法を用いた三胚葉層形成機構の解析」
をもってこれに代える。