Detection of Incipient Failure in Structure
Using Random Decrement Technique

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ABSTRACT

When you hear a mysterious new sound when driving your car you know that it usually means trouble. Now such signals can be translated into a "signature" which identifies the problem by a technique called "Random Decrement". First the vibrations have to be picked up by a sensor like the pickup in a record player. Then these signals which appear meaningless in their original form are sorted and a characteristic signature is established which engineers can relate to the mechanical properties of the system. If a flaw such as a fatique crack develops, the signature changes, thus warning the operator of impending failure.

The "Random Decrement" technique is particularly well suited to the class of problems in which characteristics are desired of an in-service structure subjected to unknown random excitation such as wind, earthquakes, waves, sound, traffic loads, etc.. Analysis requires only the measurement of the dynamic response of a structure, and not the excitation. Continuous automatic monitoring is possible. The method has been applied in flight flutter testing of the F-16 aircraft, in monitoring the seals during operation of a wind tunnel, in detecting cracks and measuring damping in structures such as ships, bridges, pipes and machinery. More recently it is being used in a joint ONR-USGS research program for remote detection of underwater structural failures in ocean platforms.

INTRODUCTION

In recent years a wide range of structural monitoring techniques have been developed such as ultrasonic, acoustic emission, vibration, etc. There are advantages and limitations to all these techniques. Some of the limitations are the inability of monitoring on line and on large systems, of detecting internal cracks and on the reliability due to the effect of input excitation.

Random Decrement analysis is a fast-converging method for extracting meaningful information from random data. When applied to the random output of a transducer placed on an object which is subjected to random excitation, a signature is obtained which can be used to measure damping or to detect incipient failures. The method is particularly useful in field measurements of structures and mechanical systems because excitation is provided naturally by such random inputs as acoustic noise, wind, seismic disturbances, traffic loads, etc.

The randomdec analysis was developed by Mr. Henry A. Cole about a decade ago. In his work for NASA on flutter problems associated with the Sature launch vehicle he found the autocorrelation function of random vibrations to change not only with the development of a fatigue crack in a structure but also with variations in the random environment, thus giving false indications of failure. Theoretically, the problem of changes in vibrations which result from changes in the input environment could be overcome by measuring both the input forces and the output vibrations and then calculating cross-spectra or cross-correlations. But this is extremely difficult to do in practice because the input forces occur at so many points that quantification is almost impossible.

The problems with spectral and correlation methods are further complicated if a structure has damping which is nonlinear with amplitude, which is often the case.

The Random Decrement method analyzes the measured output of a system subjected to some ambient random input. After analysis a signal results that is the free vibration response or signature of the mechanical structure. This signal is independent of the input and represents the particular structure tested. The ability to obtain response signatures for different modes (usually accomplished by filtering the output) enables one to detect early damage before overall structural integrity is affected. Local flaws, such as cracks, too small to affect the overall structural integrity, have a significant effect on the signatures of the higher modes. As a flaw grows, progressively lower modes are affected until overall fialure occurs. Damage is detected by studying and comparing the signatures of the higher structural modes.

When a fatigue crack develops, it introduces additional degrees of freedom which are then excited by random forces. Small cracks show up as small blips in the "hashy" high modal density region of the response, and as these cracks grow, the failure mode frequencies decrease and approach the fundamentals where failure becomes imminent. The detection of flaws consists of intercepting failure modes at high enough frequencies such that corrective action can be taken. This procedure is accomplished by passing a random signal through a bandpass filter which is set at a high frequency band. If a failure develops it will have a dramatic effect on the signature because it will dynamically couple with structural modes within these bandpass frequencies. Figure 1 illustrates the acquisition of Randomdec Signatures, and hypothesis on the sensitivity of the signatures to flaws.

For the failure detector, once the standards have been established only parts of the signature at peaks need to be recalculated with warning devices sensitive to voltage changes in the peak values.

A procedure for failure detection is outlined on figure 2, which shows only a single peak for illustration. The standard signature region is first established to a confidence level consistent with percent of false alarms which could be tolerated. For the 95-percent confidence level shown, of course, false warnings would occur 5 percent of the time. Detection would be a shown on the figure. The check on standard deviation, σ, is to prevent false indications due to extraneous input sources other than the normal random excitation, i.e., a sinusoidal force or signal in the elctronics. For example, if a sinusoidal force was applied to the structure, the signature would become an undamped cosine wave and fall outside the standard region, but the standard deviation would fall to zero. In this case the amber light would go on.

Several publications [1-5] have already examined the theoretical background of the Random Decrement method and have pointed out its usefulness. A brief, rather intuitive explanation of the principles of Random Decrement Technique is given.

RANDOM DECREMENT TECHNIQUE

The response x(t) of a linear system is governed by the following basic euqation:

$$m\,\ddot{x}(t) + c\,\dot{x}(t) + k\,x(t) = f(t) \tag{1}$$

The solution of this differential equation depends on its initial conditions and the excitation f(t). Since, for linear systems the superposition law applies, the response can be decomposed into three parts: response due to initial displacement $x_d(t)$, response due to initial velocity $x_v(t)$ and finally the response due to the forcing function $x_f(t)$.

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The Randomdec analysis consists of averaging N segments of the length τ_1 of the system response in the following manner: the starting time τ_i of each segment is selected such that $x_i(t_i)=x_s=$constant and the slope $\dot{x}_i(t_i)$ is alternating positive and negative. This process can be represented in mathematical form:

$$\delta(\tau) = \frac{1}{N}\sum_{i=1} x_i(t_i+\tau)$$

(2)

where $x_i(t_i) = x_s$ $i = 1, 2, 3 \ldots.$

$\dot{x}_i(t_i) = \geq 0$ $i = 1, 3, 5 \ldots.$

$\dot{x}_i(t_i) = \leq 0$ $i = 2, 4, 6 \ldots.$

The function $\delta(\tau)$ is called the Randomdec signature and is only defined in the time interval $0 \leq \tau \leq \tau_1$. The meaning of the Randomdec signature can now be determined. If the parts due to initial velocity are averaged together, they cancel out because alternately parts with positive and negative initial slopes are taken and their distribution is random. Furthermore, if the parts due to the excitation are averaged they also vanish because, by definition, the excitation is random. Finally only the parts due to initial displacement are left and their average is the Randomdec isgnature representing the free vibration decay curve of the system due to an initial displacement, which corresponds to the bias level x_s. (Fig. 3)

In reality the Randomdec computer converts each segment into digital form and adds it to the previous segments (Fig 4); the average is then stored in the memory and can be displayed on a screen. the number of segments to be averaged for the Randomdec signature depends on the signal shape, usually 400 to 500 averages are sufficient to produce a repeatable signature.

CONCLUSION

The Random Decrement Technique is a crack detection method, which analyzes the overall vibrational behavior of a system subjected to some unknown, random excitation. This concept features some significant advantages:

- The entire structure can be tested and analyzed with a very limited number of transducers.
- Points or components with access difficulty pose no problem.
- The structure does not need to be disassembled for the testing.
- The recording of the response signal requires only a very short time.
- No heavy equipment or instrumentation is needed.
- The structure can be tested in service, as long as the natural input is relatively random, which is the case for many facilities (bridges, piping systems, aircrafts, etc.).

REFERENCES

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5. Yang, J.C.S., Caldwell, D.W., "A Method for Detecting Structural Deterioration in Piping Systems," ASME Probablistic Analysis and Design of Nuclear Power Plant Structures Manual, PVB-PB-030, Dec. 1978, pp. 97-117.
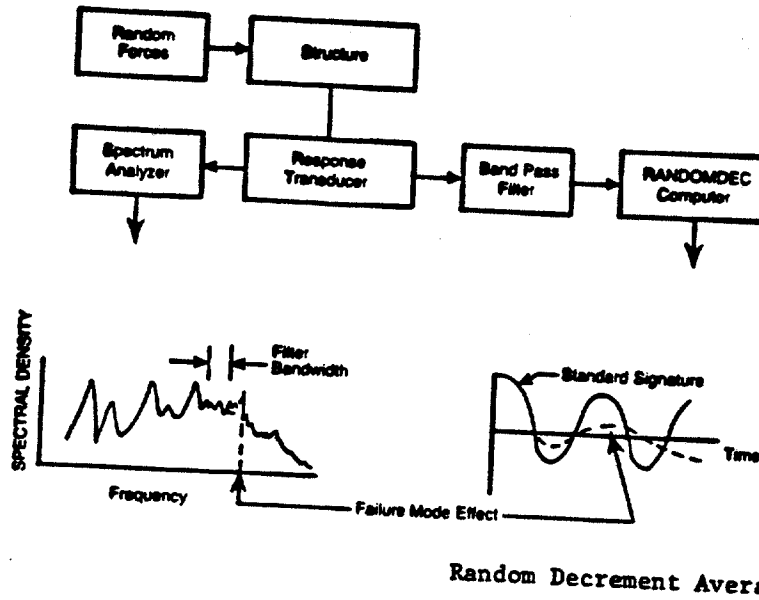
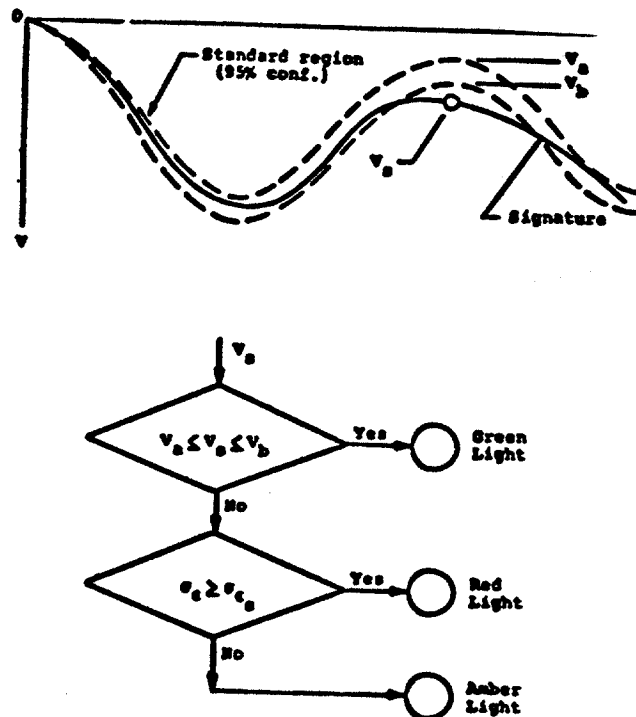Figure 1: Sensitivity of random decrement signature to flaws

Figure 2: On-line failure detection at a single point on the signature

Total response:
$$x - x_d + x_v + x_f$$

| Total response | Response due to initial displacement | Response due to initial velocity | Forcing Function |

$$\frac{1}{N}\sum_{i=1}^{N}x(\tau) \qquad \frac{1}{N}\sum_{i=1}^{N}x_d(\tau) \qquad \frac{1}{N}\sum_{i=1}^{N}x_v(\tau) \qquad \frac{1}{N}\sum_{i=1}^{N}x_f(\tau)$$
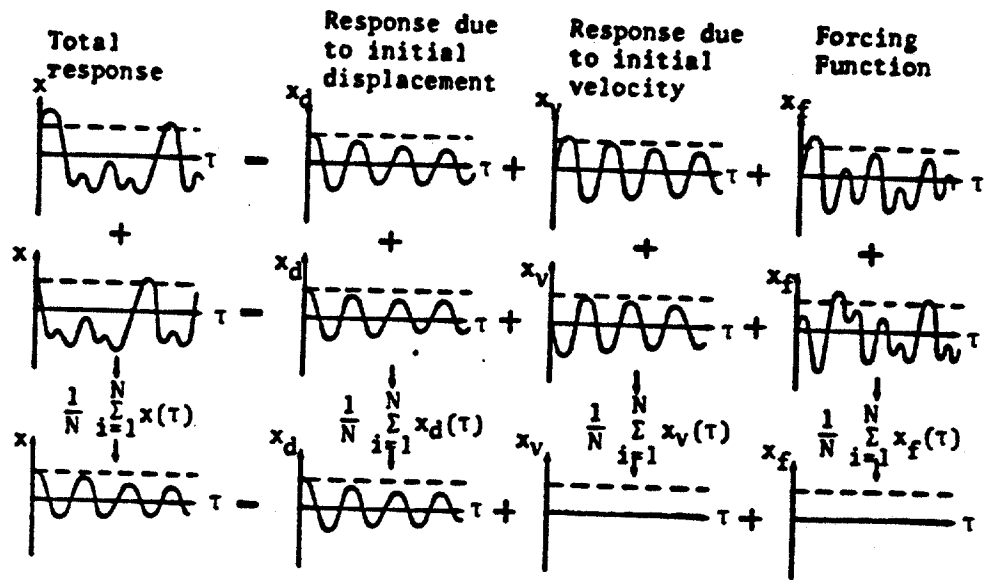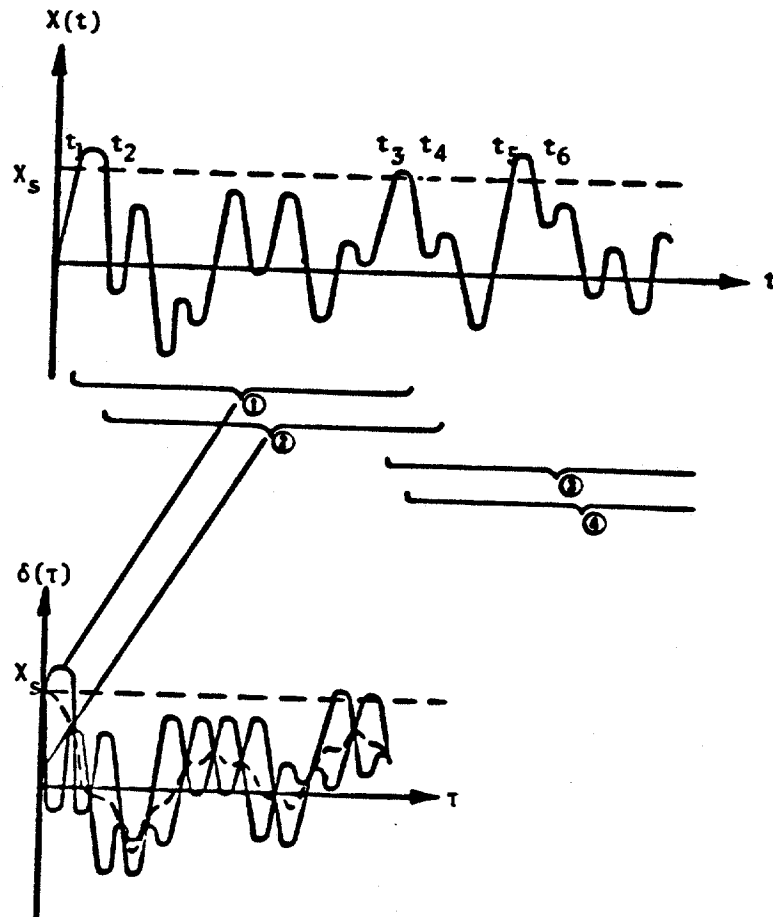
Fig. 3 Principles of Random Decrement Technique

Fig. 4 Extraction of the Random Decrement Signature

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