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FAILURE DETECTION OF A SPACE SHUTTLE WING FLUTTER MODEL BY RANDOM DECREMENT

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ABSTRACT

A random decrement method for obtaining on-the-line characteristic signatures of a structure while operating in its natural environment is explained. The method is then applied to the buffet-flutter random response of a space shuttle wing model which was tested to destruction. Signature changes obtained from a high frequency band-limited signal 50 seconds prior to the final failure were of sufficient magnitude to be of use in a failure detection system.

INTRODUCTION

The reuseability and fast turn around capabilities of the space shuttle will depend on development of fast, efficient methods of inspection and repair. This will be especially difficult because large areas of the structure will consist of layers of heat shield material, insulation, expansion joints, and basic structure which will be concealed from visual inspection. The possibilities of detecting structural changes while the vehicle is operating in its natural environment have been under study at the Structural Dynamics Laboratory at Ames Research Center. The proposed technique consists of continuous monitoring of a characteristic structural signature which is obtained while the vehicle is under excitation by random disturbances due to airflow or landing on a runway. The signature is compared with a standard signature and changes are interpreted in terms of possible structural failures. The present report shows the results obtained by this method on a wing flutter model which was tested to destruction in the 11- by 11-Foot Transonic Wind Tunnel.

It is well known that a structure may be characterized by its impulse or frequency responses and that these curves may be obtained, respectively, by taking cross correlations or cross spectra of the input and output when the input is a stationary random force. (See references 1 and 2.) However, there are many practical situations in which the input occurs at so many points that it cannot be measured (i.e., the present case of a wing driven by a turbulent airflow), and the above methods cannot be employed. Fortunately, the forms of the spectral density of inputs due to turbulent flow do not vary greatly, and it was shown in reference 3 that the form of the autocorrelation of the output is not very sensitive to the practical variations in input spectral densities. Thus, the structure may be characterized by the autocorrelation of the output even though the exact form of the input is unknown. The curve obtained is representative of the free vibration curve of the structure following a step displacement, and, as suggested in reference 3, may possibly be used as a means of failure detection.

The main problem with the use of autocorrelation signatures is that the level of the curve is dependent on the intensity of the random input, and in a natural environment this cannot be controlled. If the structure is a linear system, the level changes can be compensated for by normalizing the curves, but if the structure is nonlinear as is often the case, a different signature will be obtained with each level of excitation. This problem can be overcome by amplitude filtering one channel as shown in reference 3, but the computational difficulties are considerable.

A third method for obtaining signatures is to average segments of the time history which start at a given constant amplitude. This method, called "random decrement", is suggested by Section II of reference 3, in which it is pointed out that the multiplications performed in autocorrelation merely serve to prevent the summation from tending to zero. Furthermore, the nonlinear systems part of that paper indicates that the curve obtained by autocorrelation is actually a linearly dimensioned curve which represents the free vibration curve of the system with an initial amplitude equal to the root mean square of the response. It follows that such a curve may be more easily obtained by averaging the time history directly rather than multiplying and averaging as in autocorrelation. The averaging process has the further advantage that the results obtained do not vary with the intensity of the input and consistent results are obtained for nonlinear systems. For these reasons the "random decrement" method was used in the present report to explore possibilities of its use as a failure detector.

MODEL DESCRIPTION

The model was one of a series of experimental straight wing dynamic models which were constructed of laminated fiberglass on a foam core with a birch spar. The wing had an aspect ratio of 5-1/2, a taper ratio of 0.35, a leading edge sweep of 14° and an 00XX-64 airfoil with 10.8% thickness at the root and 7.9% at the tip. The first bending frequency was 42 Hz, second bending 110 Hz and first torsion 149 Hz. The wing was part of an experimental series and was not connected with a particular space shuttle design so scale cannot be accurately given, but, approximately, the model would be 1/9 scale of a full size orbiter.

COMPUTER DESCRIPTION

A special purpose computer was built[1] to obtain the random decrement signatures and its functional operation is described on figure 1. The input is a random voltage, $y(t)$, from a transducer on the structure. A D.C. bias voltage is set and the response about the new reference is shown as $y_0(t)$.

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[1] William D. Cameron, Raymond S. Lim of the ARC Simulator Computer Systems Branch and Lt. Cmdr. Ramon R. Owens of the Naval Postgraduate School, Monterey, California designed and built the computer.

The computer detects the zero crossings of $y_o(t)$ and sums the transients starting at t_1, t_2,........t_n, which are selected alternatively with + and - slopes. Because a single channel access to the storage sum was used, zero crossings which occurred during the sweep time of the transient were ignored. Faster operation would be achieved by adding more channels so that all of the transients starting at zero could be summed.

The number of transients summed to obtain $\delta(\tau)$ was selectable in binary steps (N = 1, 2...512). The output $\delta(\tau)$ was plotted directly on an x-y recorder.

RESULTS

In this section the Randomdec signatures obtained from the output of a torsion strain gage located at the wing root are shown for the period four minutes prior to destruction of the model. During this time the model underwent continuous buffet-flutter vibration at a Mach number of 0.95 and an angle of attack of 0°. A 200-1500 Hz band pass filter was used to filter out the primary modes below 200 Hz and the upper range was selectec to prevent aliasing (reference 2) with sample rates used from 4,000 to 20,000 samples/second. The higher frequency range was believed to offer a better indicator of damage to a small area since a rather major damage would be needed to effect the lower frequency modes. The signature of the unfiltered signal was also obtained to demonstrate this effect.

In order to show the nature of the signal from which the computer was extracting signatures, samples of the time history taken at various times are shown on figure 2. Sample times are given in minutes: seconds. The random nature of the records makes it difficult to pick out any distinctive changes in the character of the record in the time immediately preceeding the failure.

Figure 3 shows Randomdec signatures taken sequentially over the first two minutes with a variation in the number of transients, N, averaged. It is believed that there was no damage in the structure during this period and that the curves represent normal variations in the signature. With N = 512, the signature appears to be quite consistent, and the band containing these curves was used as a standard in judging signatures taken at later times.

Figure 4 shows signatures (N = 512) taken sequentially from 2:30 on. The time span given is the approximate time it took the computer to obtain the signature. The times required are not uniform because the Randomdec computer only samples when a zero crossing in $y_o(t)$ occurs. It should be noted that a multi-channel computer would obtain the signatures on an average in 1/4 of the time required by the single-channel computer used here.

The first signature (2:30 - 2:45) falls within the standard range shown on figure 3. At 3:00 - 3:09, a slight deviation may be noted, but the first significant change occurs at 3:09 - 3:15. Following this time, a continuous change in the signature may be noted right up to the final failure during the 3:50 -- end signature.

It is interesting to note that a complete signature ($\tau = 0$ to τ_{max}) need not be computed to detect a change once the standard signature is established. On figure 3, it appears that a single value of τ on the second peak could be used as a failure detection point, and that a failure would have been detected at 3:09, approximately 50 seconds before final failure occurred. On a full-scale vehicle the warning time would be increased by the scale factor, in this case 9 X 50 or 450 seconds. Of course, in a less severe environment, the warning time would be even greater and it is hoped longer than the flight time so that repairs could be made. In any event, sufficient warning could be given to allow corrective action. (e.g., change in trajectory to reduce loads)

Figure 5 shows the Randomdec signature of the unfiltered torsion gage signal. Because of the lower frequency content, the sweep time was increased to 0.050 seconds, and the number of transients averaged was lowered to $N = 128$ so that the signatures would be taken over comparable time intervals. At 2:30 - 2:45 the most prominent feature is a wave at a frequency of about 85 Hz which is between the wing first and second bending frequencies. At 3:00 - 3:09 a high frequency component appears which corresponds to the frequency of the signatures on figure 4. However, the signature does not appear to change much following the initial change, and lacking the higher resolution of figure 4, one might assume that the structure had reached a new stable state. Also, there does not appear to be a good location for a failure detection point (τ) for which a large change in amplitude occurs.

CONCLUDING REMARKS

The random response of a space shuttle wing model has been studied during buffet-flutter vibrations which preceded structural failure. For a frequency band above the first three structural modes, the structural signatures obtained by the random decrement method were relatively constant until 50 seconds prior to final failure at which time progressive changes in the structure were indicated. The signature changes were of sufficient magnitude to be of use in a failure detection system. Similar signatures obtained from the unfiltered signal also indicated changes in the structure, but the higher frequency signature appeared to be more sensitive to the small progressive fractures which apparently occurred before final failure.

REFERENCES

1. Lee, Y.W.: Statistical Theory of Communication. John Wiley & Sons, Inc., 1963.

2. Bendat, J.S. and Piersol, A.G.: Measurement and Analysis of Random Data. John Wiley & Sons, Inc., 1966.

3. Cole, H.A., Jr.: On-The-Line Analysis of Random Vibrations. AIAA/ASME 9th Structures, Structural Dynamics and Materials Conference, Palm Springs, California, April 1-3, 1968. Paper No. 68-288.

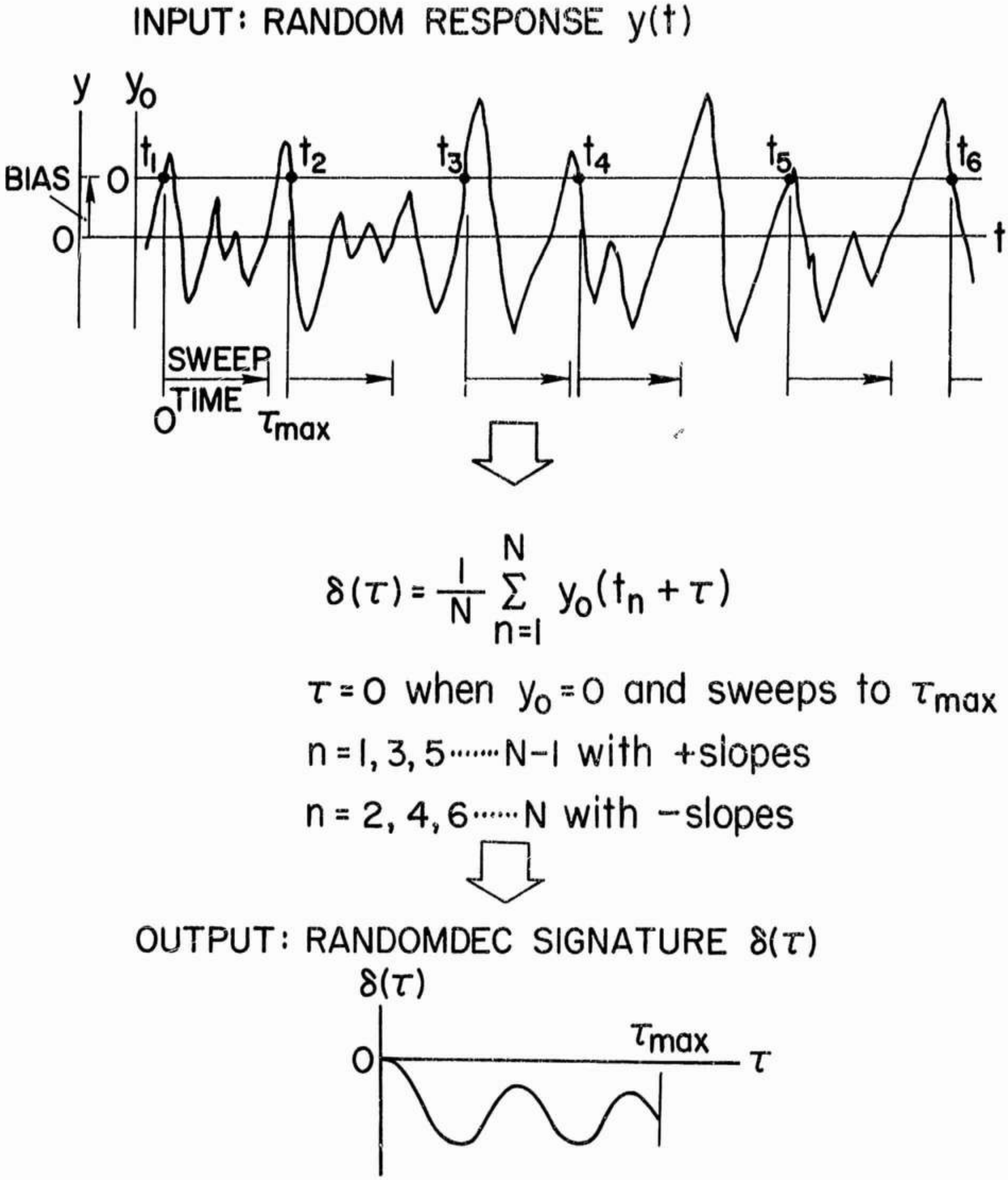

Figure 1.- Operations performed by the random decrement computer.

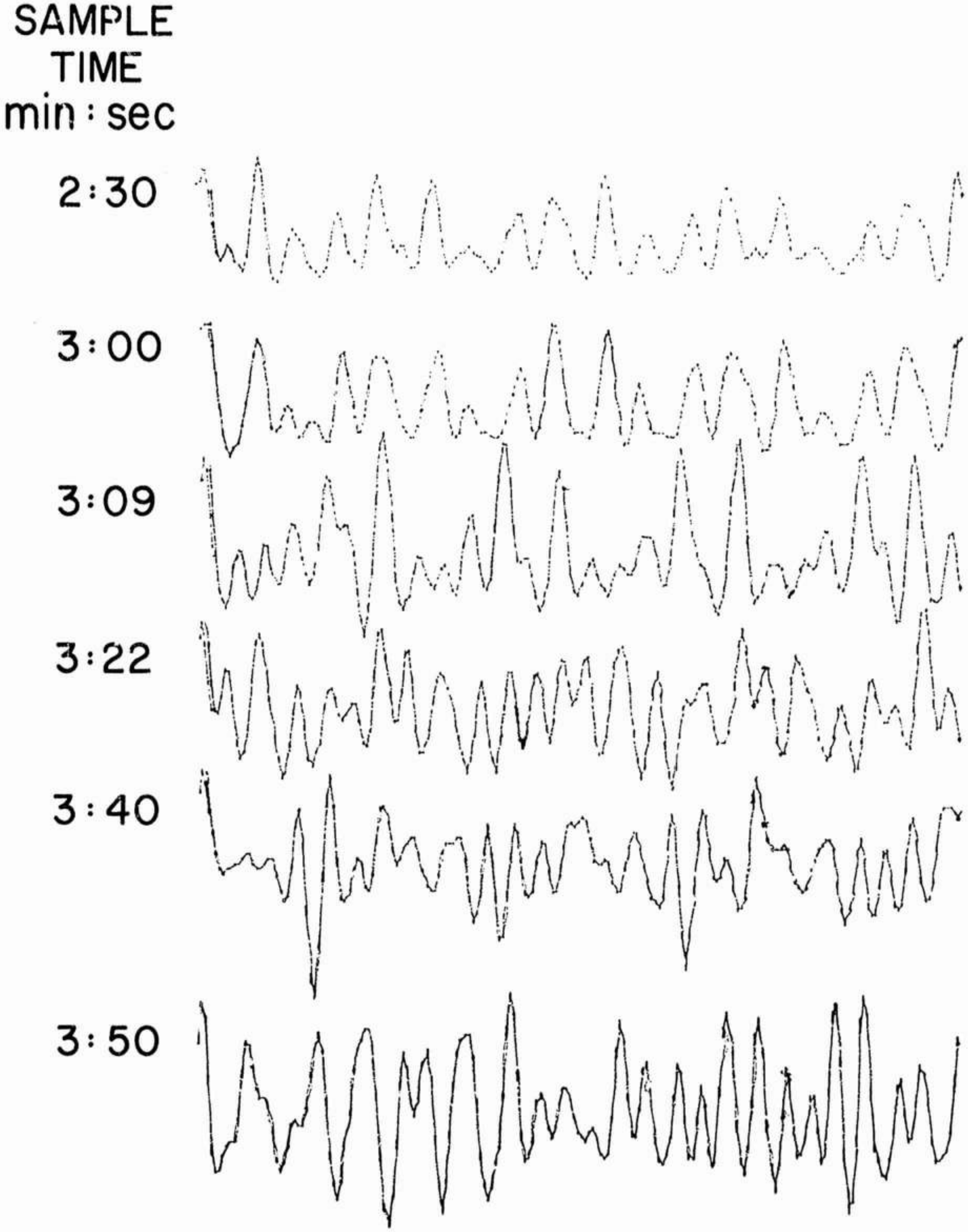

Figure 2.- 0.050 - second samples of the time history taken at various times from the torsion strain gage record, (Bandpass Filter = 200-1500 Hz).

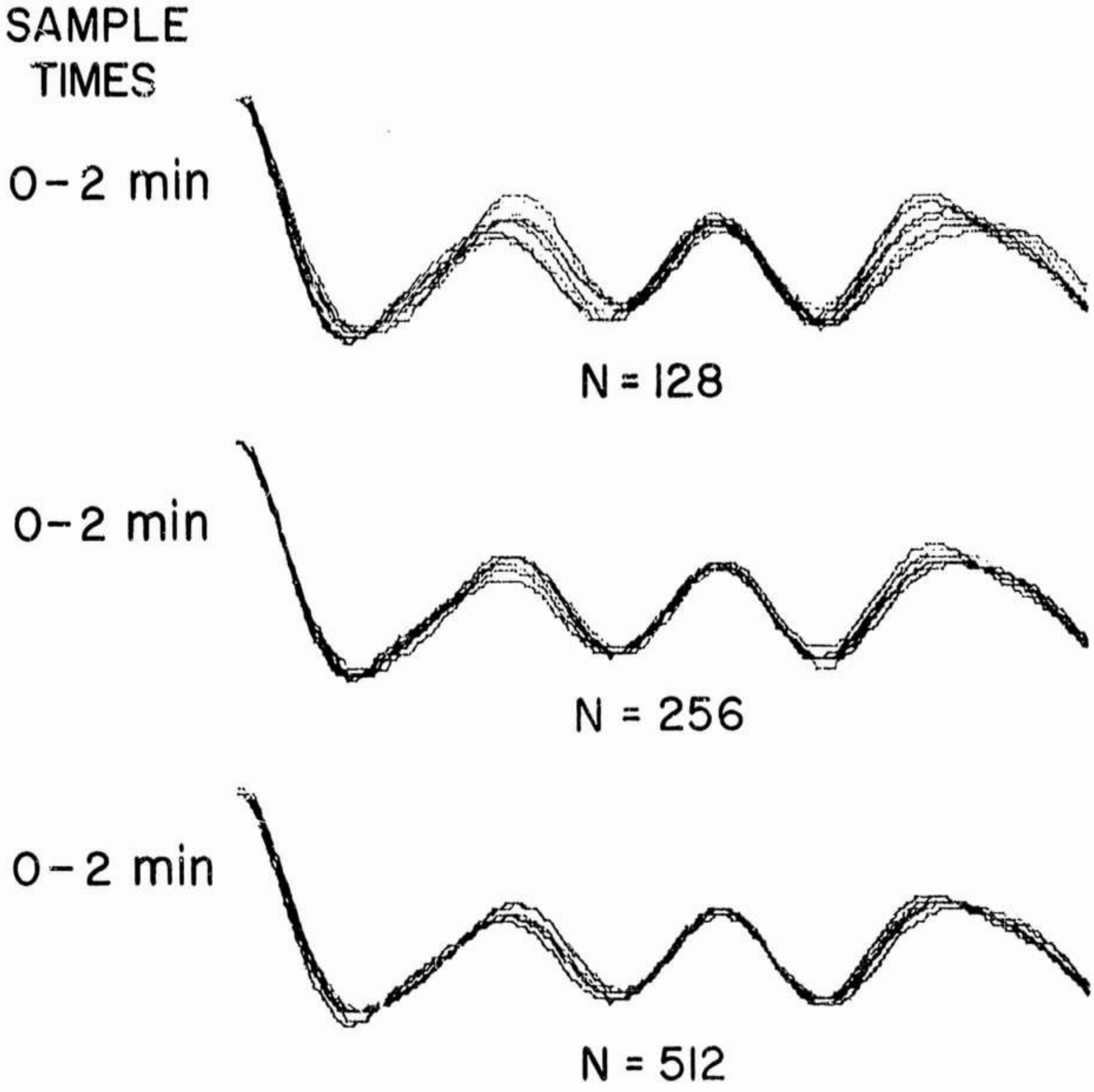

Figure 3.- Effect of the number of samples on the variation of randomdec signatures taken at various times from the first two minutes of the torsion strain gage record. (Sweep time = .010 seconds, Bandpass Filter = 200-1500 Hz.)

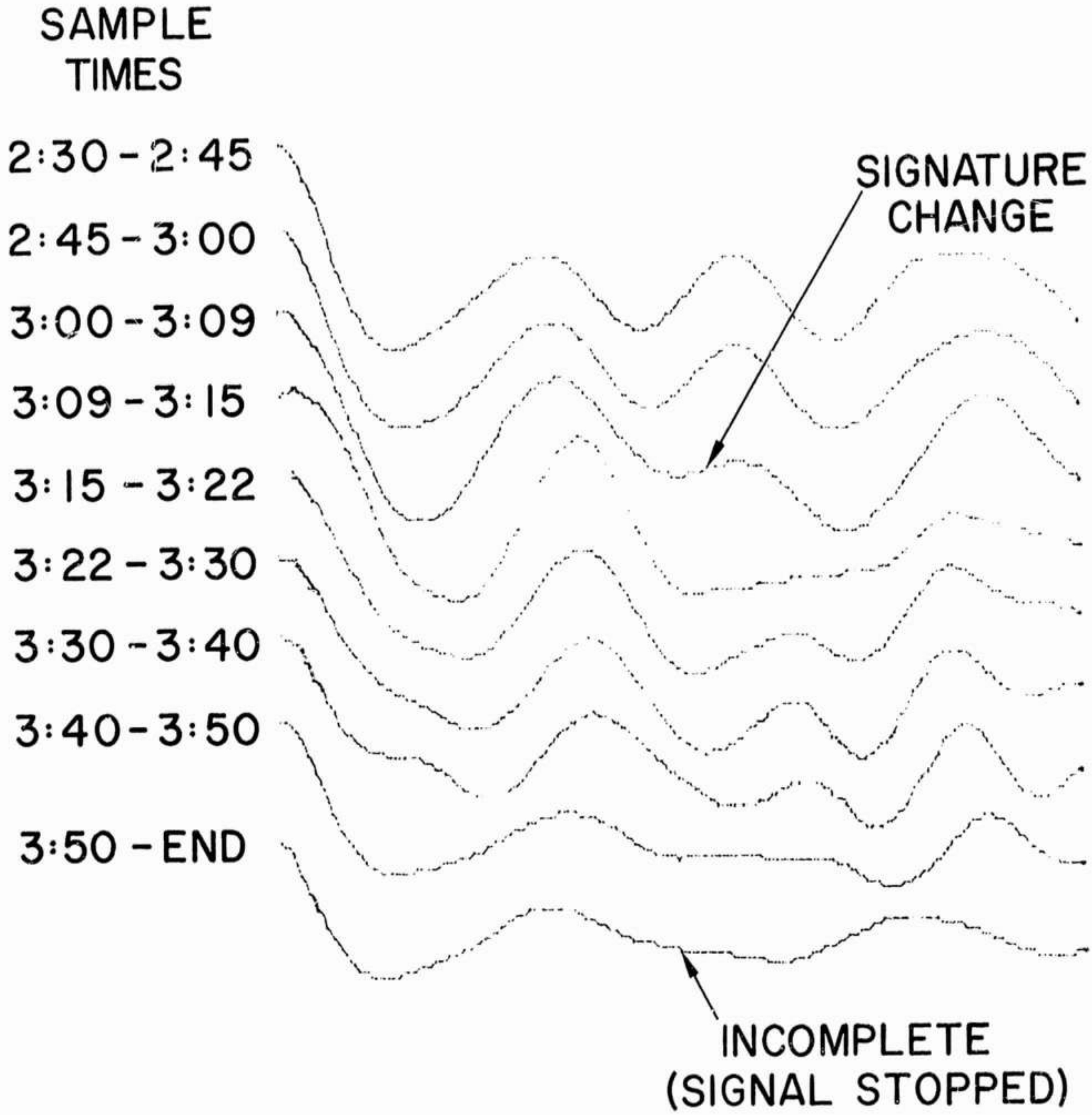

Figure 4.- 512-sample randomdec signatures taken sequentially from the torsion strain gage record. (Sweep time = 0.010 seconds, Filter Bandpass 200-1500 Hz.)

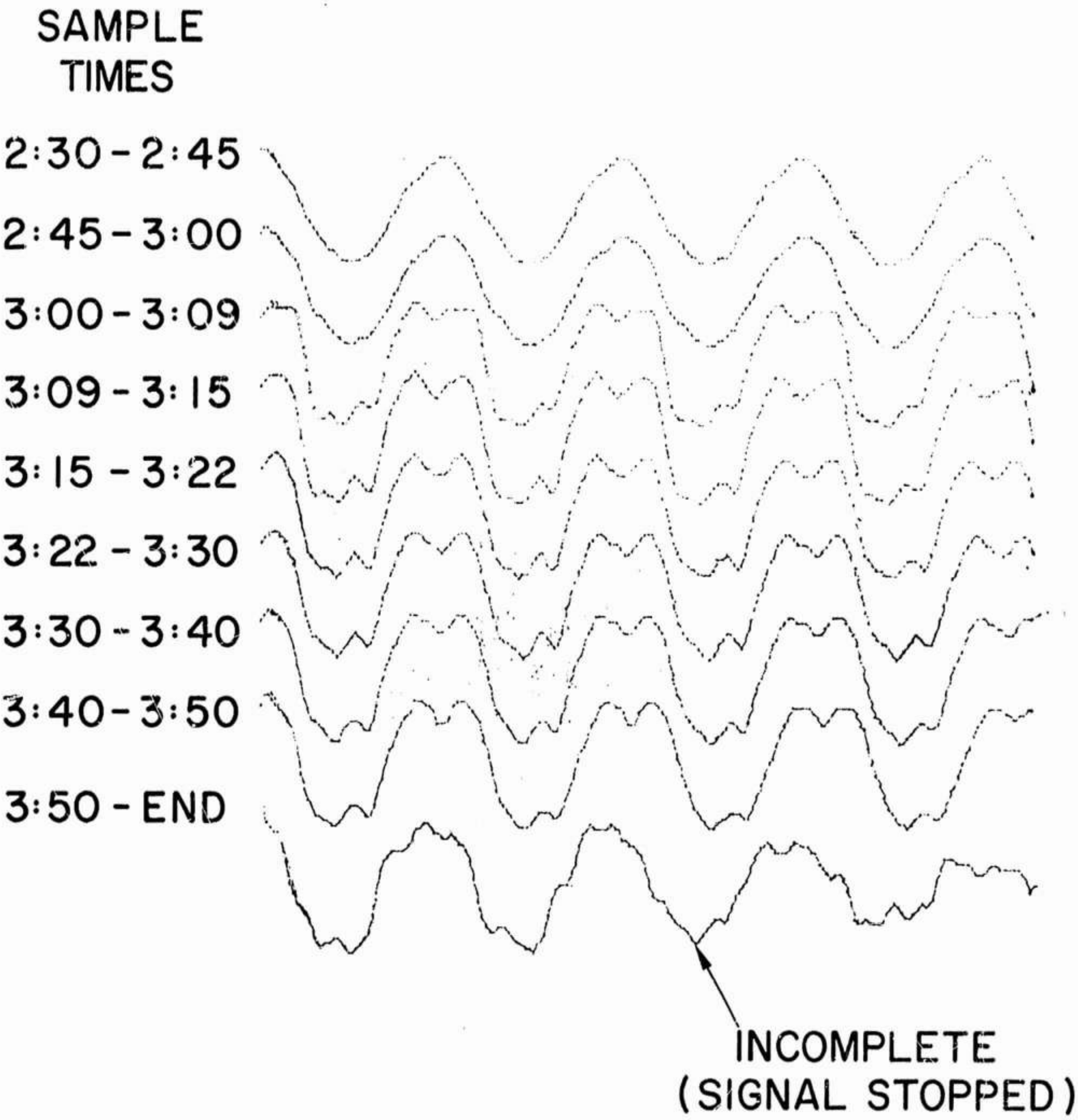

Figure 5.- 128-sample randomdec signatures taken sequentially from the torsion strain gage record. (Sweep time = 0.050 seconds, no filter.)