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APPLICABILITY OF RANDOMDEC TECHNIQUE TO FLIGHT SIMULATOR FOR ADVANCED AIRCRAFT

By Robert E. Reed, Jr. and Henry A. Cole, Jr.

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INTRODUCTION

The Flight Simulator for Advanced Aircraft (FSAA) at NASA/Ames Research Center is a six-degree-of-freedom system which provides a realistic simulation for the motion of an aircraft subjected to typical flight environments. To ensure that the response of the simulator cab is acceptable, periodic check procedures are used. A computer program, SAFE (ref. 1), has been developed to evaluate the response to specific sinusoidal and step inputs. To supplement this program, an on-line system to detect malfunctions is needed to minimize the time it can operate under conditions which produce invalid results. Because the motion during normal operation is of a random character, this short study was undertaken to see if Randomdec analysis is applicable as a method for detecting degradation of the system. Randomdec analysis is a method of averaging a random time history to obtain a signature which is characteristic of the structure rather than the excitation. In order for Randomdec signatures to be applicable to this type of system, standard signatures which are repeatable when the system is within some accepted range of performance first have to be established. Difference between subsequent signatures and their corresponding standards would then indicate changes in the system characteristics. As a first step, the goal of this study was to determine the repeatability of signatures from the time histories of at least two of the six accelerometers located in the simulator cab.

In the following, a short description of Randomdec analysis is given, the recording and analysis procedures are described, the results of the study are given, and the adaption of Randomdec to monitoring a system is discussed.

BACKGROUND OF RANDOMDEC

Randomdec analysis was originally developed (ref. 2) as an on-line system for measuring damping in wind-tunnel flutter models. During a flutter test in which the model failed, large changes in the signatures were detected before the failure occurred. This led to the development of Randomdec analysis as a flaw detection method. Flaws that develop in a system are detected by first establishing a repeatable standard signature for the system that is insensitive to variations in excitation but is sensitive to changes in the system. Changes in the system can then be detected by periodically obtaining signatures and comparing them with the standard. A brief description of the technique is given here with a more detailed discussion of the basic method and flaw detection development being given in references 3 and 4.

The Randomdec signature is obtained from the response time history of a structure subjected to random excitation. The signature is a linear ensemble average of the time history, as shown in figure 1 and is a plot of the time history variable (displacement, velocity or acceleration) versus time. Each sample of the time history is chosen to have the same, but arbitrary initial amplitude $\ddot{y}_s$ (or, say, y_s for displacement record) and alternating samples have positive and negative slopes so that the resulting signature has an initial amplitude of $\ddot{y}_s$ (or y_s) and an initial slope of zero. The shape of the signature, for a linear system, is identical to the free vibration decay of the system subjected to the initial amplitude. The option of choosing the initial amplitude is especially useful when the time history is composed of short runs separated by motionless segments in which the time history is mostly noise. By choosing the bias level, $\ddot{y}_s$, above the low level noise, only the segments of programmed motion are analyzed. In addition, nonlinear effects of amplitude on the signature can be studied by varying the bias level. The length of the signature, τ_{max}, is also optional. It generally should be several, say five to ten, cycles of the predominant frequency in the signature because signatures compared to detect flaws often do not show differences until a few cycles have elapsed.

The length of record (number of samples N) is optional but is directly related to the accuracy of the signatures. A discussion of record length versus accuracy is given in reference 2 and in Appendix A.

It is usually desirable to filter the time history before it is analyzed in order to accent the frequency ranges of interest and to eliminate noise or other unwanted signals. However, filters must be used carefully since they can affect the signatures. Appendix A shows some examples of filter effects.

In addition to the standard analysis, Cross-Randomdec analysis has been used in this study. This is analogous to Cross-Correlation techniques in that the dependence of one signal (say, a separate location or different acceleration component) on another is determined. This is done by treating one time history in the usual manner but starting each sample of the second signal at the starting time of the corresponding sample of the first signal. In other words, the second signature is composed of samples, each of which begins when the first time history has an amplitude of $\ddot{y}_s$. If the two random time histories are independent, the second signature will be zero, whereas, if the two time histories are identical, the two signatures will be identical. This method can be useful in detecting changes in the phase relation between systems that are linked together.

APPLICATION OF METHOD TO SIMULATOR

The application of Randomdec for detecting degradation in the simulator is not a straightforward procedure because of the complexity of the system and the many possible types of malfunctions. It is important to recognize the type of degradation one needs to detect and the type that can be detected. One needs to detect those changes which are small enough to escape detection by the pilot or operator, but large enough to significantly affect the simulated aircraft performance or cause costly damage if they are not detected. The type of degradation that can be detected by Randomdec analysis is, typically, the wearing out of components where significant changes occur over a period of time comparable to the time between signatures. On the other hand, those malfunctions which occur suddenly, such as an electrical connection breaking, cannot be predicted before they occur. Intermittent failures such as loose electrical connections or faulty switches would not be detectable if their intermittency was over a period of time much shorter than that needed to obtain a signature. For example, if a switch usually operates properly but fails sporadically, the degraded effect could be lost in the averaging process with no change being apparent.

Another characteristic of the type of system that complicates the problem of flaw detection is that the response of the simulator cab is composed of programmed response and structural response. That is, a given aircraft will have its response characteristics programmed into the system. These characteristics will change with different aircraft and will obviously change the signature in the frequency range that is programmed (see fig. 2). The detection of flaws by comparing signatures is not feasible in this frequency range for different configurations. It may be seen on the figure that the SAFE program evaluates the operation of the simulator over this frequency range by comparing frequency responses to a sum of standard sinusoidal inputs. For the FSAA, it appears that 5 Hz is about the upper limit of any programmed response. However, random excitation of the system is present at much higher frequencies. The structural response above 5 Hz, where structural resonances exist has been the subject of interest in this study. The reasoning behind the method for detecting flaws was that the signatures in the range, say, 5 to 30 Hz, would depend on the structural characteristics and the type of excitation. The structural characteristics would remain the same, unless some failure occurred, and the excitation, in this frequency range, would not be affected by programmed changes. The excitation in this range drops off as a function of frequency, similar to isotropic turbulence, but this drop-off is partially governed by the related electronics and degradation of the electronics would affect this portion of the excitation. Signatures composed of resonances within the drop-off range will be altered by changes in the excitation since the relative amplitudes of modes will change. Therefore, to avoid the programmed effects and to detect changes in the roll-off characteristics of electronic components and changes in structural characteristics, the records were generally bandpass filtered over the range of about 5 to 30 Hz.

After preliminary study of several accelerometers, the analysis was concentrated on the lateral acceleration $\ddot{y}$ and the pitch acceleration $\ddot{\theta}$ although signatures were obtained of additional coordinates to shed light on problems that arose.

It should be pointed out that in the normal application, Randomdec signatures are very insensitive to variations in level of excitation (see ref. 3 for example), but this is because the shape of the spectrum of the excitation is normally relatively invariant over the frequency range of interest.

RECORDING PROCEDURE

The output of the six accelerometers (three linear and three angular transducers) located in the simulator cab were recorded onto magnetic tape for later analysis. Figure 3 shows the instrumentation used to obtain signatures. The raw accelerometer signals were monitored at the first junction before they are conditioned for simulator application. Voltage limiters were used to limit the signals to avoid saturating the tape recorder. Most of the large amplitude accelerations that were limited were at low frequencies which were high-pass filtered. Other isolated peaks that were clipped were few in number so their effect on the signatures should not be significant.

The method, to be a successful on-line monitoring system, must be able to detect changes in the simulator regardless of what type of aircraft or what mission is being simulated. Because of this, data was recorded during the simulator's normal operation with no regard given to detailed characteristics of the simulation. A log of the recorded runs is given in Table I. Figure 4 shows a typical record of the six accelerometers. A large DC bias made $\ddot{x}$ nonusable and, apparently, a component in the $\ddot{z}$ circuit failed during part of the program since the $\ddot{z}$ signal suddenly became too noisy for analysis. A segment of the noisy signal is superposed in figure 4 to show the change in signal character. Small DC bias shifts were removed on other channels with amplifiers at the monitoring junction. The yaw signal $\ddot{\psi}$ was lost toward the end of the program but the remaining three channels of transverse, $\ddot{y}$, roll, $\ddot{\phi}$ and pitch $\ddot{\theta}$, were recorded throughout the study.

The acceleration time histories were recorded onto 1-inch, 14-track magnetic tape at 3-3/4 ips. The data usually consisted of two or three minutes of motion separated by several motionless minutes during which adjustments or mission changes were made. To avoid introducing many starting transients from the recorder and for convenience, the recorder was left on continuously through an afternoon or evening run. The low amplitude signal during the quiet periods was nearly all noise but this data was avoided in the analysis by setting the bias level above this amplitude.

RESULTS

All tests shown in Table I except tests 9 and 10 were recorded during normal operation of the simulator and are discussed in the following. Tests 9 and 10 were prescribed inputs to the system and will be discussed later.

Although several accelerometers were recorded, the analysis was concerned mainly with the lateral axis $\ddot{y}$ and the pitch axis $\ddot{\theta}$. These were chosen for several reasons. Preliminary analysis indicated that the $\ddot{y}$ and $\ddot{\theta}$ accelerometers produced suitable records and the lateral drive axis has the largest range of travel (80 ft). The pitch drive axis produces large motions and the $\ddot{y}$ and $\ddot{\theta}$ motions should be independent. In the figures that follow, except as noted, the length of the signatures is 0.40 second so the frequency in Hertz is given by $f = 2.5\ n$, where n is the number of peaks, not counting the initial value, in the signature.

Figures 5 and 6 show signatures for $\ddot{y}$ and $\ddot{\theta}$ that are filtered as shown. These signatures are shown in chronological order with the dates given in Table I. It soon became evident, for example, tests 2 and 3, that differences existed. The first question that arose was whether the differences were due to analysis errors (i.e., insufficient record length, equipment variations, etc.), programmed changes or changes in the simulator system. It is not easy to answer this question without an extensive study of the simulator system. For example, in figure 5, tests 1 and 2 give similar signatures for different aircraft with five weeks between records whereas tests 2 and 3 show differences with the same aircraft and the records obtained on two consecutive days. Other comparisons can be made from figure 6 with $\ddot{\theta}$ but a general observation is that all of the signatures of both $\ddot{y}$ and $\ddot{\theta}$ have strong similarities but also have distinct variations. The analysis procedure can be checked by the repeatability of signature versus record length and bias level for the same test record. Figure 7 shows such a comparison for both $\ddot{y}$ and $\ddot{\theta}$ and it is seen that the signatures are quite independent of bias level and that $N = 2^{11}$ samples gives sufficient repeatability. Believing, therefore, that the signatures are accurate, the cause of the variations must be within the simulator system. Test 4 in figure 5 shows a prominent higher frequency component superposed. To isolate this mode, the signatures shown in figures 8 and 9 were obtained with the bandpass filter narrowed from 7.5 to

22.5 Hz to 13.75 to 22.5 Hz. Some signatures are missing because the low level of the records did not provide sufficient data to give accurate signatures. Comparison of figures 8 and 9 shows striking similarities. Both $\ddot{y}$ and $\ddot{\theta}$ contain a 18 Hz signal in tests 4, 7, 8, and 9 but not in tests 5 and 6. Figure 8 also shows this signal exists in test 1 and 3 although it is more highly damped. To determine the mode shape of this peak would require a study with more transducers but some characteristics can be seen from the records of other channels. Figure 10 shows signatures of $\ddot{\phi}$ and $\ddot{\psi}$ for test 4. The 18 Hz frequency is contained in $\ddot{\phi}$ and is visible, to a much lesser degree, at the end of the signature for $\ddot{\psi}$ but is largely masked by another mode. This can be distinguished more clearly from the cross-Randomdec signature shown in figure 11. The notation, $\ddot{\phi}_y$, $\ddot{\theta}_y$, $\ddot{\psi}_y$, means that the time histories $\ddot{\phi}$, $\ddot{\theta}$, and $\ddot{\psi}$ are triggered when $\ddot{y}$ has an initial amplitude of $\ddot{y}_s$. The signatures for $\ddot{\phi}_y$, $\ddot{\theta}_y$, and $\ddot{\psi}_y$ would average to zero if the time histories were independent of $\ddot{y}$. However, figure 11 shows the existence of the 18-Hz signal on the other channels. The initial phase lags of $\ddot{\phi}$ and $\ddot{\psi}$ may indicate that driving the system in the y direction introduces the large damping in the yaw and roll drive systems whereas the 180° phase lag of $\ddot{\theta}$ indicates that $\ddot{\theta}$ is linked mechanically to $\ddot{y}$, with very little resulting damping, in this mode. Figure 12 shows signatures for $\ddot{z}$ which show no trace of an 18 Hz frequency. This indicates that the motion is in the horizontal plane but involves several coordinates. Also, it is not a localized resonance, such as an accelerometer mounting, because the angular and linear transducers are separated by about a meter and are attached to different structural members.

This vibration obviously varies in magnitude as shown in figures 8 and 9. Either this vibration represents some change in the simulator (damage, etc.) or some effect that must be accounted for in order to obtain repeatable standard signatures. Possible damage was considered and discussions with maintenance personnel and review of their records indicated that the lateral drive system which runs on a series of wheels and rollers, requires considerable maintenance. The wheels have plastic rims which fail at a rate of sometimes several per month. Also, near the end of this study, the simulator was shut down for major maintenance and additional damage was found in the roller system. This type of damage could have provided the necessary excitation. However, referring to figure 8, it is hard to explain the radical change occurring between tests 6 and 7, which were taken on consecutive days. The characteristics of the simulator suddenly returned to the form of test 4 but no maintenance or repair was done at this time. The one common denominator is that all cases having substantial levels of 18 Hz vibration were with the AMSTM simulation. However, test 2 was the AMSTM but the signal is not apparent, which indicates the simulated aircraft is not the cause. One source that could couple with aircraft characteristics or missions is the turbulence input. Although no turbulence was used in test 2, the AMSTM usually was subjected to heavy turbulence inputs. However, a high level of turbulence does not necessarily infer high frequencies. Looking further, the digital computer updates the analog computer every 0.056 second. This series of step commands has a basic frequency of $f = 1/(2)(0.056) = 8.94$ Hz. The first harmonic of this frequency is 17.9 Hz, which is the same as the measured signal (within the accuracy of measurement) and, therefore, is a possible cause. The turbulence models drop off in amplitude as frequency goes up but are not cut off at any particular frequency. Using this information, a possible explanation of the source of excitation is that the use of heavy turbulence which has a small but perceptable level of input in the range of 9 Hz, causes a small harmonic output from the analog at 17.9 Hz, which excites a resonant mode somewhere in the system. The low damping of this mode produces a large amplification of the low level input signal. If this is correct, then standard signatures would either have to be based on an input containing the same level of turbulence or would have to be low pass filtered below 18 Hz. The disadvantage of using a narrow band-pass filter to exclude unwanted resonances is that you also limit the ability to detect changes in the system.

An important point shown by this signature analysis is that significant high frequency vibrations are present in the simulator and if these are important in the present operation or if it is contemplated to model higher frequency modes of aircraft, then a thorough study of simulator resonances should be made. Single frequencies that are prominent in signatures can usually be intrepreted as resonant frequencies of the system. Examples of this are the 18 Hz signal discussed above and the 12.5 Hz frequency for $\ddot{z}$ seen in figure 12. However, this may not always be the case. If the frequency of the signature is near a filter setting, such as the 7.5 Hz frequency of test 2 in figure 5, the apparent resonance may actually be the result of filtering a sloping spectrum. Also, a sinusoidal signal in the input will appear in the signature if its amplitude is much larger than other frequency components of the input.

Tests 9 and 10 were specified inputs consisting of the normal SAFE Runs which are a sum of sinusoidal inputs in the range of 0.035 to 3.1 Hz. All axes except the y axis were driven simultaneously and also the z and θ axes were driven separately. Test 9 was performed without pilots and test 10 was without pilots or seats so some differences could be expected. However, the same 12.5 Hz frequency was apparent in the signatures for $\ddot{z}$ which were similar to those in figure 12 except for the case in test 9 when θ was driven. In this case, a 20 Hz signal was superposed on $\ddot{z}$. This signal did not appear in test 10, so possibly this was a resonance of the seats without pilots. The repeatability between tests 9 and 10 for $\ddot{\theta}$ was good but the signatures differed substantially from those in figure 6. Further studies are needed to explain these differences.

In between the high frequency structural mode region and the variable programmed frequency region, there may be ranges in which signatures are repeatable. For example, figure 13 shows tests 2, 3, 4, and 5 superposed. The bandwidth of the filter is 3.75 to 15 Hz, so the 18 Hz signal has been eliminated. This shows the signatures for different aircraft to be repeatable. To use this frequency window, or other ones to monitor the system, one has to determine what type of malfunctions would cause signature changes in this range.

IMPLEMENTATION OF RANDOMDEC ANALYSIS

Before the Randomdec method can be effective as a monitoring tool for the simulator, several tasks have to be accomplished. Repeatable standard signatures have to be established which means the effects of turbulence level (assuming this causes variation in signatures) has to be studied. Location of accelerometers to best monitor specific components (for instance, the wheels and rollers in the lateral drive system) and the sensitivity of signatures to specific malfunctions should be investigated. This program would have to be given the priority of a research project on the simulator so that adequate running time was available.

Assuming the Randomdec method were developed to the point where standard signatures were determined and monitoring for degradation were feasible, there are two basic ways for performing the analysis. One is to use a special purpose computer and the other is to use software on a standard computer. Each method has advantages and disadvantages and some discussion is worthwhile.

The first approach of a special purpose computer was used entirely in this preliminary study. The instrumentation is shown in figure 3. This method has the advantage of speed when many signatures are desired. Variations in filter settings, bias levels, etc., can be studied without having computer turn-around delays as with a standard computer. The visual output is convenient for comparing signatures and determining repeatability. However, the special purpose computer at Ames has one channel so only one accelerometer can be examined at a time.

Once standard signatures with known filter settings have been determined and monitoring of a system is desired, the software approach becomes attractive. The accelerometer histories, after being low-pass filtered at the Nyquist frequency to prevent aliasing of frequencies, can be converted to digital time histories which are amenable to analysis using a computer program on a standard computer. The digital records should contain at least 8 points per cycle of the highest frequency in the signature so the digitizing rate for 15 Hz, for example, should be greater than 120 points per second. A typical record from the simulator has periods of motion lasting two to four minutes separated by several minutes of nonmotion. To minimize the amount of digitizing and the amount of stored digital data, it would be advantageous to only digitize the motion segments of the record. By doing this, an approximate number of required points for each accelerometer, assuming 8 points per cycle, would be 30,000. This would be ample for accurate signatures. In practice, this amount of data represents about 15 minutes of actual running time. Therefore, a normal afternoon or evening operation would provide more than enough data for signatures. This implies that the system could be so monitored that every shift would have signatures available to check the system. Standand signatures could be stored in memory and later ones compared automatically.

CONCLUSIONS

The following main conclusions developed from this study:

1. The use of Randomdec analysis to detect certain changes in the simulator system is feasible but additional studies would have to be done to ensure its effectiveness.

2. A trade-off exists between development complexity and level of malfunction to be detected. The cost and time of development has to be weighed against the need to detect, first, the degradation that is not obvious to the operators but still affects the validity of the simulation, and second, the insignificant degradation that can lead to costly damage if not detected.

3. Although the system generally limits the input signals to less than about 5 Hz, higher frequency components in the range of 9 Hz and its harmonics may be possible because of the digitizing rate of the digital computer.

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APPENDIX A

EFFECTS OF RECORD LENGTH AND FILTERING

When analyzing random data, it is important to know the relationship between record length and accuracy of the analysis result. This is especially true when signatures are compared to previous ones to detect changes in the system. A good indication of signature accuracy can be obtained by studying signatures of random noise. The signature for white noise is an initial spike with all other values equal to zero. For band limited white noise, which is typical of a random noise generator, the signature becomes a damped oscillatory curve for which the damping decreases as the bandwidth decreases. A random noise generator with a cutoff frequency of about 750 Hz was used to study the convergence as a function of record length. Results are shown in figure 14. If one were analyzing a system that produced an oscillatory signature, the errors in amplitude caused by effects of noise could be expected to be of the order shown in figure 14. Clearly, $N = 2^5$ to 2^7 samples allow unacceptable errors; whereas $N = 2^{10}$, more or less, depending on the amplitude of the system signature, gives acceptable accuracy. The single cycle of oscillation shown at the beginning of the signature is caused by the band limited noise with the time increment between the starting value and the first zero-crossing of the signature being, for a sharp cutoff, one-half the period of the cutoff frequency. This oscillatory effect becomes more pronounced and will affect the signature at larger values of time as the bandwidth narrows.

Figure 15 shows examples of bandpass filtered white noise. These signatures are repeatable since $N \geq 2^{13}$. Also the signature shapes depend on the percentage bandwidth and can be scaled up or down in frequency by simply scaling the time axis. The time interval between the starting value and the first zero-crossing is between the 1/4 and 1/2 of the low-pass cutoff frequency. As the bandwidth narrows and approaches a single frequency component, the signature approaches a cosine wave of that frequency with the first zero-crossing at the 1/4 period point. When comparing signatures, one should be aware of the effect of the filter and that the first cycle may be characteristic of the filter rather than the system.

The characteristics of the filter used in this program are shown in figure 16. It is seen that there is practically no attenuation of a sine wave when the filter bandwidth is wider than $f_{input}(1 \pm 0.2)$. Also, the power is attenuated 3 db with $f_{filter} = f_{input}$.

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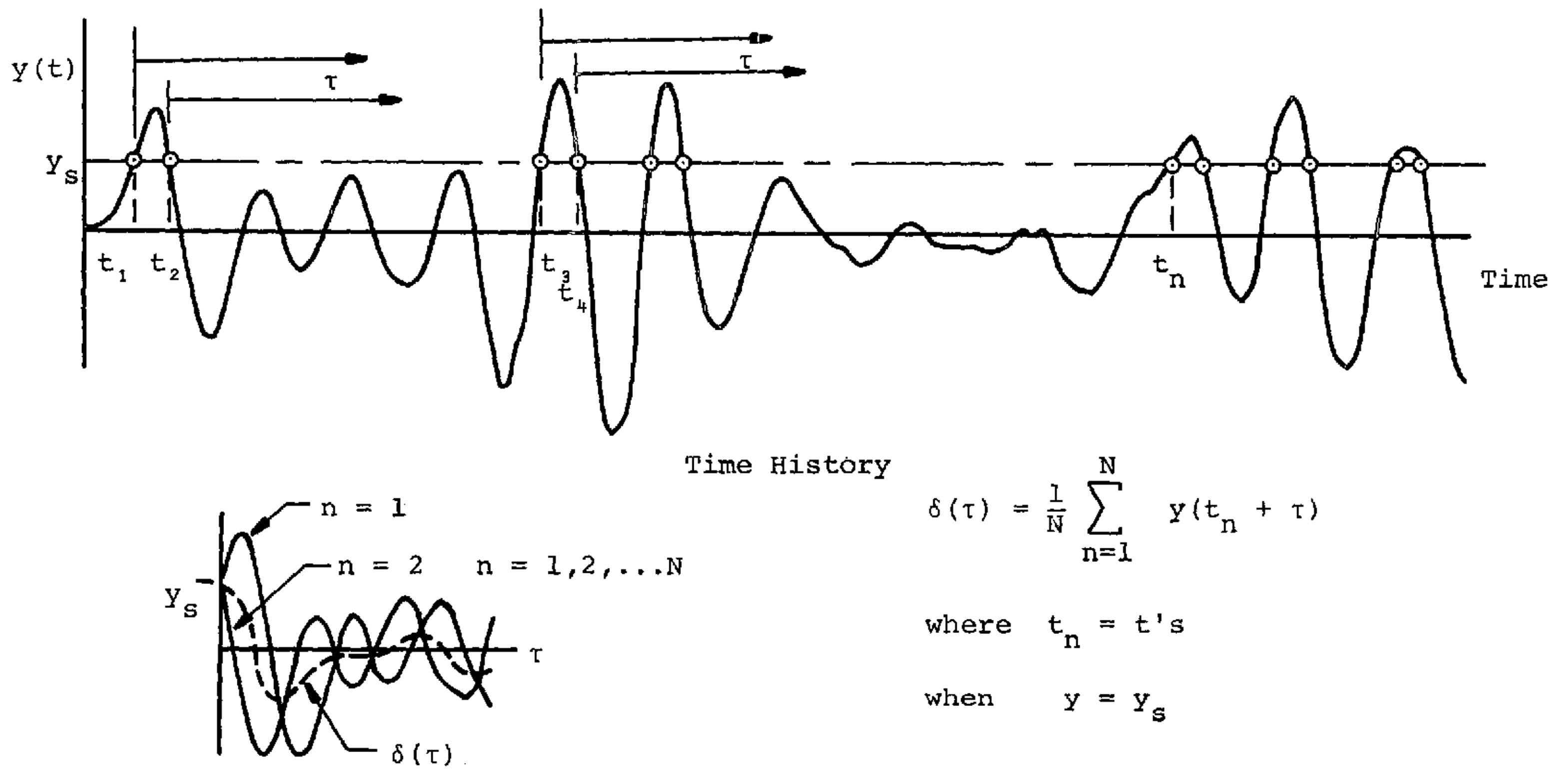
TABLE I.- LOG OF RECORDINGS

Test	Date	Aircraft	Comments
1	6/18/74	Tilt Rotor	
2	7/24/74	AMSTM	$\ddot{x},\ddot{z}$ Not useable
3	7/25/74	AMSTM	$\ddot{x},\ddot{z}$ Not useable
4	7/26/74	AMSTM	$\ddot{x},\ddot{z}$ Not useable
5	7/30/74	Orbiter	$\ddot{x},\ddot{z}$ Not useable
6	11/18/74	FAA/STOL	$\ddot{x},\ddot{\psi}$ Not recorded
7	11/19/74	AMSTM	$\ddot{x},\ddot{\psi}$ Not recorded
8	11/25/74	AMSTM	$\ddot{x},\ddot{\psi}$ Not recorded
9	11/25/74	SAFE Program	$\ddot{y}$ Not driven
10	12/03/74	SAFE Program	$\ddot{y}$ Not driven
11	12/06/74	AMSTM	$\ddot{x},\ddot{\psi}$ Not recorded



Ensemble Average

Randomdec Signature

Figure 1.- Evolution of Randomdec Signature.

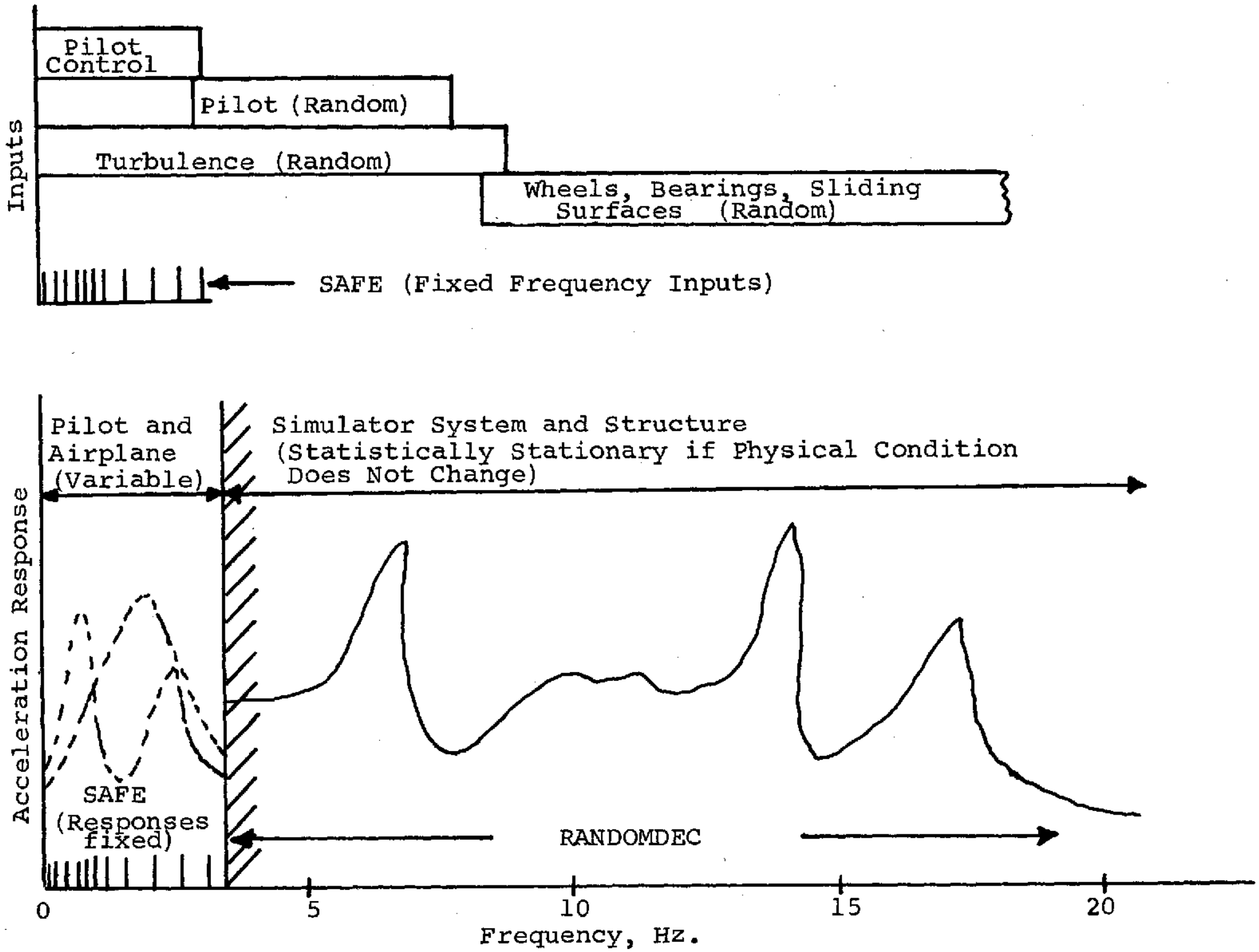


Figure 2.- Input and Response Frequency Domains.

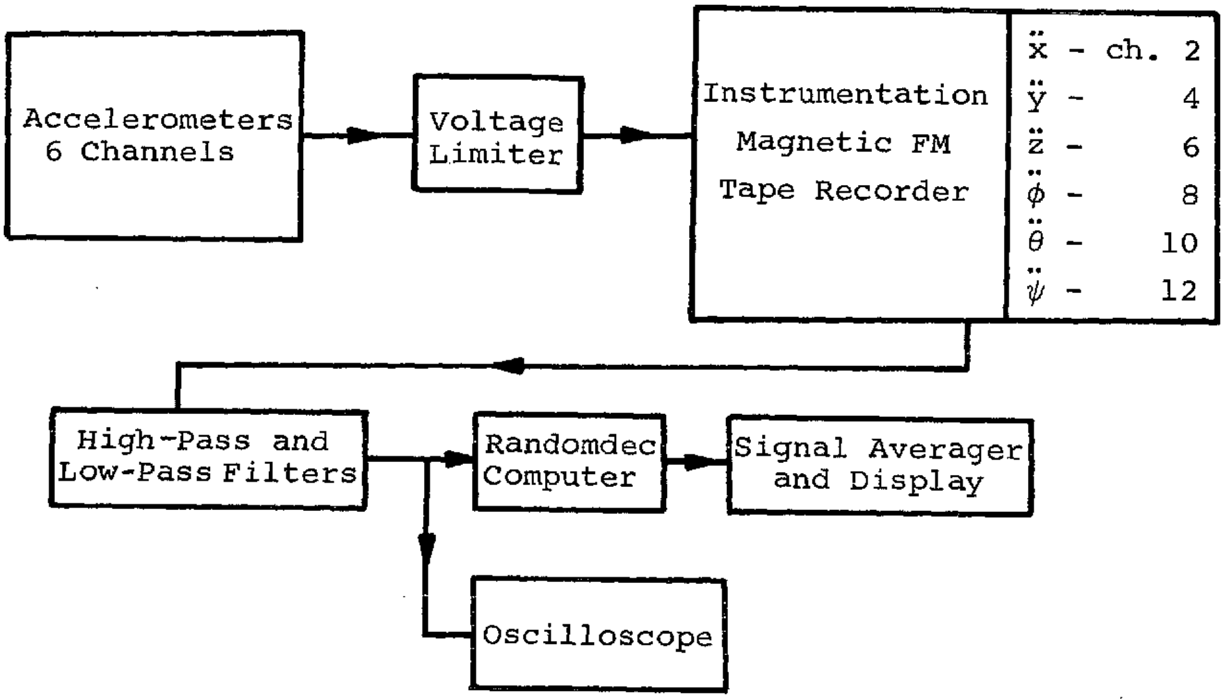


Figure 3.- Instrumentation.

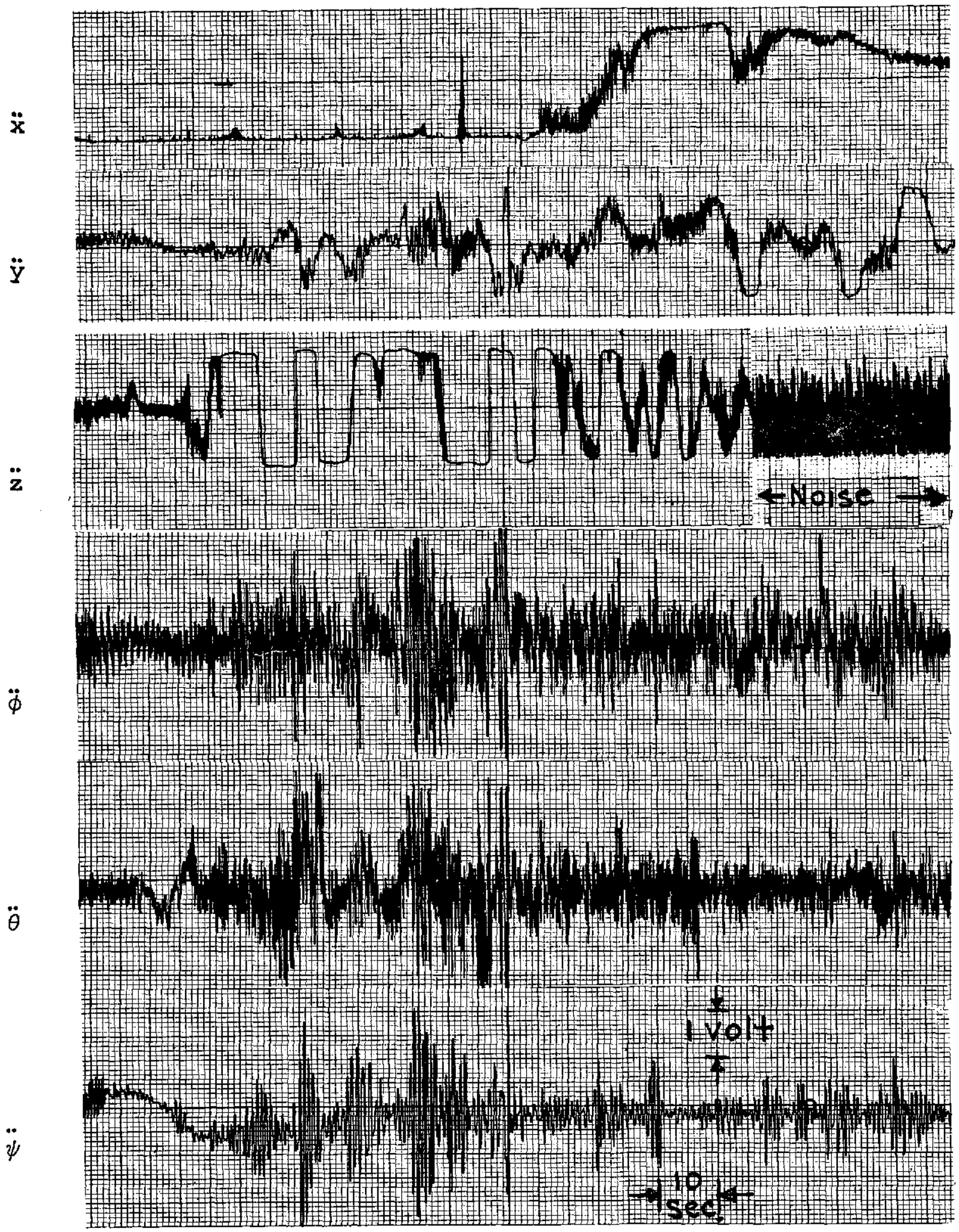


Figure 4.- Accelerometer time histories.

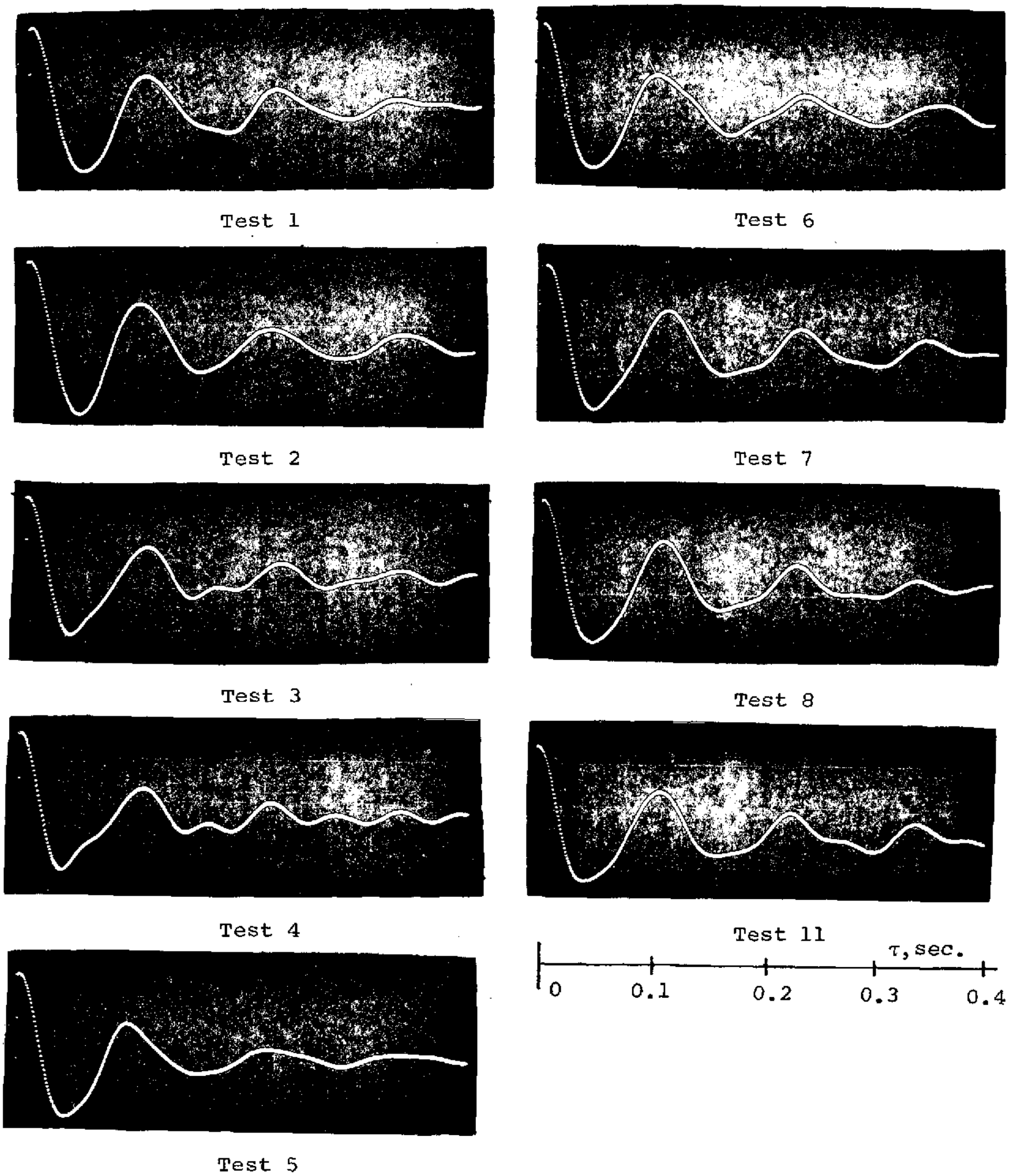
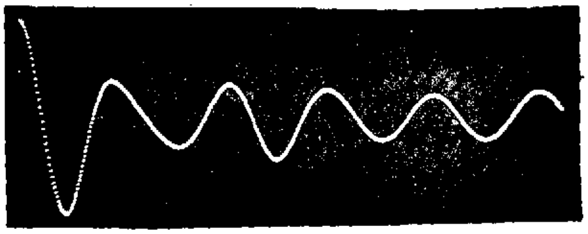
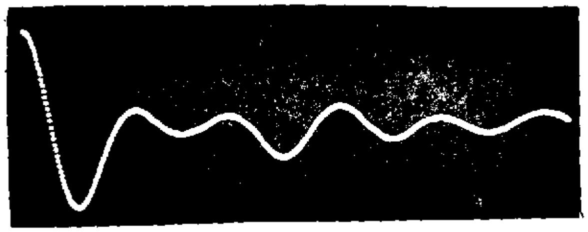


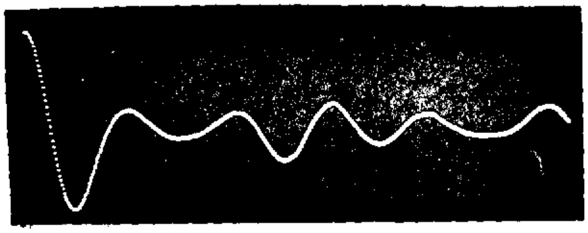
Figure 5.- Signatures of $\ddot{y}$, Filter: 7.5 to 22.5 Hz.



Test 1



Test 2



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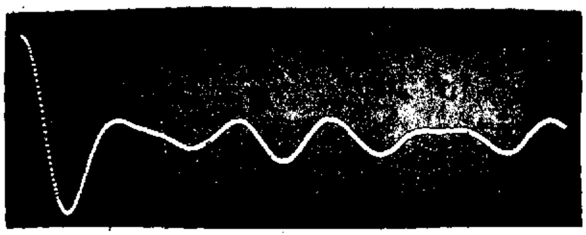

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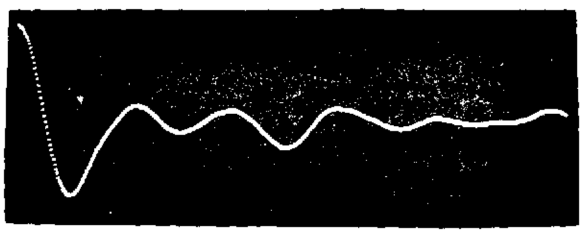

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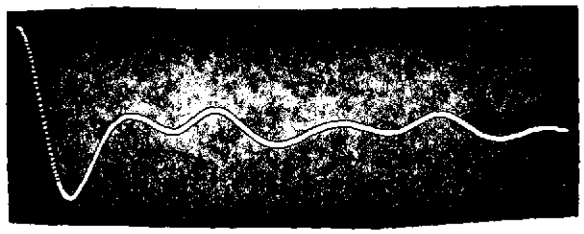

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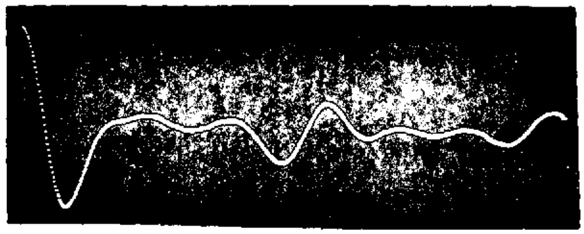

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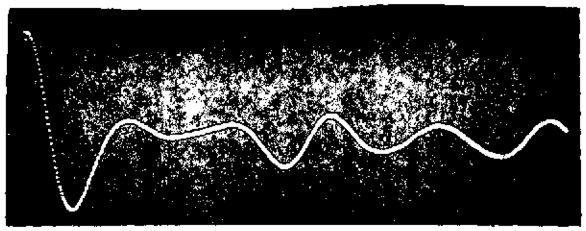
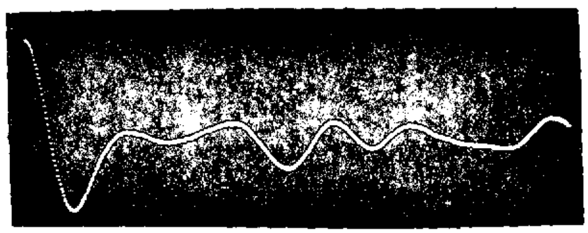
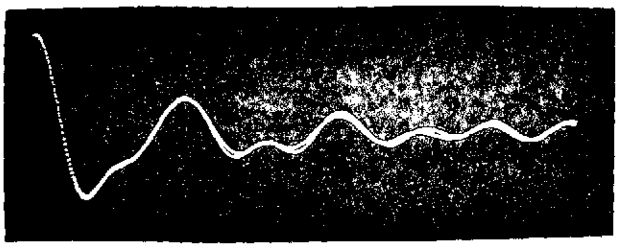


Test 8

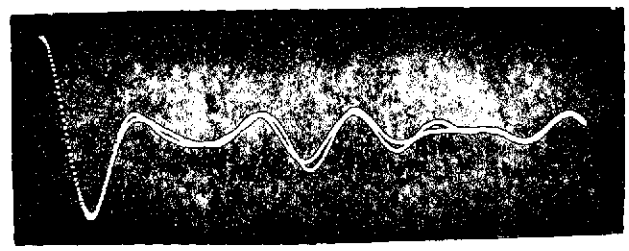


Test 11

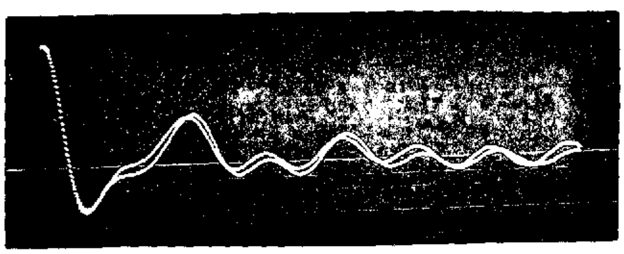
Figure 6.- Signatures of $\ddot{\theta}$, Filter: 7.5 to 22.5 Hz.



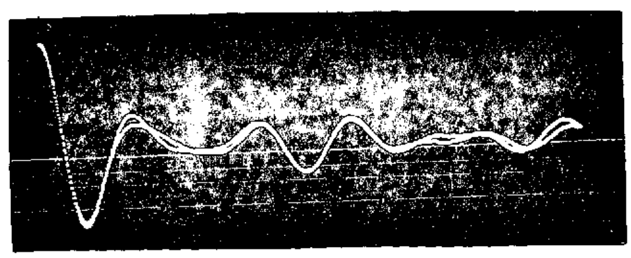
$\ddot{y}$, $N = 2^{11}$, Bias = 1



$\ddot{\theta}$, $N = 2^{11}$, Bias = 1

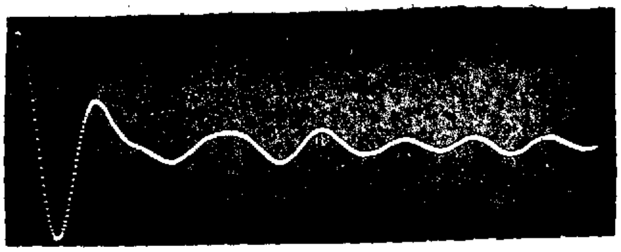


$\ddot{y}$, $N = 2^{10}$, Bias = 2

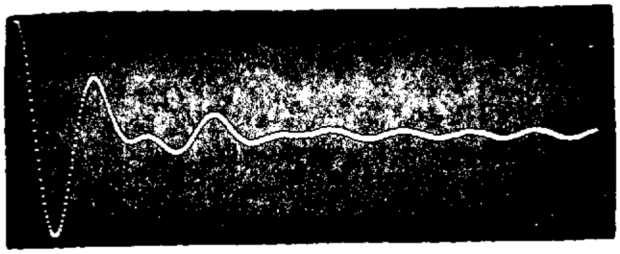


$\ddot{\theta}$, $N = 2^{11}$, Bias = 2

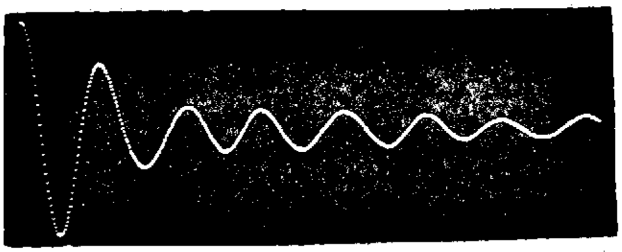
Figure 7.- Repeatability versus record length and bias level.



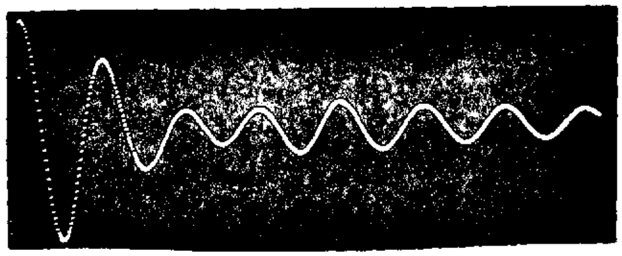
Test 1



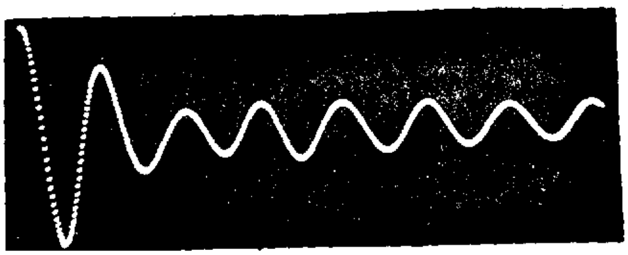
Test 6



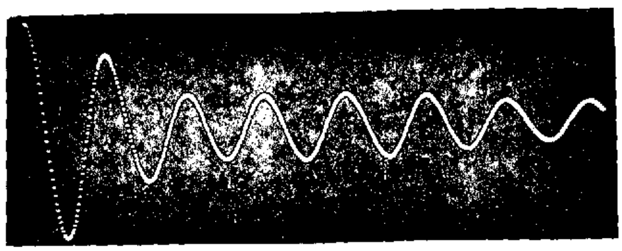
Test 3



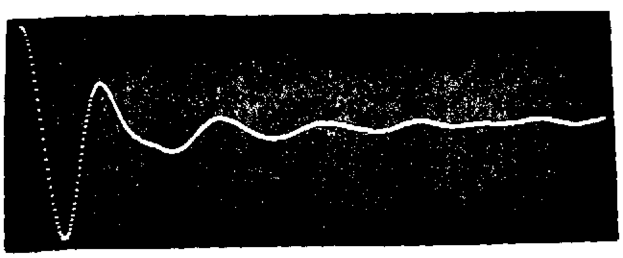
Test 7



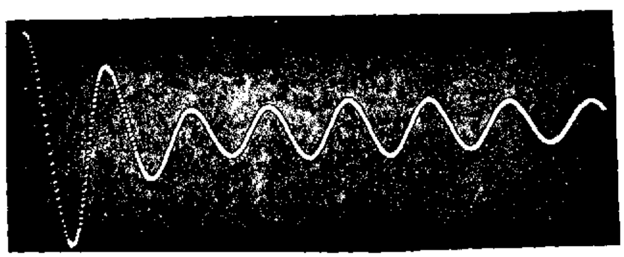
Test 4



Test 8

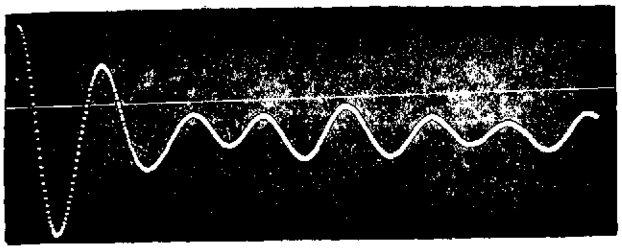


Test 5

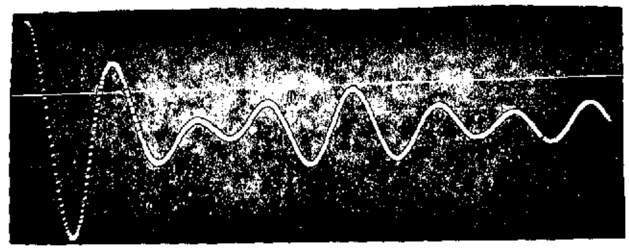


Test 11

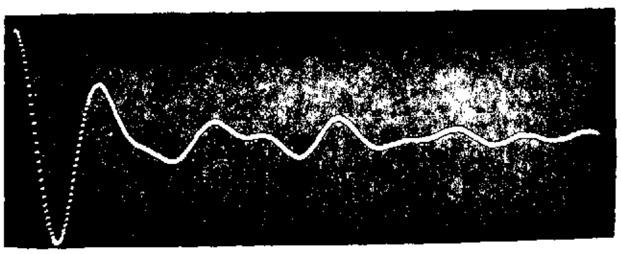
Figure 8.- Signatures of $\ddot{y}$, Filter: 13.75 to 22.5Hz.



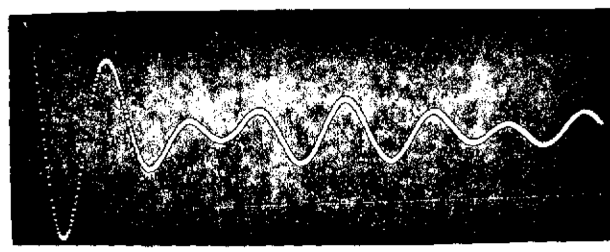
Test 4



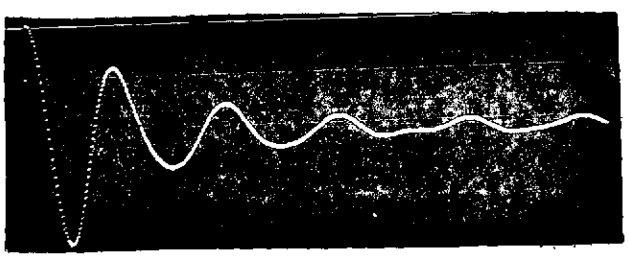
Test 7



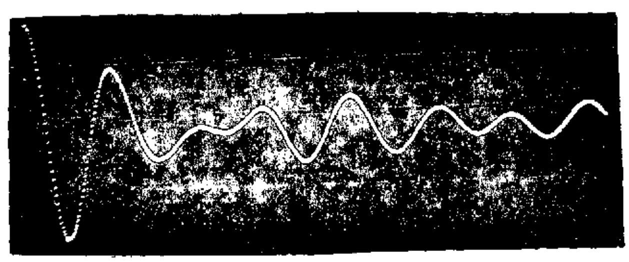
Test 5



Test 8

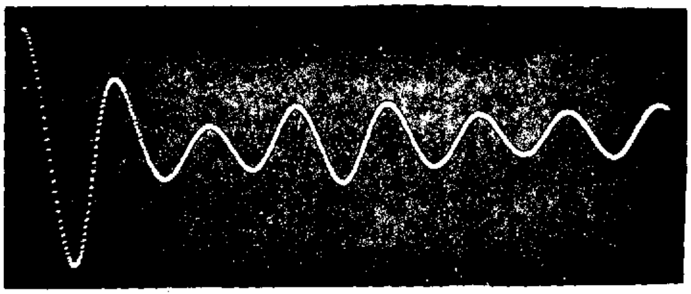


Test 6

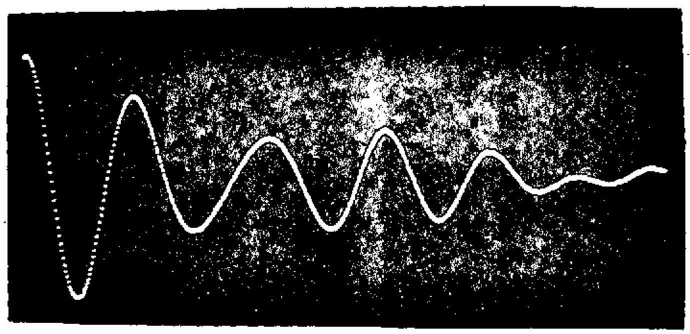


Test 11

Figure 9.- Signatures of $\ddot{\theta}$, Filters: 13.75 to 22.5 Hz.



$\ddot{\phi}$, Test 4



$\ddot{\psi}$, Test 4

Figure 10.- Signatures of $\ddot{\phi}$ and $\ddot{\psi}$,
Filter: 13.75 to 22.5 Hz.

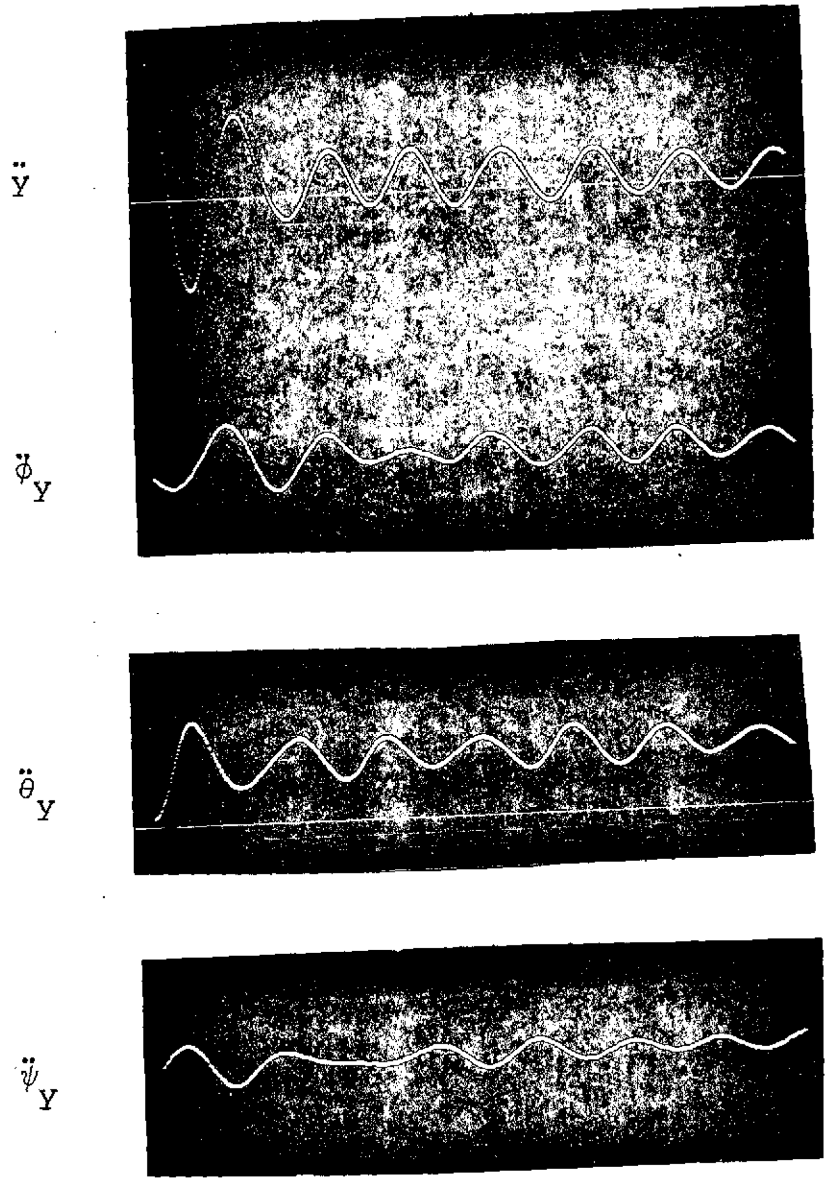
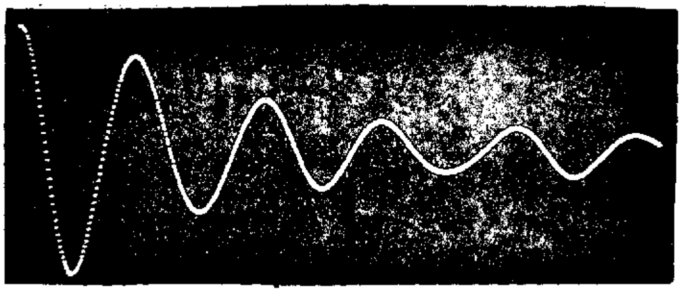
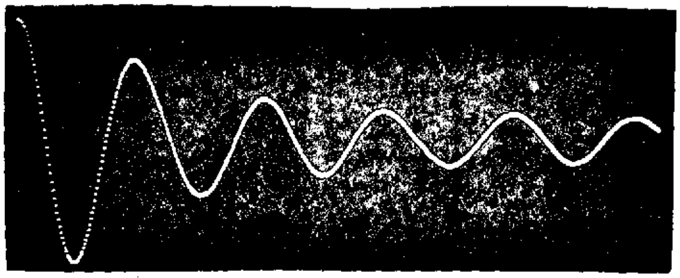


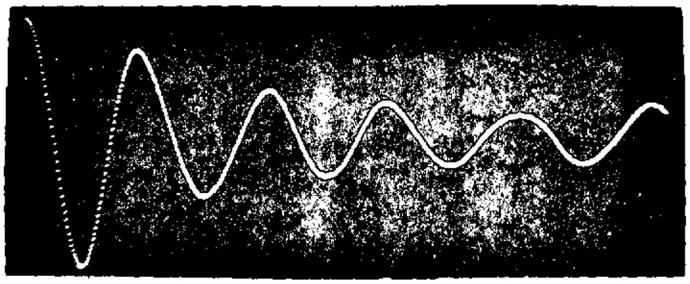
Figure 11.- Cross-Randomdec signatures,
Filter: 13.75 to 21.25 Hz, Test 4.



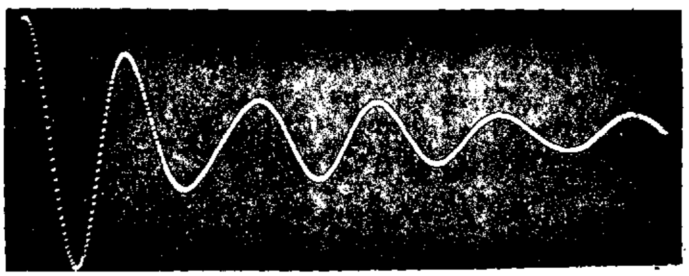
Test 5, Filter 7.5 to 22.5 Hz.



Test 6, Filter 7.5 to 22.5 Hz.

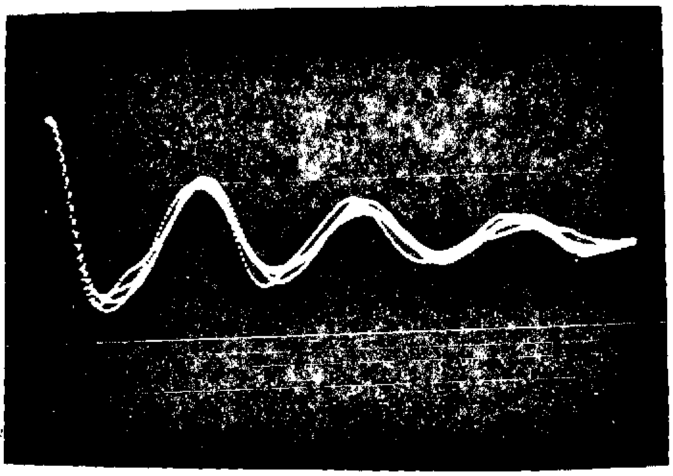


Test 7, Filter 7.5 to 22.5 Hz.



Test 7, Filter 13.75 to 22.5 Hz.

Figure 12.- Signatures of $\ddot{z}$.



Frequency = 1.25 n

n = number of peaks

Filter: 3.75 to 15 Hz.

Figure 13.- Signatures of $\ddot{y}$, Tests 2, 3, 4, and 5.

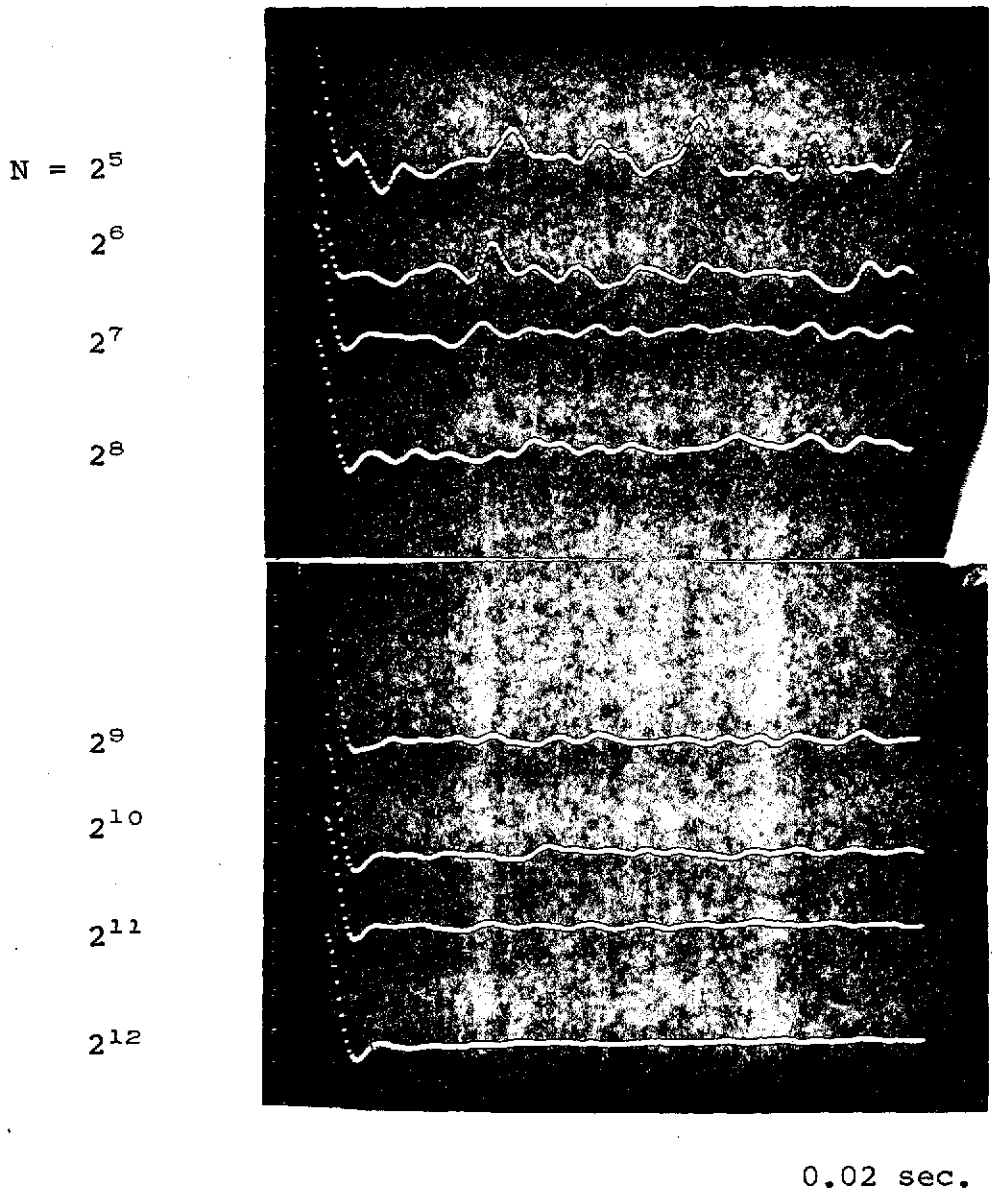


Figure 14.- Signatures of random noise versus record length.

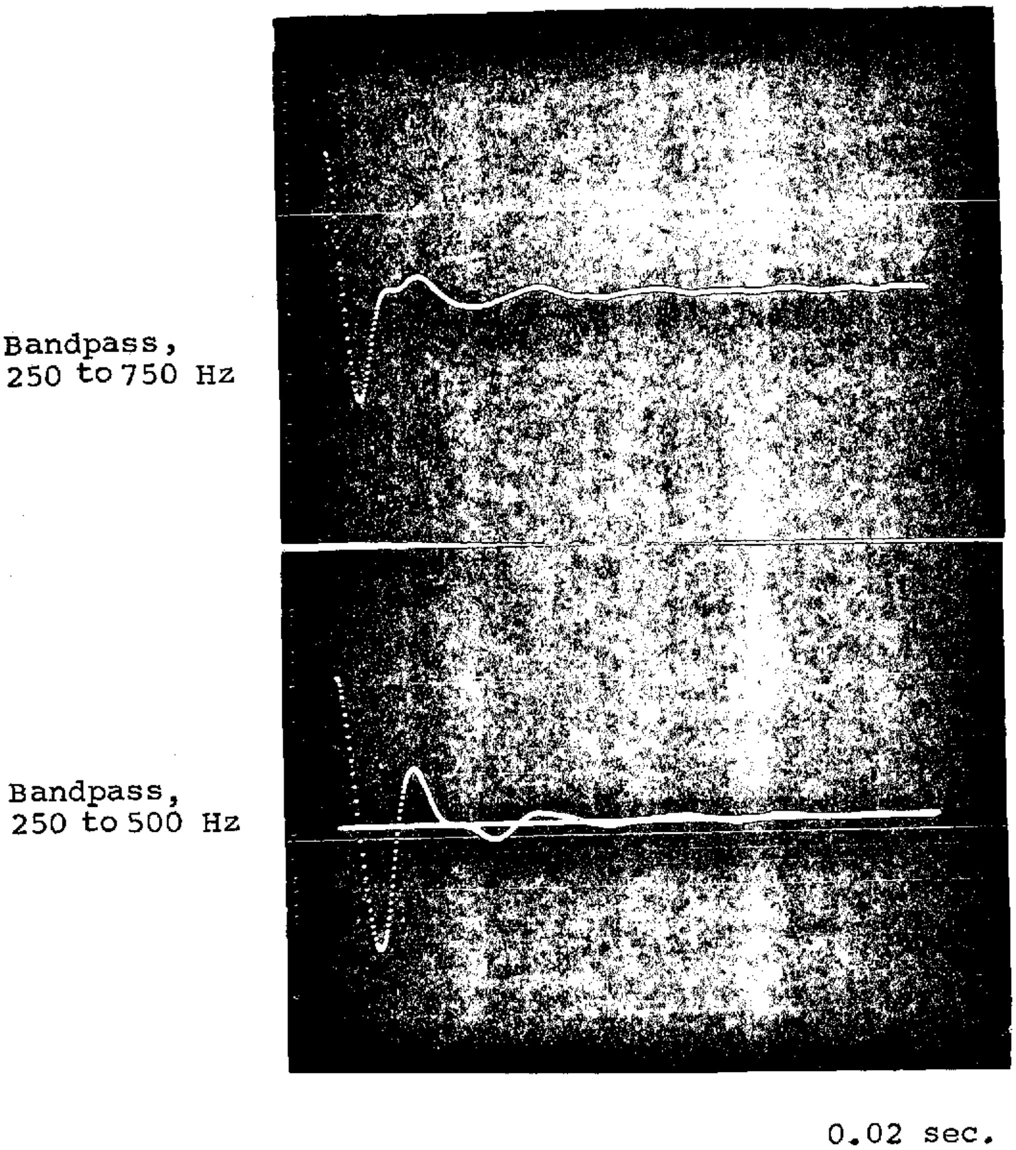


Figure 15. - Signatures of bandpass filtered white noise, $N \geq 2^{13}$.

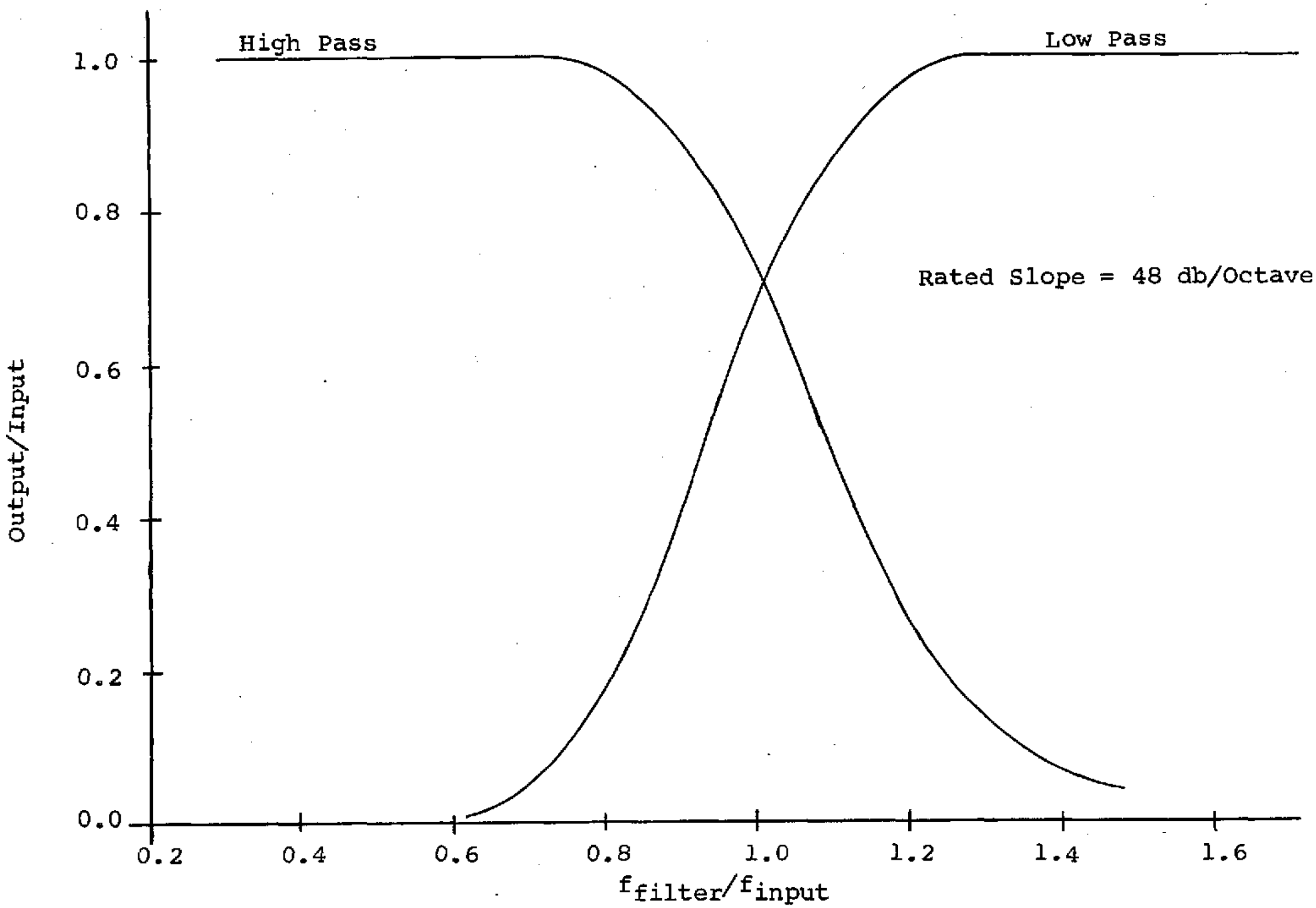


Figure 16.- Filter Characteristics.