NASA TECHNICAL MEMORANDUM

NASA TM X-73,121

(NASA-TM-X-73121) AN ANALOG TECHNIQUE FOR THE MEASUREMENT OF DAMPING FROM TRANSIENT DECAY SIGNALS (NASA) 19 p HC $3.50 CSCL 09C

N76-26452

Unclas
G3/35 44486

AN ANALOG TECHNIQUE FOR THE MEASUREMENT OF DAMPING FROM TRANSIENT DECAY SIGNALS

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June 1976

1. Report No. TM X-73,121	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle AN ANALOG TECHNIQUE FOR THE MEASUREMENT OF DAMPING FROM TRANSIENT DECAY SIGNALS		5. Report Date
		6. Performing Organization Code
7. Author(s) William G. Bousman*		8. Performing Organization Report No. A-6535
9. Performing Organization Name and Address NASA Ames Research Center and Ames Directorate, U.S. Army Air Mobility R&D Laboratory, Moffett Field, CA 94035		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546, and U.S. Army Air Mobility R&D Laboratory, Moffett Field, CA 94035		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

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17. Key Words (Suggested by Author(s)) Damping measurement; Tracking filter; Moving-block; Transient decay	18. Distribution Statement Unlimited; STAR Category - 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	19	$3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

A tracking filter that includes an output that is logarithmically proportional to the amplitude of the filtered signal may be used to measure the damping exponent of a transient decay. This method is analogous to the digital technique referred to as the moving-block or peak-plot method. The method is simple to use and quite accurate, avoids the numerical computations associated with similar digital techniques, but is constrained by the poor time-domain response characteristics of commercial tracking filters presently available.

INTRODUCTION

The damping of a linear system may be estimated from the exponential decay of the system response to transient excitation. The moving-block or peak-plot method (ref. 1) is a digital analysis technique that provides a good estimate of the damping of a transiently excited mode, and has been used successfully to measure damping in near real time for both wind tunnel and flight tests (refs. 2 and 3). The moving-block method is especially useful in reducing the effects of noise or other modes on the damping estimate, and provides qualitative information as to the linearity of the signal, the length of the signal that is suitable for a damping estimate, and the amount of excitation required to obtain a good signal-to-noise ratio. A disadvantage of the method, however, is that it does require a significant investment in a data analysis system to be used for the damping measurements. From this point of view, it is desirable to develop an analog technique for estimating the damping that is analogous to the moving-block method. This is possible with present commercial equipment. The purpose of this report is to discuss the accuracy and capabilities of such a device.

MOVING-BLOCK METHOD

The moving-block or peak-plot method has been discussed in detail in references 1-3 and is briefly outlined here. Consider a transient response of the form

$$x(t) = A e^{\sigma t} \sin(2\pi\omega_0 t + \phi)$$

where σ is the damping exponent and is the quantity to be measured. An example of this response is shown in figure 1(a). A block length is defined as the first N_b data points of the digitized signal, and the Fourier coefficients a_k and b_k are computed at a single frequency ω_k for this block. The frequency ω_k is defined by

$$\omega_k = \frac{k}{N_b \Delta t}$$

where k is the harmonic number, and Δt is the sampling interval. Both the harmonic number and the block length may be adjusted to allow ω_k to approximate the actual frequency ω_0, or ω_k may be chosen to reduce the effects of a nearby mode. The block of size N_b is moved through the data, and the Fourier coefficients are recomputed for each time step Δt. The natural logarithm of the Fourier coefficient magnitude for the selected frequency is plotted as a function of time (see fig. 1(b)) and, as shown in reference 1, has the form

$$\ell n|F(\omega_k)| \cong \sigma t - \frac{\sigma}{4\pi\omega_k} \sin 2(2\pi\omega_k t + \phi) + C$$

where C is a constant. The slope of the log magnitude as a function of time is simply the damping exponent σ. Superimposed over this is an oscillation at twice the analysis frequency that is proportional to the damping. Thus, for lightly damped systems, the oscillation is barely noticeable, while for more heavily damped systems, the oscillating component can become quite large.

The moving-block method has a number of attributes that make it useful in analyzing transient data. The ambulatory calculation of the Fourier coefficients at a discrete frequency is analogous to passing the data through a narrow bandpass filter. Just as in the case of a bandpass filter, the effect of noise due to other modes can be eliminated if they lie outside the passband. However, the equivalent passband of the moving-block method is not readily defined, since in Fourier analysis of a signal it is necessary to consider the side lobes of a contaminating frequency as well as the primary frequency. Thus, the filter characteristic of the moving-block method will take on the appearance of a $\sin x/x$ function. This character can be used to advantage in the case of a nearby contaminating signal by selecting the Fourier analysis frequency so that a zero point in the $\sin x/x$ function corresponds to the contaminating frequency (ref. 3).

An additional attribute of the moving-block method is the qualitative information provided by the behavior of $\ell n|F(\omega_k)|$ with time. When the transient signal has decayed to its quiescent level, this is clearly indicated by the tendency of $\ell n|F(\omega_k)|$ to oscillate randomly about a mean value instead of decreasing in value. In addition, the linearity of $\ell n|F(\omega_k)|$ with time provides an indication of system nonlinearity, the extent of noise within the effective passband, and the quality of the data being analyzed.

TRACKING FILTER METHOD

The moving-block method acts in a manner similar to a narrow bandpass filter in isolating the frequency of interest. This suggests that a tunable bandpass or tracking filter could be used to isolate the frequency, and a circuit could be designed to generate a voltage proportional to the log of the signal amplitude. Such a system would be analogous to the moving-block method, have many of its attributes, and yet remain a fairly simple analog device.

A commercially available tracking filter* is, in fact, such a device. It includes an output referred to as "log dc" that is proportional to the log of the filtered signal amplitude. The proportionality acts over a number of cycles of the tuning frequency but is weighted to emphasize the most recent part of the filtered signal. Such a weighting is, in effect, a spectral window in the same class as "boxcar" or cosine weightings used in Fourier analysis and has no effect on the behavior of the equivalent $\ell n|F(\omega_k)|$ function of the tracking filter. This log dc signal is a direct analog of the digital function $\ell n|F(\omega_k)|$.

The use of this tracking filter to measure damping is straightforward. The tuning frequency and filter passband are selected so that the mode of interest is with the passband. The log dc output from the tracking filter is then plotted as a function of time, and the slope is a measure of the damping exponent as shown in figure 2. As can be seen, the tracking filter causes a lag in the filtered response, and due to its time-domain response characteristics, there is some initial overshoot in the log dc output signal. The time-domain performance of the tracking filter has no effect on the damping estimate for the case shown in figure 2, but as discussed below, this filter characteristic can make some damping estimates impossible. The log dc output is easily calibrated with respect to the tracking filter input, using an oscillator to generate a series of constant-amplitude input signals.

The tracking filter shares some of the attributes of the moving-block method, in particular its ability to provide qualitative information about the data - effects of noise, excitation strength, and data quality. The fact that it is an analog device makes it especially useful in situations where access to a digital computer is limited by cost or time constraints. However, its passband is constrained by the poor time-domain characteristics of the tracking filter, and is, therefore, more susceptible to contamination from other modes, forced responses, or noise lying within the passband.

Accuracy of Tracking Filter Method

The accuracy of the tracking filter method was examined by using an analog computer to generate a transient decay signal, such as shown in figure 2. An envelope was fitted to the unfiltered signal, and the damping was estimated by calculating the log decrement of sequential points on the envelope. The slope

*SD121 Tracking Filter, Spectral Dynamics Corporation.

of the log dc output of the tracking filter was determined, and the two values are compared in figure 3. The tracking filter result shows good agreement with the log decrement estimate. Although the effect of data scatter is more noticeable at high damping levels, there is no discernible trend in the error.

As another check on the accuracy of the tracking filter, a comparison was made between the moving-block method and the tracking filter using a body of experimental data reported in reference 4. The comparison is shown in figure 4, and although it is restricted to low damping levels, it shows good agreement between the moving-block method and the tracking filter.

The tracking filter method, like the moving-block method, gives an indication of the quality of the data; that is, how well behaved it is and how easily a straight line may be fitted to the log amplitude decay. This is illustrated in figure 4; the flagged symbols indicate cases where the damping estimate from the tracking filter was considered poor prior to any comparison with the moving-block results, and for the most part these points show more scatter. The additional scatter in this figure at the higher damping levels reflects the fact that these cases are influenced by two coupled modes, and analysis was more difficult.

Filter Bandwidth Constraints on Tracking Filter Performance

Tracking filters have been used in the past as a vibration test control component, for power spectral density measurements, phase comparisons, and a number of other applications (ref. 5). For these applications, the phase response of a filtered signal is unimportant in an absolute sense; rather, it is the relative phase shift of two or more signals that is important. Therefore, linear phase characteristics and, hence, good time domain response are not required. It is the nature of transient signals to vary widely in their signal strength with time, and therefore, a proper filter for transient signals requires good time-domain response. The time-domain response of the filter used in these investigations was sensitive to the filter bandwidth and thus limited in its application.

The effect of filter bandwidth on the damping estimate is illustrated in figure 5 for a transient signal generated on an analog computer. The filter bandwidth takes on discrete values of 10.0, 5.0, 2.0, 1.0, and 0.5 Hz. The damping in this case is fairly high, $\sigma = -2.02$, as determined from the unfiltered signal by measuring the log decrement. The frequency of the transient signal is 9.6 Hz, and this value is used as the tracking filter tuning frequency ω_c. For the tracking filter to operate within specification, the filter bandwidth must be less than half the tuning frequency. In this case, then, the filter bandwidth must be less than 4.3 Hz to operate within specification. However, the tracking filter is usable for a filter bandwidth up to the tuning frequency. In figure 5(b), the log dc output provides a good estimate of the damping even for a filter bandwidth of 10 Hz. The effect of operating at a filter bandwidth greater than half the tuning frequency is apparent in the oscillatory content of the log dc signal at the low end of its dynamic range. In figure 5(c), for a bandwidth of 5.0 Hz, the filtered signal is somewhat degraded due to the filter characteristics, but a segment of the log dc signal is straight enough to allow an accurate damping estimate. As the filter bandwidth is reduced to 2.0 Hz, as shown in figure 5(d), the filtered output is degraded considerably. A section of the log dc signal is sufficiently straight to attempt to estimate the damping, but the result is 14 percent high. At bandwidths of 1.0 and 0.5 Hz, as shown in figures 5(e) and 5(f), the filtered signals are so degraded that no estimate of the damping is possible.

The simulated transient signal used in figure 5 contains many frequencies in its initial rise. As the filter does not have a linear phase shift with frequency, each of the frequencies in the initial jump experiences a different time lag, and this causes the distortion that is seen in the filtered responses. This suggests that playing the signal backwards through the tracking filter, as proposed by Mazet (ref. 6), will cause the distortion to be at the end of the signal rather than the beginning, and thereby allow an improved damping estimate. This, in fact, does occur as shown in figure 6 where the signal in figure 5 has been played backwards through the tracking filter with the bandwidths of 2.0, 1.0, and 0.5 Hz. For both the 2.0- and 1.0-Hz bandwidth settings, the backwards analysis provides a suitable estimate of the damping as shown in figures 6(b) and 6(c). This technique is an improvement in that it extends the bandwidth range that may be used with the tracking filter. However, as bandwidth is narrowed, even the backwards analysis will not provide an accurate estimate as shown in figure 6(d) where the signal is filtered with a 0.5-Hz bandwidth.

The tracking filter shows the most distortion when the signal contains frequencies other than the primary analysis frequency. At very low damping levels, it does not matter whether the signal is analyzed forwards or backwards, since in the former case the initial distortion has sufficient time to die out while there is still substantial signal strength remaining, and in the latter case the distortion is delayed to the end of the signal. As the damping is increased, the difference between forward and backward analysis becomes important. The backward analysis avoids distortion until the end of the signal and thereby provides a goo output for estimating the damping, while the forward analysis must cope wit. a reduced useful signal due to the initial distortion. Eventually a damping level is reached where the initial distortion completely obliterates the output signal in the forward analysis case. For even higher damping values, distortion in the backward analysis also makes an estimate of the damping impossible.

The operating constraints of the tracking filter are therefore a function of both filter bandwidth and signal damping. The filter performance was tested to identify these constraints using signals generated by the analog computer for a range of filter bandwidths and damping levels. The results are shown in figure 7 for the forward analysis of an impulsively excited transient signal. The effect of filter bandwidth is represented by the log of the ratio of the bandwidth to the center frequency, and this is plotted versus the damping ratio. The open symbols represent valid estimates of damping (error $\leq \pm 10$ percent), while the solid symbols represent combinations of filter bandwidth and damping where the estimate was impossible to make or the error was greater than ±10 percent. Marginal cases, where the data was judged a priori to be of poor quality but the resulting estimate was within ±10 percent, are shown as half-solid symbols. The shading on this figure is a subjective estimate of the region where damping estimates are feasible but where errors greater than ±10 percent are likely.

Backward analysis of signals offers a substantial improvement in filter performance as shown in figure 8. In the case where a transient signal is excited using sinusoidal excitation instead of impulsive excitation, initial distortion depends on the difference between the exciting frequency and the modal frequency. When the excitation frequency is exactly at the mode frequency, the filter performance is substantially the same as shown in figure 8 regardless of whether the analysis is forward or backward. For deviations in excitation frequency, there are corresponding reductions in filter performance in forward-analysis cases.

In using the tracking filter for estimating damping exponents, the necessary first step is to select a filter bandwidth that will allow accurate measurement of damping over the range expected. Normally, to obtain good measurements, it is necessary to use a relatively wide filter bandwidth, but this has the attendant disadvantage of allowing contamination from nearby modes or forced responses. However, if contaminating signals are located primarily on one side of the frequency of interest, then the center frequency of the filter may be adjusted to place the frequency of interest near the edge of the filter characteristic that will eliminate the contaminating frequencies. If contamination exists on both sides of the frequency of interest, then analysis is not possible.

The method described in this report was developed using a commercially available tracking filter. Other commercially available devices may exhibit similar capabilities. As an example, any narrow bandpass filter equipped with a circuit to measure the rms voltage of the filtered signal over a relatively short time scale and a linear/log converter should operate in a manner similar to the tracking filter described here. In addition, some real-time spectrum analyzers have the capability of tracking one spectral line (harmonic number) as a function of time. Depending upon the cycle or recompute time of the spectrum analyzer, enough points will be available to obtain an equivalent $\ln|F(\omega_k)|$ as a function of time and, hence, an accurate estimate of the damping of transient signals.

CONCLUSIONS

1. An analog method has been developed to measure the damping exponent of a transient decay using a commercially available tracking filter. The method is analogous to the digital technique referred to as the moving-block or peak-plot method and shares many of its attributes.

2. The tracking filter method of measuring damping is simple to use and quite accurate if constraints on filter bandwidth and damping level are observed. The method probably has its greatest utility in analyzing data with only one predominant mode. Additional modes will require additional tracking filters or additional passes of the data.

3. The poor time-domain response characteristics of the tracking filter used in the experiments reported here constrain the range of filter bandwidths that can be used and, hence, the ability of the method to isolate the frequency of the mode of interest from other modes or forced responses. The capabilities of the tracking filter are extended considerably if the data are played backwards through the filter to reduce the effects of the initial impulse; however, there are still limitations on performance. The use of a narrow bandpass filter with linear phase response would remove these constraints.

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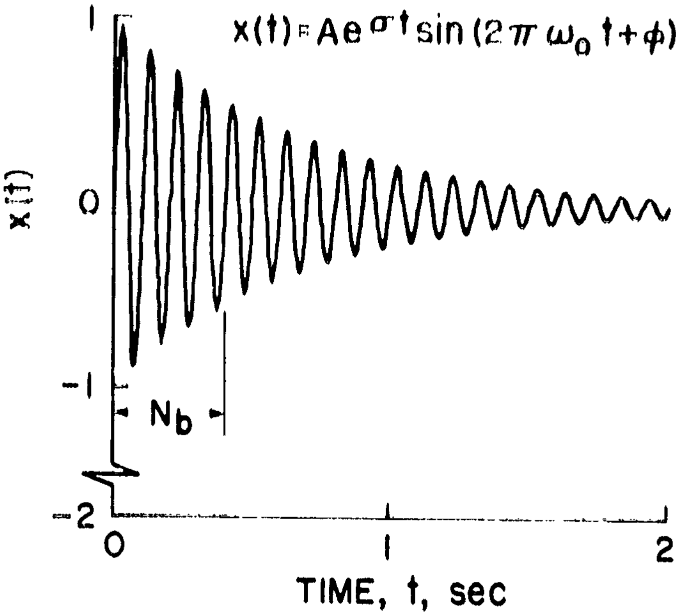
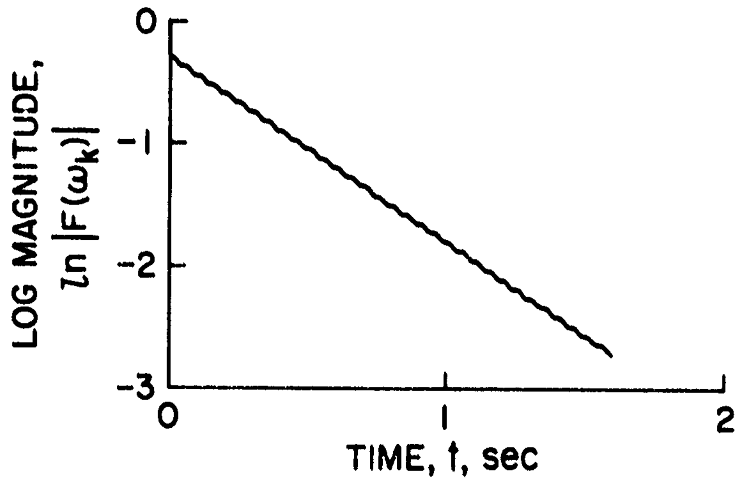
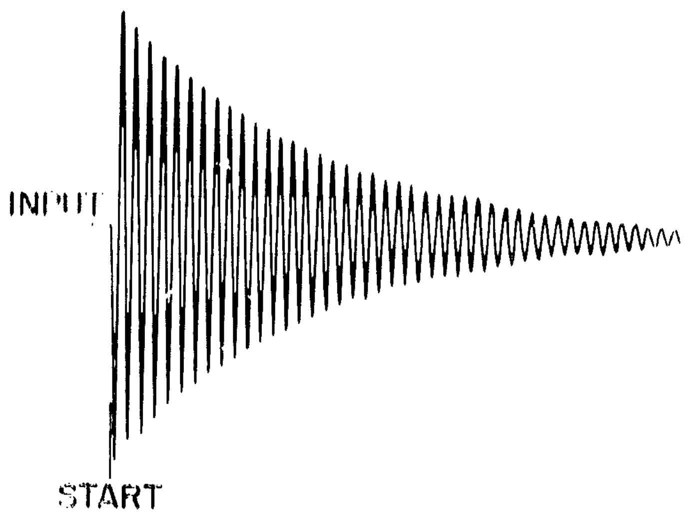


(a) Damped sinusoid: $A = 1$, $\sigma = -1.5$, $\omega_o = 10$ Hz, $\phi = 0$.

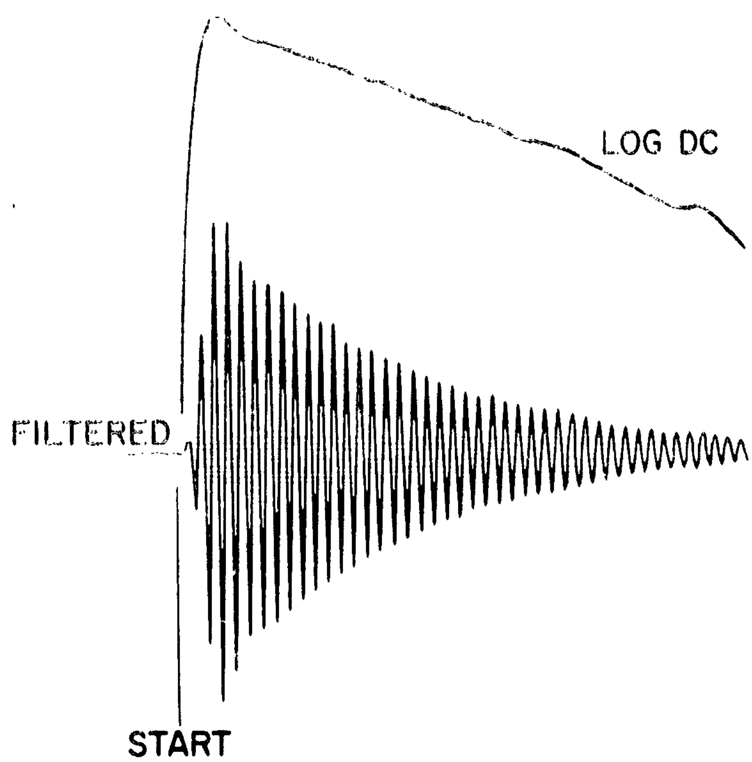


(b) Log magnitude of Fourier coefficients.

Figure 1.- Transient response of a simulated second-order system and corresponding moving-block function.



(a) Test input: $\omega_0 = 9.5$ Hz, $\sigma = -0.64$.



(b) Filter and log dc outputs: $\sigma = -0.66$.

Figure 2.- Test transient signal and resulting filtered and log dc outputs from tracking filter.

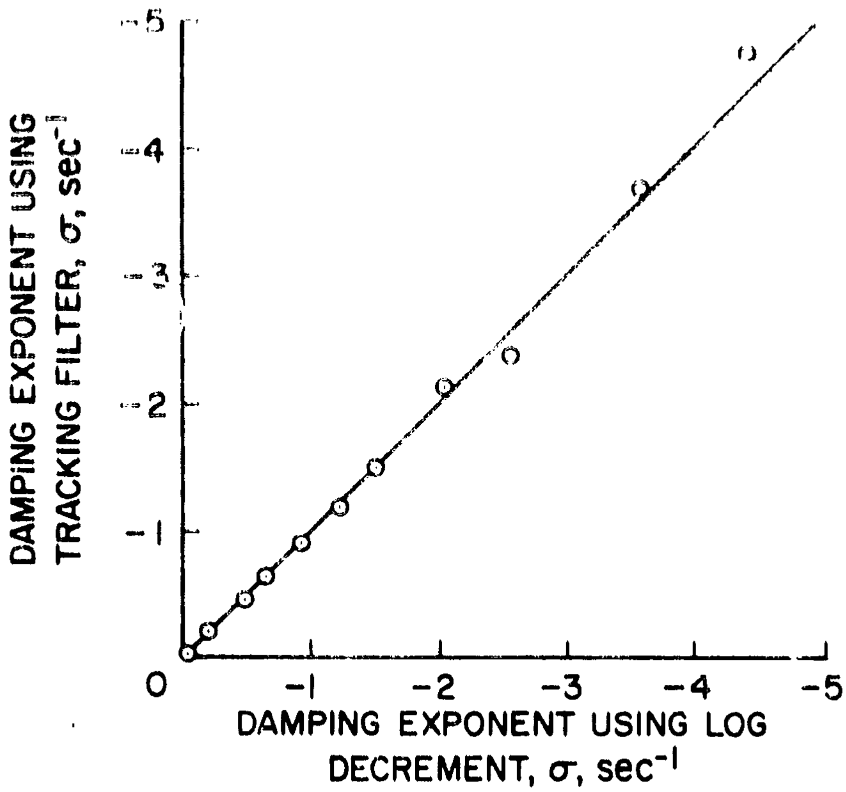


Figure 3.- Comparison of tracking filter estimate of damping exponent with log decrement estimate for a simulated transient decay, ω_0 = 12.7 Hz.

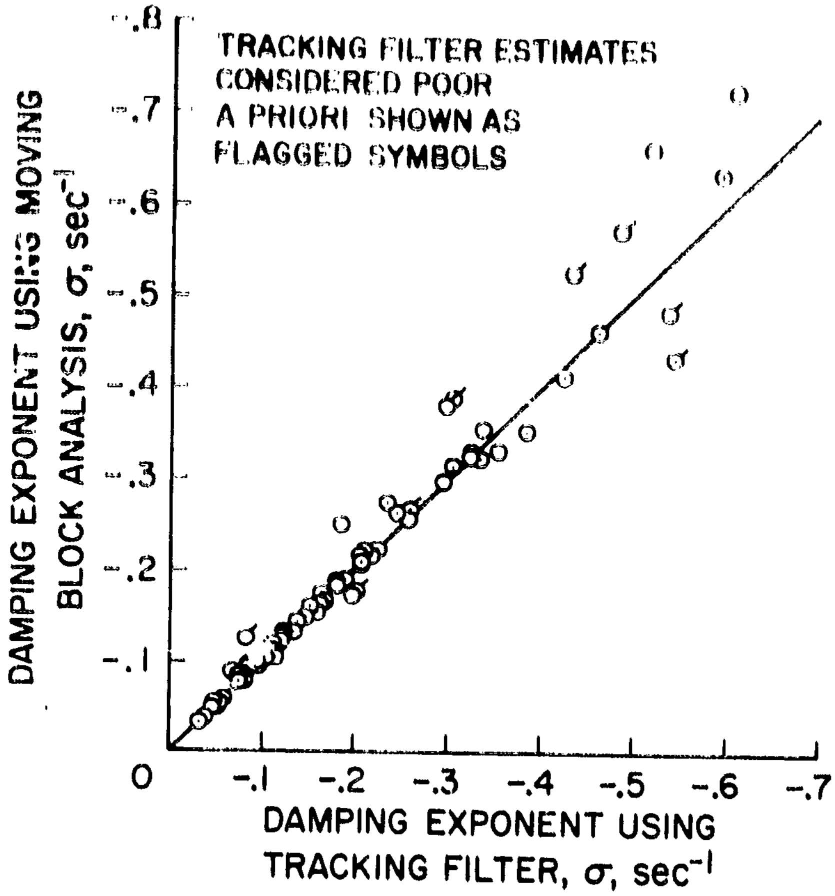
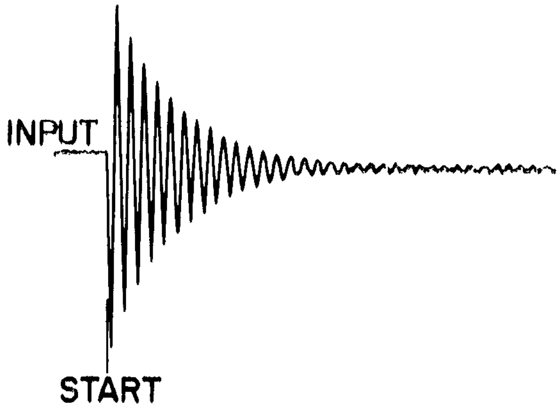
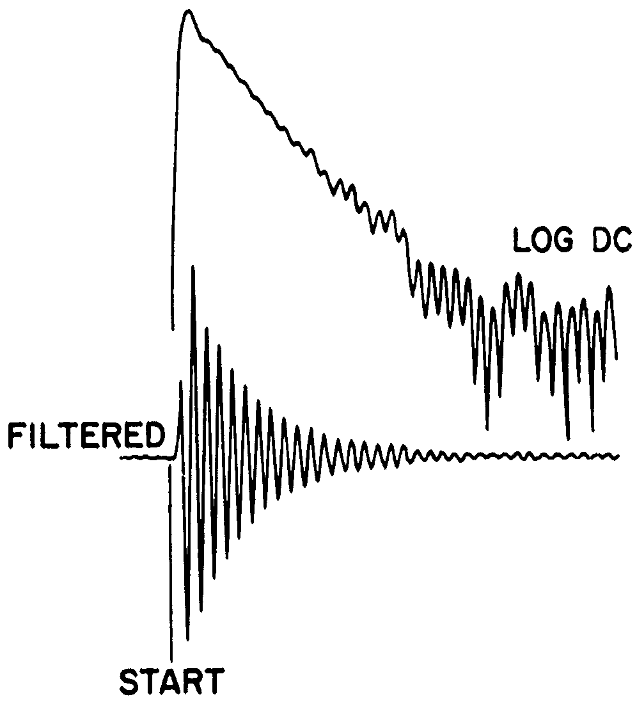


Figure 4.- Comparison of damping exponent estimates using moving-block method and tracking filter for experimental data from reference 4.

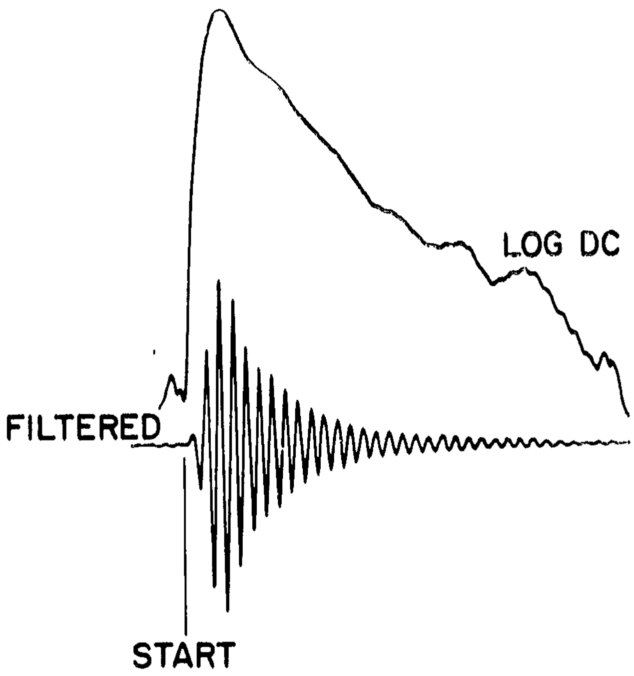


(a) Simulated transient decay: ω_0 = 9.6 Hz, σ = -2.02.

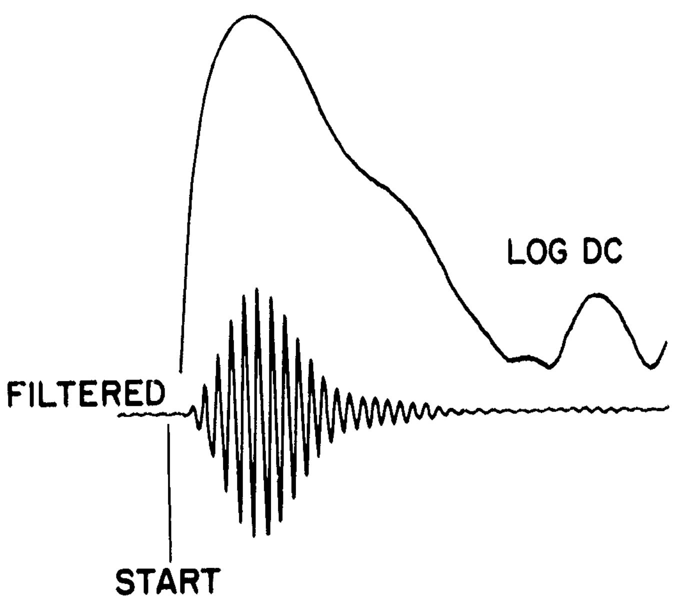


(b) Filtered response and log dc output for $\Delta\omega$ = 10 Hz, σ = -2.09.

Figure 5.- Simulated transient decay, filtered response, and log dc output for five different filter bandwidths.

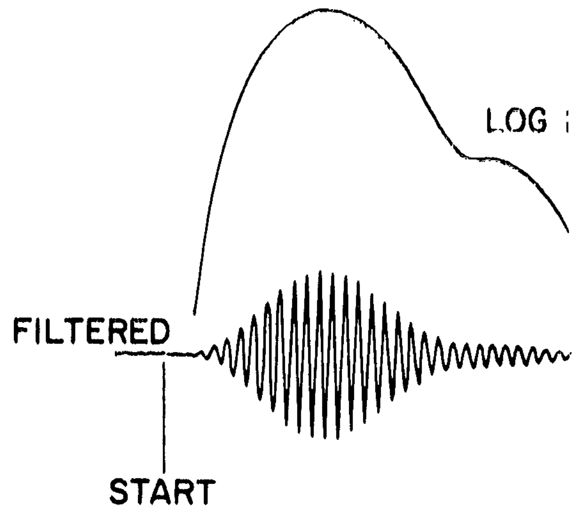


(c) Filtered response and log dc output for $\Delta\omega$ = 5 Hz, σ = -2.04.

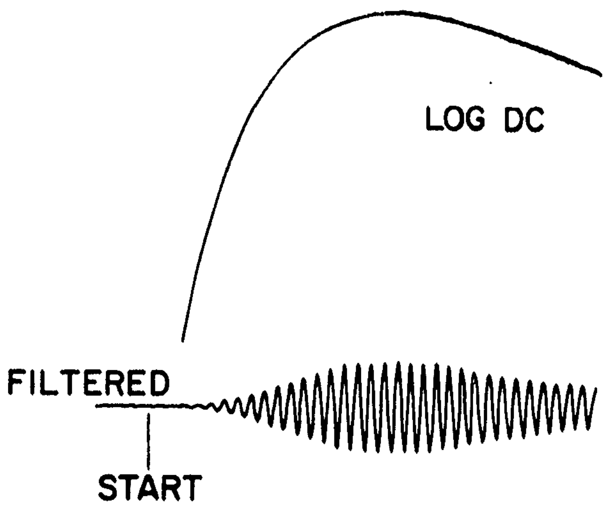


(d) Filtered response and log dc output for $\Delta\omega$ = 2 Hz, σ = -2.31.

Figure 5.- Continued.

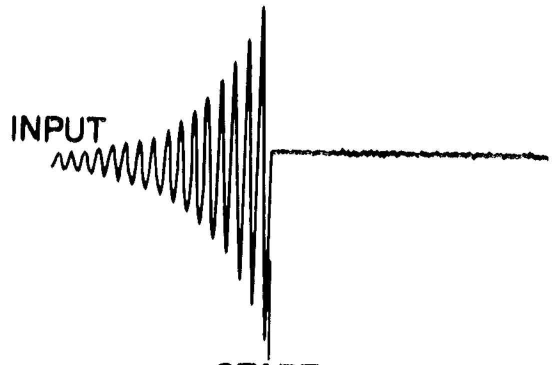


(e) Filtered response and log dc output for $\Delta\omega$ = 1 Hz

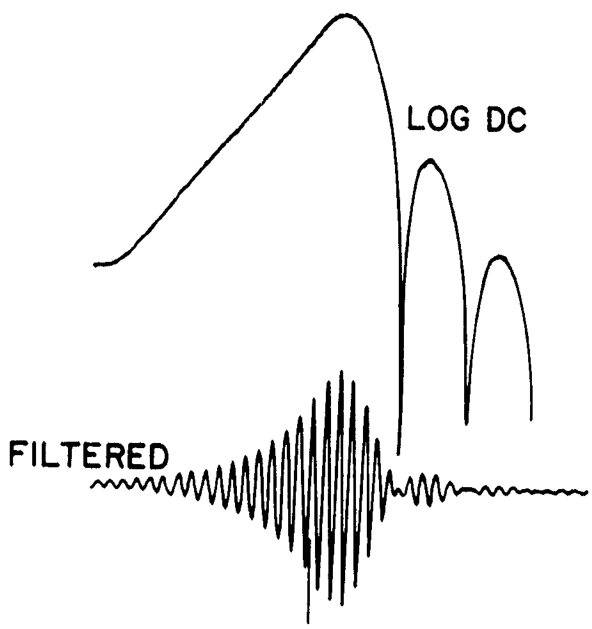


(f) Filtered response and log dc output for $\Delta\omega$ = possible.

Figure 5.- Concluded.

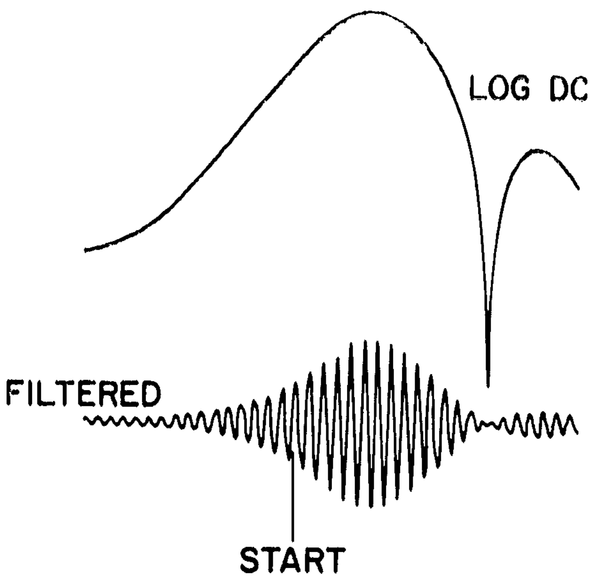


(a) Simulated transient decay played backwards: ω_0 = 9.6 Hz, σ = -2.02.

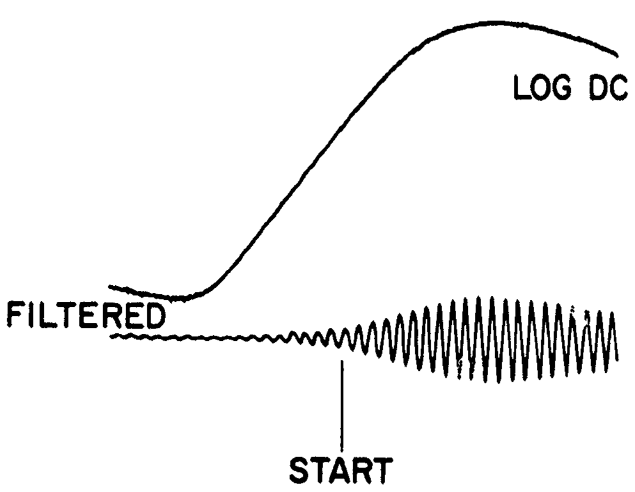


(b) Filtered response and log dc output from signal played backwards: $\Delta\omega$ = 2 Hz, σ = -2.11.

Figure 6.- Simulated transient decay, filtered response, and log dc output for signal played backwards.



(c) Filtered response and log dc output from signa
$\Delta\omega = 1$ Hz, $\sigma = -2.08$.



(d) Filtered response and log dc output from signal
$\Delta\omega = 0.5$ Hz, no estimate possible.

Figure 6.- Concluded.

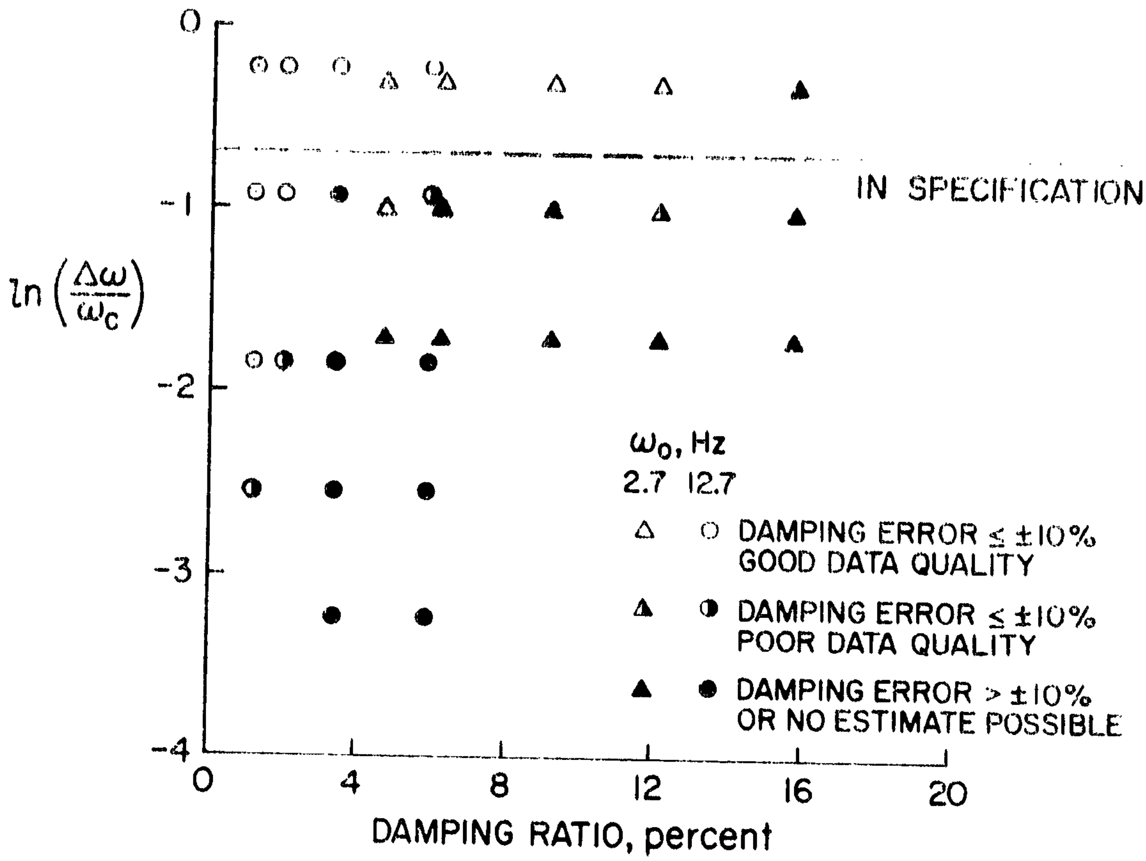


Figure 7.- Tracking filter operating limitations in terms of center frequency and bandwidth in analyzing impulse-excited transient signals (forward analysis).

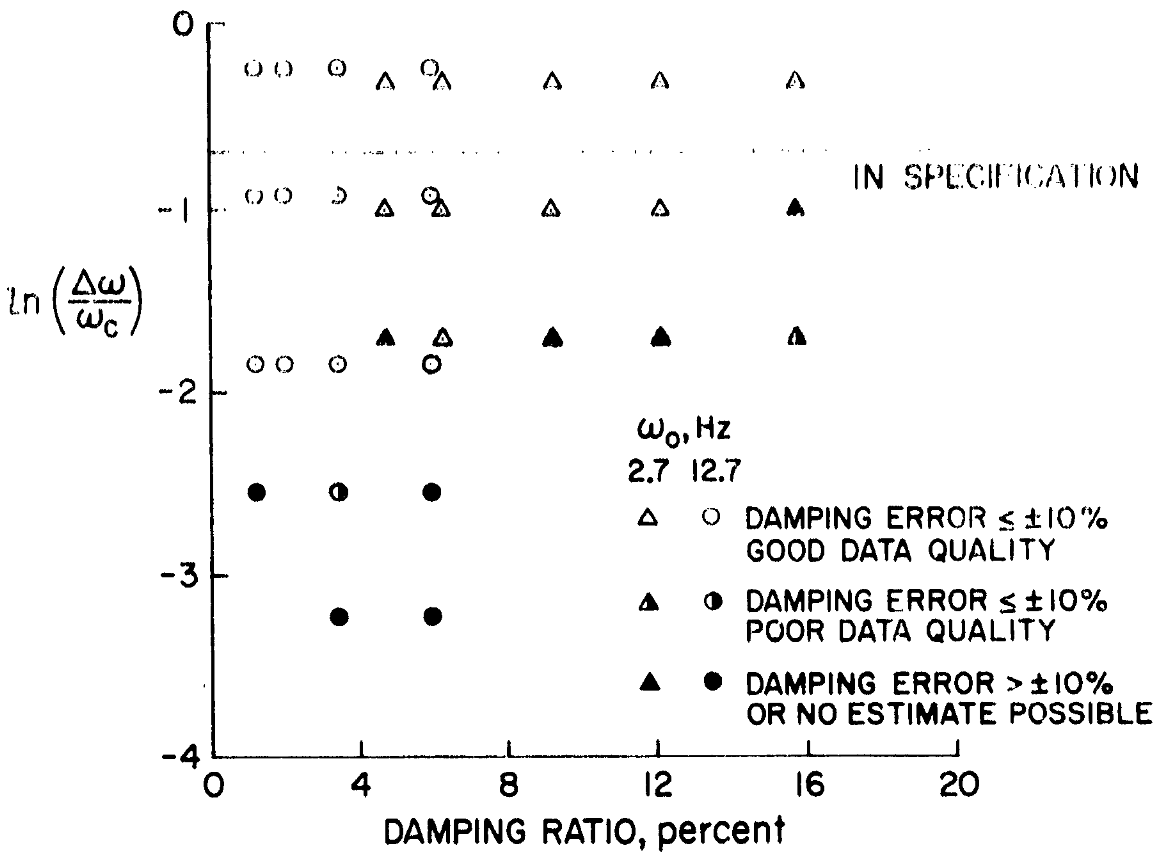


Figure 8.- Tracking filter operating limitations in terms of center frequency and bandwidth in analyzing impulse-excited transient signals (backward analysis).