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Sequential transient filtering: an automated method of frequency derivative detection

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Of several techniques currently available for recognition of swept-frequency transient signals, most are limited fundamentally in their ability to detect signals with high normalized sweep rates (e.g. 100 sec^{-1} and up‡), and immersed in a noisy environment. Furthermore, common techniques incorporating Phase Lock Loops (PLL) and Voltage Tunable Filters (VTF) are not inherently noise immune and are easily unlocked by noise of various types.

A scheme is presented which has the capability of detecting fast, swept-frequency transient signals in the presence of many varieties of disturbances within the frequency range of the sweep. The disturbances tolerated being not completely without restriction, can be characterized by the relationship of their power spectra to factors including filter bandwidths and resonant frequencies, signal sweep rate, and signal to noise ratio. With a slight modification incorporated in the circuit realization, the detection scheme is able to cope with swept signals of continuously varying amplitude.

1. Introduction

This paper is concerned with a detector of families of swept-frequency transient signals. The detector provides an output at the time of occurrence of a swept-frequency transient signal having particular characteristics and buried in a noisy background. The basic class of signals of interest here are those in which the characterizing frequency shifts rapidly in a monotonic fashion. An example is a Doppler-shifted signal in which the rate of displacement of the target is high.

A novel technique for detecting signals having a high sweep rate is described. The noise immunity properties of this technique are then discussed and a typical circuit realization is given. In the final section, several practical applications of this technique are suggested.

2. Phase-lock detection limitations

Although it may seem possible to use a PLL to detect transient frequency ramp-type signals, it is contended that it is impractical to use one for high rates of deviation. Further, the PLL is unsuited to those important cases in which the swept-frequency signal to be detected is immersed in noise which is within the swept band and of comparable amplitude to that of the desired signal. Two factors prevent success under these circumstances. One is the inherent instability of the very high gain unlocked loop required for fast acquisition (Gardner 1966), while the other is the limitation in attainable gain due to saturation restrictions of a practical loop.

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‡ Normalized sweep rate is defined to be rate of frequency deviation/band centre frequency.

In addition, the PLL has the disadvantage that, by its very nature, it locks onto the largest signal within its capture range. Unfortunately, for the conditions mentioned, the capture range is necessarily large for fast tracking PLL's (Frazier and Page 1962). One concludes therefore that a PLL is inappropriate for the detection of these types of swept-frequency signals having high rates of normalized frequency deviation.

3. Fundamentals of sequential transient filtering

The method proposed implements a piecewise approximation to filtered time-domain characteristics of the signal and may be described as a form of signature detection (Cousin *et al.* 1974). A conceptual block diagram is presented in Fig. 1.

The input signal is processed through N relatively narrow, fixed bandpass filters that are arranged in parallel but with the distinction that their outputs are related sequentially through logic networks. By maintaining equal bandwidths in all of the filters two important results are obtained. First, the output envelope from the filter nearest to the instantaneous frequency of the signal rises more rapidly than the output envelopes from the other filters, and second, in the case of constant rate of frequency deviation, the amplitudes of all output envelopes are the same. The method of analysis which leads to these results is described in the Appendix.

The output of a responding filter (the Kth filter) is monitored by an output interrogator whose signal is used to enable sequentially the $[(K+1)\text{th}]$ output interrogator of the filter next expected to respond after a time set by the

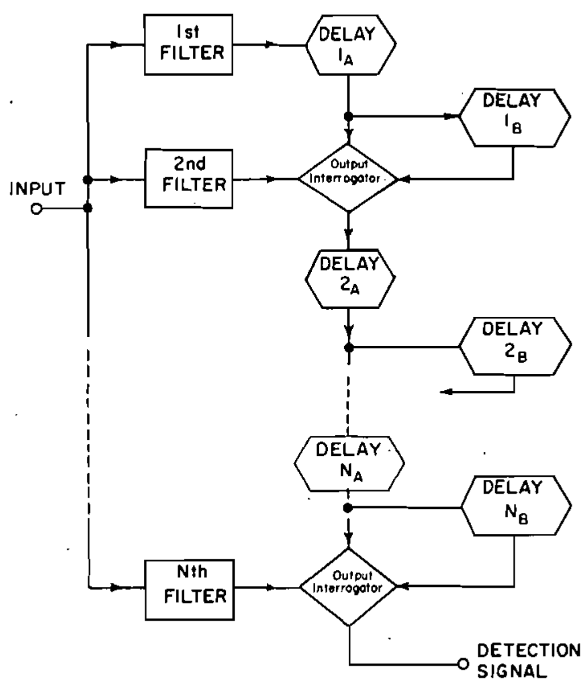

Figure 1. Block diagram of sequential transient filtering technique.

corresponding K_A delay. If an appropriate output is present within the time window set by the corresponding K_B delay, the process continues. An output from the interrogator of the Nth filter indicates that a swept event has occurred. By establishing controlled delays as indicated, it is possible to detect non-linearly sweeping events as well.

Thus an input signal belonging to a particular family of swept-frequency events is detected by comparison with a sweep-rate window. If a signal has a swept component within this window, a digital indication results. Essentially, rate of frequency deviation has been converted to N time markers and it is then a matter of determining if the time between markers falls within preset values. Depending on the requirement, the system can be armed either synchronously via an external trigger or asynchronously by either an intermediate output interrogator or the Nth output interrogator.

4. Noise immunity

To demonstrate some properties of noise immunity of this scheme, consider the result of a delta impulse excitation on the system shown in Fig. 1. Theoretically, the impulse has a constant frequency spectrum and would excite the entire bank of filters simultaneously. The output from the first filter would then initiate Delay 1_A. At the end of this delay, the output of the second filter is interrogated. If its output is present at the beginning of Delay 1_B (examined on a comparative amplitude basis), the detection cycle is disabled. In order that the transient be classified as a member of the specified family of swept-frequency events, the filter must not respond until an interval of time has elapsed which includes both the Delay 1_A time of the previous filter plus a further period characteristic of the transient of interest.

Without too much difficulty, one can examine various other types of input signals and conclude that they too will not be falsely detected as swept events.

5. Circuit realization

Referring to Fig. 2, the system was first implemented using the minimum number of bandpass filters—namely two. These are formed from IC1–IC3 and IC4–IC6. This state-variable configuration of equal-bandwidth fourth-order filters allows for independent adjustment of filter bandwidth and resonant frequency.

The output interrogator for the first filter (lower resonant frequency) comprises IC9A, IC10, and IC11A. These form an envelope detector, an exponential peak detector, and a comparator, respectively. With this configuration it is possible to determine when the envelope of the present signal is greater than some fraction of the previous signal. By utilizing an exponentially decaying peak detector, the system can adjust to varying input amplitudes. In addition, the effect of finite rise time of the transient response of the bandpass filters is reduced by detecting the signal before the peak in the envelope of the filter response. Potentiometer, P1, then can effect several trade-offs between noise immunity, amplitude variation, and accurate swept-frequency detection.

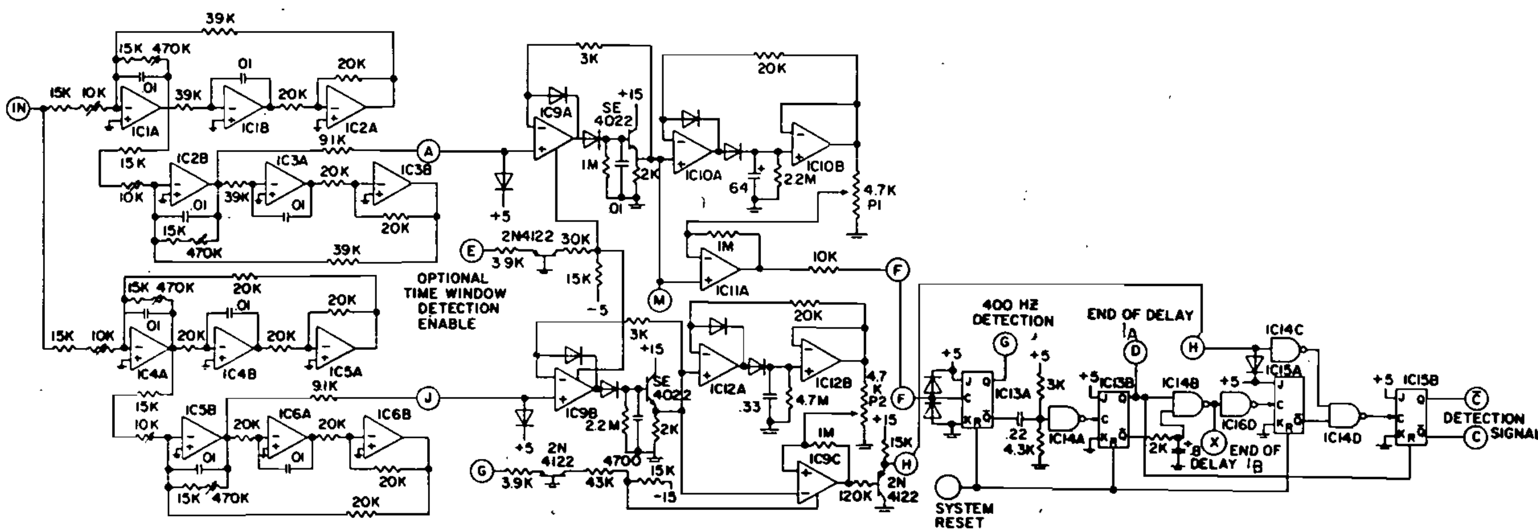

Figure 2. Circuit realization.

The output (F) initiates Delay 1_A which consists basically of IC13A and B and IC15B. The second output interrogator is composed of IC9B, IC12, and IC9C. Its output (H) is stored in IC15B and the digital output signal indicating detection is present as a level transition (C).

Enabling of the second filter is accomplished using the bias terminal of an operational transconductance amplifier as a gating control. In addition operational transconductance amplifiers IC9A and B provide a means for synchronous operation if required and can be used to activate the detection circuitry only during prearranged time windows (E).

6. Noise tests

In order to obtain some measure of immunity to random noise, the following tests were performed using the circuit realization of § 5. A Gaussian-distributed noise generator was added to a linear frequency sweep. By controlling the amplitudes of these components, the signal to noise ratio of the composite input signal was varied. Unless otherwise specified, the bandwidth of the random noise used was 50 kHz.

As the tests performed are of a statistical nature, a proper measurement interval must be established. Tests for each signal to noise ratio were repeated for a minimum of 100 times and the measured time of occurrence of the swept event remaining within 1 millisecond of the zero noise value counted as valid measurements. The test signal consisted of a sinusoid whose frequency range began at 50 Hz and increased to 1200 Hz in the sweep-time intervals noted in the figures.

The first test summarized in Fig. 3 was aimed at showing the inherent signal to noise ratio capability of the technique. The signal was applied at

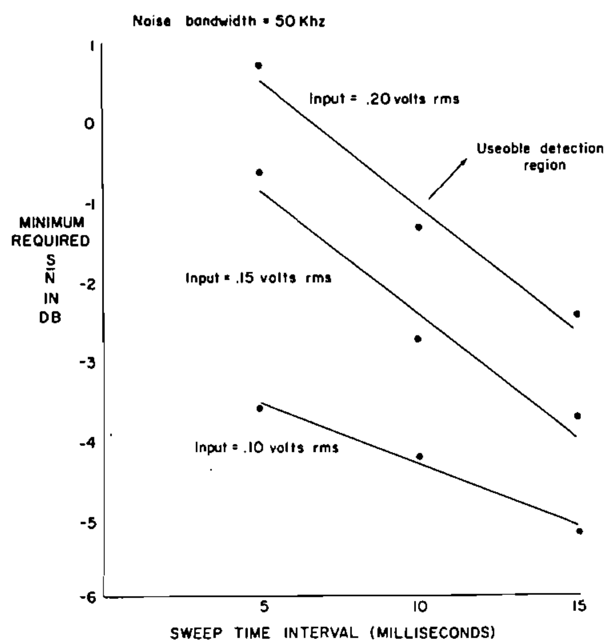

Figure 3. Empirical plot of inherent signal to noise ratio as a function of signal amplitude and sweep-time interval.

three different signal levels with varying sweep-time intervals. The curves represent a lower bound on the usable detection region below which the frequency sweep cannot be detected. From Fig. 3 it can be seen that for slower sweep-time intervals, a lower minimum signal to noise ratio can be tolerated.

The second test summarized in Fig. 4 shows the inherent noise immunity of the technique as a function of noise bandwidth and sweep-time interval. Accordingly, signal amplitude is held constant for the particular sweep-time interval used.

The second test provides a better indication of the inherent signal to noise ratio available for lower bandwidth noise signals which characterizes interfering signals present in a real system. For noise energy far below the resonant frequency of the filters, the minimum required signal to noise ratio is extremely small, as might be expected. The apparent decrease in signal to noise ratio at higher frequencies probably results from the limited duration of the tests imposed for practical reasons.

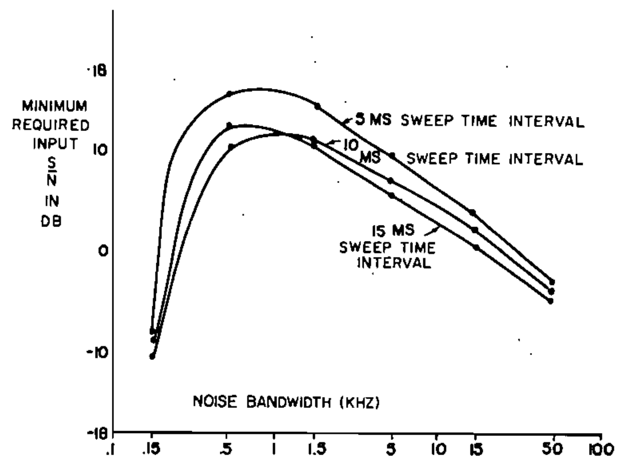

Figure 4. Empirical plot of inherent signal to noise ratio as a function of sweep rate and noise bandwidth.

7. Applications

The present system is currently being used as part of specific instrumentation that detects the opening of cardiac valves. Using a Doppler technique, a signal is obtained which contains a frequency-sweep deviation corresponding to valve velocity. By detecting the occurrence of this ramp of frequency, it is possible to determine the opening time of a heart valve in a manner suitable for clinical use.

Other applications for this scheme include establishing time parameters for intonation curves in linguistics, obtaining time of occurrence of resonance in mechanical elements using a suitable transducer, and determining the onset of turbulence in high speed flow mechanisms. It is also possible to operate a bank of units each with N filters in order to perform ‘spectral’ analysis of rate-of-frequency deviation versus time.

The technique described is quite general in nature and has the capacity to detect a wide variety of frequency signals. It is hoped that its demonstrated usefulness will inspire an initiation of effort towards formalizing the technique into a concise mathematical form.

Appendix

In order to provide a flexible prototype circuit, each fourth-order filter channel is composed of a cascade of second-order stages that are identically tuned. Thus, in the calculations below, the dependent parameter, BW, is the bandwidth (3 dB) of the second-order filter. Because of the linear relationship between the effective bandwidth of the cascade (approximately equal to $0{\cdot}643BW$) and BW, all conclusions made with respect to the second-order filter will apply equally as well to the resultant fourth-order filter. As it is desired to obtain analytical results, a Laplace Transform analysis was attempted.

The general form of the previously described fourth-order filter is given by

$$H(s)=\frac{s^2}{[s^2+(2\pi BW)s+\omega_0{}^2]^2}$$

From this impulse response, $h(t)$, can be calculated as

$$h(t)=\left[\frac{\dfrac{1}{4Q^2}+1}{2\omega_0}-\frac{t}{2Q}\right]\left[\exp\left(-\frac{BWt}{2}\right)\sin\omega_0 t\right]-\left[\frac{\dfrac{1}{4Q^2}-1}{2}\right]\left[t\exp\left(-\frac{BWt}{2}\right)\cos\omega_0 t\right]$$

where

$$BW=\frac{\omega_0}{2\pi Q}$$

This is plotted in Fig. 5 for equal BW values of 40 and 80 Hz. The important conclusion to be drawn here is that equal BW's yield coincident peaks in the envelope of the signal. Essentially, it is these coincident peaks that provide the transient noise immunity by allowing the delay configuration of Fig. 1 to inhibit detection on simultaneous filter outputs.

Using a linearly sweeping signal of the form

$$x(t)=\sin(t^2)$$

its Laplace Transform is found to be

$$X(s)=\frac{\pi}{2}\left[\left[\tfrac{1}{2}-C\left(\frac{s^2}{4}\right)\right]\cos\frac{s^2}{4}+\left[\tfrac{1}{2}-S\left(\frac{s^2}{4}\right)\right]\sin\frac{s^2}{4}\right]$$

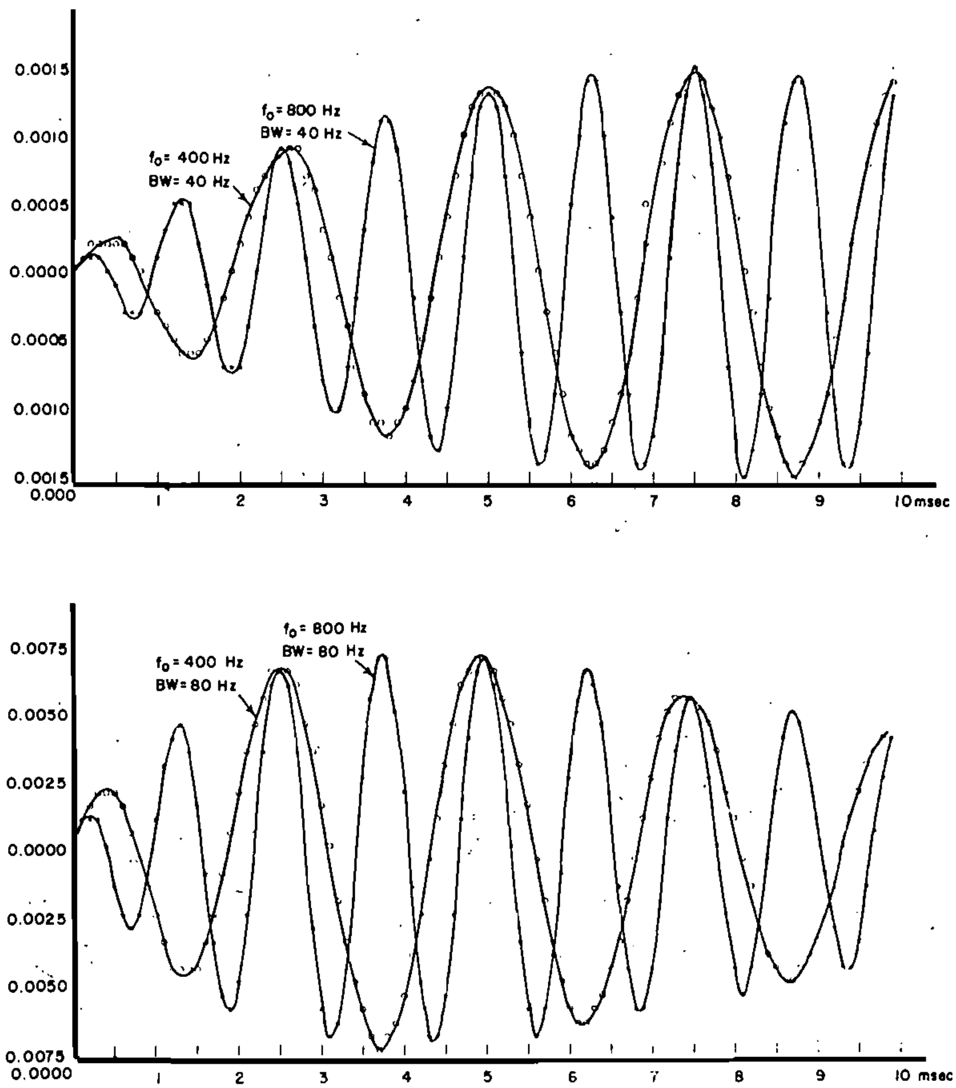

Figure 5. Impulse response of equal BW bandpass filters.

where $C(p)$ and $S(p)$ are the respective Fresnal Integral Functions :

$$C(p) = \frac{1}{\sqrt{(2\pi)}} \int_0^p \frac{\cos \mu}{\sqrt{\mu}} d\mu$$

$$S(p) = \frac{1}{\sqrt{(2\pi)}} \int_0^p \frac{\sin \mu}{\sqrt{\mu}} d\mu$$

Once $X(s)$ is determined, the output $Y(s)$ can be formed as

$$Y(s) = H(s)X(s)$$

Taking the Inverse Laplace Transform of $Y(s)$ appears rather formidable and other methods of solution were pursued.

One possibility is that of modelling the differential equations of the system using a state-space approach and iterating a numerical solution. By using suitably cascaded second-order analogue computer networks, the desired functions can be realized. The results of two filters at 400 and 800 Hz with several values of equal BW's (Fig. 6 (*a*), (*b*)) and unequal BW's (Fig. 6 (*c*), (*d*)) are shown in Fig. 6. The apparent initial delay of several milliseconds shown in the figures is a result of the quantization of the plotting routine. It has been purposely scaled in this fashion to allow for the dynamic range of the transient peak.

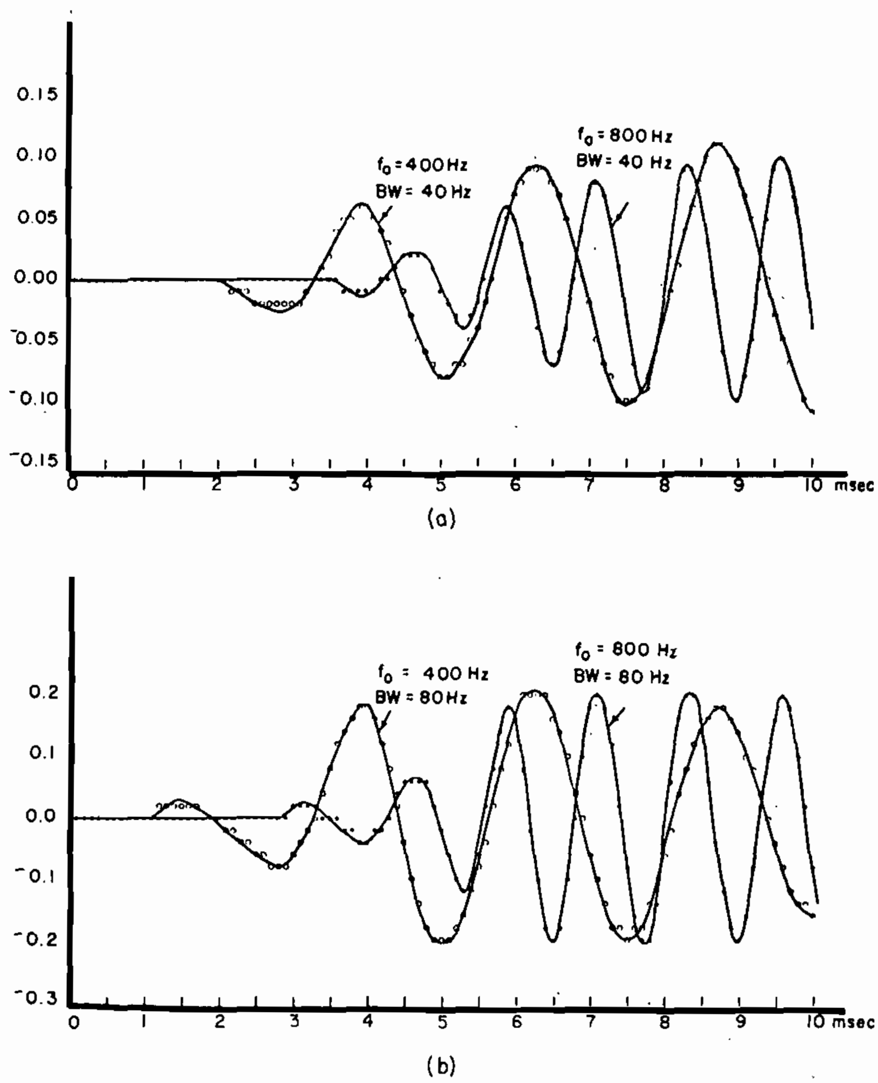

Figure 6

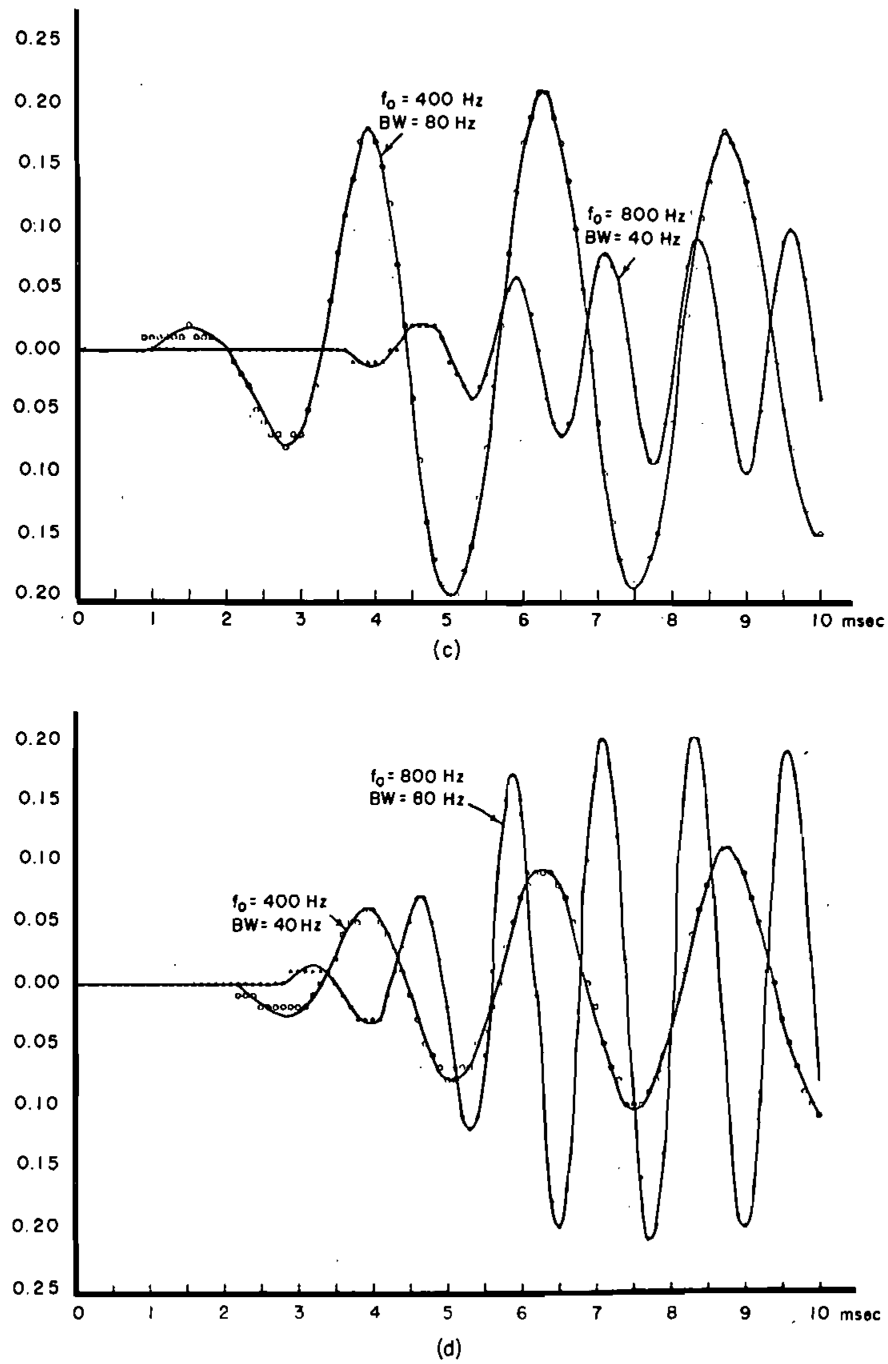

Figure 6. Bandpass response to frequency ramp signal.

Two important conclusions can be made from these plots. Firstly, as expected, it can be seen that narrow BW filters respond more slowly than those with wider BW's and different amplitudes are obtained for filters with different BW's. Secondly and most importantly, in the two cases of equal BW (Fig. 6 (*a*), (*b*)), there is a time delay between the peak of the envelope of the two filters which provides a characteristic that can be detected. By unbalancing the BW's, it is possible to change this delay for any given sweep rate. However, the respective amplitudes will change as well. From a practical point of view, it is more desirable to have equal amplitude signals merely delayed in time and to maintain coincident peaks for transient inhibition as previously mentioned.

From a detection viewpoint it is advantageous to detect the output before the peak of the envelope. By doing this, two benefits are achieved. Firstly, the two outputs are space farther apart in time at this portion of the transient, and, secondly, this allows for partial compensation of the errors in detection of the beginning of the sweep resulting from finite rise time of the filters.

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