The Lenkurt Demodulator

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Delay Distortion

Within the last decade, high-speed data transmission has become one of the most vital services provided by the great communications networks. The explosive growth of electronic data processing and the construction of elaborate defense data communications networks from existing telephone facilities has placed new importance on some rather old transmission problems. One of the most important of these is delay distortion. This article reviews some of the more important aspects of delay distortion — why it occurs and how it may be overcome.

For many years, the quality of a communications channel has been judged by its ability to reproduce the moment-to-moment level or amplitude of the original signal. In judging the ability of voice communications systems to satisfy the listener, amplitude response has proved to be a good measure of performance. About 1930, when pictures were first transmitted by wire, it was discovered that a channel having excellent amplitude response might be quite unsatisfactory for picture transmission. The harmful effect, originally called *phase distortion,* and now more correctly called *delay distortion,* resulted from the phase-shift characteristics of the transmission path, and had little relation to the amplitude response or fidelity of the transmission path. Since then, other communications services have sprung up which are equally vulnerable to this type of distortion — facsimile, television, and high-speed data transmission are typical.

About this article

This article is a revision of the July, 1960 issue of The Lenkurt Demodulator. Because of the interest in this subject, resulting especially from the increase in the amount of data transmitted over telephone transmission systems, the original article has been modified slightly and issued again for the benefit of our present readers.

What Is Delay Distortion?

Electromagnetic waves travel 186,000 miles per second in free space. Electrical signals, however, do not travel this fast through communications channels. In fact, signals may travel over certain types of circuits as slowly as 15,000 miles per second, and will rarely travel faster than about 100,000 miles per second over a microwave radio path. These lower velocities result from the nature of the communications equipment or the transmission path.

A telephone line behaves like a low pass filter, particularly if inductive loading is used to reduce attenuation. Multiplex systems use very sharp filters to separate one channel from another, and the tuned circuits in a radio receiver serve the same purpose. All these filters and filter-like elements introduce delay.

The slowing down of a signal in its passage through a communications channel is of little importance. Delay becomes a problem only when it interferes with the ability of the receiver to understand the message. In the case of speech, delay distortion causes little interference since the ear is relatively insensitive to phase variations. Thus, it has not been necessary to correct for delay distortion in telephone systems. Facsimile, telegraph, and data signals, however, are quite vulnerable to delay distortion.

For example, if two tones, such as 1200 and 2200 cycles per second, are used to transmit binary data (shifting from one frequency to the other), it is important that these two tones experience approximately the same transmission delay in going from one end of the circuit to the other. If the data is being transmitted at 1000 bits per second, each bit will be one millisecond long. If these transmissions consist of alternate **1**'s and **0**'s, the signal will be alternately shifting between 1200 and 2200 cps. The transmission propagation time for these two tones between the two ends of a given circuit can vary considerably. For example, 60 miles of loaded telephone cable may introduce a delay to the 2200 cycle tone of 6.1 milliseconds as compared to the 5.1 milliseconds for the 1200 cycle tone, a difference of 1 millisecond. If the 2200 cycle tone is transmitted first followed by the 1200 cycle tone (each transmitted for 1 millisecond), it can be seen that they will both be received at the same time, rather than one following the other. In 120 miles they would be received in the reverse order!

In high-speed data transmission, the problem of delay distortion becomes more and more serious and troublesome as the transmission rate increases. Data bits usually originate as rectangular-shaped pulses which are used to modulate a carrier at a particular keying rate for transmission over a communications circuit. The pulses resulting from this

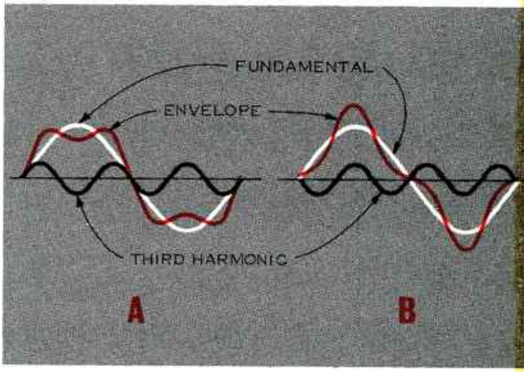

Figure 1. As shown in diagram A, the normal vectorial addition of the energy at the fundamental and third harmonic frequencies produces a slightly rectangular-shaped pulse. If the third harmonic is delayed by one-half cycle relative to the fundamental, as shown in diagram B, the pulse envelope becomes seriously distorted.

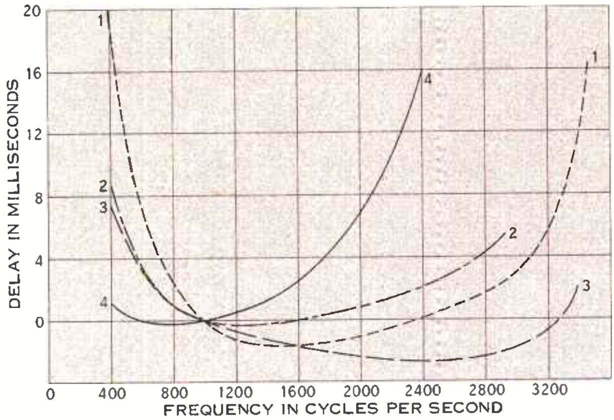

Figure 2. Comparison of the envelope delay in typical voice communications channels. Curves 1 and 3 represent the delay in several thousand miles of a toll-quality carrier system. Curve 2 shows the delay produced by 100 miles of lightly loaded cable; curve 4 shows the delay in 200 miles of heavily loaded cable.

modulation process are composed of many frequencies whose amplitudes and phases have a fixed relationship in time. The envelope of these pulses results from the energy at the fundamental and harmonic frequencies adding together vectorally. If the pulses are processed through circuit components with very non-linear phase characteristics, such as multiplex channel filters, the pulse shape can become seriously distorted. As shown in Figure 1 if the third harmonic is delayed by one-half cycle relative to the fundamental, the pulse shape is severely distorted.

Higher data speeds are achieved by increasing the rate at which the carrier is keyed, thereby shortening the width (or duration) of the signal pulses. Because of the shorter pulses, slight shifts in time or phase of the component frequencies have a greater effect in distorting the signal, with a corresponding increase in error rate.

Also, the higher the data speed, the greater the channel bandwidth required for successful transmission. The reason for the increased bandwidth lies in the nature of a high-speed pulse. When the pulse begins or ends, the rapid change causes signal energy to be distributed over a wide band of frequencies on either side of the pulse frequency. The exact amount of energy appearing at each frequency on either side of the pulse frequency depends on the nature of the pulse — its shape, rise-time, and so on. If, for any reason, some of the energy from either sideband is displaced in time or amplitude from the original value, the pulse will be distorted when it is reconstructed by the receiver. If the delay is great enough, some of the energy from a signal pulse may actually be delayed enough to interfere with the following pulse, thus destroying information carried by both pulses. It is evident, therefore, that delay introduces distortion only when various frequencies in a communications channel are delayed by different amounts of time.

Phase Shift

The phase and frequency of a signal are, by definition, inseparable. In fact, a good definition of frequency is the rate of change of phase with respect to time, or $d\phi/dt$, where ϕ is the phase shift (usually in radians — π radians equal 180°, 2π radians equal one cycle) and t is time in seconds. Thus, it follows that the more the phase of a signal is shifted in passing through a channel, the more time is required for it to get

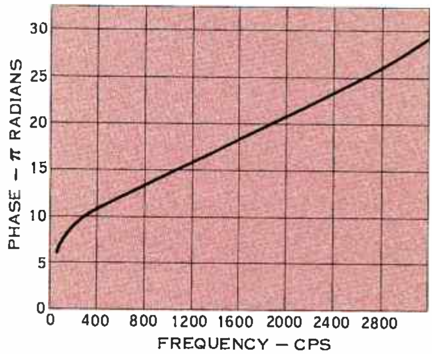

Figure 3. Phase shift characteristic of a high-quality 100-mile carrier telephone circuit.

through the channel. Where phase shift is known, the phase delay of a single frequency is

$$time = \frac{\text{phase shift (radians)}}{\text{frequency (radians per sec.)}}$$

This is usually expressed

$$t = \frac{\phi}{\omega}.$$

It is important to note that in practical systems, phase delay, as expressed above, is applicable only to single, steady-state frequencies.

In an ideal system, phase shift is directly proportional to frequency. All signals passing through such a system would be delayed equal amounts, regardless of their frequency. Unfortunately, phase shift in a communication channel is never linear. In a high-quality system, the overall phase shift characteristic may look like that shown in Figure 3.

Envelope Delay

Whenever a complex signal (such as a modulated or keyed carrier frequency) is transmitted, the relationship given above for phase delay no longer holds true, unless the system is perfectly distortion-free. Since phase shift is always non-linear in actual systems, some of the component frequencies undergo more phase shift than they would in a linear system. As a result, they travel through the system slightly slower than some of the other frequency components.

For simplicity, assume that the complex signal consists of only two component frequencies. Added together, the two frequencies form a beat-frequency or modulation envelope. Since the two component frequencies travel at different velocities through the channel (because of non-linear phase shift), the relationship between them constantly changes, and the modulation envelope travels through the channel at a third velocity. If phase shift were linear, both component frequencies would travel at the same velocity, and there would be no displacement of one frequency with respect to the other, and no independent delay of the modulation envelope or envelope delay.

The more non-linear the phase shift, the greater the envelope delay. In other

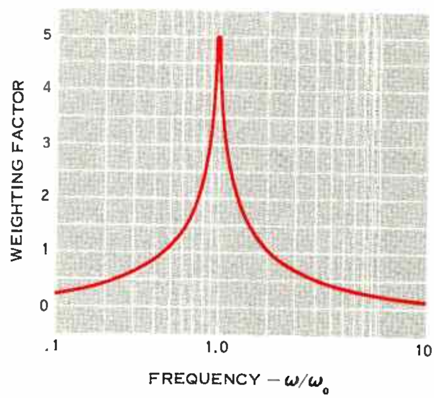

Figure 4. Weighting factor for the phase shift near the resonant or cutoff frequency of a network or line. Phase shift is very high at resonance, but falls off rapidly at higher and lower frequencies.

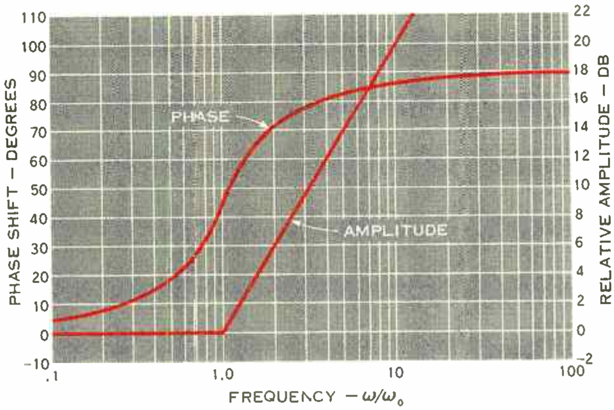

Figure 5. Fictitious amplitude characteristic of a network and the phase shift that would result. The smooth phase shift curve shows the weighting effect diagrammed in Figure 4.

words, the greater the rate of change of phase shift, the more envelope delay will result. The delay in seconds can be calculated by differentiating phase shift with respect to frequency:

$$\textit{envelope delay} = \frac{d\phi}{d}.$$

Since virtually all forms of electrical communication employ signals which require a band of frequencies for successful transmission, envelope delay is the form of delay of greatest general importance. In this article, further reference to "delay" will mean envelope delay unless other indicated.

Usually, only relative delay — the maximum range or difference in delay values in a channel — is of importance, since only the delay *difference* causes distortion in the received signal. Absolute delay—the total delay experienced by signal elements — is usually not important except where signals or parts of a signal are transmitted from one point to another over different routes and must arrive at the same time.

Delay Equalizers

Where amplitude response of a circuit is unsatisfactory, an equalizer is used to introduce a controlled amount of loss at certain frequencies to obtain the desired performance. In the case of excessive relative delay, a network which would correct the phase shift characteristics of the communications channel might very well neutralize the desired attenuation of the filters responsible for the delay. Special delay equalizers are required to overcome this problem. Ideally, a delay equalizer is a network which introduces a controlled amount of phase shift at various frequencies, but causes no signal loss at all. Practical delay equalizers, however, cannot avoid affecting amplitude response to some degree.

Although it is possible to design filters which will reduce or postpone the appearance of delay distortion (by adding special kinds of filter sections), the more common practice is to add a so-called "all-pass" network which adds delay at selected frequencies, but which adds negligible attenuation at any frequency.

In a carrier system, the channel band-pass filters which isolate individual channels from each other are the principal sources of delay distortion. These filters should have uniform amplitude response within a desired band of frequencies, but must exhibit a very rapid attenuation of all frequencies outside the desired band. Unfortunately, such rapid change in the attenuation characteristic of a filter is also accompanied by rapid changes in the phase shift, as indicated in Figure 5. As a rule, phase shift is maximum at the cutoff frequency or resonant point of a circuit, but declining at other frequencies, as shown in the weighting curve, Figure 4. Thus, a circuit having flat attenuation characteristics would still have non-linear phase shift and would introduce envelope delay distortion.

Figure 6 shows a typical all-pass network and some of the delay characteristics that may be obtained with such a network. The different delay characteristics are obtained by changing the values of components. Since the network impedance and the frequency at which the delay is obtained are also affected by component values, design of such equalizers is a complex art.

A typical equalizer will have several sections, each of which may have a different reference frequency (f_c) and a different "width factor" (B). Such equalizers may be custom designed to correct the delay characteristics of a certain type of equipment or communications path or may be continuously adjustable for universal application. Figure 7 compares the envelope delay characteristics of a carrier system channel without equalization, the amplitude response of an experimental 3-section equalizer, and the delay characteristics of the equalized channel. Note that there are three "humps" or ripples in the equalized delay characteristics—one for each section in the equalizer.

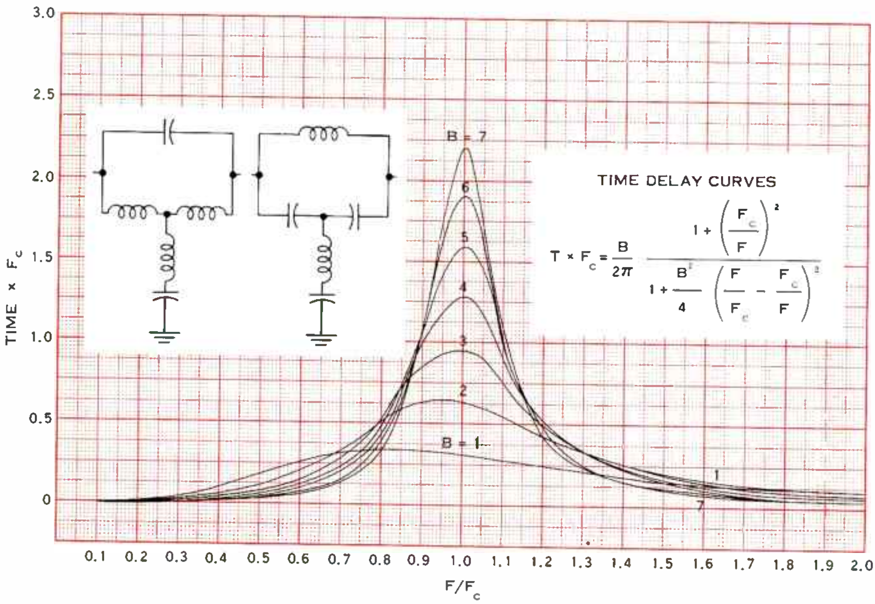

Figure 6. Two typical all-pass network configurations and a family of envelope delay curves which they might produce. Width factor (B) and critical frequency (f_c) are controlled by the values of the network components. Typical delay equalizer will consist of several sections, each designed to add a carefully-determined amount of delay to a small portion of the channel passband.

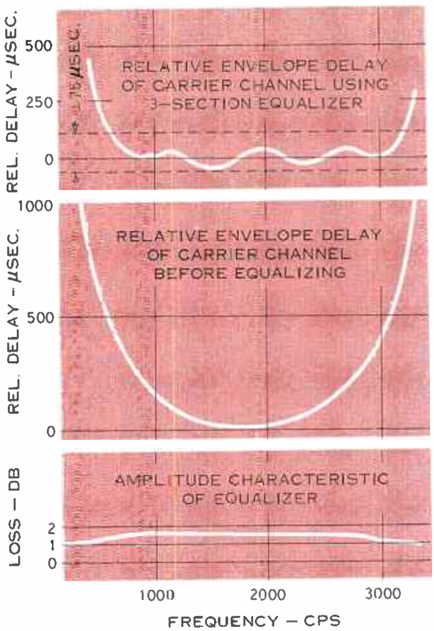

Figure 7. Center panel shows the envelope delay characteristic of a typical carrier system voice channel before equalization. Addition of a 3-section equalizer reduces relative envelope delay to ±75 microseconds over a large portion of the bandwidth, as shown in top panel. Bottom panel shows that amplitude response of the equalizer varies less than 1 db despite effect on envelope delay.

The more sections that are used in a phase equalizer, the finer the ripple in the delay characteristic. The residual delay causes distortion in the form of echoes. Where the ripples are coarse, as when few equalizer sections are used, the echoes are separated very little from the signal and may have only the effect of changing the amplitude of the signal. Where the ripples are fine, the echoes are delayed more. It has been shown that a system is considerably less tolerant of noise interference as the time separation between signal pulse and echo is increased. Thus, the fewer equalizer sections required to achieve a given relative delay tolerance, the less susceptible the system is to interference. This sensitivity does not increase, however, after the echo is delayed more than one pulsewidth for data, or about 60 picture elements in the case of facsimile.

Future Needs

The long-range trend in the communications industry is toward more and more pulse transmission, both for data and for speech. It is primarily pulse transmission that is vulnerable to delay distortion. In modern systems, a message may be transmitted from one point to another over one of several possible routes which may differ greatly from one another in their phase response. To make better use of the existing communications networks, it will be necessary to obtain uniform delay characteristics, regardless of the routes. Techniques for automatically equalizing the phase response of an entire circuit after a connection has been obtained, regardless of circuit length or the nature of the means of transmission, are now being developed. Although these techniques are now rather expensive, they will undoubtedly play an important role in the development and growth of future data transmission systems.

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DELAY EQUALIZER

Lenkurt's versatile Delay Equalizer corrects for both attenuation and delay distortion on voice frequency circuits and is suitable for any line. Adjustments can be accomplished quickly and easily using either a delay-measuring set or the "eye pattern" technique with an oscilloscope. The technical characteristics and design features of the Lenkurt Delay Equalizer are described in Form 30231-P4, available on request from

THE EDITOR
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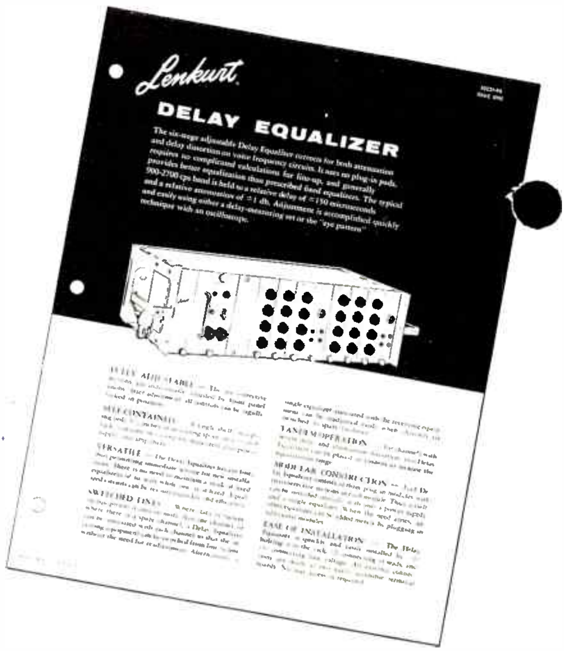

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