EFFECTS OF FREQUENCY CUTOFF CHARACTERISTICS ON SPIKING AND RINGING OF TV SIGNALS

1. GENERAL

1.01 This section describes the effects of frequency cutoff and delay characteristics of a transmission system on spiking and ringing of TV signals. It is based on a paper presented before the Institute of Radio Engineers in March, 1959 by A. D. Fowler and J. D. Igleheart of the Bell Telephone Laboratories. References indicated by number in the text are listed at the end of the section.

1.02 Spiking and ringing, as the terms shall be used, refer to damped, high-frequency transients accompanying a step, or other rapid change, in instantaneous amplitude of a signal. If the transient is oscillatory, it is called ringing; if it has a single, or very prominent overshoot, it is called spiking. When strong enough, such transients impair TV pictures, and are most noticeable near vertical edges between bright (or dark) and gray areas. Spiking may appear as a single thin dark line parallel to the edge and following the bright area; ringing, as several parallel lines, alternately dark and light, closely spaced and close to the edge of brightness change.

1.03 The degree of spiking and ringing depends upon the amplitude and phase characteristics associated with the high-frequency cutoff of the transmission system. The purpose of this section is to illustrate how various cutoff characteristics of both ideal and practical transmission systems affect spiking and ringing (associated with sharp changes in brightness). The illustrations are arranged to show (1) waveform and frequency spectrum of the test signal at input of the system, (2) amplitude and envelope-delay characteristics of the transmission system, and (3) waveform of the test signal at the output of the system. From these illustrations, and from some theoretical considerations, some conclusions have been drawn about the relationship of spiking and ringing to the cutoff characteristics of transmission.

1.04 The output waveforms presented here were all calculated either from well-known formulae or by well-known processes when the transmission characteristics could not be expressed analytically. In both cases, however, recourse was had to electronic computers, without which the tedious computations might never have been undertaken. In assembling these rather elementary results in this section, it is hoped to contribute to a better understanding of the problem and of the limitation on the reduction of ringing that can be achieved by equalizing the transmission system.

2. TEST PULSES — WAVEFORMS AND SPECTRA

2.01 Test signals used for exploring the high-frequency transmission characteristics of a system are sent periodically at the horizontal line scanning rate, and include sync pulses to insure proper functioning of receiving equipment. Because the systems for transmitting standard broadcast signals have a video bandwidth of 4 mc or more, the transients of spiking and ringing will subside to negligible values within a small fraction of the 63.5-μsec repetition period. For this reason, it is sufficient to consider the response of the system to a single test pulse and ignore the effects of repetition and those of sync pulses as well, provided the latter are separated from the test pulses by a few microseconds or more.

2.02 In Fig. 1 are shown the waveforms and continuous spectra of two very simple and popular test pulses. In part (a) of that figure is shown the waveform of a rectangular, or square wave, pulse with its width designated t_w, together with the frequency spectra of three such pulses having widths of 5, 1/4 and 1/8 μsec, respectively. For analytical purposes, these spectra should extend into the negative frequency range and be symmetrical about the Y-axis. Similarly, in part (b) of Fig. 1, is shown the waveform of a sine-squared, or elevated cosine, or cosine-squared pulse as it is variously called. This pulse is commonly designated by its width, t_w, at one-half maximum amplitude. When t_w is equal to a Nyquist interval, $T = 1/2f_c$, of the transmission system under test, f_c being the upper cutoff frequency, the test pulse is called by some writers[1,2,3] a "T-pulse." For example, a T-pulse for a 4 mc system is a sine-squared pulse having t_w equal to 1/8 μsec; a 1/4 μsec pulse would be a 2T-pulse for this system. Frequency spectra of sine-squared pulses of widths 1/4, 1/8 and 1/16 μsec are also shown in part (b) of Fig. 1.

2.03 There are good arguments for using a sine-squared T-pulse for testing a transmission system: (1) the pulse represents one complete cycle of the upper cutoff frequency; (2) it has approximately the same shape as the output pulse of a camera scanning a minimum resolvable element; and (3) it has substantial frequency components in the vicinity of cutoff frequency (only 6 db less than those near dc), making the pulse sensitive to cutoff characteristics. However, in examining the spectrum of the 1/8 μsec pulse (T-pulse for a 4 mc system), as shown in Fig. 1, part (b), we see that a substantial part (actually about 30 percent) of the energy of the pulse is excluded by a 4 mc cutoff, resulting in an inevitable amount of distortion or ringing. Similarly, the 1/8 μsec rectangular pulse, as revealed by its spectrum in part (a) of Fig. 1, would also be sensitive to

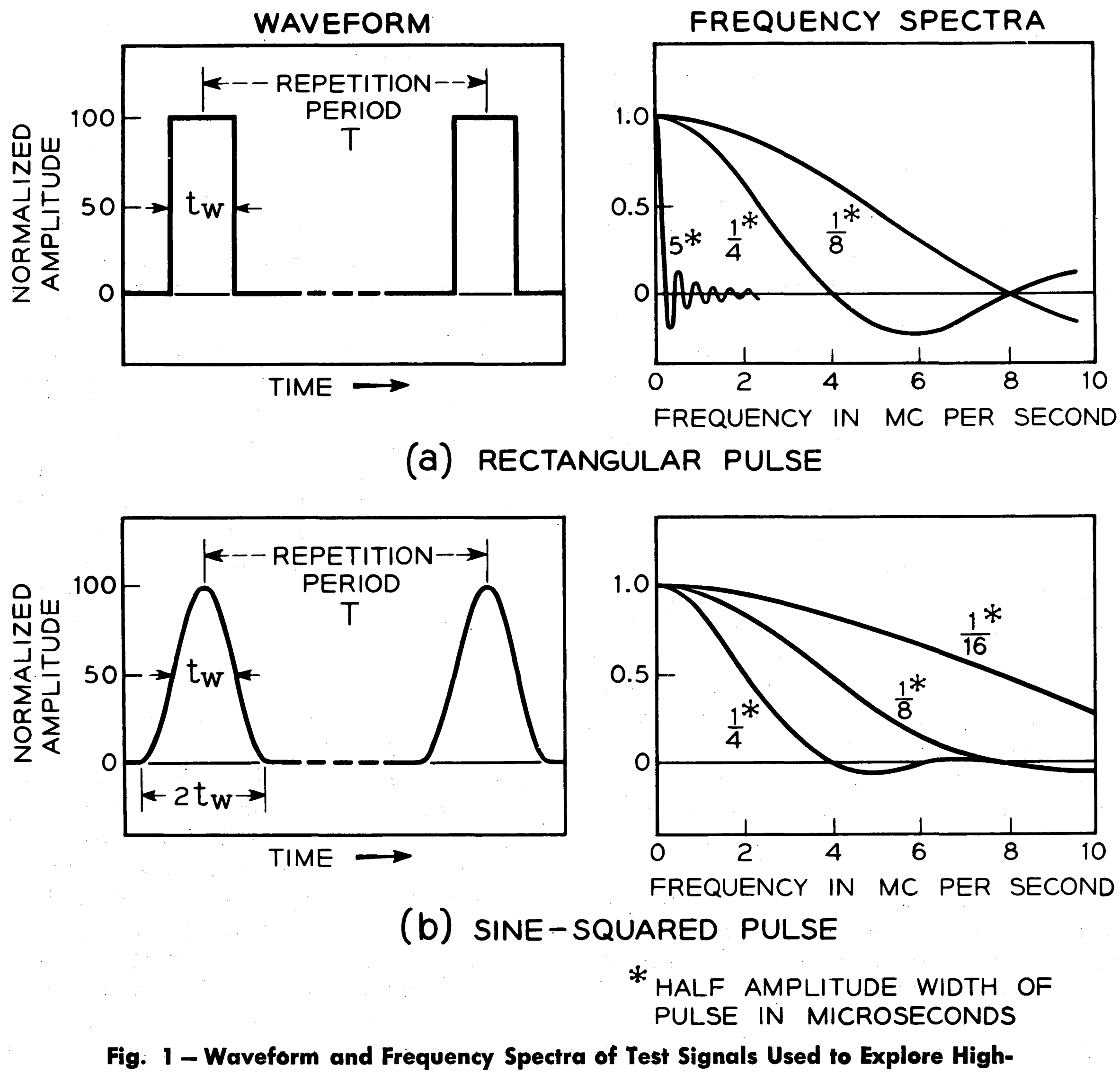

Fig. 1 — Waveform and Frequency Spectra of Test Signals Used to Explore High-Frequency Transmission Characteristics of a System.

cutoff effects near 4 mc, where the amplitude of its components are about 64 percent of those near zero frequency, and would also show considerable ringing because about 23 percent of the pulse energy is excluded by a 4 mc cutoff.

3. RESPONSE OF AN IDEAL LOW-PASS SYSTEM

3.01 In appraising transmission performance by means of test pulses, it is important that the observer at the receiving end of the system know not only the shape and size of the test pulse being transmitted, but also what the output pulse would look like in the absence of any distortion of amplitude or delay within the pass band of the system. To illustrate the effect of "distortionless" transmission of the pulses, the transmission system was assumed to be an ideal low-pass filter having unity gain (zero loss) and a flat delay characteristic up to a cutoff frequency of 4 mc, beyond which infinite loss obtains. This ideal system has two attractive features: its response to test pulses is fairly well known, and its characteristics rather closely approximate those of some actual systems in use today.

3.02 In Fig. 2 are shown the responses of the ideal low-pass filter: in (a), the steady-state frequency characteristics of amplitude and delay, and below, in (b), (c) and (d), the output pulses corresponding to rectangular input pulses having widths of 5 μsecs, 1/4 and 1/8 μsec, respectively. Looking, first, at the response to the 5 μsec pulse, which was included to represent a sync pulse (if negatively poled) or a white window, one notes several interesting features: (1) the general shape and the size of the original pulse are reproduced, (2) the rise time has been increased, but the width of the pulse at half maximum amplitude is still 5 μsecs, (3) the general outlines of the pulse are now ornamented with spiking and ringing, (4) the spiking and ringing appear in equal amounts preceding and following the main pulse, and (5) the ringing frequency is 4 mc, the cutoff frequency. An important fact, not evident from Fig. 2b, but readily apparent from the theoretical response, is that the amplitudes of the successive overshoots and undershoots are independent of the cutoff frequency employed, provided the cutoff frequency is substantially greater than $1/t_w$. Hence, increasing the bandwidth of the system transmitting a 5 μsec pulse would not reduce the ringing amplitudes, but, because the cycles of ringing would be more closely spaced, the ringing transient would decay in a shorter time.

3.03 Turning now to the responses to narrower rectangular pulses, as shown in the two lower parts of Fig. 2, one notes considerably less similarity of shape and size of the output pulse to that of the input pulse. In particular, the 1/4 μsec pulse response has a maximum amplitude that is nearly 18 percent greater than that of the input pulse, and the ringing appears somewhat reduced; for the 1/8 μsec pulse, the maximum amplitude is only about 87.3 percent of the original pulse, and the ringing amplitudes are greatly increased. In the instance of the 1/4 μsec pulse, whose width is exactly the reciprocal of the cutoff frequency, the first overshoot accompanying the rise of the pulse is coincident with that accompanying the fall of the pulse, each contributing about 9 percent to the total overshoot apparent at the center of the received pulse. The reduced ringing is accounted for by the tendency of the two sets of ringing transients to cancel at all other times. These special circumstances pertinent to the 1/4 μsec pulse are somewhat reversed when the pulse width is cut in half to 1/8 μsec: the ringing transients — one set for the rise and one for the fall of the pulse — now augment each other at all times except near the center of the pulse where they fail to add up to the full value of the original pulse. As the width of the pulse is made still narrower, the response approaches that of the $(\sin x)/x$ function, where $x = 2\pi f_c t$ and the maximum amplitude is $2f_c t_w$.

3.04 As will have been noted, the responses have not been depicted with the amplitudes normalized to make the maximum value unity. Instead, they have been represented as they would actually appear at the end of a unity-gain system. In addition, the time scale for the output pulses has been shown with an origin that is not delayed from that for the input pulses, since the delay chosen for the system was zero. These practices have been followed throughout the section.

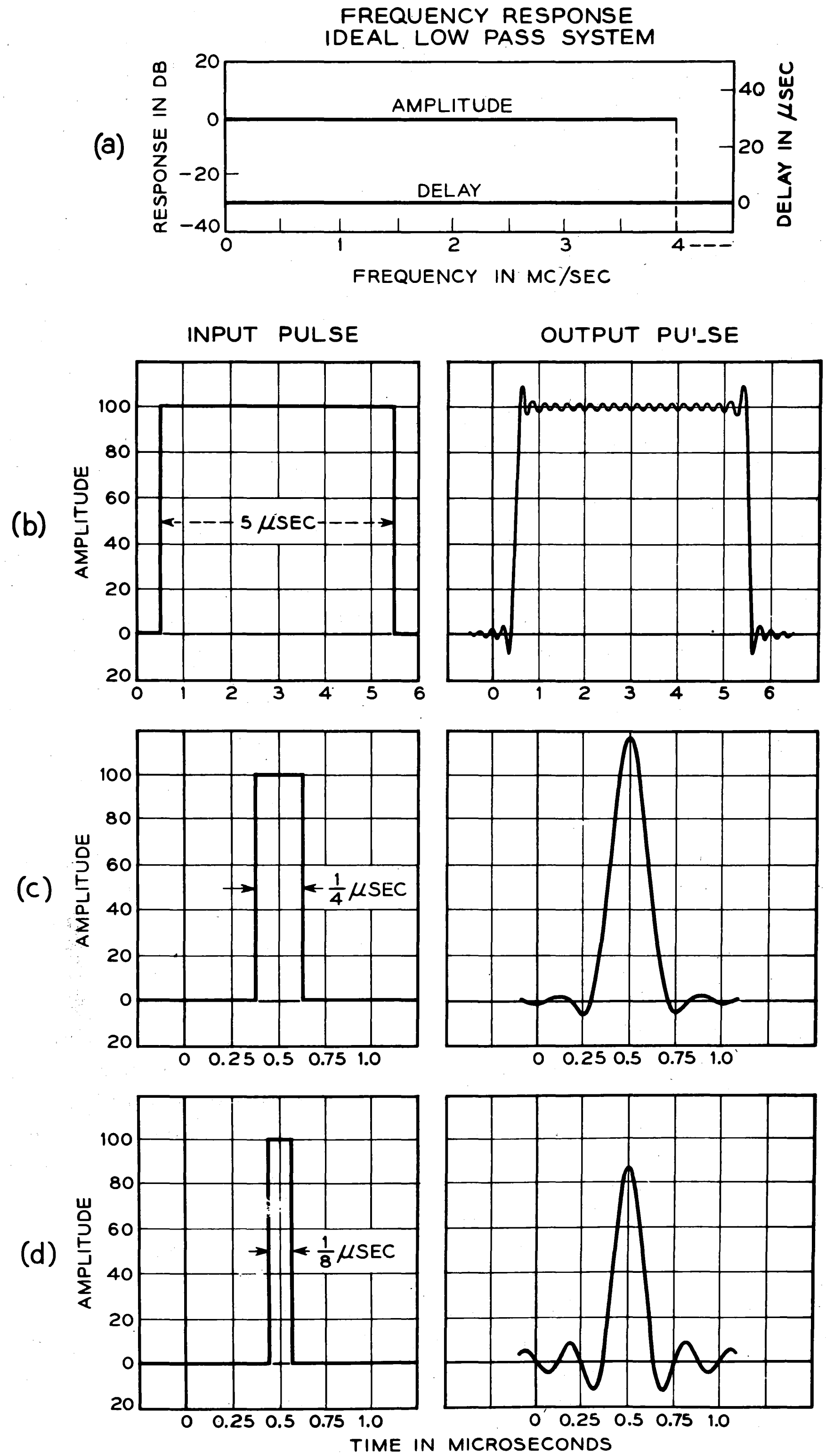

Fig. 2—Input and Output Waveforms of Rectangular Pulses as They Appear in Testing an Ideal Low-pass System.

3.05 In Fig. 3 are shown the responses of an ideal low-pass filter to three sine-squared pulses of widths 1/4, 1/8 and 1/16 μsec, values currently available in sine-squared signal generators of at least one manufacturer. The output pulse corresponding to a 1/4 μsec, or 2T, pulse is seen to be a fair replica of the original with only a 1 percent overshoot at the maximum amplitude, and less than 2 percent spike, or maximum ringing amplitude. The 2T-pulse, having very little energy in its spectrum near 4 mc and at higher frequencies, would be very insensitive to cutoff effects above 4 mc. The T-pulse (1/8 μsec), on the other hand, gives rise to a response which differs considerably from the original: the maximum height is about 81.5 percent of normal, the width at half maximum amplitude is increased to about 1/6 μsec, and the amplitude of ringing is increased to the point where the first undershoots, or spikes, are about one eighth of the maximum amplitude. The 1/16 μsec pulse (1/2 T-pulse) gives rise to a response differing still further from the original and closely resembling a (sin x)/x response with maximum amplitude only 47.4 percent of normal and with spikes amounting to about one fifth the maximum amplitude. The width of this pulse at half maximum amplitude is about 25 percent greater than $T = 1/2f_c$, and is within 4 percent of the minimum value of 1.21T which obtains for the (sin x)/x response when $t_w \rightarrow 0$. As before, the ringing frequency is 4 mc and the ringing is symmetrical about the main pulse.

3.06 The output pulses of an ideal low-pass system corresponding to either rectangular or sine-squared input pulses are symmetrical about a central axis. This fact warrants special notice and comment. If the input pulse exhibits symmetry about a central axis it can be shown from transmission theory[4] that the output pulse will exhibit symmetry about a delayed central axis if the phase frequency characteristic of the system is linear with a phase intercept that is zero or an integral multiple of π. The Amplitude-frequency characteristic of a transmission system, regardless of its shape, has even symmetry about zero frequency, hence plays no part in determining symmetry of the output pulse. Thus the ideal low-pass system yields a symmetrical output pulse in response to a symmetrical input pulse because its delay-frequency characteristic is constant (insuring a linear phase-frequency characteristic) with an implied zero phase intercept. The phase-intercept requirement is rather academic and need not concern us here; the delay constancy requirement is very important as will be seen in subsequent examples.

4. RESPONSE OF A PRACTICAL TRANSMISSION SYSTEM

4.01 In Fig. 4 are shown a 5 μsec rectangular input pulse, the amplitude and delay characteristics of the system over which the pulse is sent, and the corresponding output pulse. The steady-state frequency characteristics of amplitude and delay, shown in part (a) of the figure, are those of an actual short-haul transmission system before the addition of supplementary delay equalization. The output pulse, shown in part (b), shows some noteworthy differences from its counterpart as received over the ideal low-pass system as shown earlier. The main difference is in the ringing which now is asymmetrical — in fact there is hardly a vestige of ringing to be seen occurring prior to a transition of the signal. In addition, the amplitudes of spiking and ringing are substantially increased, and, as a consequence of the higher cutoff frequency, the ringing frequency and its damping are increased as well.

4.02 Additional responses of the same practical system are shown in Fig. 5 for two sine-squared pulses having widths of 1/8 and 1/16 μsec, respectively. In the lower part of the figure are shown the responses to the same input pulses after an assumed perfect delay equalization is applied to the system. Referring, first, to the response of the system without delay correction, as shown in parts (a), (b) and (c) of Fig. 5, we see no advance ringing, but considerable spiking and ringing after the main pulse. For the 1/8 μsec pulse the negative spike is about one sixth of the maximum amplitude of the pulse, and about one third for the 1/16 μsec pulse. The effect of delay equalization of the system is shown in the lower half of Fig. 5 in parts (d), (e) and (f), where it will be seen that the symmetry of the ringing has been restored and the ringing amplitudes strikingly reduced.

4.03 The amplitude-frequency characteristic of the practical system has a gradual roll-off above 5 mc and an effective cutoff of about 8 mc.

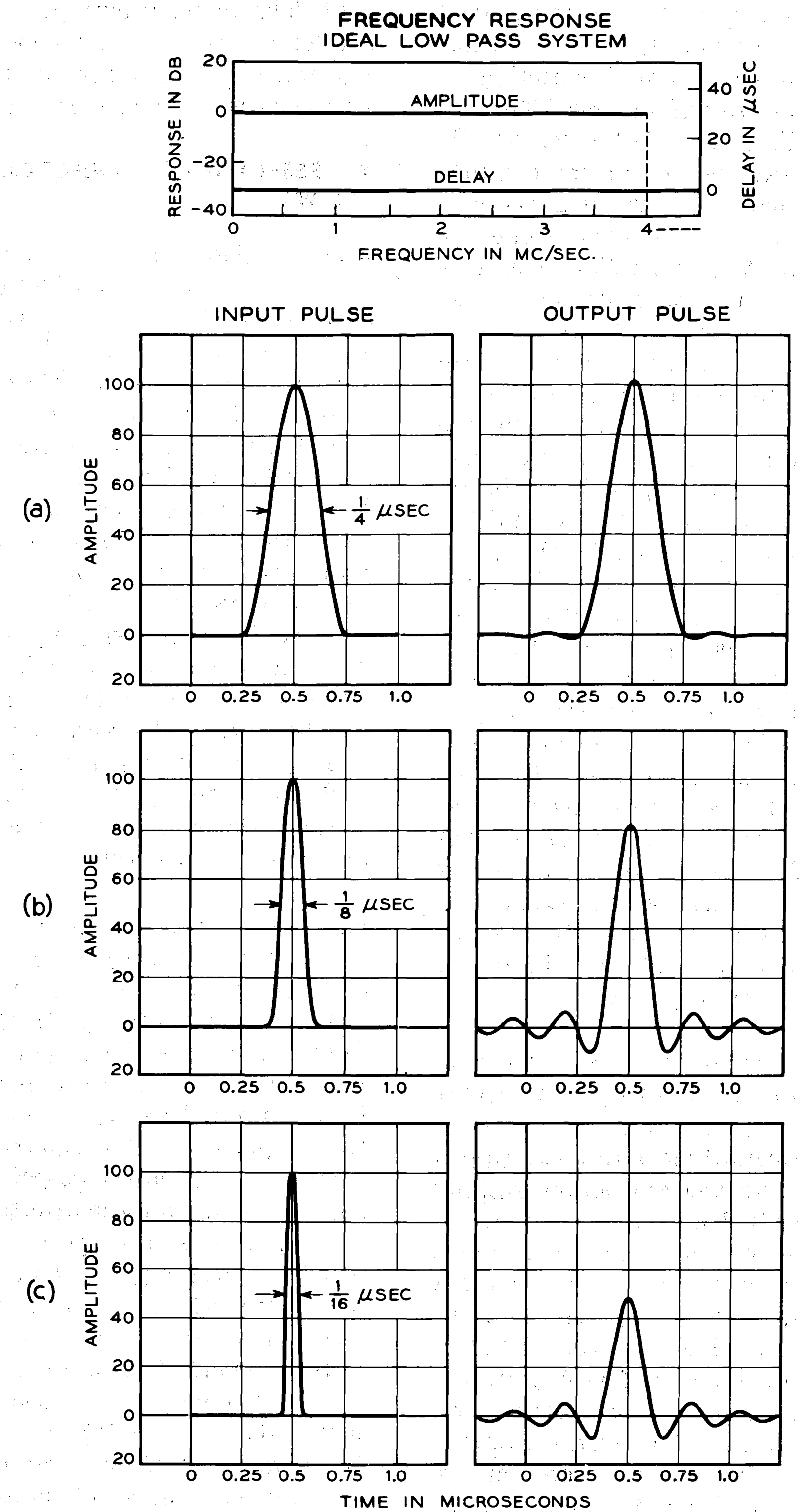

Fig. 3 – Input and Output Waveforms of Sine-squared Pulses as They Appear in Testing an Ideal Low-pass System.

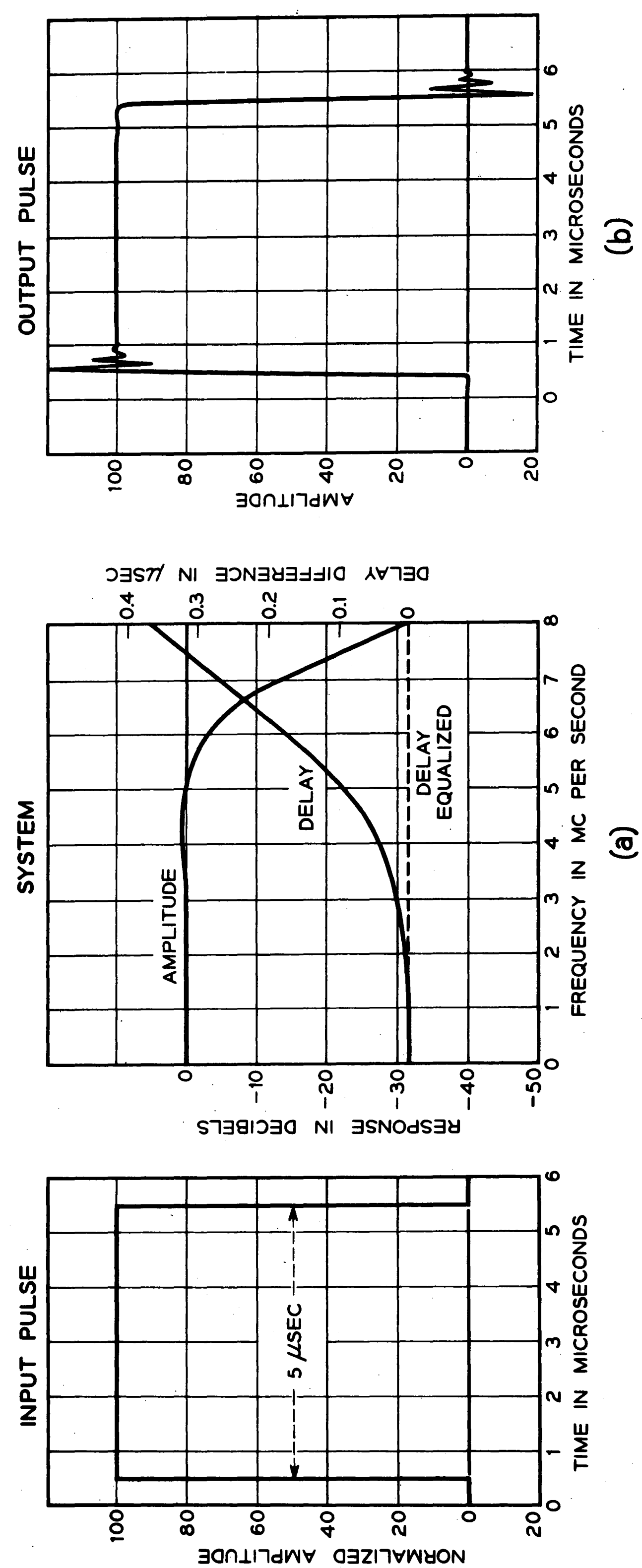

Fig. 4 – Effect of a Practical Transmission System Having Amplitude Roll-off and Delay Distortion on the Waveform of a Wide Rectangular Pulse.

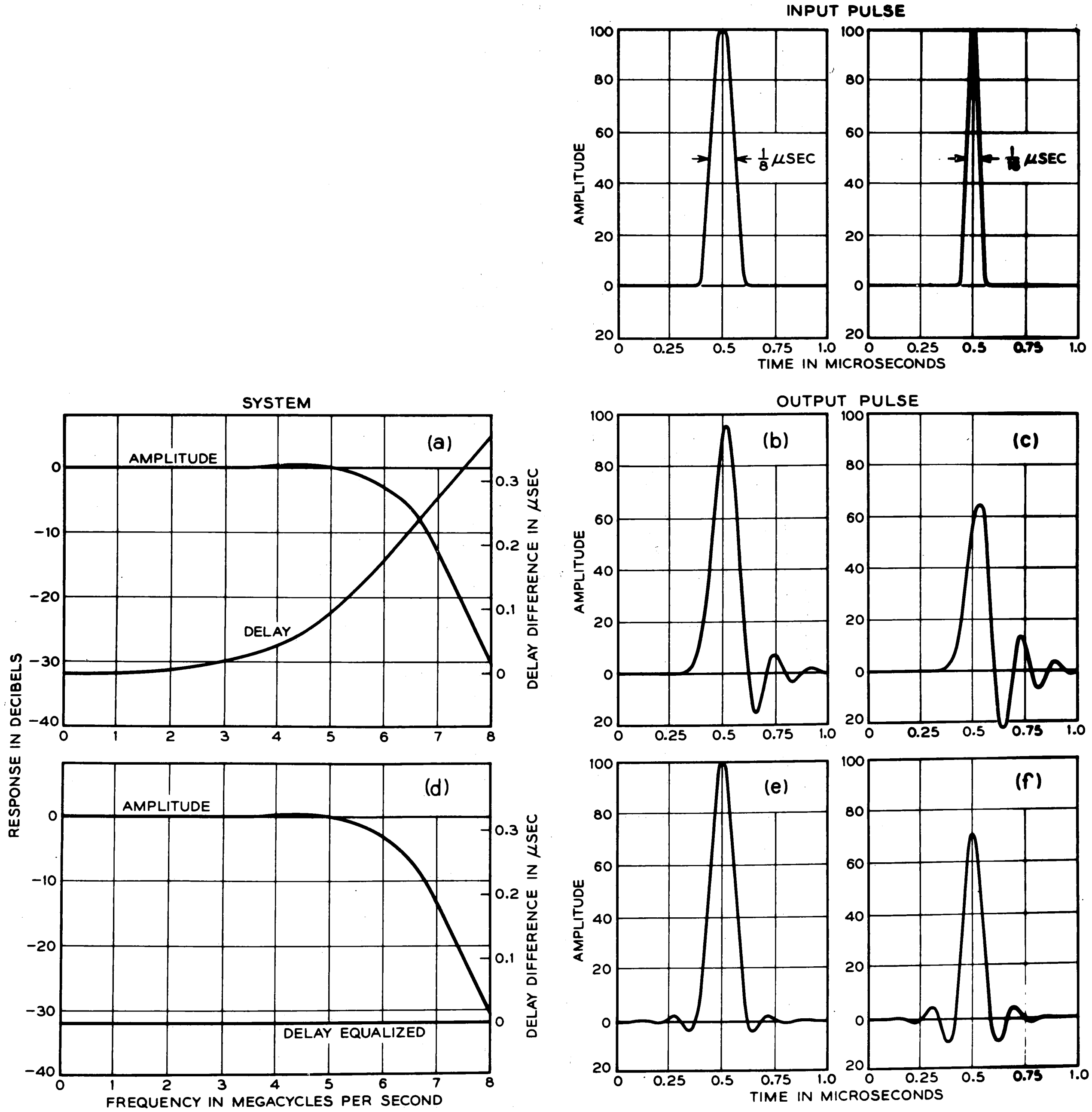

Fig. 5 — Effect of a Practical Transmission System Having Amplitude Roll-off With and Without Delay Distortion on the Waveforms of Sine-squared Pulses.

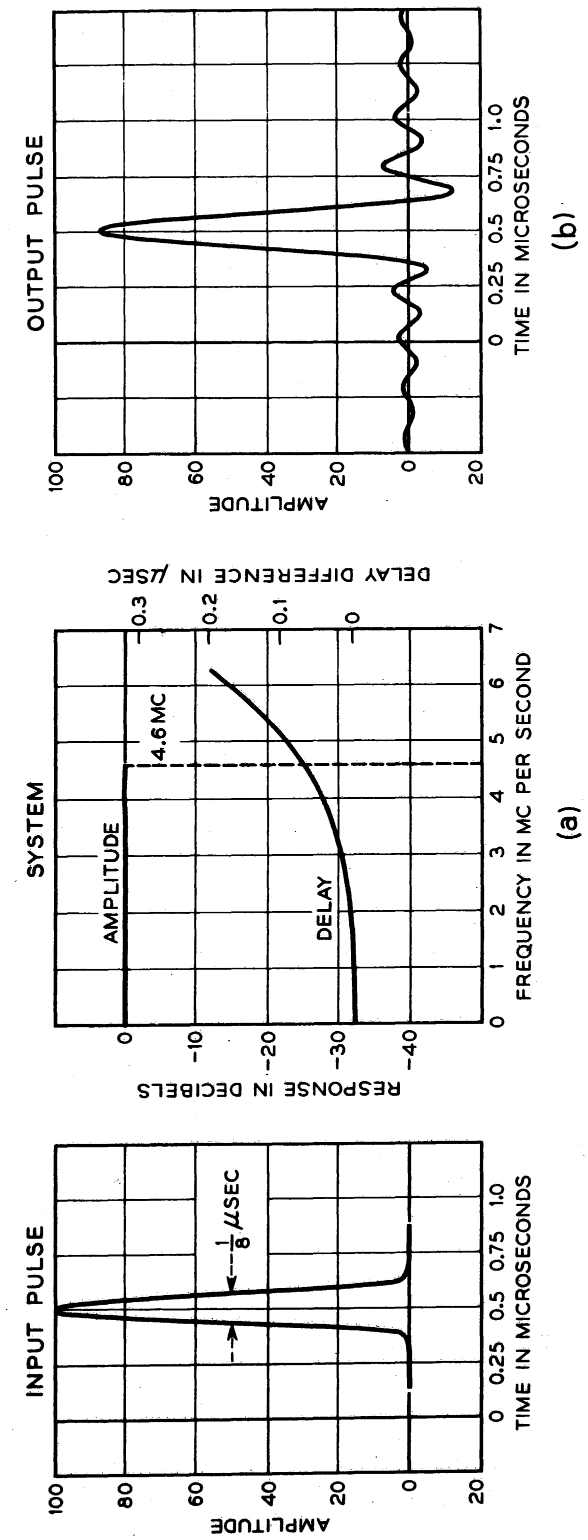

Fig. 6 — The Effect of In-band Delay Distortion on the Output Waveform of a 1/8 μsec Sine-squared pulse.

If the frequency scale of this characteristic were cut in half, it would represent a substantially flat characteristic up to about 2.5 mc with a roll-off to a cutoff frequency of about 4 mc. To see the effects of such an in-band roll-off on a T-pulse (1/8 μsec pulse for the 4 mc cutoff), we have merely to look at the response of the original practical system to a 1/16 μsec pulse as shown in parts (c) or (f) of Fig. 5, and multiply the time scales of the received pulses by two.

4.04 Before supplementary correction of the delay distortion was added to the practical system, the delay characteristic exhibited its most impressive deviations in the 4—8 mc region which is outside of the nominal 4 mc band appropriate for signals used in standard TV broadcasting. If an ideal low-pass filter were inserted at the output of the practical system, it would pass all components of the signal up to its cutoff frequency without further distortion, and would completely remove all of the higher frequency components. By making the cutoff frequency 4.6 mc, all the components that could be used by a TV receiver would be included, and within this pass band the maximum delay distortion, or deviation, would be 70 millimicroseconds. That this small amount of delay deviation is important will be evident from an inspection of Fig. 6, which shows a 1/8 μsec input pulse, the amplitude and delay characteristics of the practical system with a 4.6 mc cutoff indicated, and the corresponding output pulse. The most noteworthy aspect of the output pulse is its asymmetrical ringing, which, prior to the main pulse, is about one-half as much as would be expected had there been no delay distortion, and, after the main pulse, about 20 percent more in the form of a negative spike.

5. DISCUSSION

5.01 From the foregoing presentation and from theoretical considerations one is able to draw some simple, but rather fundamental, conclusions. First, with regard to the frequency spectra of pulses, it is clear that the narrower the pulse, the greater the frequency range covered by its important frequency components, and the broader must be the bandwidth of the transmission system to reproduce the pulse with equal faithfulness. Pulses of similar waveforms have frequency spectra of similar shape: if F(f) is the spectrum of a pulse having a waveform G(t), then aF(af) is the spectrum of G(t/a). The spectra shown in Fig. 1 are depicted with their amplitudes normalized to unity at zero frequency. In each case, relative amplitudes of various spectra are obtained from those of the normalized spectra by multiplying the latter by a factor of t_w for either rectangular pulses or sine-squared pulses.[5] Thus, in Fig. 1, the spectral amplitudes of the 5 μsec pulse when normalized appear small compared to those of the 1/8 μsec pulse; whereas, in fact, to make the amplitudes of the 5 μsec pulse comparable to those of the 1/8 μsec pulse, we should have to multiply the former by a factor of 40.

5.02 In conjunction with the discussion of Fig. 2b it was noted that, for sufficiently wide pulses, the magnitude of the successive overshoots and undershoots will not be altered by changing the cutoff frequency, f_c, of the system. This effect is conveniently demonstrated in Fig. 7 by the response of the ideal low-pass system to a unity step input for f_c of the system equal to 2, 4 and 8 mc. Observe that as the cutoff frequency increases the ringing frequency increases and the rise time of the response decreases.

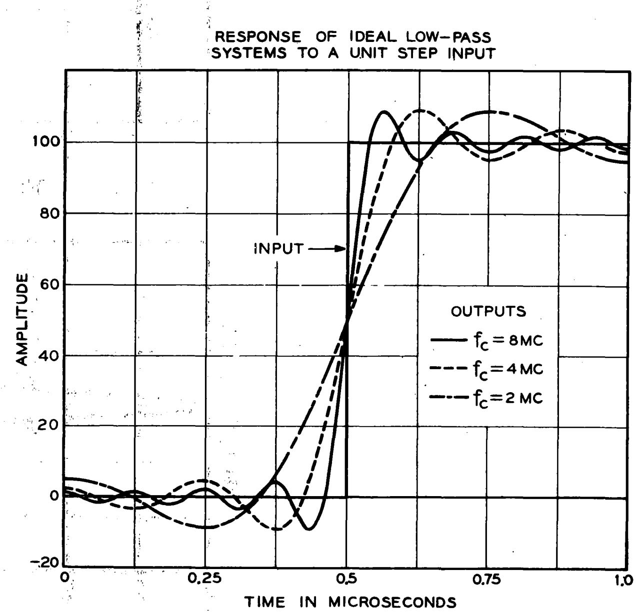

Fig. 7 — Illustration of the Effects of Changing the Cutoff Frequency of the Ideal Low-pass System.

5.03 The use of idealized rectangular pulses in the study does not necessarily lead to results that are unrealistic when compared to the results obtained with actual pulse generators. If the rise time of the actual signal used in testing is less than or equal to a Nyquist interval, $T = 1/2f_c$, of the system under test there will be very little difference in the output waveforms of the idealized and actual pulses. However, if the actual pulse has a rise time greater than $T = 1/2f_c$ the resulting output waveform will appear as the response to an idealized pulse of a transmission system that has been modified by an additional roll-off.

5.04 The subject of roll-off, which is of considerable interest, is rather complicated. However, some simple but useful ideas of its effects can be gained from a study of a system having linear amplitude roll-off and of its response to a unit step. Let us consider a model system as shown in Fig. 8 having frequency characteristics such that: (1) the delay is zero over the entire pass band and (2) the amplitude characteristic is constant, at unity, from zero frequency up to a frequency $f_1 = f_c - \Delta$, then decreases linearly to zero at $f_2 = f_c + \Delta$, having a value of 1/2 at $f = f_c$. Define the degree of roll-off by $K = \Delta/f_c$ so that $K = 0$ represents the ideal low-pass system, and when $K = 1$ the amplitude characteristic of the system decreases linearly from unity at zero frequency to zero at $f = 2f_c$. Our interest will lie in the range $0 \leq K \leq 1$. Let $H_K(t)$ represent the response of the system to a unit step. Then a measure of the effectiveness of the roll-off in suppressing the oscillations of the transient response can be taken as $d_n = | H_K(n/2f_c) - H_K[(n+1)/2f_c] |$, where d_n is the magnitude of the response fluctuation between successive Nyquist intervals, $t = n/2f_c (n = \pm1, \pm2, \ldots)$, for a given K. This will be a valid measure since the response will exhibit maxima, minima, or points of inflection only when $t = n/2f_c$.

5.05 From the values of d_n given in Table I, and from theoretical considerations, we find that as the degree of roll-off increases: (1) the damping of the transient ringing will increase and (2) the magnitude of the spike (first overshoot) will decrease. This latter effect, however, will be negligible for a moderate degree of roll-off, $K \leq 1/4$. If instead of fixing the one-half amplitude frequency, f_c, we fix the zero amplitude frequency, f_2, (i.e. maintain a constant absolute cutoff frequency) we find that, in addition to the effects noted above, as the degree of roll-off increases, the ringing frequency and the picture resolution will decrease.

5.06 The physical factors noted above will have interrelated subjective effects on picture quality, a subject beyond the scope of this section. However, the discussion of roll-off, delay distortion, and pulse spectra should be helpful in understanding the physical aspects associated with spiking and ringing of television signals particularly as they affect synchronizing pulses and other square wave forms.

TABLE I

Magnitude of the Transient Oscillations in a System Having Linear Roll-off

	Degree of System Roll-Off			
	K=0	K=1/4	K=1/2	K=1
d_1	0.1381	0.1090	0.0449	0.0236
d_2	0.0817	0.0389	0.0132	0.0082
d_3	0.0581	0.0085	0.0074	0.0042

REFERENCES

[1] N. W. Lewis, "Waveform Computations by the Time Series Method," Part III Proc IEE 99, p. 294, September, 1952.

[2] N. W. Lewis, "Waveform Response of Television Links," Part II Proc IEE 101, p. 258, July, 1954.

[3] R. C. Kennedy, "Sine-Squared Pulses Test Color-TV Systems," Electronics, December, 1954.

[4] Colin Cherry, pp. 146-151, "Pulses and Transients in Communications Circuits," Chapman & Hall Ltd., 1949.

[5] The well-known expressions for these spectra are $t_w(\sin 1/2x)/1/2x$ for rectangular pulses; and $t_w(\sin x)/x[1 - \left(\frac{x}{\pi}\right)^2]$, for sine-squared pulses, where $x = 2\pi f t_w$.

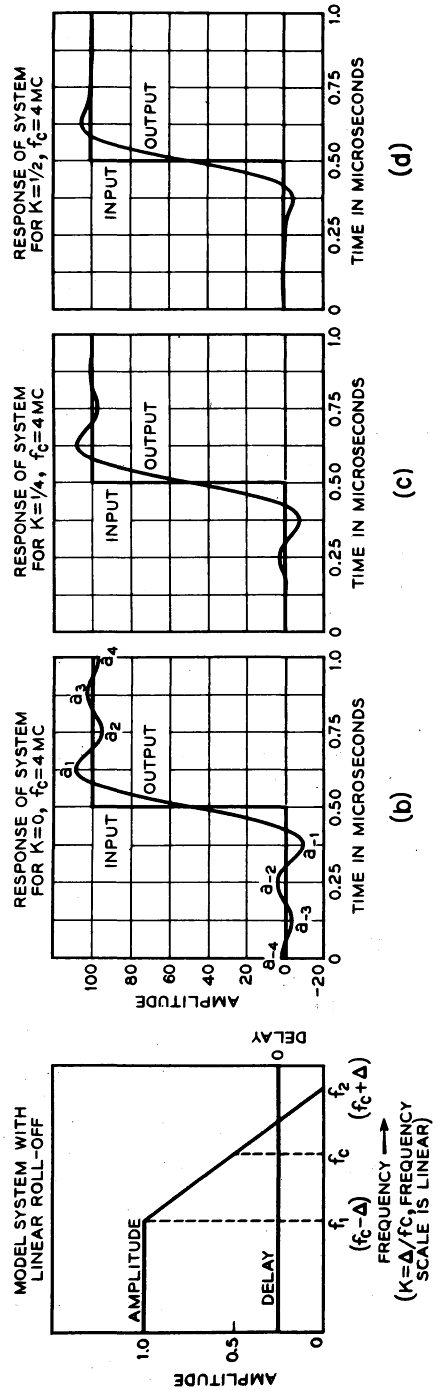

Fig. 8 — Responses of Linear Roll-off Systems to a Unit Step Input.