Phase Shift and Sound Quality

Experiments to Determine How Much Can Be Tolerated

By J. MOIR*, M.I.E.E.

MANY recent amplifier designs have included among their claims to fame in the high-quality sound reproducer field, such statements as "zero phase shift down to 10 c/s or up to 100 kc/s." It is proposed in this article to discuss briefly the meaning of phase shift, to consider the circuit elements responsible and then to examine its effect on the quality of sound reproduced by loudspeakers, to see whether figures for phase shift are worth including in an amplifier specification.

In any circuit that includes a reactive element such as a capacitor or an inductor the alternating current will not reach its maximum value at exactly the same instant as the voltage reaches a maximum. If the circuit includes inductance and resistance only, the current lags, as indicated by the curves of Fig. 1; but if the circuit is composed of capacitance and resistance the current will lead the voltage under steady-state conditions.

The time difference between voltage and current maxima is a significant indication of circuit conditions, but it has become conventional to indicate the time difference not in seconds but as a fraction of the time (period) of one complete cycle at the frequency being considered. Thus the phase shift is one quarter cycle when the circuit is composed entirely of inductance (Fig. 1) or capacitance. Alternatively the difference may be expressed in degrees, and a quarter-cycle phase shift then corresponds to a 90° phase shift. There are other methods of specifying the time difference, but as amplifier designers appear to favour the use of degrees this convention will be generally used in the ensuing discussion. The reasons for the displacement in time of the voltage and current maxima will not be discussed here, our present concern being the final acoustic effects.

The phase shift introduced by a simple circuit of one reactive element and one resistor can never exceed one quarter cycle or ninety degrees, and can only reach this value when the resistor is reduced to zero. The phase difference between voltage and current for a simple combination of resistance and capacitance is plotted in Fig. 2(a) as a function of the ratio of circuit resistance to circuit reactance. This dependence on circuit reactance makes any particular pair of components introduce a phase shift which varies with frequency in exactly the manner shown in Fig. 2(a) if f_o/f is substituted for X_c/R and f/f_o for R/X_c, f being the frequency under consideration and f_o the frequency at which $X_c=R$.

These simple circuits of Fig. 2(b) will be recog-

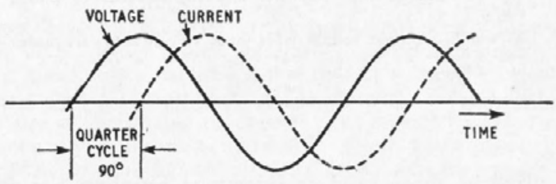
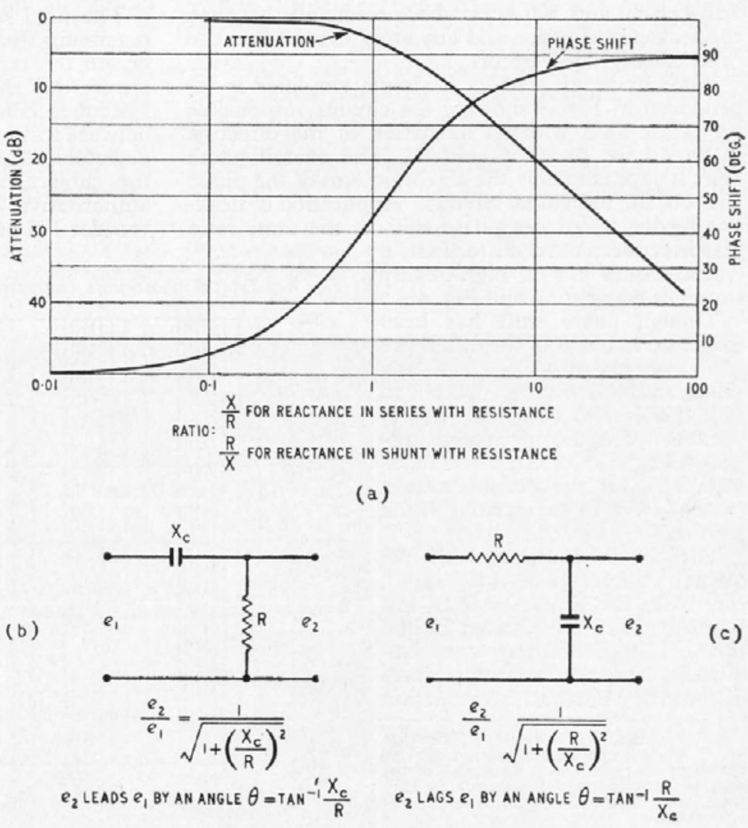


Fig. 1. Conditions in a reactive circuit with voltage and current waves displaced by 90° or one quarter cycle.

Below: Fig. 2. (a) Phase shift and attenuation introduced by single combinations of reactance and resistance such as those at (b) and (c).



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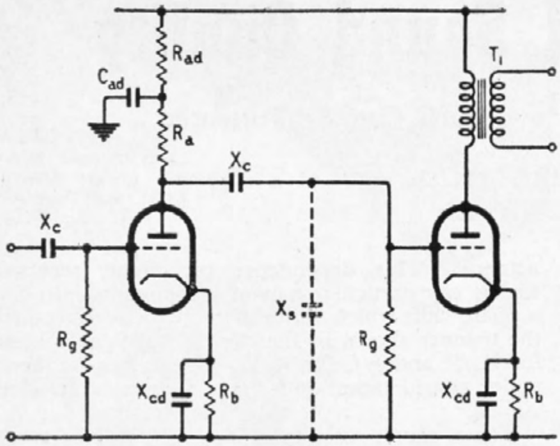


Fig. 3. Elementary amplifier showing sources of phase shift.

X_c and R_g—Output voltage leads input voltage at low frequency
C_{ad} „ R_{ad}— „ „ lags „ „ „ „ „
R_b „ X_{cd}— „ „ leads „ „ „ „ „
R_a „ X_s — „ „ lags „ „ „ high „
T^1 { — „ „ leads „ „ „ low „
— „ „ lags „ „ „ high „

nized as those used as interstage coupling circuits in RC amplifiers (b) being the grid coupling capacitor and resistor and (c) the anode load resistor with the effective shunt capacitance in parallel with it.

Iron cored devices such as input and output transformers introduce phase shifts at low frequencies of the same order as an RC stage, but may introduce more rapid changes of phase in the region between 30 and 100 kc/s where resonance between the leakage reactance and any stray capacitance can (and usually does) occur.

The circuit diagram of a simple amplifier is reproduced in Fig. 3 showing the circuits responsible for phase shift with an indication of the direction in which the phase is shifted. The overall phase shift is approximately the algebraic sum of the phase shifts of the individual circuits. Application of negative feedback reduces phase shift in the same ratio that it reduces other distortions, a typical result for a high-quality amplifier being shown in Fig. 4.

Though phase shift has been discussed in terms of the difference in time between voltage and current maxima it will be appreciated that this is also the phase difference between the input and output voltages in a circuit such as Fig. 2(b), for the output voltage is in phase with the current in the resistor.

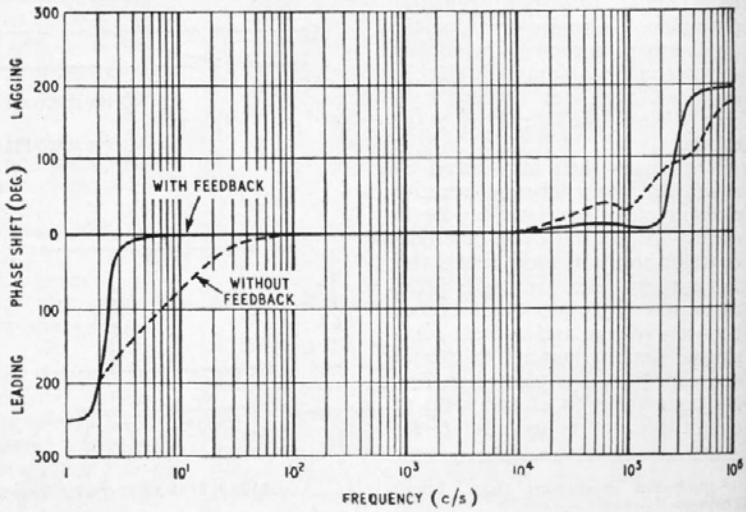
The change of phase with frequency appears to be fairly rapid, even with the simple circuits, but basically it is the change in the *time* of transmission with frequency that introduces waveform distortion. Further investigation shows that the time of transmission between input and output terminals of a network such as Fig. 2(b) is fairly constant at all frequencies at which the circuit attenuation is low. A time of transmission that does not vary with frequency implies a phase-shift/frequency characteristic in which the phase shift is proportional to frequency and not a phase shift that is constant at all frequencies.†

It takes very little consideration to decide that the waveform of a complex wave composed of many frequencies will be drastically distorted in passing through any device in which the time of transmission varies for each of the component frequencies. An example is illustrated in Fig. 5, the output signal on the right, bearing very little resemblance to the square-wave input signal, though all the distortion shown is the result of phase shift and not the result of any frequency-dependent attenuation.

It will be clear that there is considerable difficulty in designing an amplifier (or any other piece of equipment) in which the phase shifts are reduced to zero at all frequencies. If it is considered that waveform distortion must be avoided there are four possible solutions. The first is merely to avoid phase shift completely, a council of perfection. The second is to avoid phase shift within the audio-frequency band of say, 30 to 10,000 c/s. The third solution is the use of a phase/frequency characteristic in which the phase shift in degrees is linearly proportional to frequency, for if this is done all the frequency components are delayed by the same time interval. It is generally of little consequence if a complex signal takes even several milliseconds to pass through an amplifier, provided that all the components take the same time.

The final solution is separately to determine the maximum amount of phase shift that can be allowed before the result is aurally detectable, and then to ensure that the actual phase shift introduced by the system is below this limit. In an extensive audio network this is the only practical solution. The "just detectable" phase shift is a problem that has been the subject of many investigations, but the most authoritative works known to the writer are due to van der Pol of the Philips Research Laboratory and

Fig. 4. Typical phase-shift characteristics of a high-quality domestic amplifier.



† This aspect is developed by "Cathode Ray," whose contribution this month (p. 188) happens to include a discussion of the basic relationships between phase/frequency distortion and amplitude/frequency distortion.—Editor.

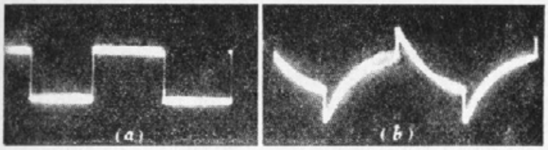


Fig. 5. Effect of phase distortion on a square-wave signal after passing through a reactive network in which there is no variation of attenuation with frequency. Repetition rate, 300 per sec.

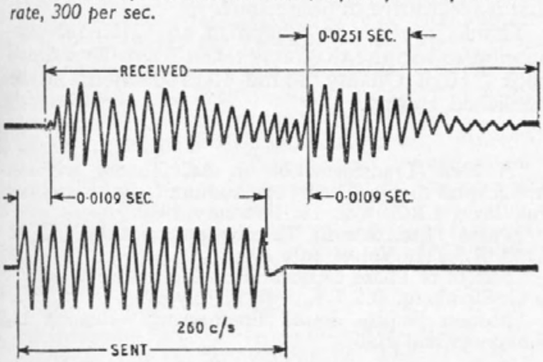


Fig. 6. Distortion of tone pulse due to phase shift.

to Steinberg and Lane of the Bell Telephone Laboratories.

Van der Pol made a limited investigation using a special circuit that allowed him to change the phase of the higher harmonics of a complex wave relative to the fundamental by any amount up to 360°. He noted that any phase shift within this limit introduced no effects detectable when listening to speech.

Steinberg and Lane used an experimental technique that permitted much greater amounts of phase shift to be introduced into the reproducer system. Low-pass or high-pass filters of the normal ladder type introduce appreciable amounts of phase shift near the ends of the transmitted range. Filters of this kind may be added in series to produce any desired amount of shift at any point in the frequency range. The "just detectable" amount of phase shift proved to be so large that it is more convenient and indeed more indicative of the mechanism to express the shift in milliseconds.

To produce effects detectable on speech it was found necessary to shift the frequency components in the 5-8 kc/s band by about 8 milliseconds relative to the 1 kc/s components. Frequency components in the 50-100 c/s region had to be shifted by as much as 70 milliseconds before the effect was detectable. These time differences correspond to a relative phase shift of 64 complete cycles or 23,000 degrees at 8 kc/s and to a shift of 7 complete cycles or 2,520 degrees at 100 c/s.

Delays of this order are recognized as separate hollow ringing echoes, an effect often heard on long telephone lines and somewhat akin to acoustic reverberation.

The electrical effects can be demonstrated by injecting short pulses of tone into the equipment under test. The transmitted and a typical received signal are shown in Fig 6 (based on Fig. 10, p. 503, *B.S.T.J.*, Vol. 9, 1930) for a filter having a time delay of 0.01 seconds, and it will be seen that both head and tail of the transmitted pulse are badly distorted, the pulse being stretched until the received pulse is almost twice as long as the transmitted pulse.

Reference to Fig. 4 will remind the reader that an ordinary amplifier of the type likely to be used by the high-quality enthusiast is more likely to have phase shifts of a few degrees, quite innocuous in comparison with the phase shifts found necessary to produce audible distortion.

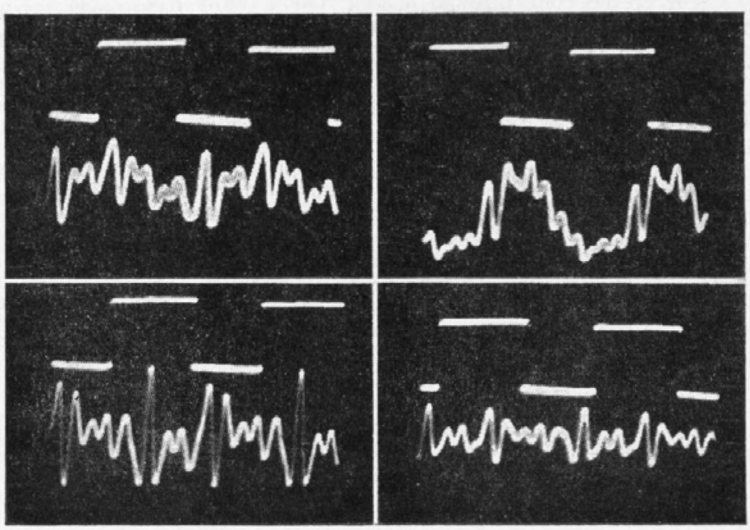
To the best of the writer's knowledge these results remain as authoritative, no subsequent investigation having thrown the slightest suspicion on the results of van der Pol, Lane and Steinberg.

It is commonly stated that though phase shift may not have much effect on the quality of steady tones it does have a much greater effect on the quality of transients. Steinberg did in fact comment upon this point, noting that phase distortion was much more objectionable on speech than on music. However, the minimum detectable phase shifts quoted earlier are the figures obtained from tests on speech. Though transient in nature, speech may not represent the ultimate in this respect so that to gain some personal experience tests were instituted using square waves.

A high-quality reproducer system was set up employing amplifiers capable of passing square waves without perceptible waveform distortion when the output signal at the speaker terminals was viewed on an oscilloscope. Loudspeakers may be the weak link, but those used were representative of the highest quality currently available, several different types having been employed at different times.

The input signal was the square wave shown in Fig. 5, lattice all-pass filters being employed to introduce phase shift without any frequency-dependent attenuation. The result of introducing phase shift

Fig. 7. The lower traces are the acoustic waveforms at points on or near the axis and at distances not more than 3ft from the diaphragm of a loudspeaker to which a square voltage wave has been applied. Repetition rate 900 per sec.



was to convert the waveform of Fig. 5(a) into that of Fig. 5(b) but even this drastic change could not be detected by any member of an experienced listening crew. The equipment has subsequently been used as a demonstration at several lectures, but to date, no listener has ever claimed to be able to detect the difference between the two waves.

This cannot be claimed as an absolutely conclusive test for there are an infinite variety of transient waveforms and it will always be impossible to claim that all have been tested; but taken in conjunction with other results it does suggest that phase shift is certainly not of great importance and may not be of any importance. This point of view has been confirmed in private communication with other workers on the subject.

When the results of laboratory tests appear to contradict common sense it is always worth looking round for confirmation or contradiction from everyday experience. A little consideration of the acoustic conditions in any concert hall will suggest that it is perhaps providential that our sensitivity to phase shift is low.

Sound from any source, original or a reproduction, reaches the listener first by the direct and shortest path and then by successive reflections along paths of increasing length. At listening positions only a few inches apart the acoustic pressure pattern in space varies enormously as different reflection paths of varying length become of predominating importance, and yet the sound quality remains unaltered. This is illustrated by the oscillograms of Fig. 7 indicating the changes in acoustic waveform at points a foot or so apart when a square wave (voltage) is impressed on the loudspeaker terminals. At some points the acoustic pressure waveform approximates that of the electrical signal but at other points there is little resemblance to a square wave. All the check points were on or close to the speaker axis and not more than three feet from the speaker.

Current loudspeaker designs provide another simple indication of the unimportance of phase shift in small amounts. In the sound reproducer field many of the loudspeakers having the highest reputation consist of units radiating the high frequency components either directly from the front of the cone or via a short straight horn, while the low frequency components below perhaps 500 c/s are radiated from the rear of the cone through a long folded horn. The difference in path length traversed by the low and high frequency components may amount to 5-8 feet (5-8 milliseconds, about 360 degrees at 150 c/s) and yet loudspeakers of this type such as the Lowther, Tannoy and Klipschorn have an acknowledged reputation for quality of reproduction.

Quite clearly the evidence suggests that phase shift does not have the importance usually attached to it by the high quality enthusiast. The phase shift introduced by any amplifier of normal design is so low in comparison with the minimum detectable phase shift that it is hardly worth considering. A broadcasting or telephone administration operating an extensive interconnection system that might involve 80-100 amplifiers connected in series would, however, have to pay a little more attention to the phase shift introduced by the individual amplifiers in order to keep the total shift below the minimum detectable figure. Even in this instance the audible effects of phase shift are usually due to shifts introduced by filters or by the line itself near the ends of the transmitted frequency band and are not due to the amplifiers.

This discussion suggests that the phase shift introduced by a domestic amplifier is of little consequence as an indication of the quality of reproduction and is not really worth quoting. Phase shift is of importance when considering the stability of an amplifier with feedback but this is an entirely different matter.

It is perhaps an indication of the omnipotence of nature that she has developed a hearing system that is insensitive to phase shift.

Thanks are due to Chapman and Hall for permission to use the diagrams taken from the writer's book "High Quality Sound Reproduction" to be published shortly.

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