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Non-Sinusoidal Wave Forms

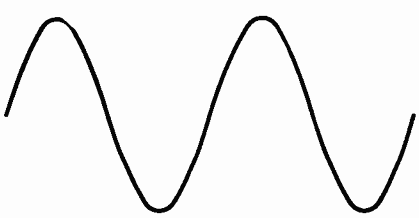
Part 1, Passive Wave-Shaping Circuits

By the Engineering Department, Aerovox Corporation

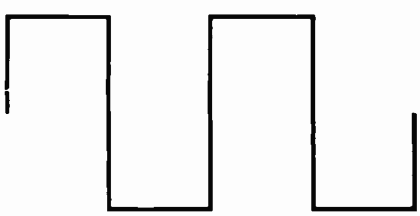
THE recent rapid advance of such developments as radar, all-electronic television, pulse modulation systems[1], electronic navigational aids, computers, and other electronic devices has focussed attention to an ever-increasing extent upon the "care and feeding" of non-sinusoidal electrical impulses of special shapes. As used in modern terminology, a non-sinusoidal voltage or current may be described as one whose variation with time does not satisfy the equation:

$$E_t = E_{max} \sin \omega t \qquad (1)$$

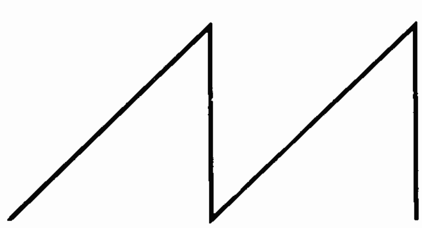
This admittedly "back-handed" way of defining what a non-sinusoidal impulse *isn't* is perhaps simpler and more concise than a lengthy definition of what one *is*. Fig. 1 depicts graphically several of the more common types of voltage waveforms which may be encountered in modern timing circuits. A more or less general discussion of the generation, shaping, amplification, and use of some of these waveforms, using techniques available to the circuit engineer, will comprise the bulk of this



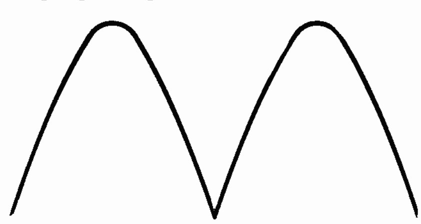
(a) SINE WAVE



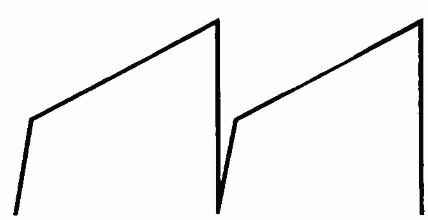
(b) SQUARE WAVE



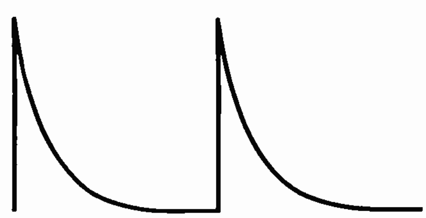
(c) SAWTOOTH WAVE



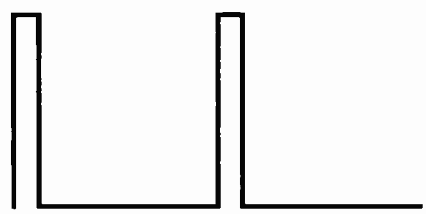
(d) RECTIFIED SINE WAVE



(e) TRAPEZOIDAL WAVE



(f) EXPONENTIAL WAVE



(g) PULSE

FIG.1

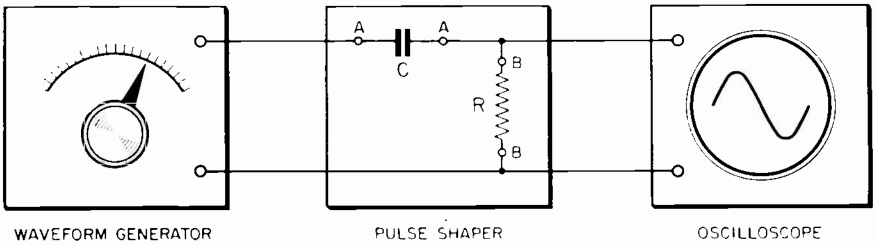


FIG. 2

paper. The present issue is confined to the passive circuits which may be used to form non-sinusoidal waves, while the succeeding part will treat self-sustaining generators and other wave forming circuits which employ non-linear elements such as vacuum tubes.

Perhaps the simplest types of waveform shapers, or "pulse shapers" as they are called, are the circuits composed of various combinations of the passive, linear network elements, namely; resistors, capacitors, and inductors. Consider first for example the circuit of Fig. 2, in which are shown a hypothetical signal generator capable of producing any of the waveforms of Fig. 1, a pulse shaper in which AA and BB denote terminals to which may be connected any of the passive circuit elements so that various network configurations may be studied, and an oscilloscope for viewing the output voltage of the pulse shaper. The series combination of resistance and capacitance shown connected to the terminals in this case is usually termed an "R-C differentiator" or "pulse sharpener," since the output voltage measured across the resistor is, within certain limits, closely proportional to the *time derivitive* of the input voltage. Other basic configurations of passive elements which are of importance are shown in Fig. 3.

We will first consider the R-C differentiator in some detail. It may be seen from a mathematical consideration that if the applied voltage in Fig. 2 is a pure sine wave, such as may be obtained from a good audio oscillator, the steady state output of the shaper will also be a pure sinusoid of identical frequency and waveform. In general, the only difference between the two will be their relative amplitudes and phases; the output leading the input by a phase angle given by:

$$(2) \qquad \phi = \text{arc tan}\left[\frac{1}{\omega RC}\right]$$

and reduced in amplitude as shown by the equation:

$$(3) \qquad E_{out} = E_{in}\left[\frac{1}{\sqrt{1 + 1/\omega^2 R^2 C^2}}\right]$$

Inspection of Eqs. 2 and 3 shows that the phase angle and attenuation both decrease with increasing frequency. It should also be noted that the phase angle may approach but never quite reach 90 electrical degrees for a single R-C differentiator, since a phase shift of 90 degrees requires that the total series circuit resistance be zero — in which case the output voltage would also be zero. Thus, the output voltage of an electrical differentiating circuit is never, in the mathematical sense, an exact time derivitive of the input voltage.

A set of somewhat similar equations governing the phase and attenuation characteristics of the so-called R-L differentiators (Fig. 3b) for which the output voltage is proportional to the time derivitive of the input *current,* rather than the input voltage as in the previous case, may be found in the literature[2]. The phase shifting characteristic of resistor-capacitor and resistor-inductor networks is made use of where an accurately predetermined time or phase difference is required between trigger pulses. A typical phase shifter circuit which may be used to accomplish this is shown in Fig. 4. With this device, relative phase differences of almost 180 electrical degrees between input and either of the outputs, or nearly 360 degrees between outputs, may be readily achieved. Thus, although the phase shift for a single R-C or R-L network is limited to somewhat less than 90 degrees, it is possible to increase the total shift to any desired value by cascading two or more networks.

The "integrator" circuits (Fig. 3c and 3d) are so-named because of the fact that the output voltage is proportional to the time *integral* of either the circuit current (3c) or the applied voltage (3d). It should be mentioned in passing that the phase and attenuation characteristics of integrator circuits, which are essentially low-pass filters, are frequency dependant, like those of the differentiators (or high-pass filters) mentioned above. The major difference between the two is that integrators display (1) a lagging, rather than a leading phase angle, and (2) attenuation and phase angle which increase rather than decrease with increasing frequency.

Another type of differentiator circuit which, although little used in the past, is of sufficient interest to warrant a brief discussion here is the transformer or "mutual inductance" type shown in Fig. 5. This circuit offers several distinct advantages over the previously described types. As in the standard R-L differentiator, the output voltage is again proportional to the time derivitive of the input current as shown by the equation:

$$(4) \qquad E_{out} = M\frac{di}{dt}$$

where M (the mutual inductance) is the proportionality factor relating the coefficient of coupling and the primary and secondary inductances. The transformer, like the R-C differentiator, is an a.c. coupled device, and as such provides more flexability than does the R-L circuit, in which the input and output are conductively coupled. Thus, it is possible to use the transformer differentiator as a coupling device between two circuits operating at different d.c. levels (as in the plate and grid circuits of amplifier

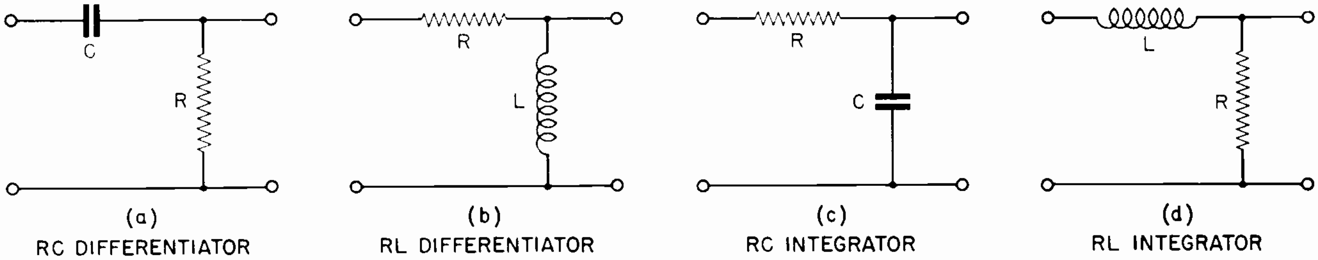


FIG. 3

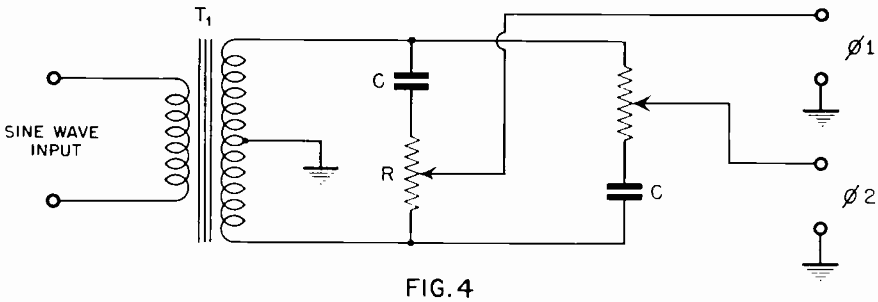
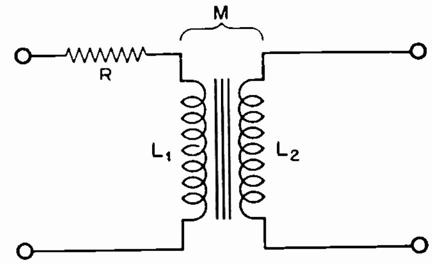


FIG. 4



MUTUAL INDUCTANCE DIFFERENTIATOR

FIG. 5

stages) without resorting to complicated biasing arrangements. Another advantage to the circuit is the comparative ease with which polarity reversal and voltage step-up may be effected, if desired.

An important concept which will aid in gaining a clearer understanding of the behavior of the passive wave shaping circuits of Fig. 3 is that of the *time constant*, T. Simply defined, T is the time in seconds required for an uncharged condenser C to charge through a resistor R to 63% of the applied voltage V. Conversely, for a charged condenser discharging through a resistance, T is equal to the time required for the voltage to decay exponentially to 37% of its initial value. In similar manner, T may be defined for an R-L circuit as the time required for the *current* to rise to 63% of its maximum value E/R, or as the time in which the current will fall to 37% of the initial value. The equations;

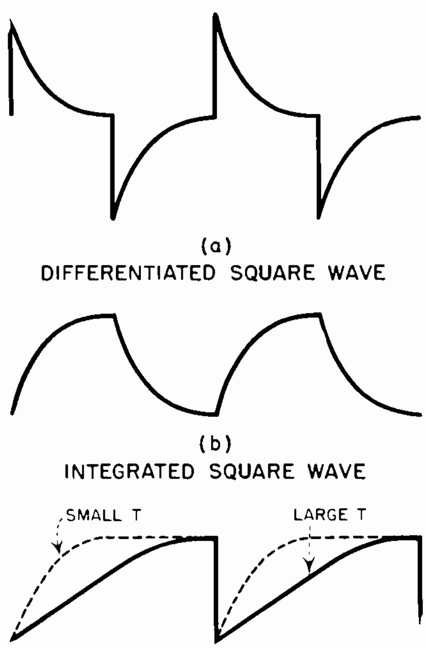
$$(5) \qquad (a)\ T = RC \qquad (b)\ T = L/R$$

are the mathematical conventions which have been adopted.

Let us now consider the response of the circuits of Fig. 3 to non-sinusoidal waveforms. It will be remembered that for these circuits the input and output waveforms were identical under conditions of sine wave excitation, as mentioned above. Such is not the case for the non-sinusoidal waveforms, however. If, for example, a square wave of voltage (Fig. 1b) is applied to the input of either type of differentiator shown in Fig. 3, the nature of the output voltage developed depends on the value of the time constant T in relation to the period t occupied by one cycle of the input voltage. If the ratio T/t is small, the output under these conditions will appear as a succession of alternatively positive and negative pulses which are narrow near the peaks but broader at the base as in Fig. 6a.

The output of an integrator circuit, on the other hand, with similar square wave excitation and time constant, will resemble Fig. 6b. As may be inferred by comparison of Figs. 6a and 6b with the original square wave, it can be said in a more or less qualitative manner that the differentiator circuits transmit only the higher order frequencies contained in a complex waveform, while the integrator networks, conversely, pass only the lower frequency components. The resolution of a complex waveform into its component frequencies is illustrated in Fig. 2 of Ref. 1.

The qualitative analysis of the preceding paragraph may be extended to include waveforms other than the square wave. For example, consider the sawtooth wave shown in Fig. 1c. The output of a differentiator with sawtooth excitation will, for large values of T, resemble the input in shape. As T decreases, the waveform will in general be distorted as shown by Fig. 6c. This distortion of a given complex waveform by passive networks has been recognized by Waidelich[3], Rockett[4], and others as providing a rapid method of checking circuit and amplifier characteristics. Since the sawtooth waveform contains both even and add harmonics of the fundamental, as compared with the square wave which contains only odd harmonics, the use of the former in such applications will result in a much more complete picture of amplifier performance.



(a) DIFFERENTIATED SQUARE WAVE

(b) INTEGRATED SQUARE WAVE

(c) SAWTOOTH RESPONSE

FIG. 6

Integrator and differentiator circuits have received their widest applications in the home television receiver field. Here they serve the function of separating the high frequency horizontal pulses and the low frequency vertical pulses from the composite "sync" signal which contains both horizontal and vertical synchronization information. The time constants of the sync separators must be so adjusted that none of the horizontal sync pulses appear at the output of the integrator, and none of the vertical sync pulses appear at the output of the differentiator. In this application, the integrators are usually made up of two or three cascaded sections in order to assure more perfect separation and also to provide comparative freedom from random electrical disturbances such as auto ignition interference.

The **AEROVOX RESEARCH WORKER** for July will discuss typical generators for the production of non-sinusoidal waveforms as well as wave shaping networks employing non-linear elements.

REFERENCES

(1) Aerovox Research Worker. April, 1950.

(2) "Reference Data for Radio Engineers". Federal Telephone and Radio Corp. 3rd edition, Page 98.

(3) D. L. Waidelich, "Steady State Testing With Saw Tooth Waves." Proc. I. R. E. June, 1944; Page 339.

(4) Frank Rockett, "Impedance measurements With Square Waves." Electronics, Sept. 1944; page 138.

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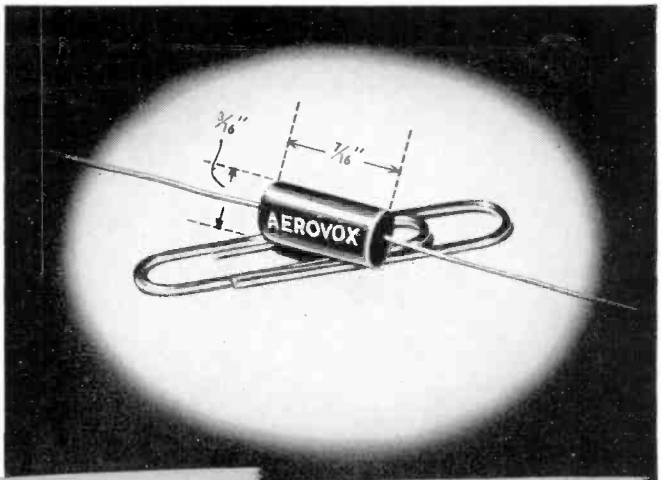

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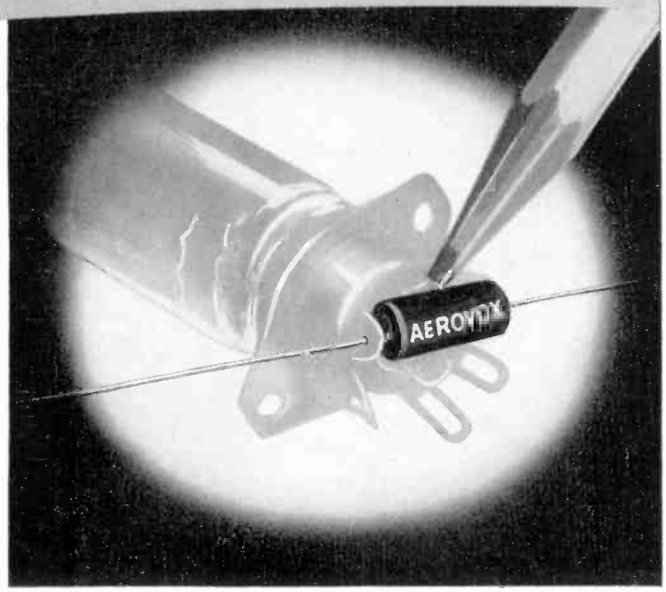

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