IRE Standards on Pulses: Methods of Measurement of Pulse Quantities, 1955*

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I. INTRODUCTION

1.1 Definition of a Pulse (51 IRE 20. S1)

A pulse is defined as "a variation of a quantity whose value is normally constant; this variation is characterized by a rise and a decay, and has a finite duration.

Note 1: The word 'pulse' normally refers to a variation in time; when the variation is in some other dimension, it shall be so specified, such as 'space pulse.'

Note 2: This definition is broad so that it covers almost any transient phenomenon. Features common to all 'pulses' are rise, finite duration, and decay. It is necessary that the rise, duration, and decay be of a quantity that is constant (not necessarily zero) for some time before the pulse and has the same constant value for some time afterwards. The quantity has a normally constant value and is perturbed during the pulse. No relative time scale can be assigned."

* Reprints of this Standard, 55 IRE 15.S1, may be purchased while available from The Institute of Radio Engineers, 1 East 79 Street, New York 21, N. Y., at $0.60 per copy. A 20 per cent discount will be allowed for 100 or more copies mailed to one address.

1.2 Zero Axis

It is important to realize that since a pulse is defined as a variation of a quantity, the variation is zero at the start and end of the pulse. Therefore, in these standards the graphical representation of the normally constant value will be called the "zero axis" of a pulse.

1.3 Delineation of Pulses

It should be noted that the variation considered to be the pulse may be accompanied by other variations that are not of interest. For example, spikes, overshoots, and polarity reversals may be present, but may be ignored if they are not pertinent to the measurement being taken. The word "pulse" as used in these standards refers to that portion of a waveform delineated as the pulse, after exclusion of those portions of the waveform determined to be nonpertinent. This determination of the nonpertinent portions of a waveform may depend upon the function of the pulse in a particular circuit or system. For example, a negative excursion following a positive pulse may be ignored in the measurement of Pulse Decay Time if it is determined that this negative excursion has no important effect upon the operation of the circuit or system under consideration. The portion of a waveform delineated as pulse may also be determined by a time interval of interest outside of which the waveform is not considered part of the pulse. These standards have been written with as much generality as possible and are applicable to pulses with or without spikes, overshoots, or polarity reversals. Whether or not these are considered part of the pulse is a decision which is left up to the individual user. The delineation of the pulse should be made arbitrarily only if *a priori* knowledge is not available, and in either case the results should be clearly stated.

1.4 Definition of a Pulse Train (51 IRE 20. S1)

A pulse train is defined as "a sequence of pulses."

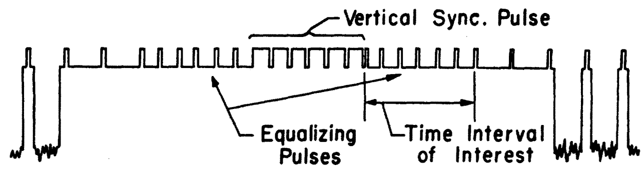
1.5 Delineation of Pulse Trains

Measurements of pulse trains often require knowledge of the component pulses making up the pulse train. A picture of the pulse train alone may not permit the component pulses to be determined.

The following trains are given as examples of the difficulty of measuring the characteristics of a pulse train unless delineation of the component pulses is made.

Example I. Rectangular Pulses

In example 1, the pulse train could be either a sequence of short positive pulses, long negative pulses, or alternating short positive and long negative pulses depending upon what constitutes the component pulses. Example 2 presents the same difficulty as example 1, with the additional complication that several types of



Example 2. Television Signal

component pulses are present. Even if it is known that this is a television signal, the determination of the characteristics of particular component pulses, for example the equalizing pulses, requires the additional concept of an interval of interest, which will be used frequently in these standards. For example, to determine the repetition rate of the equalizing pulses, one might choose a a time interval of interest as shown in the example. If one were required to determine the repetition rate of the vertical sync. pulses, another time interval of interest would have to be chosen. The determination of the characteristics of a complex pulse train may require the delineation of more than one type of component pulse and the use of more than one time interval of interest. The delineation of the component pulses and choice of an interval of interest should be made arbitrarily only if *a priori* knowledge is not available, and in either case the results should be clearly stated.

2. General Considerations

Although the methods of measurement given below cover a wide variety of pulse quantities, many of these methods involve the same measuring instruments, the same general techniques, and the same precautions. The following preface discusses some of these general precautions and techniques in greater detail than would have been possible under each separate method of measurement.

2.1 The Oscillograph

A pulse is best described graphically. The oscillograph, which provides pictorial representations of electrical quantities as functions of time, is commonly and constantly employed in pulse work. The term "oscillograph" as it is used here includes the entire family of devices such as cathode-ray oscilloscopes, ink-writing recorders, etc., which give either a permanent or nonpermanent record of an electrical quantity. It will be understood that the pulse may be current, power, frequency, etc. Since the oscillograph is usually voltage operated, a conversion device (transducer) may be required in connection with the oscillograph to convert the quantity being measured to a voltage. The transfer characteristics (amplitude and time scale factors, linearity, response function, etc.) of the test setup, the transducer, and the oscillograph must be known to enable measurements of the desired quantity to be made in terms of the calibrated deflections of the oscillograph.

In many cases it will be convenient and desirable to select a transducer having simple transfer characteristics (for example, linear, wide-band devices), so that conversion from the oscillograph deflections to the quantities being measured can be readily obtained. It is recommended that the instruments used and their transfer characteristics be stated when reporting the results of measurement.

Some other type of instrument (for example, a vacuum-tube voltmeter, elapsed time meter, calorimeter, etc.) may provide a more convenient or accurate means of measurement than an oscillograph. However, in order to avoid possible serious errors, it is usually necessary first to observe and measure the desired quantity with an oscillograph.

Many oscillographs have features that aid in presenting a stable picture of the pulse and provide amplitude and time scale calibrations. These are very helpful in pulse work and should be used whenever accurate measurements are desired.

2.2 Bandwidth and Phase Response

The accuracy of measurement of a pulse quantity depends on the bandwidth and phase response of the measuring instrument and any associated transducer. Accuracy is usually improved by increasing the upper frequency limit and decreasing the lower frequency limit. In order to determine a minimum required upper frequency limit, it is generally necessary to decide upon a minimum time resolution. If the required minimum time resolution is T_1, then the upper frequency limit (3db) of the measuring instrument should be approximately $1/(2T_1)$, to give a minimum acceptable degree of accuracy in measuring the pulse quantity. For example, if in a certain circuit the constants are such that disturbances less than 0.1 microsecond in duration will not influence the operation, the required upper frequency limit is 5 megacycles. In many applications the minimum time resolution is determined by the bandwidth of the circuits associated with the pulse to be observed. The time resolution may also be determined by the degree of detail of a pulse the observer requires. For example, a pulse with a sharp spike requires a measuring instrument having a shorter resolution time (higher frequency limit) than does a pulse with no such spike or one in which the pulse spike is to be ignored.

In order to determine the required lower frequency limit, it is necessary to decide upon a time interval of interest. If T_2 is the time interval of interest, then the lower frequency limit (3db) is K/T_2, where K is the maximum error (or fractional droop) that can be tolerated. For example, if a 1 per cent accuracy is required and the time interval of interest is 1,000 microseconds, then the lower frequency limit should be at least as low as 10 cycles per second.

For proper response the phase characteristic of the instrument should be such that the time of transmission of all significant frequency components is constant (in other words, linear phase shift with frequency).

2.3 Precautions

In pulse measurements, the precautions generally necessary in rf work may be required. These include attention to such matters as (a) adequate shielding of measuring equipment to prevent undesired coupling to other parts of the circuit; (b) detuning or loading effects caused by measuring equipment input admittance; (c) lead length which may introduce resonance effects; (d) proper terminations; (e) choice of components to function properly at the frequencies encountered (e.g., the use of noninductive resistors); (f) residual parameters in circuit elements (e.g., inductance present in capacitors); (g) proper physical location of ground leads; and (h) the nonlinear behavior of circuit elements.

2.4 Units

The units (volts, amperes, coulombs, seconds, etc.) should be specified in reporting the results of a measurement.

2.5 Operating Conditions

The equipment or circuits on which the pulse measurements are to be made should be in normal operating condition unless otherwise specified, but in any case the operating conditions should be stated.

3. Methods of Measurement

3.1 Average Absolute Pulse Amplitude

3.1.1 Definition (51 IRE 20. S1)

The average of the absolute value of the instantaneous amplitude taken over the pulse duration.

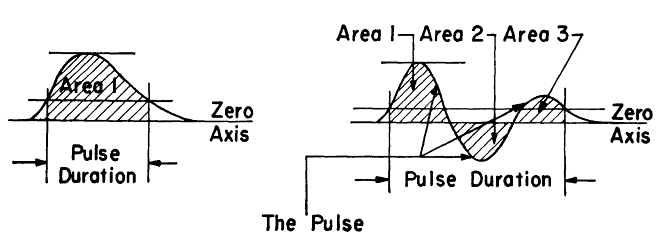
Note: By "absolute value" is meant the arithmetic value regardless of algebraic sign.

3.1.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse and mark the end points of the pulse duration on the picture. (*See* 3.11)
3. Determine the areas between the end points above and below the zero axis, taking into account any nonlinearity of scales.
4. Add the areas without regard to sign.
5. Divide the sum of the areas by the pulse duration to obtain the average absolute pulse amplitude.

3.1.3 Pictorial Examples

$$\text{Average Absolute Pulse Amplitude} = \frac{\text{Area 1} + \text{Area 2} + \text{Area 3}}{\text{Pulse Duration}}$$



3.2 Average Pulse Amplitude

3.2.1 Definition (51 IRE 20. S1)

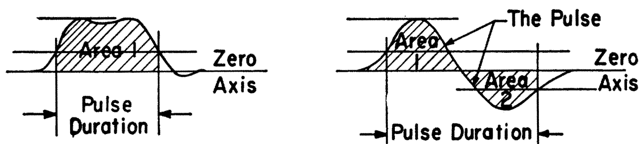
The average of the instantaneous amplitude taken over the pulse duration.

3.2.2 Method of Measurement

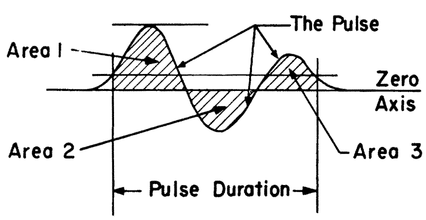
1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse and mark the end points of the pulse duration on the picture. (*See* 3.11)
3. Determine the areas between the end points above and below the zero axis taking into account any nonlinearity of scales.
4. Add the areas with regard to sign; that is, areas on opposite sides of the zero axis have opposite signs.
5. Divide the net area by the pulse duration to obtain the average pulse amplitude.

3.2.3 Pictorial Examples

$$\text{Average Pulse Amplitude} = \frac{\text{Area 1} - \text{Area 2}}{\text{Pulse Duration}}$$



$$\text{Average Pulse Amplitude} = \frac{\text{Area 1} - \text{Area 2} + \text{Area 3}}{\text{Pulse Duration}}$$



3.3 Crest Factor of a Pulse

3.3.1 Definition (51 IRE 20. S1)

The ratio of the peak pulse amplitude to the rms pulse amplitude.

3.3.2 Method of Measurement

1. Measure the peak pulse amplitude. (*See* 3.7)
2. Measure the rms (effective) pulse amplitude. (*See* 3.15)
3. Divide the peak pulse amplitude by the rms pulse amplitude to obtain the crest factor of the pulse.

3.4 Leading Edge Pulse Time

3.4.1 Definition (51 IRE 20. S1)

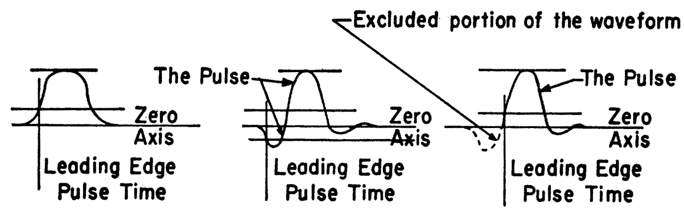
The time at which the instantaneous amplitude first reaches a stated fraction of the peak pulse amplitude.

3.4.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the peak pulse amplitude. (*See* 3.7)
4. Draw two lines parallel to the zero axis, spaced on each side of the zero axis by the stated fraction of the peak pulse amplitude. The time of the first point of intersection of the pulse trace and either line is the Leading Edge Pulse Time.

Note: The stated fraction may not correspond to that used in the measurement of Trailing Edge Pulse Time.

3.4.3 Pictorial Examples



3.5 Trailing Edge Pulse Time

3.5.1 Definition (51 IRE 20. S1)

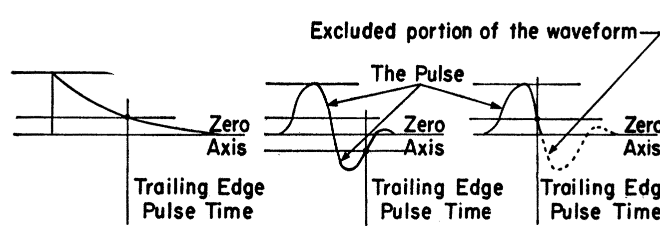
The time at which the instantaneous amplitude last reaches a stated fraction of the peak pulse amplitude.

3.5.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the peak pulse amplitude. (*See* 3.7)
4. Draw two lines parallel to the zero axis, spaced on each side of the zero axis by the stated fraction of the peak pulse amplitude. The time of the last point of intersection of the pulse trace and either line is the Trailing Edge Pulse Time.

Note: The stated fraction may not correspond to that used in the measurement of Leading Edge Pulse Time.

3.5.3 Pictorial Examples



3.6 Mean Pulse Time

3.6.1 Definition (51 IRE 20. S1)

The arithmetic mean of the Leading Edge Pulse Time and the Trailing Edge Pulse Time.

Note: For some purposes the importance of a pulse is that it exists (or is large enough) at a particular instant of time. For such applications the important quantity is the Mean Pulse Time. The Leading Edge Pulse Time and the Trailing Edge Pulse Time are significant primarily in that they may allow a certain tolerance in timing.

3.6.2 Method of Measurement

1. Measure the Leading Edge Pulse Time. (*See* 3.4)
2. Measure the Trailing Edge Pulse Time. (*See* 3.5)
3. Calculate the arithmetic mean of the Leading Edge Pulse Time and the Trailing Edge Pulse Time. The result is the Mean Pulse Time, which is midway between the Leading Edge Pulse Time and the Trailing Edge Pulse Time when the pulse is portrayed graphically.

3.7 Peak Pulse Amplitude

3.7.1 Definition (51 IRE 20. S1)

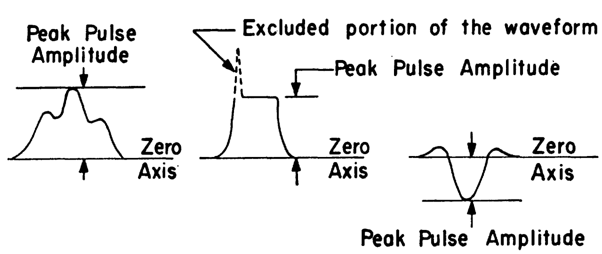
The maximum absolute peak value of the pulse, excluding those portions considered to be unwanted, such as spikes.

Note: Where such exclusions are made, pictorial illustration of the amplitude chosen is desirable.

3.7.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the maximum departure of the pulse trace from the zero axis (regardless of sign). This departure is the peak pulse amplitude.

3.7.3 Pictorial Examples



3.8 Pulse Spectrum (Pulse frequency spectrum)

3.8.1 Definition (51 IRE 20. S1)

The frequency distribution of the sinusoidal components of the pulse in relative amplitude and relative phase.

Note: The definition of this term was phrased to convey the idea that the spectrum is a complex (phasor) function of frequency and to express this function most nearly in a manner which corresponds to the method of measuring it (i.e., measuring amplitude and phase separately).

3.8.2 Method of Measurement

1. *Amplitude spectrum*

If only the amplitude spectrum is desired, and if the pulse can be repeated periodically to form a pulse train, the amplitude spectrum of the pulse train may be obtained with a spectrum analyzer using the method given under Pulse Train Spectrum. The envelope of the amplitude spectrum of the pulse train is the amplitude spectrum of the single pulse for positive frequencies.

Note: The pulse repetition period should be long in comparison with the pulse duration, so as to provide sufficient density of the spectrum lines to determine the envelope to the desired degree of accuracy.

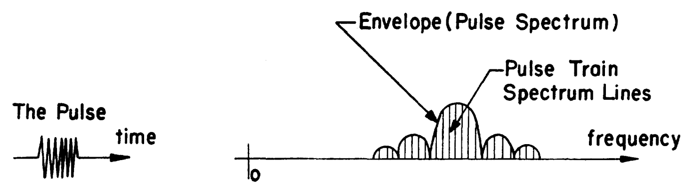
2. *Amplitude and phase spectrum*

a. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.

b. Obtain the Fourier transform of the waveform to obtain the amplitude and phase spectrum.

3.8.3 Pictorial Examples

Note: This example applies to Method 1 only.



3.9 Pulse Bandwidth

3.9.1 Definition (51 IRE 20. S1)

The smallest continuous frequency interval outside of which the amplitude of the spectrum does not exceed a prescribed fraction of the amplitude at a specified frequency.

Caution: This definition permits the amplitude of the spectrum to be less than the prescribed amplitude within the interval.

Note 1: Unless otherwise stated, the specified frequency is that at which the spectrum has its maximum amplitude.

Note 2: This term should really be "Pulse Spectrum Bandwidth," because it is the spectrum and not the pulse itself that has a bandwidth. However, usage has caused the contraction and for that reason the term has been accepted.

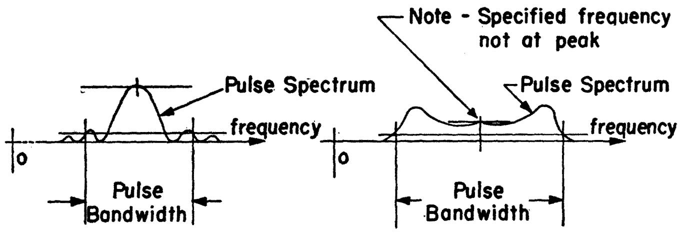
Note 3: Unless otherwise stated, only positive frequencies are to be considered.

3.9.2 Method of Measurement

1. Obtain a calibrated picture of the amplitude spectrum. (*See* 3.8)
2. Determine the amplitude at the specified frequency.
3. Draw a line parallel to the zero axis spaced from the zero axis by the prescribed fraction of the amplitude at the specified frequency.
4. The first and last points of intersection (consider only positive frequencies) of the spectrum trace and the line determine the frequency limits outside of which the amplitude of the spectrum does not exceed the pre-

scribed fraction. The difference between these two limits is the Pulse Bandwidth.

3.9.3 Pictorial Examples



3.10 Pulse Decay Time

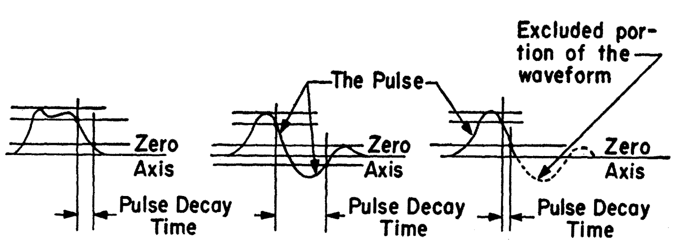
3.10.1 Definition (51 IRE 20. S1)

The interval between the instants at which the instantaneous amplitude last reaches specified upper and lower limits, namely, 90 per cent and 10 per cent of the peak pulse amplitude unless otherwise stated.

3.10.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the peak pulse amplitude. (*See* 3.7)
4. Draw two lines parallel to zero axis spaced on each side of zero axis by 90 per cent (or stated fraction) of peak pulse amplitude, and two parallel lines spaced on each side of zero axis by 10 per cent (or stated fraction) of peak pulse amplitude. Time interval between last point of intersection of pulse trace and either 90 per cent line and last point of intersection of pulse trace and either 10 per cent line is Pulse Decay Time.

3.10.3 Pictorial Examples



3.11 Pulse Duration

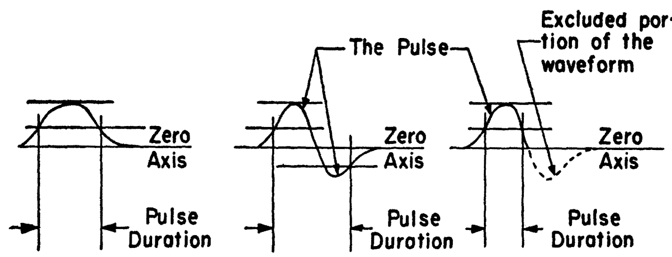
3.11.1 Definition (51 IRE 20. S1)

The time interval between the first and last instants at which the instanteous amplitude reaches a stated fraction of the peak pulse amplitude.

3.11.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the peak pulse amplitude. (*See* 3.7)
4. Draw two lines parallel to the zero axis, spaced on each side of the zero axis by the stated fraction of the peak pulse amplitude. The time interval between the first and last points of intersection of the pulse trace and either line is the Pulse Duration.

3.11.3 Pictorial Examples



3.12 Pulse Duty Factor

3.12.1 Definition (51 IRE 20. S1)

The ratio of the average pulse duration to the average pulse spacing.

Note 1: This is equivalent to the product of the average pulse duration and the pulse repetition rate.

Note 2: The terms "average pulse duration" and "average pulse spacing" imply a time interval over which the averaging takes place. In the method of measurement below, this time interval is called the time interval of interest.

Note 3: The above definition defines pulse duty factor basically as a ratio of time "on" to total time. This is not in agreement with the use of the term "duty factor" as a ratio of average to peak power, except in special cases, such as that of a rectangular pulse. Care should be taken not to confuse the two meanings of "duty factor" when dealing with unusual pulse shapes.

Note 4: If the Pulse Duty Factor desired is that of a sub-group within a complex train (for example, vertical sync. pulses in a TV signal, channel pulses in a time-division multiplex system, etc.), the particular subgroup must be specified.

3.12.2 Method of Measurement

1. Measure the pulse duration (*see* 3.11) of each individual pulse in the pulse train included in the time interval of interest.
2. Divide the sum of the pulse durations by the time interval to obtain the pulse duty factor.

3.13 Average Pulse Duration

3.13.1 Definition

The average, over the time interval of interest, of the durations of the individual pulses of a pulse train.

3.13.2 Method of Measurement

1. Decide on the time interval of interest.
2. Measure the pulse duration (*see* 3.11) of each pulse in this time interval.
3. Find the average pulse duration by dividing the sum of the individual pulse durations by the number of pulses in the time interval of interest.

3.14 Pulse Rise Time

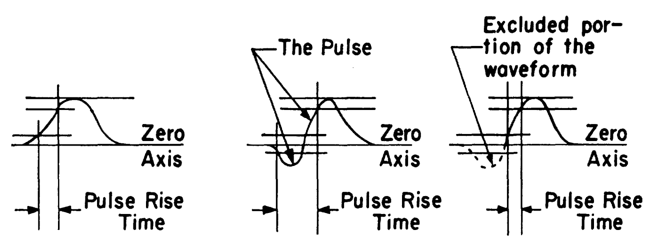
3.14.1 Definition (51 IRE 20. S1)

The interval between the instants at which the instantaneous amplitude first reaches specified lower and upper limits, namely, 10 per cent and 90 per cent of the peak pulse amplitude unless otherwise stated.

3.14.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse.
3. Find the peak pulse amplitude. (*See* 3.7)
4. Draw two lines parallel to the zero axis and spaced on each side of the zero axis by 90 per cent (or stated fraction) of the peak pulse amplitude, and two parallel lines spaced on each side of the zero axis by 10 per cent (or stated fraction) of the peak pulse amplitude. The time interval between the first point of intersection of the pulse trace and either 10 per cent line and the first point of intersection of the pulse trace and either 90 per cent line is the Pulse Rise Time.

3.14.3 Pictorial Examples



3.15 RMS Pulse Amplitude

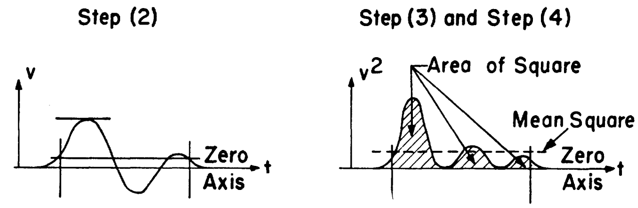
3.15.1 Definition (51 IRE 20. S1)

The square root of the average, over the pulse duration, of the square of the instantaneous amplitude.

3.15.2 Method of Measurement

1. Obtain a calibrated (time and amplitude) picture of the waveform including the pulse. Delineate the pulse by excluding those portions of the waveform determined to be nonpertinent.
2. Draw the zero axis of the pulse and mark the end points of the pulse duration on the picture. (*See* 3.11)
3. Plot the square of the instantaneous amplitude between the end points and measure the enclosed area.
4. Divide the area by the pulse duration to obtain the mean-square amplitude.
5. Take the square root to obtain the RMS Pulse Amplitude.

3.15.3 Pictorial Examples



3.16 Average Pulse Repetition Rate

3.16.1 Definition

The number of pulses in the time interval of interest divided by that time interval.

Note 1: The time interval of interest must be clearly understood or stated, since it affects the results of measurement in many cases.

Note 2: If the Average Pulse Repetition Rate desired is that of a subgroup within a complex train (for example, vertical sync. pulses in a TV signal, channel pulses in a time-division multiplex system (etc.) the particular subgroup must be specified.

3.16.2 Method of Measurement

1. Decide upon the time interval of interest.

Note: A picture of the pulses may be needed in order to decide upon this time interval.

2. Determine the number of pulses in the time interval.

Note: There are instruments that may be used to count the number of pulses automatically, such as a gated counter. It may also be possible to determine the number of pulses by comparison with an oscillator generating a known number of cycles or pulses during the time interval.

3. Divide the number of pulses by the time interval to obtain the Average Pulse Repetition Rate.

3.17 Pulse Spacing (Pulse Interval)

3.17.1 Definition

The interval between the corresponding pulse times of two pulses.

Note 1: The two pulses should be clearly specified, whether consecutive or not. The particular pulse time used should be stated.

Note 2: The term "pulse interval" is deprecated because it may be taken to mean the duration of the pulse. Neither term means the space between pulses (Pulse Separation).

3.17.2 Method of Measurement

1. Measure the pulse times of the pulses.
2. The difference in time of the corresponding pulse times is the Pulse Spacing.

3.17.3 Pictorial Examples