Section 7 - Measurement of Transient Pressure Pulses

Special problems are encountered in transient pressure pulse measurement, which place stringent requirements on the measuring system. Some of these problems are:

> High levels.
> Wide frequency content of pulses.
> Transient characteristics of instrumentation.

As a result, each part of the instrumentation system should be evaluated and selected for:

> Adequate linear dynamic range (including safety factor).
> Adequate linear frequency response over a wide range.
> Ability to respond to transient inputs.
> Negligible phase-shift errors over the frequency range of interest.

Kulite pressure transducers provide a unique combination of high performance in all of these critical characteristics.

7.1. Dynamic Range

The transducer should be selected for its ability to meet the linear dynamic range required. All Kulite transducers are rated for both linear dynamic range and for burst pressure (maximum static input without damage). Care should be taken that the signal output does not overload the associated electronics.

For a transducer of known sensitivity and a given pressure input, the signal which the amplifier must handle can be computed. The gain of the related amplifier must be constant over the entire dynamic range of the input pressure and be adequate to provide full-scale output for the expected input.

7.2. Low Frequency Response

Inadequate low frequency response in the measurement system will result in failure to accurately reproduce the transient pulse. Piezoresistive transducers respond to steady-state or zero static pressure. When they are connected to dc amplifiers or dc readout instruments, there is no limit to the duration of a pulse they can measure.

In some applications, where true steady-state measurements are not required, and where low frequency drift may be a problem, ac coupling can be used.

When ac amplifiers or other equipment with limited low frequency response are connected in a system, the pulse wave shape will not be maintained. The nature of this inaccuracy can be seen by examining the effect on a rectangular pulse of duration T and amplitude A applied to the input of a signal conditioner which does not respond to dc (steady state) signals.

If this transient is passed through an ac system with first-order low frequency response, the resultant output will be as shown in Figure 7-1.

A first-order system has the same low frequency response as a single resistor-capacitor high-pass filter whose time constant in seconds is equal to RC (ohms x farads). Such a system exhibits a low frequency cutoff equal to 1/ 2π RC and is 5% down at a frequency of 3/ 2π RC. A critically damped mechanical system has a first-order response.

$$a = Ae^{-\frac{t}{RC}}$$

$$(7.1)$$

The output does not remain at the peak value for the full pulse duration, but decays exponentially, "droop." The output amplitude at any time, t, (during the pulse) can be expressed as:

where RC is the system time constant. At the termination of the pulse, the output does not return to zero, but overshoots in a negative direction. Recovery from this "undershoot" occurs at the same exponential rate as droop.
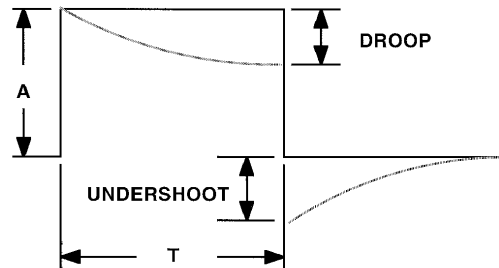

Figure 7-1: Response of System With First Order LF Response to a Rectangular Pulse

The ratio of total pulse height to droop is a function of the ratio RC/T. The larger this ratio, the less error (and the less undershoot). For example, if this ratio is 20, there will be approximately 5% error in the rectangular pulse amplitude; if the ratio is 50, there will be only a 2% error.

Although slightly more complex to analyse, it can be shown that similar low frequency effects occur for other pulse shapes. If the requirement for adequate RC/T is not satisfied, it is possible to predict the degree of error for these pulses and apply appropriate correction factors to the data obtained.

7.3. High Frequency Response

Consider again a rectangular pulse of duration T and amplitude A. If this transient is passed through a system with first-order high frequency response (corresponding to a single RC low-pass filter combination), the resultant output will be as shown as shown in Figure 7-2. The effect of the high-frequency rolloff is to slow the rise and fall time of the pulse, thus rounding both the leading and trailing edges.
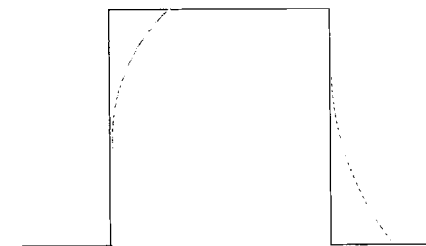

Figure 7-2: Response of System with First Order HF Response to a Rectangular Pulse

It is also of interest to note the effect of passing the rectangular pulse through a system possessing second-order high frequency response (Such a system corresponds to the electrical frequency response of a single LC low-pass filter combination, or a damped mechanical system). Figure 7-3 shows the resulting output, A high-frequency ringing at approximately the resonance frequency is superimposed on the pulse. The amplitude and duration of the ringing depends on the damping factor.

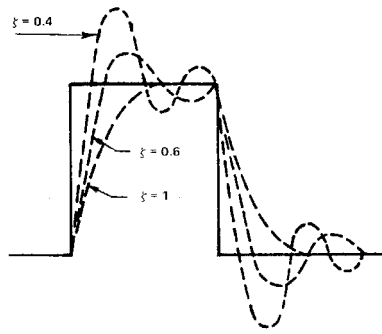**kulite** Semiconductor Products, Inc.

Figure 7-3: Response of System with Second Order HF Response to a Rectangular Pulse

Fourier analysis show that short transients ,contain significant high-frequency components. Faster rise-time transients contain higher frequency components. Both the transducer and associated systems must have adequate high frequency response to avoid undesirable measurement distortion.

Although the diaphragm is actually a higher-order structure with multiple high-frequency modes, the high frequency response of a piezoresistive transducer with very little damping is approximately a second-order function and is determined by the transducer fundamental (first) modal resonance frequency. The use of such devices provides desirable high frequency response along with minimum phase shift in the frequency range of interest.

Transients, however, may excite such a transducer's first mode to resonance; natural frequency "ringing" will then be superimposed on the basic input transient.

In the case of short, rectangular or other transients with essentially zero rise time (very short rise time in proportion to the natural period of the transducer), almost 100% overshoot on the transient may occur along with subsequent excitation of transducer natural frequency. To minimise or prevent these distortions, the transducer should have a natural period (the reciprocal of the natural frequency) one-third the expected rise time or less.

Resonance frequencies should be as shown in the following table in order that the natural period be one-fifth the pulse duration for undamped transducers measuring half-sine or sawtooth transients:

Required Pulse Width (microseconds)	Required Natural Period (microseconds)	Resonant Frequency (Hertz)
500	100	10,000
200	40	25,000
150	30	33,000
100	20	50,000
75	15	67,000
50	10	100,000

If the matching amplifier possesses high frequency response flat. to at least one-half the pressure transducer resonance frequency, no appreciable error will be introduced by amplifier rolloff characteristics.

The most common types of readout devices are: (1) Oscilloscope, (2) Computer based dynamic data capture devices. The storage oscilloscope is probably the most versatile and easy to use. A good quality scope will have a response from dc to above a gigahertz so that it will not introduce significant errors.

7.4. Phase Shift

Faithful reproduction of transients requires that the measurement system be free of phase distortion. As we have seen, undamped Kulite pressure transducers exhibit 0° phase shift over their useful frequency range, and thus are not a source of this type of error. Matching amplifiers should be chosen for acceptable phase characteristics. Recording galvanometers, when properly damped, exhibit linear phase shift over their usable frequency range. Other readout devices do not, in general, introduce phase distortion.

If a virtually undamped transducer is subjected to a transient which excites its resonance frequency, the magnitude of the output does bear a fixed relationship to the mechanical input. This relationship, however, is so sharply dependent upon the input pulse duration and rise time that the output signal is rarely of practical value. It is usually possible to select a transducer with a high enough natural frequency that it will not resonate for a given transient input.

In some cases, when rise times are extremely short, it may become necessary to resort to electrical filtering. The data in the pass band of a low-pass filter will have quantitative value, even if the transducer is resonating, as long as the filter has a linear phase-shift characteristic (constant delay). When filtering is used in the measuring system, the actual and recorded transients may differ widely. For this reason, it is strongly recommended that the unfiltered response from the transducer be recorded, as well as the filtered signal. The introduction of filtering into the measurement chain can cause phase shifting of the data.

In many transient measurement applications, only certain frequencies (within the Fourier spectrum of a pulse) are of interest. Unwanted noises or system transients of one kind or another must be eliminated. In these cases filtering is introduced in the system to allow only the desired frequencies to pass. Even though the filter passes the desired components without attenuation, the phase relation of a signal at one frequency with respect to a signal at another may be changed; this causes an error in the composite wave shape. To minimise this, the filter should be designed to have a constant time delay within its passband. In this way the phase relation between the frequency components of a transient is maintained and only a time shift of the entire composite wave shape will occur.

7.5. Special Considerations For Air Blast Measurements

To determine the effects from explosive detonations, pressure measurements are taken of the airblasts. Four important pressure measurements are associated with this: (1) static overpressure, (2) reflected overpressure, (3) total pressure, and (4) impact, or dynamic pressure. Each measurement requires different techniques, however, all have similar peculiarities because of the measurement environment. As an example, Figure 7-4 below shows a pressure measurement record from a typical air blast.
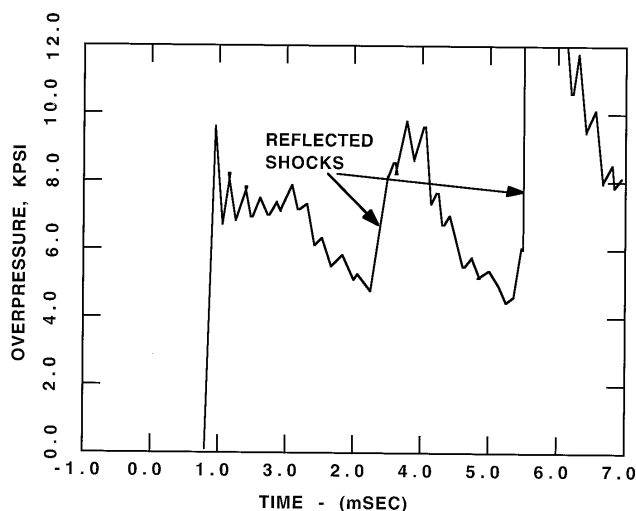

Figure 7-4: Pressure Transducer Response to an Air Blast

kulite Semiconductor Products, Inc.

In essence, air blasts involve shock waves. A shock wave is defined as a pressure wave characterised by a very steep, almost discontinuous, rise in pressure which occurs when a region of high pressure overtakes a region of low pressure, with a consequent rapid compression of the medium. The duration of a shock wave is distinguished by two phases. First, there is the positive (or compression) phase during which the pressure rises very sharply to a value that is higher than ambient and then decreases rapidly to the ambient pressure. The positive phase for the dynamic pressure is somewhat longer than for overpressure, due to the momentum of the moving air behind the shock front. The duration of the positive phase increases and the maximum (peak) pressure decreases with increasing distance from an explosion of given energy yield. In the second phase, the negative (or suction) phase, the pressure falls below ambient and then returns to the ambient value. The duration of the negative phase is approximately constant throughout the blast wave history and may be several times the duration of the positive phase. Deviations from ambient pressure during the negative phase are never large, and they decrease with increasing distance from the explosion.

A transducer that is exposed to a step pressure change will be excited at its resonance frequency if the rate of pressure rise is sufficiently fast. The rise time for a shock wave will vary, depending upon the blast source and intensity, distance from source and gas dynamic properties of the shocked medium. Nonetheless, rise times can sometimes be less than a microsecond. Damped oscillations will show up on the output of virtually any air blast pressure measurement that is not overdamped since very few (if any) sensing elements have natural frequencies that would not be excited

by high frequency energy in the shock wave. Many Kulite pressure transducers have natural frequencies of 500 kHz or higher.

Referring to the example above, this ringing response is clearly evident in the initial response of the transducer. Sources of this oscillation may be mechanical resonance of the transducer sensing element, acoustical resonance of ports and cavities, or aerodynamic oscillations in the flow set up by diffraction of the initial and succeeding shocks and rarefaction waves over the probe.

Three major problems are common to all pressure measurements in the extreme close-in region to air blasts: (1) survival of the gage and cabling, (2) thermal isolation of the sensor, and (3) minimising effects of mechanical shock motion on the transducer. Survival needs include protection from small, and even large, particles which are moving at high speed towards the pressure transducer. To provide the high frequency response, the transducer must be coupled to the pressure in close-to-flush mounted configuration, but the diaphragm :must also be protected from high speed particles. This is sometimes accomplished by using a mechanical screen or baffle (a plate with offset holes in front of the diaphragm). Thermal protection of the diaphragm is also required for a short time period. Carbon-filled vacuum grease is often placed in front of pressure transducer diaphragms to accomplish this. Mechanical shock motion can be at thousands of g'S. To minimise errors, acceleration sensitivity of the transducer must be low along with a high resonance frequency.

7.5.1. Rise and Response Times
Pressure transducers provide the user with the capability of monitoring extremely rapid rise time pressure pulses. The rise time of the transducer is much faster than the period to which it will respond accurately.

7.5.2. Spatial Averaging of Pressure Across Diaphragms
Static overpressure is the pressure a fluid exerts normal to the surface along which it flows. The stagnation pressure is the sum of the static overpressure and the pressure attributable to the kinetic energy of the flowing fluid. Measurement of the stagnation pressure usually involves orienting the diaphragm of the pressure transducer normal to the direction of fluid flow. The dynamic model historically presented to describe a flush-mounted circular diaphragm pressure transducer measuring stagnation pressure is that of a spring-mass-damper system mathematically represented by an ordinary linear second-order differential equation possessing constant coefficients.

In reality, diaphragms of the type being discussed typically deflect in accordance with theory applicable to rectangular plates. This theory does not predict only one natural frequency, but an infinite number of natural frequencies for the various plate vibration modes.

Practically, only a finite number of plate natural frequencies are of importance due to damping in the plate structural material.

When a pressure transducer is flush-mounted, if static overpressure measurements are for a travelling pressure wave, the spatial averaging effect of the transducer diaphragm can result in a dynamic response model different from that represented by just the mechanical system. This can be visualised by referring to Figure 7-5 below. At high frequency the wave lengths of an acoustic pressure wave become quite short. For example, given a sound speed in air of 300 m/s and a frequency of 10,000 Hz, the corresponding wave length is 0.033 m (or 1.3 inch). To prevent extreme pressure averaging one can see that the diameter of the pressure sensor should be many times less than the wave length.
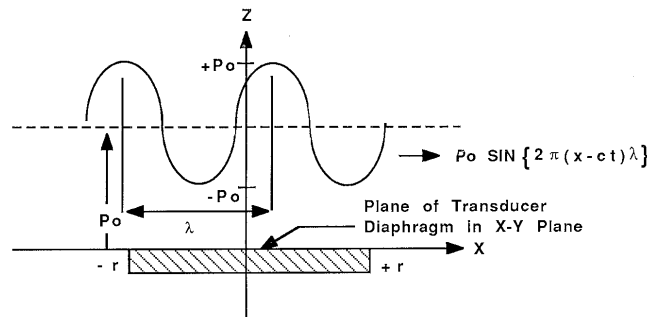

Figure 7-5: Pressure Wave Averaging Over Pressure Transducer

Calculations have been completed which permit estimates of the averaging effect. Figure 7.7 shows this transfer function, The abscissa of Figure 7-6 must be multiplied by the velocity of propagation of the pressure wave traversing the diaphragm of the transducer to dimensionally change its scale factor to Hz. When using this for the above example, the averaging results in a -5% error. for a transducer diameter of about 0.13 in.
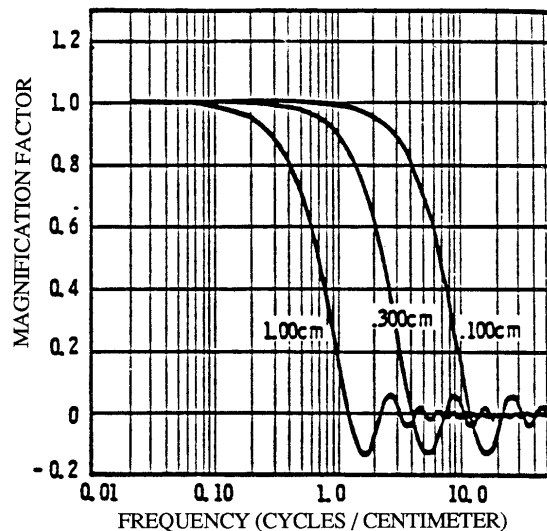

Figure 7-6: Transfer Functions when Analysed as Spatial Averaging Transducers

7.5.3. Mechanical Protection

⊕**kulite** Semiconductor Products, Inc.

In addition to protecting the diaphragm from flash and from particle impingement, the transducer case and cable must be protected from physical damage. This is best done by proper precautions in mounting and cable routing. The design of the mounting structure should allow for its dynamic mechanical response to the shock wave.

Mounting threads should be fully engaged, but contact with the relieved area at the front of the transducer should be avoided. Installation torque recommendations should be observed as well as recommended specifications for mounting hole dimensions and perpendicularity. Only the 0-rings or crushwashers provided or recommended by Kulite should be used for sealing.

The cable should be restrained to prevent whipping and flexing. Cable tension should be avoided by providing strain relief cable routing and/or clamping. The cable should also be protected from crushing. Where the cable might be subjected to high pressure pulses or shock waves, it should be protected in a rigid conduit.