



Instrumentation techniques for the measurement of gunfire

Anthony Nash¹
Charles Salter Associates
130 Sutter Street, Suite 500
San Francisco, CA USA

ABSTRACT

The peak sound pressure from near-field small arms gunfire is commonly used when assessing a shooter's hearing damage risk. Close to a shooter's ear, the peak sound pressure level from a rifle or pistol can be 155-to-160 decibels with a pulse rise time on the order of ten microseconds. Standard dosimeters equipped with conventional measurement microphones significantly under-report the true peak levels from proximate gunfire; hence, the shooter's exposure is either unknown or underestimated. The U.S. Military has established exposure limits for small arms gunfire; however, the specified properties of the measurement instrumentation are more prescriptive than performance-based. The implication is that the practitioner is responsible for pre-qualifying his or her own instrumentation. For near-field gunfire, the leading cause of measurement error occurs when the wide-band signal from the acoustical transient is transduced by a relatively large-diameter measurement microphone having limited bandwidth. Secondary measurement errors include the finite bandwidth of the microphone signal amplifier and its slewing limit, the characteristics of the anti-aliasing filter used, and the sampling rate of the digital recording device. The paper discusses these instrumentation constraints and recommends minimum performance requirements to help attain reproducible measurements of small arms gunfire.

1. INTRODUCTION

Transient noise generated by a small firearm involves very brief pulses having high peak sound pressures. Measuring gunfire pulses from pistols and rifles requires microphone systems having both an ultrasonic frequency response and a large-signal capability that are outside the specifications found in international standards governing sound level meters.

The U.S. Department of Defense (DOD) has promulgated regulations addressing hearing damage risk for military personnel; hence, the DOD has established both measuring and prediction protocols for a number of military weapon types (1).

The assessment of hearing damage risk from these impulsive weapons is based on evidence that the temporary threshold shift (TTS) of one's hearing acuity can be related to the permanent threshold shift (PTS). The TTS can be determined after a subject is exposed to a certain number of peak sound pressure levels exceeding 140 decibels. The peak SPL metric, therefore, has become the DOD basis for hearing damage risk assessments due to gunfire.

¹ tnash@salter-inc.com

2. GUNFIRE TRANSIENTS

The historical database of TTS assessments has led to a dose-response relationship based on an idealized time-domain model of a brief transient due to the discharge of a firearm. This idealized time-domain signature from a discharging weapon is called a Friedlander blast wave (see Figure 1) (2), (3).

With respect to the firing of a small-arms weapon, two distinct shock waves are generated by the discharge — the principal one is the supersonic release of expanding propellant gases as the projectile exits the barrel and the secondary shock wave is called the bow wave. The bow wave is attached to the supersonic projectile; hence, it precedes the blast wave (see Figure 2).

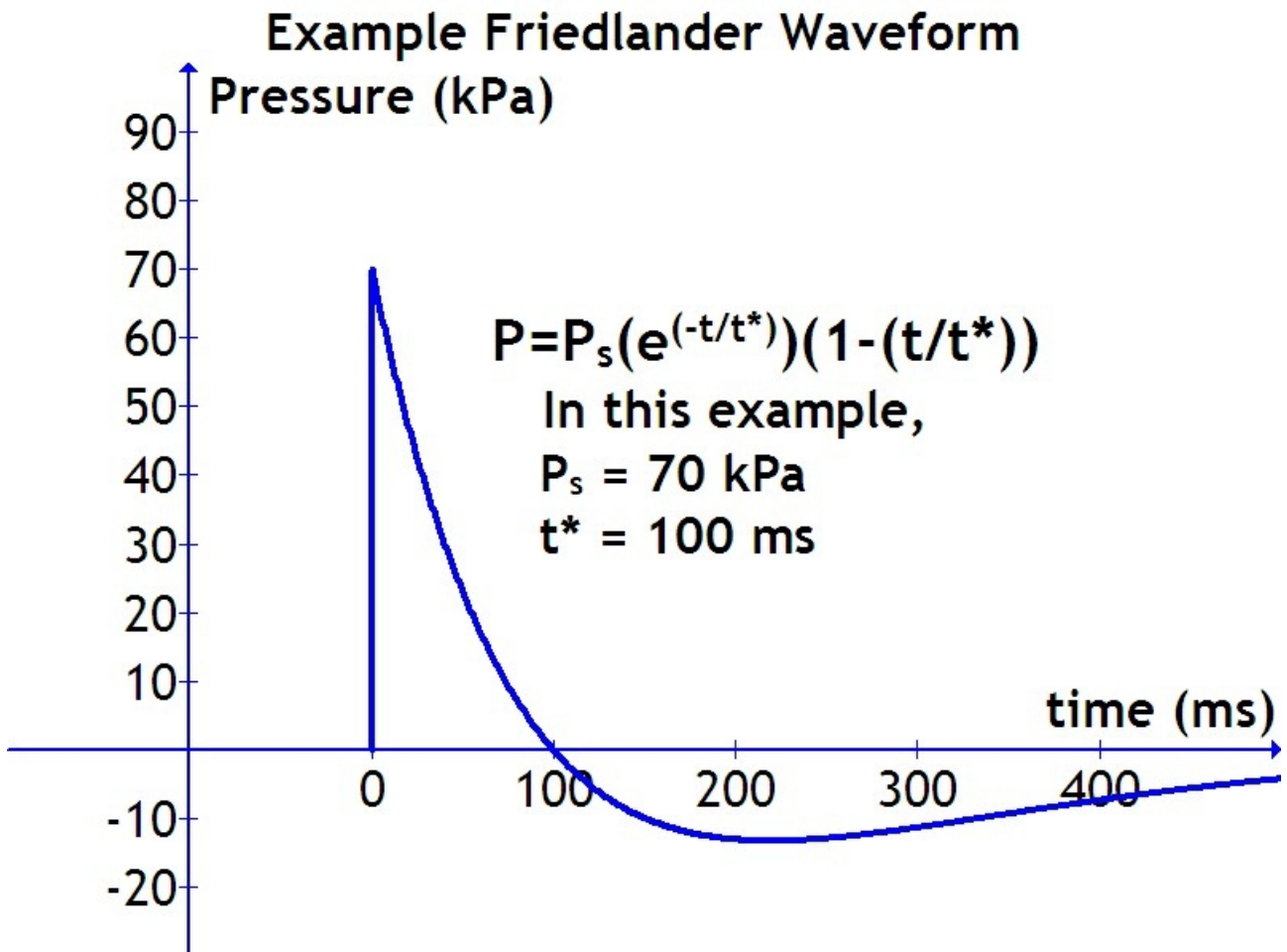
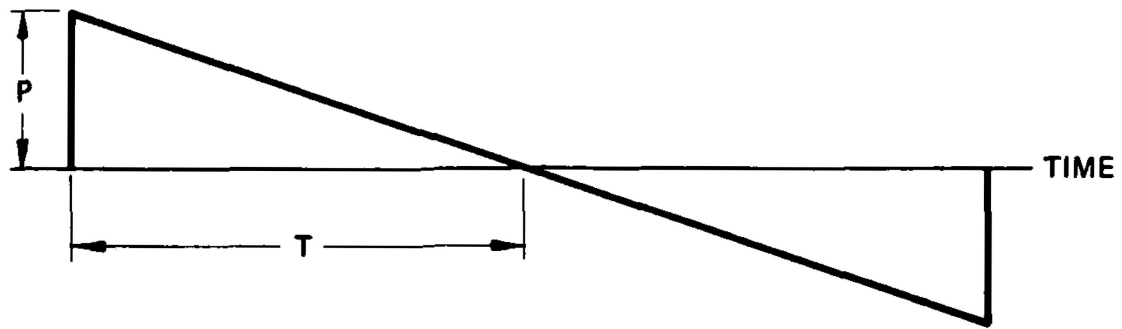
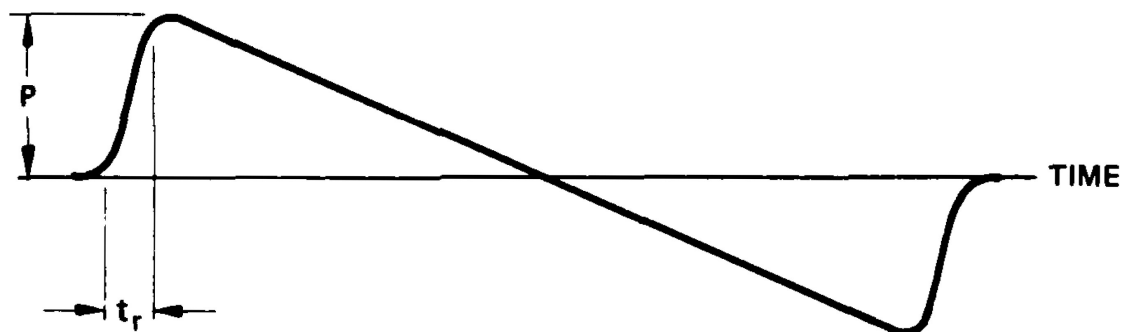


Figure 1: Graphical representation of an idealized Friedlander blast transient generated by propellant gases escaping the barrel. With respect to an acoustical measuring system, the steep rise of the leading shock wave at the onset of the transient is the most significant challenge for an acoustical measurement system (2), (3).

The bow shock wave that is attached to a supersonic projectile has symmetrical leading (“head”) and trailing (“foot”) edges that form an “N” shape as shown in Figure 2.



(a) IDEAL



(b) REAL

Figure 2: Time domain trace of a “N” wave generated by a supersonic projectile. The total duration of the transient is on the order of one millisecond. Close to the projectile, the rise and fall times (t_r) can be extremely fast (i.e., substantially less than 10 microseconds). Such sharp transitions require wideband acoustical measurement systems (5).

In theory, the rise time of a ballistic shock wave is nearly infinitesimal as pointed out by Garinther (see Figure 3) (6).

Orenstein has demonstrated, however, that the rise time increases as a function of distance from the source due to dissipation of high frequencies attributed to molecular relaxation (7). She explained that the measured rise time due to a spark discharge was about one microsecond when measured one meter away using a special microphone having an upper frequency limit of one megahertz. The rise time increased with increasing distance.

Bass measured “N” waves from a variety of weapons within a few meters of the muzzle. An example is shown in the right panel of Figure 3 (4),(7).

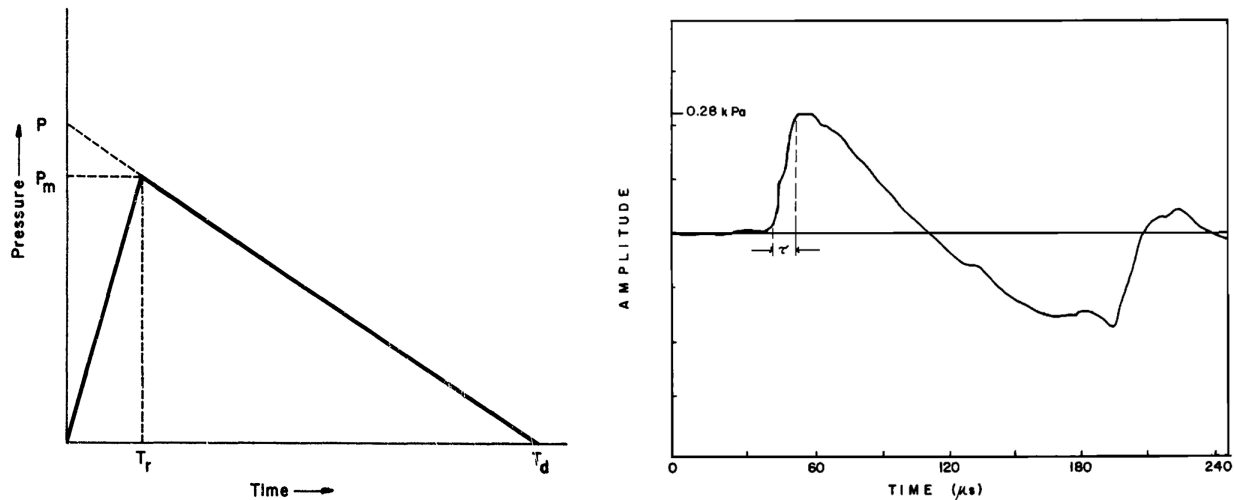


Figure 3: The left panel is an illustration from Garinther showing the first half of a hypothetical “N” wave having an infinitesimal rise time at Time = 0. The delay from 0 until T_r represents the finite rise time capability of the acoustical measurement system. P_m represents the measured peak sound pressure. Since his instrumentation had performance limitations, he proposed estimating the true peak of the “N” wave by extrapolating the assumed sloping trace back to $T = 0$.

The right panel is an “N” wave as measured by Bass two meters from a 30.06-caliber bullet fired from a rifle. The measured rise time of the waveform is ~ 10 microseconds and the peak sound pressure is 280 pascals (143 decibels sound pressure level). The bandwidth of the microphone pre-amplifier and the sampling frequency of the digital oscilloscope were both two megahertz. Bass used a microphone system similar to that of Orenstein.

Garinther, Beck, Stoughton, Rasmussen, and Routh also independently measured acoustical transients from several small-arm weapons using commercially-available condenser microphones and found that the characteristic of the acoustical transient depends on the azimuthal orientation of the microphone relative to the path of the projectile (8),(9),(10),(11),(12). For a microphone located forward of the muzzle and close to the trajectory path, a directional bow shock wave front is generated as the supersonic bullet travels past the microphone.

The initial shock wave is followed by a muzzle blast caused by propellant gases escaping from the end of the barrel as shown in Figure 4. Garinther reported that the subsequent muzzle blast generated a second supersonic wave front.

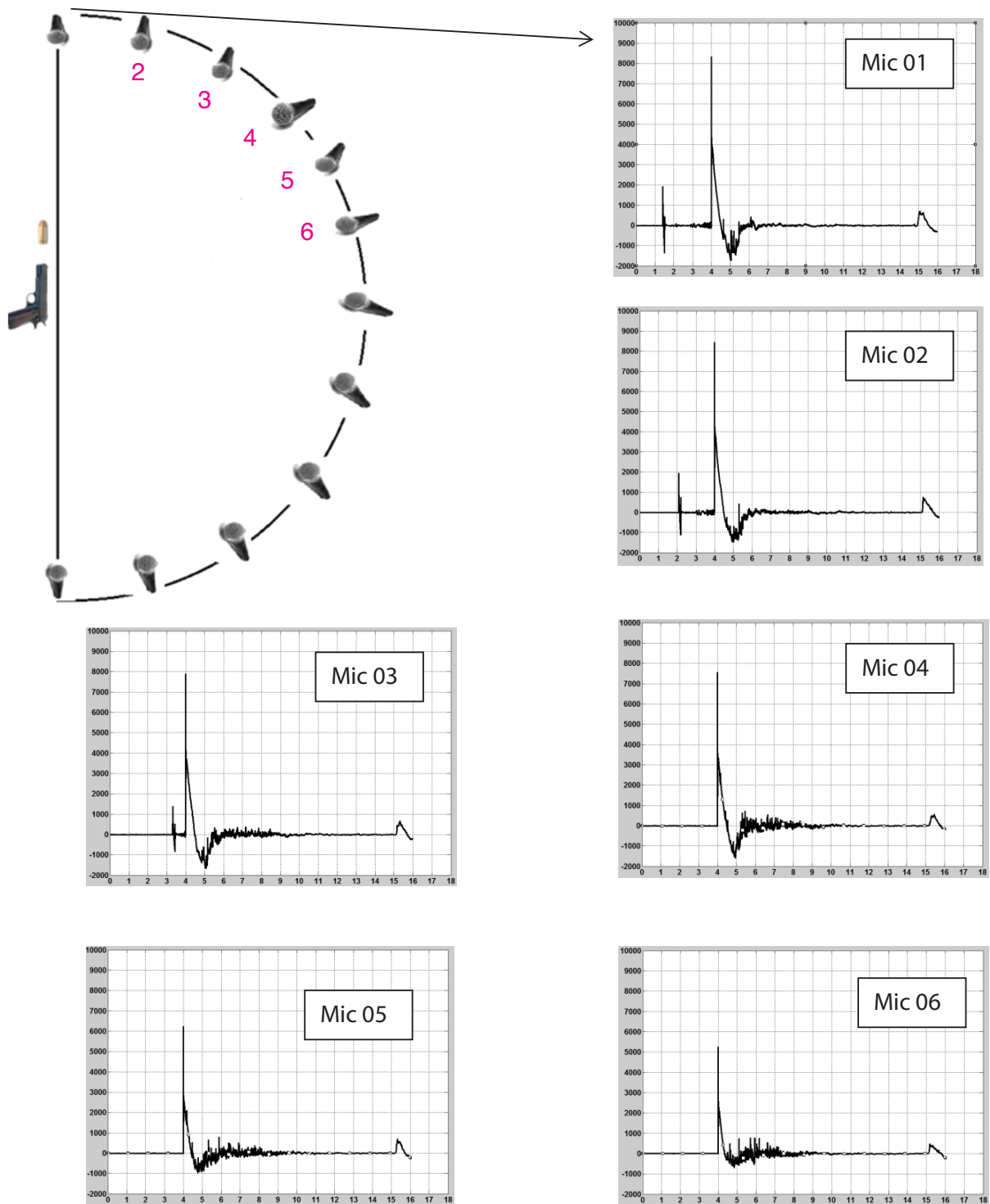


Figure 4: A gunfire acoustical event from an AR-15 type rifle measured by Routh at a constant radial distance of three meters (10). The abscissa axis is time in milliseconds and the ordinate axis is sound pressure expressed in pascals. Twelve microphones were elevated three meters above the ground and arrayed at various angles of azimuth from the bullet trajectory. The six microphones shown in this figure sensed peak sound pressures ranging from 6000 to 8500 pascals. At positions close to the muzzle, the bow shock wave precedes the blast shock wave. The total duration of the following muzzle blast transient is ~two milliseconds and its rise time is less than six microseconds (i.e., three time samples). The muzzle blast transient approximates a Friedlander waveform.

3. MICROPHONE SYSTEM CHARACTERISTICS

For contemporary measurements of small arms gunfire, it is common to employ a commercial 3-mm (1/8-inch) air condenser microphone (13). This type transducer is rated for an upper frequency limit of ~140 kHz and can accommodate a maximum sound pressure level of 174 decibels. For an externally-polarized microphone design, the rated polarization potential is typically 200 volts — this polarization potential provides a nominal open-circuit sensitivity of one millivolt per pascal (-60 decibels re: one volt per pascal). When exposed to a peak sound pressure level of 174 decibels, the open-circuit microphone signal would be 10 volts.

4. BANDWIDTH CONSIDERATIONS

Given the short rise time of the shock wave pressure signal, the requisite voltage slew rate of the microphone/pre-amplifier system should be at least 10 volts per microsecond and the rise time should be less than one microsecond. Based on oscilloscope theory, the pre-amplifier and associated signal-handling electronics would also need to have a bandwidth of at least 350 kilohertz, *viz*

$$BW \approx 0.35/T_r$$

where: BW is the bandwidth of the system
 T_r is the rise time from 10 to 90 percent of the final value

Such a bandwidth can be obtained at the output of a contemporary microphone pre-amplifier for small signals; however, the large-signal slew rate of the pre-amplifier *plus* the subsequent signal processing system need to be qualified for handling these ultrasonic signals.

5. PEAK CURRENT

Even if the pre-amplifier and its subsequent signal processing electronics both had the requisite slew rate and bandwidth, another component in the signal chain needs to be qualified as part of the measurement system — the microphone extension cable that is connected between the pre-amplifier and the remainder of the signal chain. The pre-amplifier must be able to furnish the initial current to rapidly charge the cable capacitance. Relatively high peak currents are necessary to avoid distorting the true microphone signal. In electrical engineering jargon, such distortions are referred to as “current limiting” and/or “slew-rate limiting”

For example, if the capacitance of a 10-meter-long pre-amplifier extension cable were 3000 picofarads (300 picofarads per meter), then the initial peak current demand would be the ratio of the pre-amplifier (unloaded) output voltage divided by the pre-amplifier output resistance. For a contemporary high-performance microphone pre-amplifier, the output resistance is typically 50 ohms; thus, during the initial portion of a 10-volt transient, the peak current demand would be 200 milliamperes. Such an output current is 100 times greater than the dynamic capability of most microphone pre-amplifiers that are typically rated for a peak output of ~two milliamperes.

After five RC time constants (i.e., 750 nanoseconds), the current demand would fall to 1.35 milliamperes —well within the capability of a microphone pre-amplifier operating at a high supply voltage. The pre-amplifier output, therefore, would be current-limited for at least four time constants (600 nanoseconds) after the initial onset of the transient signal.

6. RISE TIME CALCULATION FOR AN IDEAL PRE-AMPLIFIER

The rise time for an ideal pre-amplifier can be calculated presuming that 1) it has an infinite voltage slewing capability and, 2) can furnish the peak current necessary to properly charge the cable capacitance without “current limiting”.

Electrical theory can be used to predict the finite response to a suddenly-applied voltage step (14). The rise time of the circuit depends on the output resistance of the pre-amplifier and the lumped cable capacitance, *viz*

$$t_r \approx 2.2 R \times C_c$$

where: t_r is the time for the signal to increase from 10 to 90 percent of its final value
 $\ln(0.9/0.1) \approx 2.2$
 R is the output resistance of the pre-amplifier
 C_c is the cable capacitance (plus any stray capacitance at the input to the device receiving the pre-amplifier signal)

Given an output resistance (R) of 50 ohms and a cable capacitance (C_c) of 3000 picofarads, the calculated rise time (t_r) of an ideal pre-amplifier output signal would be 330 nanoseconds or one-third of a microsecond. The performance of this ideal microphone pre-amplifier is more than sufficient for transient signals sampled at one megahertz.

This simplified relationship neglects transmission line effects caused by distributed inductance in the cable. If a very long cable is involved, then transmission line theory would also need to be considered.

7. RISE TIME MEASUREMENTS OF MICROPHONE PRE-AMPLIFIERS

Rise times were measured for several contemporary microphone pre-amplifiers and signal conditioners (the signal conditioners are shown in Figure 5).

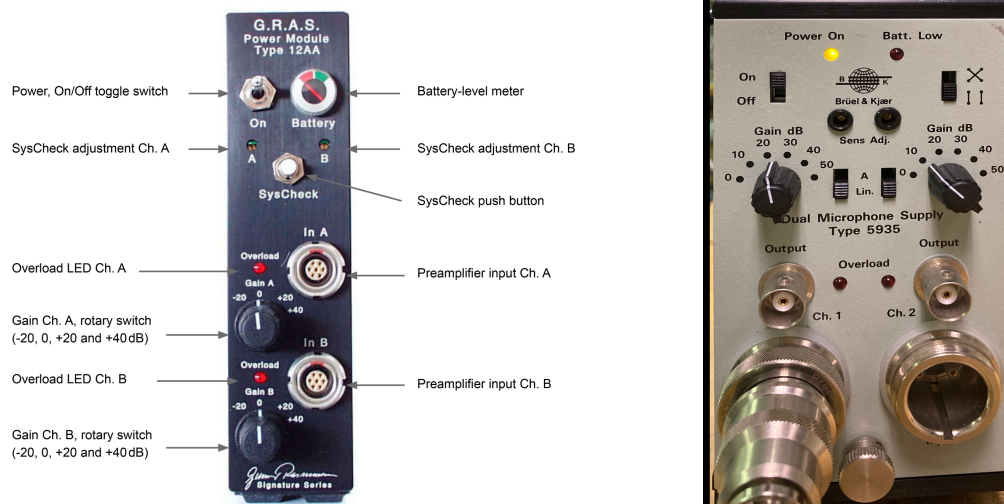


Figure 5: Images of two signal conditioners used in transient testing. A G.R.A.S. Type 12AA Power Module is shown on the left and a Brüel & Kjær Type 5935 Dual Microphone Supply is shown on the right. Since the stock B&K unit did not have sufficient bandwidth for extremely fast transients, it was temporarily modified using selected high-speed operational amplifiers. The measured performance of the *modified* B&K 5935 is similar to that of the *unmodified* G.R.A.S. 12AA; for brevity, the performance of the modified B&K 5935 is not discussed in this paper.

A function generator was used to generate repetitive bursts of a square wave at 350 kilohertz. The function generator had a rise time less than 50 nanoseconds.

The test signal was applied to the input of a G.R.A.S. Type 26AB microphone pre-amplifier via a three-picofarad series capacitor that represented the equivalent impedance of a 3-mm (1/8-inch) microphone. The pre-amplifier was connected to a G.R.A.S. Type 12AA Power Module having a bandwidth of 350 kHz (minus three decibels).

The pre-amplifier was arranged to drive a 30-meter extension cable connected to the G.R.A.S. Power Module set to +20 dB gain. Care was exercised to maintain a 50-ohm impedance in the cables and instrumentation to help prevent ringing due to stray inductance.

As a point of comparison, the Power Module was also tested directly without either a pre-amplifier or a microphone extension cable to help determine whether the pre-amplifier was slowing the rise time of the system. These rise-time data were displayed on the screen of an analog oscilloscope (see Figures 6 and 7).



Figure 6: Oscilloscope traces of square-wave signals introduced to a G.R.A.S. Type 26AB microphone pre-amplifier connected to the G.R.A.S. Power Module set to +20 and 0 dB gain, respectively. In both oscilloscope images, the left trace is the rising edge of the reference 350-kilohertz square-wave signal and the right trace is the corresponding output from the Power Module. The left image shows a 400-nanosecond rise time for an output signal of 2.4 volts peak-to-peak (50-ohm load). The right image shows a 700-nanosecond rise time for an output signal of 8.6 volts peak-to-peak (one-megohm load). The initial slew rates are 6 and 13 volts per microsecond, respectively. With respect to the left image, the initial 200-nanosecond delay for the output signal is caused by a 30-meter microphone extension cable that was temporarily inserted between the pre-amplifier and the Power Module.

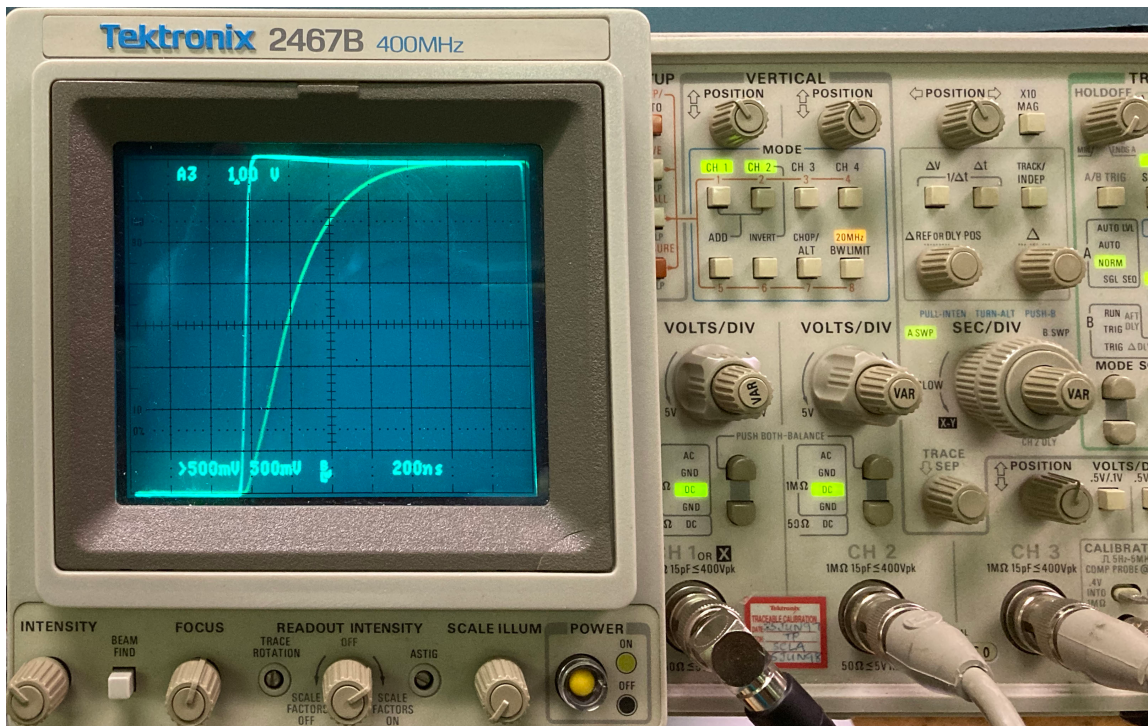


Figure 7: Oscilloscope trace of a square wave signal introduced directly to a G.R.A.S. Type 12AA Power Module set to “0 dB” gain (i.e., this test was performed without a pre-amplifier). The left trace is the edge of the reference 350-kilohertz square-wave signal (4 volts peak-to-peak). The right trace is the corresponding 4-volt peak-to-peak output signal from the 12AA (one megohm load). The right trace resembles the exponential rise of voltage across a capacitor being charged through a series resistor. The initial slope has a projected rise time of ~200 nanoseconds and a slew rate of 10 volts per microsecond.

8. REDUCING MICROPHONE SENSITIVITY

One obvious solution to the combined demand of peak current and slew-rate is to reduce the peak signal voltage from the microphone itself. Even though a reduced signal voltage helps avoid distortion due to current limiting, the microphone pre-amplifier would still need to be qualified for a bandwidth of 350 kilohertz.

If the peak voltage from the microphone were reduced from 10 volts to one volt for the same sound pressure transient, the slew rate of the signal could be reduced from 10 volts per microsecond to one volt per microsecond. The consequential peak current demand from the microphone pre-amplifier would, in turn, be reduced proportionately from 200 to 20 milliamperes — a value within the capability of certain high-performance pre-amplifiers.

There are two means for reducing the effective sensitivity of an air condenser microphone. One is to insert a capacitive attenuator to divide the dynamic voltage signal generated by the diaphragm’s displacement. Another technique is to reduce the external polarization voltage. The latter is better documented in the literature describing the characteristics of measurement microphones.

If the external polarization potential were reduced from the rated 200 volts to 28 volts, the expected decrease in sensitivity would be the ratio of the two voltages or ~17 decibels. For such a reduction, the sensitivity of a 3-mm (1/8-inch) air condenser microphone would decrease from one millivolt per pascal to 0.14 millivolts per pascal. A sound pressure transient of 10,000 pascals would generate 1.4 volts peak from the de-sensitized microphone. The lower peak voltage places less demand on the high-speed capabilities of the pre-amplifier and signal conditioner.

9. CONCLUSIONS

- 1) Measuring acoustical transients from proximate small arms gunfire is technically challenging (15)
- 2) The shock waves generated by gunfire require a measurement system frequency response above 300 kHz along with a rise time faster than 500 nanoseconds
- 3) The signal digitizing system should have a sampling rate above 500 kHz (one megahertz recommended)
- 4) The transients need to be conditioned by microphone pre-amplifiers and signal amplifiers operating within their voltage-slewing and rise-time limits at a specified amplifier gain and load configuration
- 5) Small-diameter, insensitive microphones should be used to help prevent both acoustical spatial aliasing across the diaphragm and/or time-domain electrical distortion in the subsequent signal processing system
- 6) The measuring, recording, and digitizing instrumentation all need to be acoustically and electrically qualified

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