# **Measuring Recreational Firearm Noise**

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Recreational use of firearms in the United States is commonplace. It is estimated that approximately one-third of households in the U.S. own firearms.<sup>1</sup> There are 28 million Americans who consider themselves hunters, and 13 million went hunting in 2000.<sup>2</sup> Participation in shooting sports without the use of properly worn hearing protection exposes participants to high levels of impulsive noise that may cause hearing loss or tinnitus (ringing in the ear). Firearms may cause permanent hearing loss even after a single or a few unprotected exposures. The present study was initiated to gain a better understanding of the noise exposure created by contemporary firearms using state-of-the-art instrumentation and to ultimately increase our knowledge and awareness of this unique noise hazard.

The sound created by recreational firearms used in hunting or target practice is characterized by a high-frequency, short-duration impulsive noise. This signal is perceived by the human ear as one single, loud impulse or "shot." However, when the firearm sound level is measured with microphones capable of sampling wide frequency ranges and combined with high-speed, data acquisition computer systems, the impulses can be resolved into a number of different acoustic signals related to different source mechanisms. The acoustic characteristics of firearm impulse noise put great demands on the instrumentation. Therefore, the transducers and the data acquisition system are critical, especially in terms of dynamic range, frequency response, slew rate and sampling rate, all of which need to be carefully considered.

This study focuses primarily on recreational firearms as a noise source and considers the acoustic interaction of the resulting sound field with the human head. It does not delve into the potential auditory damage experienced by an individual shooter or extend to discussions of specific auditory risk criteria.

## **Measurement Procedure**

**Microphone**. The typical signal from recreational firearms is a short impulse with an extremely brief rise time and a high crest factor. The peak level of the signal will depend on the physical distance from the firearm and the azimuth relative to the end of the barrel (muzzle). In general, levels of more than 140 dB SPL<sub>peak</sub> should be expected and may vary as a function of ammunition. Figure 1 illustrates the inverse relationship between maximum measurable sound pressure level and microphone sensitivity. It is apparent that a lower microphone sensitivity allows handling of greater sound pressure levels (SPLs). For the present measurements, a 1/8-inch microphone, Type 40DP, with sensitivity of 1 mV/Pa was selected, thereby providing a dynamic range (peak capability) of approximately 45-186 dB (3.5 mPa to 40,000 Pa).

In the frequency domain, the short acoustic impulse corresponds to a broadband signal with very high frequency content. So it is important that the microphone has enough bandwidth to capture the signal. It is also important that the transducer be small compared to the wavelength of the target sound at high frequencies. Since the diameter of the transducer becomes comparable to the wavelength, the microphone will start to change the sound field locally around the microphone. If the microphone is pointed toward the direction of propagation (0° incidence) of the sound field (see Figure 2), the presence of the microphone in the sound field will cause diffraction around the microphone and will result in an increased sound pressure gradient in front of the microphone.

The diffraction effects can be minimized by pointing the microphone perpendicular to the direction of sound propagation ( $90^{\circ}$  incidence), as shown in Figure 3. This orientation will not



Figure 1. Inverse relationship between microphone sensitivity and peak signal handling capacity.



Figure 2. Pressure increase in front of microphone caused by diffraction.



cause a pressure build-up in front of the microphone, since the sound wave will simply pass over the diaphragm unaltered. However, a 90° incidence placement will limit the useful frequency range of the microphone. As the wavelength becomes shorter at higher frequencies, different parts of the microphone diaphragm are subjected to different pressures. In the extreme

Figure 3. Signal cancellation when wavelength is equal to microphone diameter.

case where the diaphragm diameter equals the wavelength (see Figure 3), half of the diaphragm is subjected to negative pressure, and the other half to an equivalent positive pressure. This results in an average pressure over the total diaphragm surface of zero and, consequently, a microphone output signal of zero

In reality, the reduction of the output signal starts at lower frequencies than where the wavelength is equal to the diameter of the transducer. For the 1/8-inch microphone Type 40DP, the cut-off frequency is around 80 kHz.

**Preamplifier**. Preamplifier considerations included the ability to handle the output signal from the microphone without overloading, the slew rate limitation and the capacitive loading from cables connecting the preamplifier to the subsequent data acquisition system. For an excitation of 40,000 Pa at the microphone with a microphone sensitivity of 1 mV/Pa, the output signal from the microphone will be 40 V. This means that the preamplifier must be able to handle an input signal of at least 40 V; so the supply volt-



Figure 4. Measurement setup.



Figure 5. Impulse waveform at shooter's left ear location (shooter absent) for a .22 Hornet Winchester Model 43 rifle presented in the time domain.



Figure 6. Expanded view of early signal waveform from Figure 5 (.22 Hornet Winchester Model 43); early disturbance at t=-2 msec to t=-1.5 msec is the sound of the trigger pull, and the sound of powder combustion and bullet travel through the rifle structure is observed between t=-1 msec and t=1 msec.

age to the preamplifier should be no less than ±40V. In this case, a Type 26AC preamplifier was driven by a GRAS Type 12AA power module generating a ±60 V supply voltage enabling the preamplifier to handle signals up to ±60,000 Pa (189.5 dB SPL<sub>peak</sub>). The 12AA power module included 20 dB attenuation, so that the output signal from the preamplifier could be reduced as necessary to fit the dynamic range of the subsequent data acquisition system.

Data Acquisition System. A National Instruments PXI-6120



Figure 7. Time-domain waveforms of .22 Hornet Winchester Model 43 recorded from two microphone locations; blue tracing is from the shooter's head location ( $\approx$  154 dB SPL<sub>peak</sub>); red tracing is 250 mm behind the muzzle location ( $\approx$  166 dB SPL<sub>peak</sub>).

simultaneous sampling data acquisition board mounted in a fourslot PXI chassis was used for A/D conversion. This board allowed four data channels to be recorded with sampling rates up to 800 kHz with an analog trigger facility. The data were stored in a 64 MSample on-board data buffer that was set-up to record 50 msec of data before the trigger with a total data length of 0.5 sec. The data were sampled with 16-bit resolution, giving a 90-dB dynamic range. The data acquisition process was controlled by a custom LabView program with integrated calibration routines and trigger control. The data were post-processed afterward with National Instruments Diadem software.

### **Experimental Set-up**

A series of acoustic measurements were performed outside on a grass surface with no other major surfaces creating reflections within the period of interest. To test the firearm without the shooter present, the firearm was mounted in a test fixture and fired remotely, except when the shooter's head was present for the recording. The set-up shown in Figure 4 includes four channels of 1/8-inch microphones with ¼-inch preamplifiers with two Type 12AA power modules. Microphones were oriented at grazing incidence to the wave front.

## **Firing Process**

The firing of a recreational firearm like a rifle may be described by the following chain of events: the trigger is pulled and the firing pin hits the cartridge. This ignites the primer, which then ignites the powder. As the powder combusts and expands, the bullet is accelerated through the barrel until it exits the muzzle. The bullet will travel forward, usually at supersonic speed, producing a conical shock wave, often called a sonic boom, that expands backward from the bullet tip. In addition, a spherical blast wave centered on the muzzle will be produced at the moment the hot compressed gases are released. Finally, the gases containing combustion byproducts will produce turbulent airflow around and in front of the muzzle as it is carried forward by momentum and cools.

Figure 5 illustrates a typical time-based signal for a .22 Hornet Winchester Model 43 rifle with factory ammunition. The signal was recorded with a microphone at a position where a shooter would normally have his/her head but without a human actually present in the sound field.

The acoustic signal in Figure 5 is dominated by a peak of approximately 1000 Pa (~154 dB  $\text{SPL}_{\text{peak}}$ ) occurring at *t*=1 msec. Closer inspection of the signal reveals another signal 3 msec before this major peak, (Figure 6). It is apparent that the microphone at the head position starts to pick up an earlier signal, although at a much lower amplitude. This early signal is generated when the trigger is pulled. About 1 msec after triggering the firearm, the powder combusts and the noise burst is emitted directly from



Figure 8. Time-domain waveforms of .22 Hornet Winchester Model 43 recorded from four microphone locations; color corresponds to microphone location in relation to firearm; near muzzle, negative peak pressure travels slower than speed of sound, presumably due to cooling of propellant gases after they escape barrel.

the cartridge through the rifle structure to the microphone outside the firearm. Due to the attenuation of the signal by the rifle structure, the signal strength is relatively low, with peak values around 30 Pa or approximately 123 dB SPL<sub>peak</sub>. The noise generation then continues while the bullet travels through the barrel.

The barrel of the .22 Hornet Winchester has an effective length of 0.5 m. If the average bullet speed through the barrel is assumed to be around 700 m/sec, the bullet will exit the barrel approximately 0.7 msec after combustion. As the bullet exits the barrel, a pressure wave will follow the bullet and will be transmitted from the muzzle back to the microphone position. Initially, the pressure wave will travel faster than the speed of sound but this will quickly be reduced to a radiation velocity at the speed of sound. It will then take the sound wave approximately 1.4 msec to travel the 0.5 m distance from the muzzle back



Figure 9: Isolated time-domain waveforms for .22 Hornet Winchester Model 43, measured at two locations; initial N-shaped wave is the supersonic pressure wave (sonic boom) produced by the bullet; impulse that follows is shock wave caused by release of propellant gases; supersonic pressure wave interval suggests that bullet traveling 800 m/s; shock wave interval is consistent with speed of sound.



Figure 10. Time-domain waveforms as a function of microphone azimuth relative to axis of .22 Hornet Winchester Model 43 rifle.

to the microphone position. The 1.4 msec wave travel time plus the 0.7 msec bullet travel gives a total delay of 2.1 msec from the cartridge ignition until the blast wave from the muzzle is received by the microphone.

Inspection of the signal obtained near the muzzle (red curve in Figure 7) reveals a peak level much higher due to the closer proximity to the sound source. At the muzzle, the signal can also be broken down into a number of different peak signals. At the *t*=0 msec timing mark, a first peak at around 500 Pa (~148 dB SPL<sub>peak</sub>) is generated by the front of the bullet exiting the barrel. This peak is generated by the air compressed in front of the bullet as it travels through the barrel. When the rear of the bullet has exited the barrel, approximately 0.1 msec later, a second much higher peak of around 4000 Pa (166 dB SPL<sub>peak</sub>) is generated by the expanding hot gasses from the burning of the cartridge powder. Combining the time difference of the front and rear pressure pulses (0.1 msec) with the bullet exit speed (800 m/sec, see below) gives a distance between the pressure pulses of 80 mm. As the bullet itself is only 13.4 mm long, the pressure wave in front of the bullet can be estimated to be around 66 mm thick.

The peak generated by the expanding gases is repeated after about 0.8 msec. This secondary peak, at around 2000 Pa (160 dB  $\mathrm{SPL}_{\mathrm{peak}}$ ) is possibly caused by reflection of the first pressure pulse in the barrel. As the expanding pressure pulse in the barrel reaches the muzzle, the acoustical radiation impedance will change from the impedance in the narrow barrel tube to the free-field radiation impedance. This impedance change will generate a reflected wave travelling backwards into the barrel. As this reflected wave reaches the closed cartridge end of the barrel, the wave is again reflected forward within the barrel.



Figure 11. .22 Hornet Winchester Model 43 time-domain waveforms recorded at locations of the shooter's right and left ears (shooter absent).



Figure 12. .22 Hornet Winchester Model 43 time-domain waveforms recorded from microphone at locations of the shooter's right and left ears (shooter present).



Figure 13. Effect of A-weighted filtering applied to Winchester Model 43 time domain waveform.

This secondarily reflected wave will then reach the muzzle and again be radiated outward from the muzzle. Since the gas temperature in the barrel is much higher than outside the barrel, the speed of sound will be higher within the barrel than outside the barrel. Therefore, the reflected wave inside the barrel will travel faster than the normal speed of sound of 344 m/sec. Calculating backward from the time it takes the reflected pulse to travel back and forth in the barrel, and assuming the gas in the air as a first approximation to be an ideal gas, the temperature of the gas can be estimated to be around  $3000^{\circ}$  C.

The sound field in front of the rifle, parallel to the path of the bullet, was investigated with four microphones in positions as shown in Figure 8. The red curve, corresponding to the signal from the microphone closest to the muzzle is dominated by a high peak level at around 32,000 Pa (~184 dB SPL<sub>peak</sub>), followed by a longer, negative pressure wave of around 17,000 Pa. The initial positive pressure peak is transmitted from the first microphone position to the second microphone position, indicated by green, in approximately 0.3 msec The distance between the two microphone positions (100 mm) can be used to calculate the transmission speed for the peak. The result is approximately 340 m/sec, corresponding to the speed of sound.

However, the negative pressure peak is not transmitted at the speed of sound. It takes this pressure extreme 0.5 msec to travel the 100 mm from the red microphone position to the green position, corresponding to a speed of 200 m/sec. The transmission of the negative wave from the green position to the blue position, a distance of 200 mm, takes approximately 1.5 msec, corresponding to a mean velocity of 120 m/sec. The propagation speed of the negative wave is decreasing with the distance from the muzzle. This means that the negative pressure pulse is not a sound wave but a bulk movement of air. This can be explained as a volume of hot air being "blown" away from the muzzle and being decelerated by the resistance from the ambient air. As the hot air moves away from the muzzle, it is cooling down; therefore, the pressure constantly drops, resulting in a negative pressure.

At the microphone positions closest to the muzzle (corresponding to the red and green positions in Figure 8), the supersonic pressure wave generated by the bullet is buried in the initial blast from the expanding gases. Farther away, at the blue and pink microphone positions, the supersonic pressure wave generated by the bullet are clearly separated from the blast wave (see Figure 9).

The bullet pressure wave is visible at t=0.5 msec. This illustrates a typical N-profile of a supersonic boom. This waveform can be seen at t=1 msec, as the bullet passes the microphone position marked with pink. With a distance between the blue and the pink microphone positions of 400 mm and a time difference of 0.5 msec, the bullet speed can be calculated to 800 m/sec, or more than twice the speed of sound. Also, the blast wave following the bullet is slower, since it takes approximately 1.2 msec to travel from the blue to the pink microphone position, corresponding to a sound velocity of around 340 m/sec.

Comparing Figures 5 and 8 shows that the peak level of the blast wave is much higher in the forward direction than in the backward direction as expected. Figure 10 shows the directionality of the blast wave for seven different azimuths relative to the rifle axis.

Figure 10 also illustrates that the lowest sound levels are obtained to the rear of the muzzle where the shooter is typically positioned. Bystanders to the side of the shooter may actually be exposed to higher impulse levels than the shooter. Under normal conditions, persons should never be positioned in front of the muzzle for obvious safety reasons, so the high sound pressure levels generated in this direction may not be of primary concern. However, there are situations where hunting dogs are positioned in front of the hunter when shooting; it should be recognized that the dog is then subjected to much higher levels than what the hunter may personally experience.

As noted previously, the measurements presented up to this point were recorded without the head of the shooter present. When the head is introduced, the sound field around the head will be changed by diffraction and shadowing effects. Figure 11 illustrates the measurements recorded from two microphone positions where the shooters ears would normally be located, but without the head actually there. The peak levels at the two "ear" positions are almost equivalent, and the blast wave reaches the left position (marked with blue) slightly before the right (red) position due to the shorter distance from the muzzle.

Figure 12 replicates the measurements made in Figure 11, with the shooter's head now in the sound field. The pressure for the left "ear" position is increased due to diffraction around the head and closer proximity to the muzzle. At the right "ear" microphone position, the pressure is decreased due to head shadowing effects. The figure illustrates that the direct path from the muzzle to the right-hand side microphone position is blocked by the head and therefore also reduces the blast wave. So even if the right ear is physically closer to the stock of the firearm, it is the left ear that is exposed to the highest sound pressure level.

In the previous figures, the pressure impulses have been displayed as time domain signals with the full bandwidth as recorded by the microphones. Often such signals may be analyzed using A-weighting, exponential averaging or 1/3-octave filtering. This will change the measured acoustic characteristics of the gun shot impulse.

Figure 13 illustrates the effect of A-weighted filtering on the time-based signal. A-weighting reduces the frequency content in the original signal above 2 kHz; consequently, the peak level is reduced from approximately 4000 Pa (166 dB peak) to 2200 Pa (161 dB SPL<sub>peak</sub>), or a reduction of about 5 dB. At the same time, the finer details in the signal are lost.

Further analyzing the signal with exponential averaging of a sound level meter will also reduce the peak level and the pressure details of the signal. The amount of reduction will depend on the averaging time used in the measurement. With an exponential averaging in "fast" mode corresponding to 125 msec averaging time, the peak will be measured as 137 dB, and with an exponential averaging in "impulse" mode corresponding to 35 msec averaging time, the peak will be measured as 140 dB.

#### References

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