Acoustic pressure and flame generation determinations in case of mechanical and gas-dynamic processes for small caliber weapons

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Abstract: This paper presents results on the subject of the noise and flame generated by firing different weapons systems as part of determining safety measures for the weapons operators and specific safety distances for the involved personnel. Firing involves a series of mechanical and gas-dynamic processes sustained in a very short amount of time, some perceptible, some partially perceptible by humans, others not, therefore the use of high-speed camera and specialized software for assessments is required. Evaluations of the acoustic pressure produced by different small caliber weapons were achieved using Bruel & Kjaer microphone and sonometer placed at different distances of interest from the barrel. The A frequency curve, based on contour courves of constant strength, was used in order to display the results obtained as the standard values indicated by the sonometer would not be identical to the perception of sound by the human ear. Determinations to evaluate the flame at the muzzle were also conducted.

1. Introduction
The weapon, together with its ammunition, is a thermodynamic machine that fires a projectile to a target set to a normal (perpendicular) direction on it. During firing sessions, different effects may be generated depending on the weapon system used, the type of ammunition, the firing regime, the firing location, etc. These effects may manifest forms of aggression that can lead to bodily injury or even the loss of life, to the partial or total destruction of material goods [1, 2].

It is the purpose of this paper to determine and quantify the effects of acoustic pressure and flame at the muzzle generation for a set of small caliber weapon systems in terms of firing safety. The authors embraced the risks associated with the use of small caliber weapon systems in two categories:
- risks associated with firing with small caliber weapon systems occurring in the proximity of the shooter;
- risks associated with firing with small caliber weapon systems intervening on the projectile trajectory and on target impact area.
On the national legislation and the internal procedures of the Romanian national defense and security system, the risks associated with firing with small caliber weapon systems occurring in the proximity of the shooter are not taken into consideration [3].

2. General information

2.1. Regarding the acoustic pressure generated by the firing of weapon systems
The human beings perceive the sound and are able to characterize it, laying the foundation for communication and interpretation of extrinsic messages. Sound is defined as an acoustic overpressure that propagates through surface longitudinal waves that are captured by the ear and then analyzed and interpreted by the auditory system and the brain respectively [4].

The sounds are generated by the mechanical vibrations of the elastic medium and are propagated through a solid or fluid medium. The pressure measuring unit is the pascal (1 Pa = 10 μbar). Overpressure waves generated, in the event that the sound propagates through the air, will amplify the atmospheric pressure. The standard atmospheric pressure value is 100,000 Pa, and the peak pressure generated during the speech is 1 Pa at a distance of 1 m. Since the sound generator vibrates around an equilibrium position, the sound waves will have a sinusoidal evolution [4, 5].

Thus, they will be characterized by a period of oscillation, T (seconds, s), defined by the time at which a full oscillation is completed and by the frequency, \( \lambda = 1 / T \) (Hz, Hz), defined as the number of oscillations per second. The amplitude, defined as half of maximum elongation (the extreme movement from the equilibrium position) is shown as y in figure 1.

The frequency spectrum in the audible range is between 20 Hz and 20,000 Hz. Small frequencies correspond to low perceived sounds, and high frequencies correspond to high perceived sounds. The human ear disseminates the acoustic information in relation to the value of the pressure exerted. The minimum audience threshold is 0.00002 Pa, and the pain threshold is 20 Pa.

\[ L_p = 20 \log (p/p_0) \text{ [dB]} \] (1)

where \( p \) represents the measured acoustic pressure and \( p_0 \) is the reference sound pressure, generally the atmospheric pressure.

The usual values for the maximum sound pressure level for various sound generators are: 134 dB for an airplane, 94 dB for a car, 50 dB for a discussion, 30 dB for the fan of a running laptop [6]. For
several sound sources generating the same sound pressure level, the total sound level can be obtained from equation (2):

$$L_{\text{total}} = L_p + 10\log(n) \,[\text{dB}]$$

where $n$ represents the number of sound sources.

If the sound level of several emitting sound sources is different, then the total sound pressure level is given by equation (3):

$$L_{\text{total}} = 10 \log(10^{0.1L_1} + 10^{0.1L_2} + \ldots + 10^{0.1L_n}) \,[\text{dB}]$$

The human ear does not perceive the same acoustic intensity for the sounds emitted throughout the spectrum. The human auditory system measures the sounds depending on the frequency with which they are emitted. Thus, in order to quantify how sounds affect the human auditory organ, it is necessary to analyze both the sound pressure level and the emission frequency [5, 6].

From the need to facilitate acoustic interpretation, weighting curves are introduced to compensate for the variation in the perception of sound in relation to its frequency. Generally, to quantify noise exposure, the current standards use the A-scaled acoustic weight (as shown in figure 2) [5, 6].

Since the emitted sounds fluctuate over time, the sound pressure level with temporal integration is used to interpret noise exposure.

![Figure 2. A and C frequency weighting curves of the acoustic pressure.](image)

The continuous equivalent sound pressure level, $L_{eq}$, is the value of the variable sound pressure level in the considered unit of time. It can be interpreted as a mediation of the pressure values recorded over the time interval considered, as shown by equation (4):

$$L_{eq} = 10\log\left(\frac{1}{T_m} \int_0^{T_m} \frac{P^2(t)}{P_0^2} \, dt\right) \,[\text{dB}]$$

where $T_m$ represents the measurement time.

The noise exposure level $L_E$ is a measure of the influence of impulse noise over the time they occur, taking into account the time interval during which the acoustic measurements are performed.

The noise exposure level is obtained by the equation (5):
where $T_i$ represents the reference time in which impulsive noise occurs. Depending on the temporal evolution, the sounds can be divided into three categories: continuous sounds, intermittent sounds, and impulsive sounds.

Specific continuous sounds are emitted continuously at the same level of acoustic pressure and the same frequency spectrum. Intermittent sounds are characterized by a succession of phases of noise distributed over different spectral ranges.

Impulsive sounds are characterized by generating a high level of acoustic pressure within a short time span. The noises produced by firearms during use are mainly impulsive noises.

A conventional firearm operates according to a clearly established principle, the bases of which were laid down in the fourteenth century by the introduction and use of the first bombs and weapons in the army. Thus, in the cartridge-tube there are elements which ensure the propulsion of the bullet on its trajectory, the propelling charge and the percussion ignition cap, meant to initiate the explosive transformation (oxidation-reduction reaction) of the load [7].

The bullet throw process begins with the impact of the ignition cap. The ignition cap contains a primary explosive, sensitive to mechanical shocks. At the time of initiation, a shock wave that runs at speeds of up to 5000 m/s towards the launching load is generated. The explosive transformation suffered is deflagration [4, 7].

Deflagration is defined as a combustion that is maintained without the intake of oxygen from the atmosphere and for which the rate of propagation of the reaction in the unreacted material exceeds the local velocity of the sound. Following the deflagration of the load, a significant amount of gas is generated. Because the place where gas expansion occurs is limited to the inside of the cartridge tube, they will generate sufficient pressure on the back of the bullet and will imprint it on the impulse to initiate the movement in the barrel. Upon leaving the mouth of the barrel, the bullet reaches a speed of between 200 m/s and 450 m/s for conventional guns [4].

Taking into account that the normal sound velocity in the air is about 340 m/s and the fact that any overtaking of this velocity generates a sound known as "sonic boom" it can be said that the firing noise is produced by the following elements:

- detonation of the primary explosive;
- launching deflagration;
- overcoming the sound velocity by the bullet, where appropriate, and by the reaction between the gases when the bullet is exiting the mouth of the barrel;
- last but not least, the noise caused by the collision of the moving parts of the weapon during the firing action [4, 7].

2.2. Regarding the flame production at the firearm muzzle during firing

During the exit of the projectile from the barrel the effect of the gases formed by the deflagration of the load can be observed using the high speed camera.

The process of flame generation is described in the following. The chemical energy of the powder is transformed into mechanical motion of the projectile. The conversion of the powder into gas is not a perfect one, because the yield of explosive gases is a subunit number. Thus, combustion gases together with unreacted powder residues are dispersed into atmosphere when the projectile leaves the barrel [1, 8].

The residues, in contact with the atmospheric oxygen, ignite, forming the flame at the barrel. Given the fact that the temperature of these gases and the unreacted powder residues is high, contact with them can cause significant damage to personnel near the shooter.
Different stages of the flame propagation for the firing session with the 82 mm caliber mortar and the A.G.-9 are presented in figure 3. From the weapon systems tested these are the ones for which the flame generated at the barrel is the most visible.

The flame from the mouth of the barrel can be divided into several components:
- the red glow, visible as the projectile leaves the barrel, generated by the powder gas that drained beside the projectile on its movement inside the barrel;
- the main flame produced by the powder gases leaving the barrel behind the projectile;
- the intermediate flame, a reddish disc, result of overpressure waves exceeding the local sound speed, generated by projectile and the powder;
- the secondary flame generated by the mixing of the powder gases with the oxygen in the air;
- the sparks, occurring as a result of the reaction between the unburned powder and the atmospheric oxygen [3, 8].

![Figure 3. The flame generation and dispersion for the 82 mm caliber mortar and the A.G.-9 grenade launcher.](image)

3. Weapon systems tested

The following weapon systems were used for the determinations:
- the AKM assault rifle – the romanian model patterned after the AK-47, and chambered in the 7.62×39 mm cartridge [9];
- the 7.62×39 mm submachine gun, an automatic weapon using the same 7.62×39 mm ammunition [9];
- the 5.45×39 mm automatic shotgun, an individual automatic weapon for the infantry troops [9];
- the romanian 7.62×54R mm semi-automatic sniper rifle abbreviated PSL [9];
- the 7.62×54R mm machine gun, a Romanian machine gun produced under the Russian license of the PK machine gun [9];
- the Glock 17 9×19 mm caliber pistol [9];
- A.G.-40 grenade launcher, attached to the 5.45 mm 1986 automatic rifle using 40×47 mm grenades [9];
- the A.G.-7 grenade launcher, using 40 mm caliber missiles designed to handle armored targets at distances up to 200 m [9];
- the A.G.-9 grenade launcher, a 73 mm caliber non-recoil cannon intended for hunting armor targets up to 800 m. The reactive ammunition found in different configurations is being used, the most common being PG-9 [10];
- the 82 mm caliber mortar, a classic artillery piece designed to indirectly shoot explosive bombs on the opposing positions or to generate an auxiliary effect such as the illumination effect of a territory [11].

4. Flame generation determinations
A number of three tests were conducted for each type of weapon. On the firing direction, at the end of the gun barrel, a telescopic measuring ruler was mounted. Analyzing the images obtained by ultra-fast IDT X-Stream VISION XS-3 camera, the length of the flame at the mouth was determined. Using the data obtained for each firearm, a safety range can be calculated next considering the firing session conditions [3]. Results of the test are graphically presented in figure 4.

![Flame Generation Variation](image)

**Figure 4.** Results obtained for flame generated at the mouth of the barrel.

5. Acoustic pressure determinations
The experimental determinations consisted of two different positioning of the sonometer. First the recording device was located at the ear of the shooter. Next, the sonometer was placed 5 meters behind the shooter. This was realised in order to determine the acoustic pressure felt by both the shooter and the personnel in the proximity of the shooter, considering the depreciation of the acoustic transmission in correlation with the distance.

The Bruel & Kjaer sonometer equipped with the Bruel & Kjaer 4189L1 prepolarized free-field microphone, with a 50 mV/Pa sensitivity, was used as measuring device (figure 5).

The recorded values have been filtered to allow impulse noise to be determined, with large amplitude in a small amount of time, specific to firing small caliber weapons.

The weighting curve in A frequency was used, according to the measurements provided by the European legislation [12].
The results obtained for the acoustic pressure next to the firearm are graphically presented in Figure 6, while the values obtained at a distance of five meters from the firearm and the shooter are given in Figure 7.

![Figure 5. The Bruel & Kjaer devices.](image)

![Figure 6. Variation of acoustic pressure obtained for measurements near the firearm.](image)

For both test configurations the values obtained for the acoustic pressure exceed the value of 120 Db for most weapon systems. The highest values, around 135dB, are obtained using the A.G.-9 grenade launcher, the 7.62×54R mm semi-automatic sniper rifle (PSL) and the 7.62×54R mm machine gun. These are the weapons that also have the slowest decrease of the acoustic pressure value with the distance from the shooter.
Figure 7. Variation of acoustic pressure obtained for measurements at 5 meters from the firearm.

6. Conclusions
This paper presents a series of experimental determinations continuing the research activity of the authors published before [9].

Regarding the acoustic pressure generated by the firing of different weapon systems, for most of the weapons the values obtained near the shooter exceeded the limit of 120 dB, value considered in the European Union as the lowest limit of hearing pain.

With the increase of distance from the shooter the acoustic pressure values are decreasing, but still reaching values of 110-120 dB.

The peaks obtained are of short period of time, using a single firing weapon. It is needed to consider multiple weapons firing at the same time in order to conclude if the values will be obtained continuously for a longer amount of time, leading to hearing impairment. This will be considered for future research.

For the enclosed spaces (a situation frequently encountered by the special unit forces), the use of weapon silencers can be considered, while the use of protective hearing equipment is recommended in all the firing environments.

Regarding the flame production at the firearm muzzle, the values obtained can be influenced by the environmental conditions. During previous work a safety range for the personnel was proposed by the authors based on the values obtained.

At this point the authors have not considered with the data obtained that a change of the formula is needed. The use of fireproofed gauntlets and goggles that can withstand exposure to high temperatures is recommended for all the firing sessions.

7. References
[1] Goga D A 2007 Safety and performance features of small caliber weapon systems Analysis and Simulation of Semiconductor Devices (Bucharest: Scientific Universe Publishing House, in Romanian)
[2] Marinescu I and Verboncu S 1973 *Mechanisms of automatic weapons* (Bucharest: Military Publishing House, in Romanian)

[3] Zvnicu N D, Haller L O, Nistoran G D and Vedinas I 2017 *Determinations of some Firing Effects of Small Caliber Weapons* (Bucharest: MTA) Review Vol. XXVII, No. 2 pp 75-99

[4] Cirmaci-Matei M V 2010 *Small arms. Analysis. Testing. Functioning* (Bucharest: Military Technical Academy Printing House)

[5] https://www.engineeringtoolbox.com/decibel-d_59.html accessed at 15.01.2019

[6] http://chchearing.org/noise/common-environmental-noise-levels/ accessed at 15.01.2019

[7] Ion I 2009 *Contributions to the study and assessment of the small caliber weapon systems safety* (Bucharest: Military Technical Academy Editing House, in Romanian)

[8] Haller L-O 2014 *Study on physico-chemical properties of suitable materials to be installed on indoor shooting ranges in order to minimize the risk of FMJ bullet ricochets* (Bucharest: MoD PSCD program)

[9] Information regarding the weapon systems and the means of intervention of the Romanian Gendarmerie (Bucharest: Documentation file)

[10] http://www.carfil.ro/produse-militare/armament/aruncator-de-bombe-calibru-82-mm/ accessed at 15.01.2019

[11] Directive 2000/14/EC 2014 *Directive on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors*