Defence Science Journal, Vol. 71, No. 1, January 2021, pp. 12-17, DOI : 10.14429/dsj.71.14957

Numerical and Experimental Analysis of Sound Suppressor for a 5.56 mm Calibre

J.K. Huerta-Torres[@], U.S. Silva-Rivera[#], V.F. Verduzco-Cedeño[@],
L.A. Flores-Herrera[@], and J. M. Sandoval-Pineda[@,*]

[@]*Higher School of Mechanical and Electrical Engineering, Instituto Politecnico Nacional, Mexico City 02250, Mexico*
[#]*Army and Air Force University, Escuela Militar de Ingenieros, Estado de Mexico, Mexico*
[*]*E-mail: jsandovalp@ipn.mx*

ABSTRACT

A sound suppressor is an internal or external device coupled to the barrel of a firearm. Its development has been historically related to the negative effects produced by the noise. This article presents the numerical and experimental analysis of a sound suppressor for a 5.56 mm caliber rifle. It was designed, manufactured, and tested inside a shooting tunnel for 911 m/s and 344 m/s velocities. Three geometric configurations with curved deflectors, conical deflectors, and finally with a reactive spiral capable of dissipating the acoustic wave were compared considering reactive and dissipative systems. The attenuation of the sound inside the silencer depends directly on the reduction of the projectile wave velocity and the deflagration of the gases at the instant of firing. Then the MIL-STD-1474E standard was used to carry out the experiments. The results in the computational numerical simulation show an average value of 143 dB for the considered three models, the Sound Pressure Level in the reactive core model decreased by 25% with respect to other proposals, which have an average value of 141 dB. These results can be useful to improve in the design of sound suppressors based on the needs of the users and under the specific characteristics of each weapon ballistic.

Keywords: Sound suppressor; Impulsive noise; Firearm; Curved deflectors; Conical deflectors; Reactive spiral

1. INTRODUCTION

Sound suppressors, commonly named silencers, mufflers, or sound moderators, have the main function of reducing the noise produced by the firing of a cartridge through the barrel of a firearm. Historically, four stages can be observed during the evolution of these devices. In the first stage, they were developed with the rudimentary technology of the early XIX century. Subsequently, the second stage in the seventies appeared, the use of new configurations and materials characterised by the incorporation of scientific knowledge emerged. The third stage in the 90s was characterised by the use of computer systems and Finite Volume Analysis as an important tool to fight against the loss of hearing. The fourth stage began in the XXI century with the use of new materials capable of absorbing the shock wave of the ammunition, as well as the implementation of new designs and manufacturing processes. At this stage, publications related to experimental works, and the use of computational fluid dynamic (CFD) started to arise. Nowadays there exist prototypes with fluids, gels, or absorbent materials for the reduction of the sound waves[1–4]. During the fire, excessive noise is generated in the form of an expansive wave, as the energy in the cannon outlet increases, the level of impulsive noise also increases. The firearm noises can be divided into three categories related to; the explosion at the exit of the barrel, the velocity of the projectile, and the explosion when the projectile hits the target[5–8]. The sound waves, especially near the firing chamber are short, in the order of milliseconds, or small-caliber weapons systems, the duration of the positive pulse may be less than 0.5 milliseconds. During the instant of the fire and when the shock wave leaves the barrel, the first explosion is developed, a shock wave diffraction is additionally generated with a starting vortex ring and a jet stream, the suppression of the explosion at the exit of the cannon is important for both, long and short weapons. On the short ones, the main objective of the overpressure attenuation is to reduce the magnitude of the explosion[9]. This concern has led to studies and publications in which, the Euler equations were used to examine the friction effects generated by the supersonic wave at the exit of the canon[10,11]. In this regard, the main objective of this work is to observe the acoustic behaviour of the models by numerical and experimental evaluation of the sound pressure level (SPL).

2. MATERIALS AND METHODS

The conceptualisation of the sound suppressor considers a maximum length of 23 cm and a maximum diameter of 4.5 cm. The design proposals were constructed from the study of technical principles in acoustics[12,13], the study of Werbel & Berth patents[14,15], and the analysis of principles and evaluation methods for silencers as presented in[16]. The principles of design, manufacture, and modelling of mechanical systems[17–19] were analysed to comply with the permissible noise limits (MIL-STD-1474E)[20]. During the establishment of the work methodology, the main component from which the design should start is the human being[21–23]. During the study of the Carl L. patent[24], adaptations and designs of exclusive tooling were

Received : 23 August 2019, Revised : 08 May 2020
Accepted : 25 June 2020, Online published : 01 February 2021

identified and would be required to facilitate the machining process[25]. For the development of the numerical simulation of a muffle, the work of[26] was also studied and more technical extents of the problem were also identified. The study of noise reduction techniques[27] was required, which are based on the principles of wave dynamics which are now included in the CFD methods for the analysis of noise and vibration[10,28,29]. The performance of a muffle eventually requires the study of the effects of noise on humans caused by the firearm[30-32].

2.1 Numerical Analysis

According to the tactical needs of the users, three models of silencers were designed with 30 mm in diameter and 180 mm in length. On each one, expansion chambers, baffles, and a cooling system with different geometries were proposed to evaluate their performance in numerical simulations. In Fig. 1(a) curved deflectors compose the first model, the second shown in Fig. 1(b) corresponds to the conical deflectors and, in Fig. 1(c) the reactive spiral.

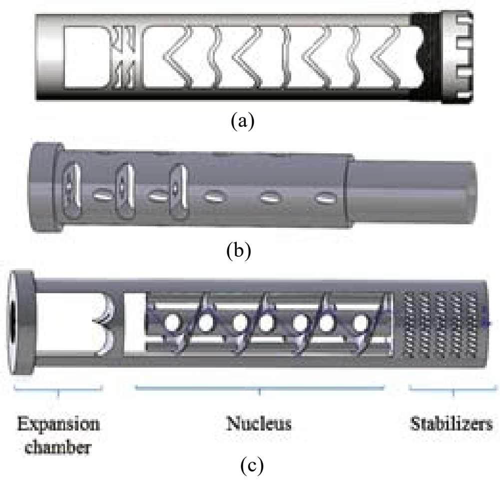


Figure 1. CAD models for the (a) Curved, (b) Conical, and (c) Reactive spiral deflectors.

The acoustic simulation was used to have a real comparison with the measurements of the shots made on site. A sound level meter for impulsive noise with a scale in dB was installed; the objective was to verify the similarity in the sound pressure level (SPL) values prior to the manufacturing of the computational designs[7]. Only the geometric design with the best results acquired in the acoustic measurement will be numerically modelled and analysed. Table 1 shows the parameters considered for the simulation.

Table 1. Physical parameters considered for the simulation

Parameter	Value
Velocity of sound	911 m/s
Air density	1.21 kg/m^3
Specific heat ratio	1.4
Bulk model	1.4319×10^5 Pa
Static pressure	1.022×10^5 Pa
Prandtl number	0.713
Maximum frequency of attenuation	250 Hz
Flow resistivity	10,800 Rayls/m

The numerical analysis was solved with the ANSYS® Fluent software. The simulation for the 5.56 × 45 mm SS109 cartridge considers a speed of 911 m/s and subsequently for the 5.56 × 45 mm SS (subsonic flow) cartridge. During the analysis, a turbulent flow was considered with a mixture of chemical compounds generated by the deflagration of the double base powder, this solution includes the turbulence dissipation model (Eddy-dissipation), with a complete conversion of the reaction. The FLUID 220 element in the 2020 R1 version of the ANSYS® Fluent software was selected for the simulation. It is a higher-order 3-D 20-node solid element developed for acoustic analysis. This element has the advantage to allow the modelling of the fluid-structure interaction[33]. A reference condition of 1atm and a stagnation temperature of 291.15 °K were considered for the initial stage of the simulation. In this case, the requested solution involves the equation of continuity (1):

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V_x)}{\partial x}+\frac{\partial(\rho V_y)}{\partial y}+\frac{\partial(\rho V_z)}{\partial z}=0 \tag{1}$$

In which, V_x, V_y and V_z are the velocity vector components of the fluid for the X, Y and Z coordinates respectively, ρ stands for the density and t for the time. These velocities suddenly change during the bullet's travel inside the suppressor. The rate of change in density can be related to the pressure variation p as shown in Eqn (2)[10]:

$$\frac{\partial \rho}{\partial t}=\frac{\partial \rho}{\partial p}\frac{\partial p}{\partial t} \tag{2}$$

In a compressible fluid, the interaction between the chemical species and the generated turbulence is described by the turbulence dissipation Eqns (3) and (4).

$$R_{i,r}=v'_{i,r}M_{w,i}A\rho\frac{\varepsilon}{k}minR\frac{Y_R}{v'_{R,r}M_{w,R}} \tag{3}$$

$$R_{i,r}=v'_{i,r}M_{w,i}AB\rho\frac{\varepsilon}{k}\frac{\Sigma_P Y_P}{\Sigma_j^N v''_{j,r}M_{w,j}} \tag{4}$$

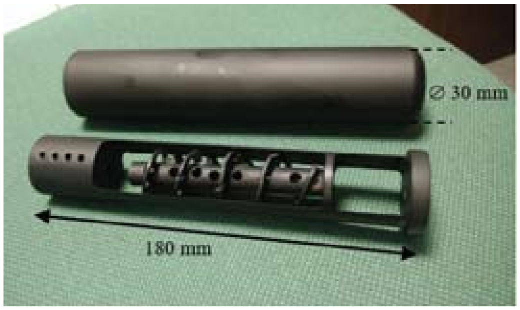
where: i is the net rate of species production due to the reaction r, in this case, Y_P is the mass fraction of the P species and Y_R is the mass fraction of a particular reagent R. The empirical constants A and B were selected to be 4 and 0.5 respectively[19].

2.2 Experimental Analysis

The final prototype was manufactured in 6062 aluminium alloy (AlMg1Si) with a GILDEMEISTER CTX41016® CNC Lathe and a MILLTRONICS H7® 5-axis CNC Milling Machine, in 32 operations. The suppressor and its external cover are shown in Fig. 2(a). The mounting of the suppressor on the front side of the rifle is shown in Fig. 2(b).

Distances and positions of the sound level meter and transducer were established according to[20] before the firing tests and they were distributed as shown in Fig. 3.

For each one of the measurements, 6 rounds of 5 shots were made, starting the first one without the sound suppressor and later placing this accessory for the following shots to establish the comparison.



(a)

(b)

Figure 2. (a) Cover with the lid and (b) mounting on the rifle.

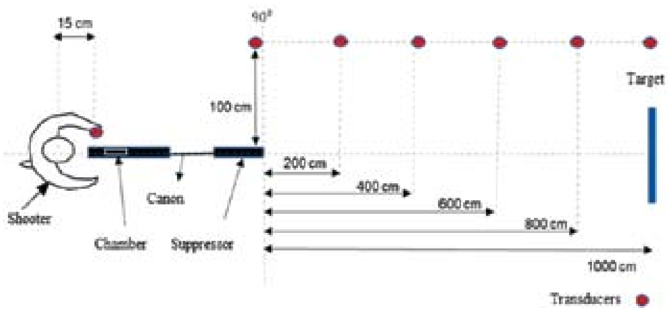


Figure 3. Sensors and target locations with respect to the shooter.

3. RESULTS

3.1 Numerical Analysis Results

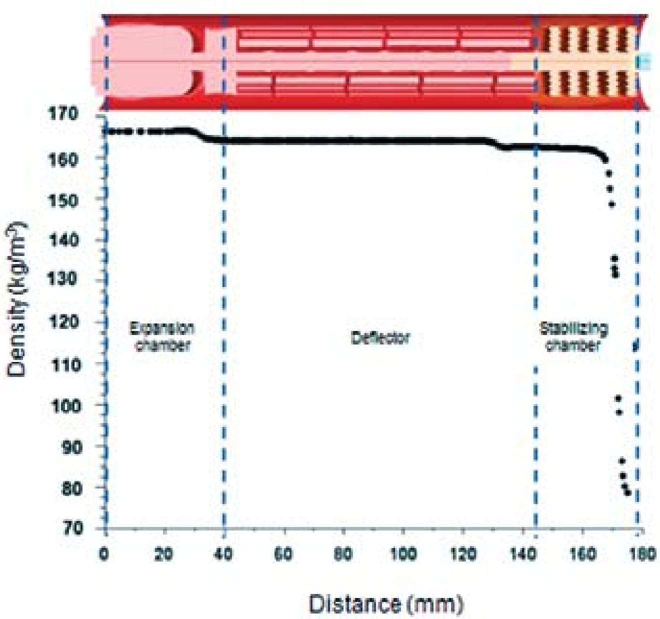
The results obtained through the computational simulation for the 5.56 mm caliber cartridge with a speed of 911 m/s and 344 m/s are shown in Table 2. They correspond to the Reactive spiral deflectors design which obtained the best performance results in the firing test. The temperature output values were reduced by 23% with respect to the initial one, proper functioning of the last section is also verified.

The effective shooting distance could be reduced by 30%. This percentage corresponds to the dispersion of the impacts fired to a circular shooting target located at 300 m limiting its use to these distances or less.

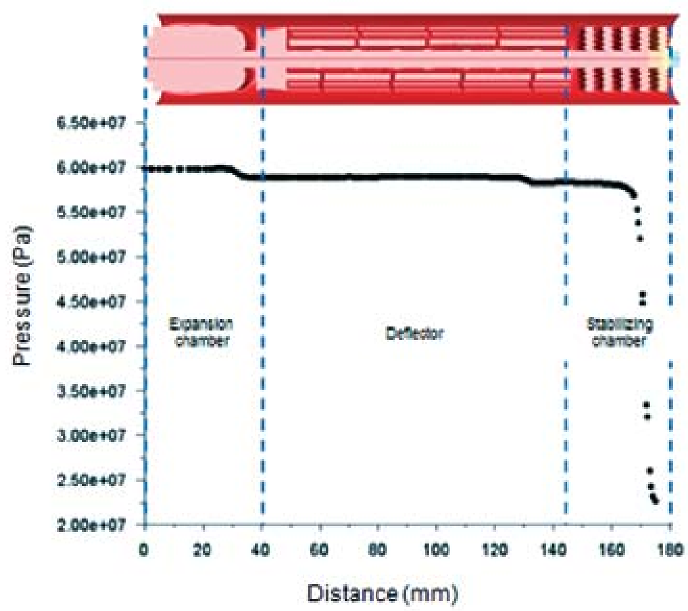
Figure 4(a) shows the changes in density with respect to the length of the suppressor, it is possible to observe (in the top side of the graph) a side cut showing the interior of the Reactive spiral design to facilitate the observation of the values. The maximum density value was 167 kg/m^3 along with the expansion chamber. Next, a small reduction is observed through the deflector zone achieving a value of 162.5 kg/m^3. In Fig. 4(b) the maximum pressure value of 6x10^7 Pa is observed with a sudden pressure drop in the stabilising chamber.

Table 2. Physical parameter measured inside the reactive spiral suppressor

Subsystem	Expansion chamber		Deflector		Stabilisation chamber	
	911 m/s	344 m/s	911 m/s	344 m/s	911 m/s	344 m/s
Density (kg/m^3)	166	110	162.5	108	161	106
Pressure (Pa)	60	39	58	38.5	25	15.9
Temperature (°K)	1,300	1,300	1,290	1,290	1,038	1,038
Velocity (m/s)	103	103	102	102	750	305

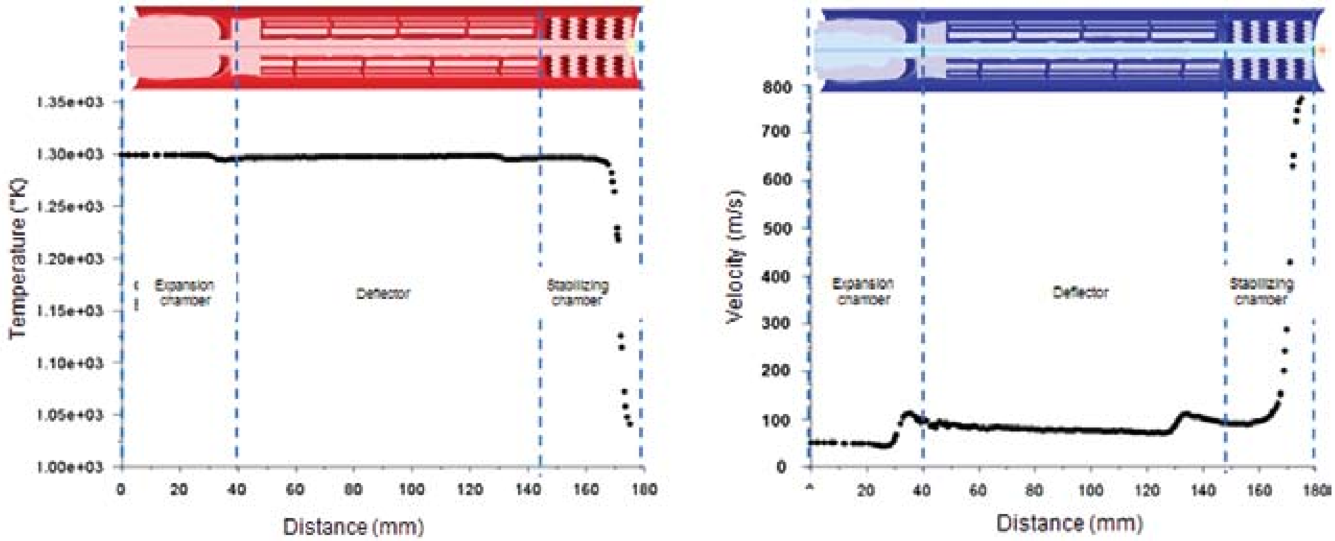


(a)



(b)

Figure 4. (a) Density and (b) Pressure measured along the suppressor length.



(a) (b)

Figure 5. (a) Temperature and (b) Velocity measured along the suppressor length.

Figure 5(a) shows the temperature changes with respect to the length of the suppressor, a maximum value of 1.30×10^3 °K was measured in the expansion chamber. Figure 5(b) shows the velocity changes with a maximum of 120 m/s in the expansion chamber and a sudden increment in the stabilising chamber.

The level of accuracy with the suppressor mounted in the weapon was constant in all firing rounds. The best performance of the sound suppressor was observed with the use of subsonic cartridges, having an average value of 114 dB of SPL at 10 m.

3.2 Experimental Analysis Results

Figure 6 shows the SPL levels measured for each design. The mechanical and acoustic design of the reactive spiral model offers the greatest decrement in the shooting sound, up to 25% more with respect to the conical and curved models.

Figure 7(a) shows the SPL values with respect to time (s), starting from the instant of fire. In the case of the Reactive spiral model, the maximum appears at 0.002 s after the shot; in contrast, the other two models have a maximum peak at 0.0024 and 0.0028, respectively. Figure 7(b) shows the average values of SPL with respect to the distance for each shot with and without the suppressors.

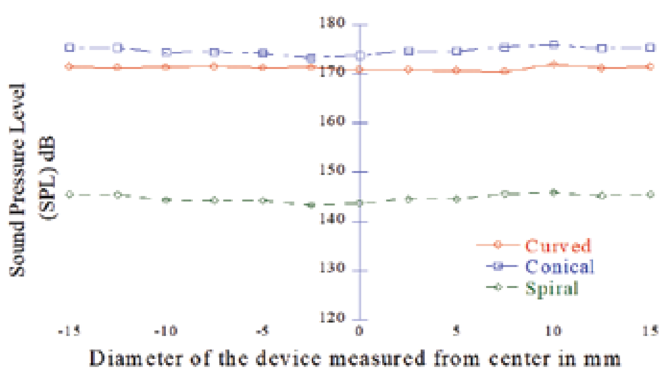
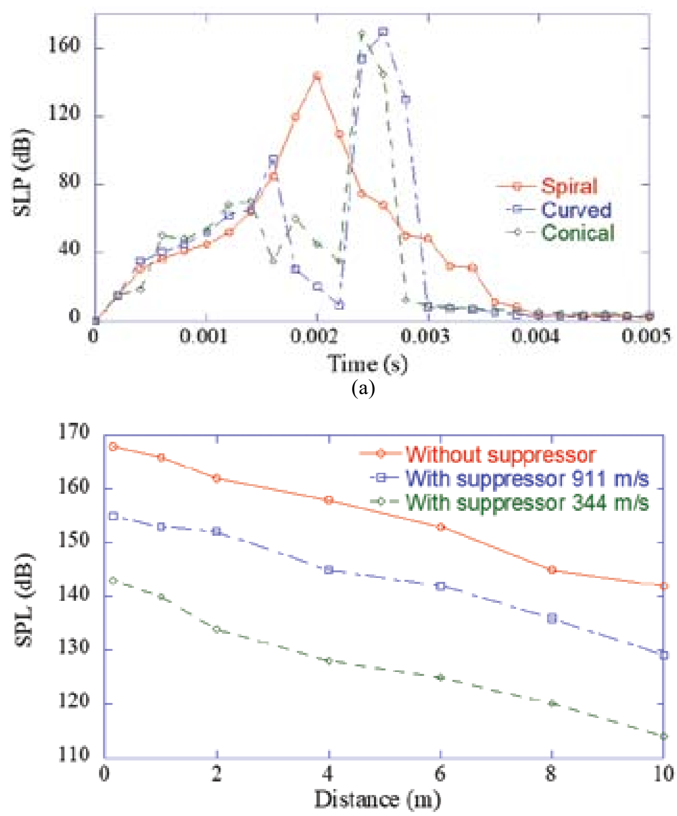


Figure 6. Sound pressure level along the suppressor diameter.



(a)

(b)

Figure 7. Sound pressure level with respect to (a) time, and (b) Distance.

4. DISCUSSION

The design and modelling of the three geometrical configurations of the sound suppressors were influenced by parameters like the length, weight, diameter, and assembling, they were determined by the operational specifications of the final user, the literature review, previous experience, and theoretical knowledge. All these elements influenced the creation of the first sketches but the substantial difference in this research with respect to previous works falls in the proper methodology conceived for the specific calibers.

5. CONCLUSIONS

The acoustic analysis comparison of three suppressors with different geometric deflector designs such as curved, conical and reactive spiral was presented. It was possible to determine that the reactive spiral sound suppressor had a better performance than the curved and conical models for the 5.56 mm calibre; the average Sound Pressure Level gets in the range of the allowed international levels. After the detonation of the propellant, the maximum sound peak occurs between 0.002 to 0.003 ms, which shows the characteristics of the impulsive noise during the shot. Regarding the numerical simulation with cartridges at a speed of 911 m/s and 344 m/s, the values obtained in density, pressure, and temperature showed a stable behaviour at the entrance and exit of the expansion chambers, verifying the effectiveness of the mechanical behaviour with respect to design and not exceeding 1.30×10^3 °K; however, the velocity shows a different behaviour, when obtaining an exit value of up to 750 m/s, determining this effect as a product of the turbulence generated within the spiral. When performing the experimental tests with the MIL-STD-1474E Standard, 5 shots were determined for each established distance; the characteristic vales of the shot were found between 168 dB and 155 dB with the use of the Reactive spiral suppressor. These values have a variation of 1.5% with respect to the ones found in the simulation. In all of the cases, the results of temperature, pressure, and density measured in the suppressor, remained stable showing the effectiveness of their performance for the proposed calibre.

REFERENCES

1. Paulson A. C. Silencer History and Performance, sporting and tactical Silencers. Paladin Press, USA, 1996, p. 424.
2. Hakonen P. Firearm Suppressors – Structures and Alternative Materials. Tampere University of Technology, Finland, 2010, p. 53.
3. MacCarthy M.; O´Neill M. & Cripps H. An investigation into the use of sound moderators on firearms for game and feral management in New South Wales, 2011, 85. https://ro.ecu.edu.au/ecuworks2011/858 (Accessed on 30 July 2019).
4. Murphy W.J.; Flamme G.A.; Campbell A.R.; Zechmann E.L.; Tasko S.M.; Lankford J.E.; Meinke D.K.; Finan D.S. & Stewart M. The reduction of gunshot noise and auditory risk through the use of firearm suppressors and low-velocity ammunition. *Int. J. Audiol*., 2018, **57**(1), 28–41.
doi: 10.1080/14992027.2017.1407459
5. Pääkkönen R., & Kyttälä I. Effects of rifle-calibre muttle brakes and suppressors on noise exposure, recoil and accuracy. *Acta Acust*., 1994, **2**(2), 143–148.
6. Pääkkönen R., & Parri A. The effect of a suppressor to environmental noise – A case study. *Appl. Acoust*., 2011, **72**(9), 702–704.
doi: 10.1016/j.apacoust.2011.03.002
7. Kang K.J.; Ko S.H. & Lee D.S. A study on impulsive sound attenuation for a high-pressure blast flowfield. *J. Mech. Sci. Technol*., 2008, **22**(1), 190–200.
doi: 10.1007/s12206-007-1023-8
8. Pfüller S. The management of shooting noise in German military training areas. In: Seoul Internoise Covan International Corporation 2003, *In* Internoise 2003, 32nd. Int. Congr. Expo. Noise Control Eng. 2003, Seogwipo, Korea: Noise Control Foundation; 2003. ISBN: 8995218916
9. Hristov N.; Kari A.; Jerković D.; Savić S. & Sirovatka R. Simulation and Measurements of Small Arms Blast Wave Overpressure in the Process of Designing a Silencer. *Meas. Sci. Rev*., 2015, **15**(1), 27–34.
doi: 10.1515/msr-2015-0005
10. Jiang Z. Wave dynamic processes induced by a supersonic projectile discharging from a shock tube. *Phys Fluids*., 2003, **15**(6), 1665–1675.
doi: 10.1063/1.1566752
11. Jiang Z.; Huang Y. & Takayama K. Shocked flows induced by supersonic projectiles moving in tubes. *Comput. Fluids.,* 2004, **33**(7), 953–966.
doi: 10.1016/S0045-7930(03)00041-0
12. Rehman H.; Chung H.; Joung T.; Suwono A. & Jeong H. CFD analysis of sound pressure in tank gun muzzle silencer. *J. Cent. South Univ. Technol.,* 2011, **18**(6), 2015–2020.
doi: 10.1007/s11771-011-0936-7
13. Rossing T.D. Springer Handbook of Acoustics. Springer, USA, 2014, p.1286.
doi: 10.1007/978-1-4939-0755-7
14. Werbell III M.L. Silencers for firearms, internal combustion engines, or the like. US patent 3667570, 6 June 1972.
15. Wilson B.J. Suppressors and their methods of manufacture. US patent 2015/0001001 A1, 1 June 2015.
16. Skochko L.W. & Greveris H.A. Silencers Principles And Evaluations. Philadelphia, USA: Frankford Arsenal Report R-1896; 1 January 1968.
17. Crowson R. Product Design and Factory Development, CRC Press, USA, 2019, p. 424.
18. Urriolagoitia-Calderón G.; Urriolagoitia-Sosa G.; Verduzco-Cedeño V.F.; Hernández-Gómez L.H.; Romero-Ángeles B.; Torres-Torres C.; Torres-SanMiguel C. R. & Wong A. Mechanical design and manufacture by powder technology of a new mandrel tool for the fabrication of assault rifle barrels. *Powder Technol.,* 2012, **224**, 76–85.
doi: 10.1016/j.powtec.2012.02.031
19. Silva-Rivera U.S.; Sandoval-Pineda J.M.; Susarrey-Huerta O.; Flores-Herrera L.A. & Tamayo-Meza P.A. Numerical Modelling of Caseless Ammunition with Coreless Bullet in Internal Ballistics. *Def. Sci. J.,* 2015, **65**(3), 203-207.
doi: 10.14429/dsj.65.8511
20. Amrein B. E. Military standard 1474E: Design criteria for noise limits vs. operational effectiveness, *Proc Meet Acoust.*, 2015, **25**(1), 1-117.
doi: 10.1121/2.0000207
21. Wolfgang E.E. Theory of Technical Systems - Educational Tool for Engineering. *Univers. J. Educ. Res.,* 2016, **4**, 1395–405.

doi: 10.13189/UJER.2016.040617

22. Cross, N. Design research: A disciplined conversation. *Des. Issues.,* 1999, **15**(2), 5–10. doi: 10.2307/1511837
23. Wheelwright S.C. & Clark K.B. Accelerating the Design-build-test cycle for effective product development. *Int. Mark Rev*., 1994, **11**(1), 32–46. doi: 10.1108/02651339410057509
24. O'Quinn CL, Raymon WAJ. Gun noise and recoil suppressor. US patent 6,302,009 B1, 16 October 2001.
25. Verduzco-Cedeño VF. Diseño y Desarrollo de Herramientas de Suajeado para la Fabricación de Cañones de Armamento. Instituto Politécnico Nacional, Ciudad de Mexico, Mexico, 2010. (M. Sc. Thesis).
26. Fansler K.S.; Cooke C.H.; Thompson W.G. & Lyon D.H. Numerical simulation of a multi-compartmented gun muffler and comparison with experiment. *Engineering*, 1990.
27. Pater L.L.; & Shea J.W. Techniques for reducing gun blast noise levels: an experimental study. *Engineering*, 1981, 81–120. doi: 10.21236/ada112290
28. Hudson M.K.; Luchini C.; Clutter J.K. & Shyy W. The evaluation of computational fluid dynamics methods for design of muzzle blast suppressors for firearms. *Propellants, Explos Pyrotech*., 2001, **26**(4), 201–208. doi:10.1002/1521-4087(200110)26:4<201::AID-PREP201>3.0.CO;2-7
29. Crocker M.J. Handbook of Noise and Vibration Control. John Wiley & Sons, Inc., USA, 2007. doi: 10.1002/9780470209707
30. Gerges S.N.Y.; Jordan R.; Thieme F.A.; Bento C.J.L. & Arenas J.P. Muffler modeling by transfer matrix method and experimental verification. *J. Brazilian Soc. Mech. Sci. Eng.,* 2005, **27**(2), 132–140. doi: 10.1590/S1678-58782005000200005
31. Ylikoski M.E.; Pekkarinen J.O.; Starck J.P.; Pääkkönen R.J. & Ylikoski J.S. Physical characteristics of gunfire impulse noise and its attenuation by hearing protectors. *Scand. Audiol*., 1995, **24**(1), 3–11. doi: 10.3109/01050399509042203
32. Stoughton R. Measurements of small-caliber ballistic shock waves in air. *J. Acoust. Soc. Am*., 1997, **102**(2), 781-787. doi: 10.1121/1.419904
33. Howard C.Q. & Cazzolato B.S. Acoustic Analyses Using Matlab® and Ansys®. CRC Press, 2017, p. 708.

ACKNOWLEDGEMENTS

Authors acknowledge the Instituto Politecnico Nacional, Project SIP 2020530, and the Consejo Nacional de Ciencia y Tecnología (CONACYT), for their contribution to the development of this academic research. Patent-pending No. MX/f/2019/000882, MX/E/2019/020743.

CONTRIBUTORS

Dr J.M. Sandoval-Pineda received the Doctorate from the Instituto Politecnico Nacional of Mexico. He is an associate professor in Manufacture and Mechanical design at the Research and graduate department of the Escuela Superior de Ingenieria Mecanica y Electrica. His research interests include: Mechanical Design, Finite Element Analysis and Dual Combustion using Hydrogen.

Contribution in the current study, he contributed in the research and formulation of the model; wrote the paper.

Mr J.K. Huerta-Torres received the Master in Sciences from the Instituto Politecnico Nacional of Mexico. He has graduated from the Escuela Superior de Ingeniería Mecánica y Eléctrica (ESIME). His research interests include: Mechanical Design, Ballistics, Computational Fluid Dynamics and Finite Element Analysis.

Contribution in the current study, he contributed in design, execution, and interpretation of simulation studies; wrote the paper.

Dr U.S. Silva-Rivera received the Doctorate from the Instituto Politecnico Nacional of Mexico. He is an Associate Professor in Manufacture and Mechanical Design at the Research and Graduate Department of the National Polytechnic Institute of Mexico. His research interests include Ballistics and Computational Fluid Dynamics.

Contribution in the current study, he contributed in design, execution, and interpretation of the simulation studies.

Dr V.F. Verduzco-Cedeño received the Master in Sciences and Doctorate in Sciences from the Instituto Politecnico Nacional of Mexico. He has graduated from the Escuela Superior de Ingeniería Mecánica y Eléctrica (ESIME). He has developed research interest in the area of Mechanical Design, Finite Element Analysis, Ballistics and Computational Fluid Dynamics.

Contribution in the current study, he contributed in research and derivation of the theoretical properties.

Dr L.A. Flores-Herrera received the Master in Sciences and Doctorate in Sciences degree from the Instituto Politecnico Nacional of Mexico. He is an associate professor in Manufacture Engineering and Mechanical design at the Research and Graduate Department of the Escuela Superior de Ingenieria Mecanica y Electrica (SEPI). He has developed research interest in the area of mechanical design, Microelectromechanical Systems (MEMS) and computer simulation.

Contribution in the current study, he contributed in analysis and edition of the article.