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Frangibility Quantification of Frangible Bullet upon Impact on a Hard Target

Xuan Son Bui[@,*], Jan Komenda[#], and Roman Vítek[#]
[@]*Department of Munition, Le Quy Don Technical University, Hanoi, Vietnam*
[#]*Department of Weapons and Ammunition, University of Defence, Brno - 662 10, Czech Republic*
[*]*E-mail: buixuanson.mta@gmail.com*

ABSTRACT

The article presents a new method of quantitative evaluation of the degree of disintegration, called frangibility of frangible bullets, based on shooting experiments. On the basis of the dependence of the Frangibility Factor of the bullet on its impact velocity, the frangibility index is determined as a quantifier of the projectile's ability to disintegrate into fragments applied for a certain range of interest. The method can be used to assess the ability to disintegrate into fragments of various types of bullets, preferably frangible bullets produced by powder metallurgy technologies. The proposed method was used to quantify the frangibility of five experimental frangible bullets.

Keywords: Frangible bullet; Frangible ammunition; Frangibility; Frangibility Factor; Frangibility evaluation

NOMENCLATURE

FF_{EM}	Frangibility factor (%)
FI	Frangibility index (%.(m/s)$^{-2}$)
FF_{EMS}	Mean value of frangibility factor between $v_{imp,max}$ and $v_{imp,min}$ (%)
FF'_{EMS}	Arithmetic average of two values of frangibility factor at $v_{imp,max}$ and $v_{imp,min}$ (%)
K_m	Size coefficient
SF	Area under the frangibility factor curve between $v_{imp,max}$ and $v_{imp,min}$ (%.m/s)
$SF_{200\text{-}400}$	Area under the frangibility factor curve between impact velocity 200 m/s and 400 m/s (%.m/s)
l_q	Length of bullet (mm)
m_{ci}	Total mass of fragments in the particular size category *i* (kg)
m_q	Original mass of bullet (kg)
v_0	Initial velocity of the bullet (m/s)
v_{25}	Velocity of the bullet at a distance of 25 m from the muzzle of the barrel (m/s)
v_{lim}	Limit impact velocity of the bullet (m/s)
v_{imp}	Impact velocity of the bullet (m/s)
$v_{imp,max}$	Maximum impact velocity of the bullet (m/s)
$v_{imp,min}$	Minimum impact velocity of the bullet (m/s)
v_{F80}	Impact velocity of the bullet corresponding to 80% Frangibility Factor (m/s)
v_{F50}	Impact velocity of the bullet corresponding to 50% frangibility factor (m/s)
a, b, α	Constants
β	Angle of the line connecting the points corresponding to 50% and 80% Frangibility Factor (rad)
γ	Angle of the line connecting the values of Frangibility Factor corresponding to between $v_{imp,max}$ and $v_{imp,min}$ (rad)

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1. INTRODUCTION

For traditional bullets, the functional evaluation of the bullets in terms of terminal ballistics often is carried out using its penetration in the target[1], its ricochet[2,3], or wound ballistics[4,5]. In addition to some basic evaluation for a traditional bullet, other evaluation methods are required for frangible bullets, which have different terminal ballistic properties. From the terminal ballistic point of view, the frangible bullet must disintegrate upon impact on a hard target into small fragments that they lose velocity almost immediately. Therefore, when evaluating the functional properties of frangible bullets, the crucial property is the ability of their disintegration into fragments upon impact on a certain fixed target, called frangibility. The frangibility determines the behaviour of the bullet in the target and its penetration, wound, and reflectivity. In order to compare the frangibility of different types of frangible bullets, it is necessary to quantify the frangibility. Some publications have dealt with frangible bullets[6-13]; however, the frangibility of the frangible bullets has not been quantified in any publications, so it is difficult to compare different types of frangible bullets.

Shooting experiments are necessary for an objective assessment of the frangibility of a projectile. For example, some agencies in the USA have constructed a steel box into which the bullets are fired. The bullet impacts on the angled steel plate, and the fragments of the bullet are captured in the water bath beneath the impact plate. Then, the frangibility of the frangible projectile is evaluated according to a certain criterion based on the size of the fragments after the impact, e.g., X numbers of fragments of Y size or larger, and the round is non-compliant; Z numbers of fragments of W to Y size, and the round is marginal, and so forth[10].

Recent research about the frangibility of frangible bullet made of Cu-Sn composite was published. This research calculated the Frangibility Factor using three process parameters: Sn weight composition, compaction pressure, and sintering temperature[14]. However, this method has not mentioned an application for comparing the frangibility of various types of frangible bullets.

In the Czech Republic, some researchers have dealt with the frangibility of frangible bullets to classify and develop frangible bullet[8,9,11,12,15,16,17], one of which is the original author's research[15-17]. This research has focused on the mass distribution of the bullet's fragments upon impact on a hard target. The frangibility of the frangible bullet is evaluated based on the fragments' mass distribution through the Frangibility Factor, described in the second part of this article.

This article presents a method for evaluating the frangibility of a frangible bullet based on the Frangibility Factor. New concepts are also defined to use as an assessment of frangibility. The dependence of the Frangibility Factor of the bullet on the impact velocity was determined experimentally.

2. FRANGIBILITY FACTOR OF FRANGIBLE BULLET

This part summarises the concept of Frangibility Factor, which is the authors' original research and was published[15-17]. The Frangibility Factor of a frangible bullet, which is determined by experimental shooting, is a quantification of the capability to disintegrate the bullet when hitting on a defined target. Fragments of the bullet after hitting the target are captured with a suitable trap. An important requirement is that the mass of captured fragments must be greater than 90 % the mass of original bullet. The captured fragments are sieved according to 5 size categories (Table 1). The mass of missing fine fragments is added into the smallest size category (1st category), the Frangibility Factor FF_{EM} is then determined as follows[16,17]:

$$FF_{EM} = 100\sum_{i=1}^{5} K_{mi} \frac{m_{ci}}{m_q}(\%) \quad (1)$$

where: m_{ci} is the mass of fragments in the size category i, m_q is the original bullet's mass, K_{mi} is the size coefficient of category i.

Based on the experience while evaluating the frangibility of frangible bullet, the size coefficients K_m are chosen (Table 1). Table 1 shows that the 1st category has a great influence in the value of FF_{EM}, while the 5th category is almost negligible.

Table 1. Size category of captured fragments

Size category *i*	Dimension of fragments (mm)	Size coefficient K_m
1	(0, 0.5]	1
2	(0.5, 1]	0.75
3	(1, 2]	0.5
4	(2, 5]	0.25
5	(5, *lq*]	0.01

When the bullet is still intact after hitting on the target, the value of Frangibility Factor is equal to zero. When the bullet completely disintegrates into fine fragments belonging to the 1st category, the value of Frangibility Factor is equal to 100 %.

The dependence of FF_{EM} on impact velocity v_{imp} is determined by shooting experiments. The results of experimental shooting for various types of frangible bullet[15-17] show that the FF_{EM} depends on the impact velocity with a mathematical function, which can be approximated by the exponential function as follows:

$$FF_{EM} = 100 - a.\exp(b.v_{imp}^{\alpha}) \quad (2)$$

where: v_{imp} is impact velocity of the bullet; *a, b* and *α* are constants.

From Eqn. (2) we can derive the limit velocity, at which the bullet begins to break into fragments:

$$v_{\lim} = \left(\frac{1}{b}\ln\left(\frac{100}{a}\right)\right)^{1/\alpha} \quad (3)$$

Typical continuous curves of the dependence of FF_{EM} on impact velocity are shown in Fig. 1. The curve (1) corresponds to an ideal frangible projectile, which completely disintegrates into small fragments (in the 1st category) at limit impact velocity (FF_{EM} = 100 %). However, such a bullet would be very difficult to use for shooting. The curves (2) and (3) correspond to real frangible bullets; the bullet (2) disintegrates more easily into fragments and is, therefore, more frangible than the bullet (3). The curve (4) corresponds to a bullet without breaking into fragments upon impact on a standard target.

The Frangibility Factor FF_{EM} expresses the disintegration ability of a bullet. However, this Frangibility Factor is valid only for one particular impact velocity and therefore, cannot be used to compare various types of bullets. Moreover, the velocity of a bullet varies as it travels from the muzzle to the target.

The disintegration ability of a bullet can also be quantified by the value of the limit velocity, which is difficult to determine experimentally, and its analytical determination through Eqn (3) is inaccurate. Therefore, it is appropriate to quantify the frangibility of a bullet by a more generally defined quantity, which is valid for a certain range of interest of the functional characteristics of the bullet. This quantity is the Frangibility Index.

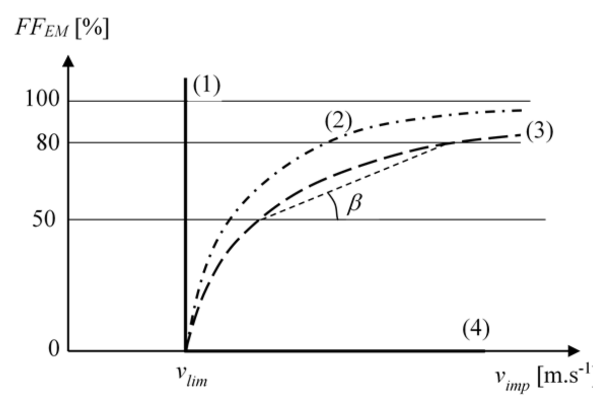

Figure 1. Typical continuous curve of the dependence of frangibility factor on impact velocity 1 – ideal frangible bullet; 2, 3 – real frangible bullets; 4 – tough bullet.

3. FRANGIBILITY QUANTIFICATION

From the practical point of view, it is not necessary to analyze the frangibility of the bullet in the whole range of impact velocities from the limit velocity to the highly supersonic velocity. It is sufficient to evaluate the frangibility of frangible bullets in the defined range of the FF_{EM} factor or the range of interest of the bullet's impact velocity. Based on this requirement, the Frangibility Index is established for a certain range of the FF_{EM} factor and the impact velocity.

3.1 Frangibility Index of a Frangible Bullet in the Range of Interest According to the Impact Velocity

From the practical point of view, it is sufficient to describe the frangibility only in the realistically achievable range of impact velocities from $v_{imp,min}$ to $v_{imp,max}$. For frangible pistol bullets, these values are the maximum achievable velocity $v_{imp,max} = v_0$ (initial velocity of the bullet), the minimum achievable velocity $v_{imp,min} = v_{25}$ (velocity of the bullet at a distance of 25 m from the muzzle of the barrel, which corresponds to the usual real firing range of the pistol).

The overall frangibility of a bullet in a certain range of impact velocities of interest from $v_{imp,max}$ to $v_{imp,min}$ can be expressed in various ways, for example:

- Area SF under the Frangibility Factor curve between $v_{imp,max}$ and $v_{imp,min}$, where

$$SF = \int_{v_{imp,\min}}^{v_{imp,\max}} FF_{EM}(v_{imp})dv; \qquad (4)$$

- Mean value FF_{EMS} of Frangibility Factor between $v_{imp,max}$ and $v_{imp,min}$ determined as follows:

$$FF_{EMS} = \frac{1}{v_{imp,\max} - v_{imp,\min}} \int_{v_{imp,\min}}^{v_{imp,\max}} FF_{EM}(v_{imp})dv; \qquad (5)$$

- Arithmetic average FF'_{EMS} of two Frangibility Factor at $v_{imp,min}$ and $v_{imp,max}$, thus

$$FF'_{EMS} = \frac{1}{2}\left(FF_{EM}(v_{imp,\min}) + FF_{EM}(v_{imp,\max})\right) \qquad (6)$$

- Slope of the line connecting the values of Frangibility Factor corresponding to between $v_{imp,min}$ and $v_{imp,max}$, thus

$$tg\gamma = \frac{FF_{EM}(v_{imp,\max}) - FF_{EM}(v_{imp,\min})}{v_{imp,\max} - v_{imp,\min}} \qquad (7)$$

The area SF and the slope γ are shown in Fig. 2.

The most objective way to quantify frangibility with SF or FF_{EMS} parameters is relatively difficult and impractical for evaluating experiments. Quantification of frangibility using FF'_{EMS} parameter is simple but less accurate. A more suitable method of quantifying frangibility is using the slope of the Frangibility Factor curve. This method is described below.

3.2 Frangibility Index of a Frangible Bullet for the Range of Interest of the Factor FF_{EM}

Based on the results of the experiments, the range of interest of the FF_{EM} factor in the range of 50 % to 80 (%)

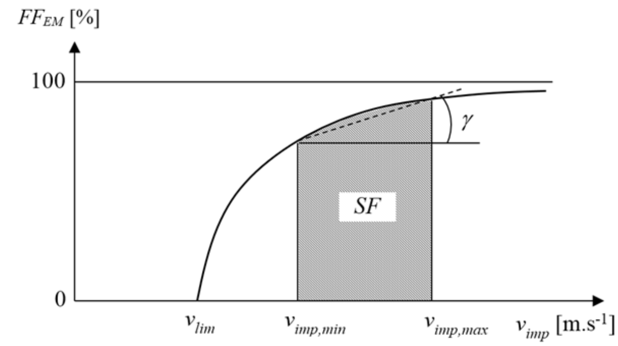

Figure 2. The total frangibility of the bullet in a certain range of impact velocities of interest.

was chosen. In this range, experimental frangibility tests are most easily performed on most frangible bullets. To obtain an FF_{EM} value of less than 50 (%), it is necessary to shoot at low velocities, which makes it more challenging to prepare the experiment. To achieve high FF_{EM} values (above 80 (%)), it is necessary to fire at very high velocities, at which the maximum allowed pressure of propellant gases is usually exceeded.

In the range of interest FF_{EM} = 50-80 (%), the slope of the FF_{EM} curve is expressed by the angle β of the line connecting the points corresponding to 50 % and 80 % Frangibility Factor. This slope is an indicator of the bullet's frangibility- with increasing value of the $tg\beta$, the ability of the bullet to disintegrate into fragments increases under otherwise identical conditions. Similarly, the lower the impact velocity at FF_{EM} = 50 %, the greater the frangibility.

Using these conclusions, we can define the frangibility index (*FI)* in the specified range of the FF_{EM} factor as follows:

$$FI = \frac{tg(\beta)}{v_{F50}} = \frac{30}{v_{F80} - v_{F50}} \cdot \frac{1}{v_{F50}} \qquad (8)$$

where: β is the angle of the line connecting the points corresponding to 50% and 80% Frangibility Factor (rad), v_{F80} is the impact velocity of the bullet corresponding to 80% Frangibility Factor (m/s), v_{F50} is the impact velocity of the bullet corresponding to 50% Frangibility Factor (m/s).

The value of index FI increases with increasing frangibility and varies in the range of [0,∞):

- $FI = \infty$, corresponds to an ideal frangible bullet - the curve (1) in Fig. 1. In this case, $v_{F80} = v_{F50}$,
- $FI = 0$, corresponds to a bullet incapable of disintegration (non-frangible bullet).

4. APPLICATION OF FRANGIBILITY QUANTIFICATION FOR VARIOUS TYPES OF BULLET

In order to determine Frangible Factor of the frangible bullet, the bullet was shot into the closed trap. The impact velocity of the bullet was measured by ballistic radar (Fig. 3). The hard target is a flat steel plate with a nominal hardness of 450 HBW (Hardox 450), whose length is 200 mm, width is 200 mm, and thickness is 10 mm. The target was placed at a distance of 5 m from the muzzle.

The experiment was carried out for 04 different types of frangible pistol bullets caliber of 9 mm Luger and 01 frangible

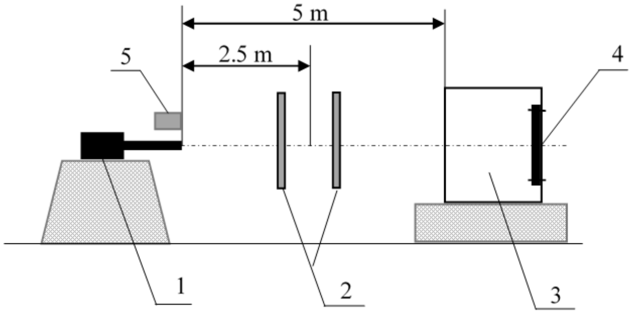

Figure 3. Scheme of shooting experiment: 1 – ballistic test barrel; 2 – optical gates of ballistic chronograph; 3 – closed steel trap; 4 – flat plate Hardox 450; 5 – ballistic doppler radar.

pistol bullet caliber of 7.62 mm (Fig. 4). The properties of the experimental bullet are shown in Table 2.

In order to change the impact velocity of the bullet, the mass of gunpowder in the cartridge was changed. The gunpowder used was nitrocellulose smokeless powder S-011. Figure 5 shows the experimental shooting results and approximation curves. The points in Fig. 5 show the experimental values of FF_{EM}; the Frangibility Factor curves are approximated by the Eqn. (2). The bullet SR also was shot with low velocity in the range of 37.3 m/s to 91.2 m/s (the points of SR_low velocity). According to the Eqn. (2), the constants *a, b* and *α* are obtained by fitting experimental data (Table 3). The *SF* values are calculated using the author's Matlab program based on the integration of the approximated Eqn. (2) through Eqn. (4). The FF'_{EMS} values and the *FI* values are directly calculated based on Eqn. (6) and Eqn. (8).

The values of the frangibility index *FI* in the range of interest of Frangibility Factor are shown in Fig. 6. The value *FI* of BiCu_7.62 bullet is the highest due to the highest steepness of the FF_{EM} curve in the range of 50 % to 80 % Frangibility Factor and the lowest impact velocity of the bullet at the value of 50 % Frangibility Factor.

In the case that the bullets were fired with 0.3 g of S-011 powder. The frangibility index of these bullets was determined according to the individual interested range of impact velocities for an individual bullet from v_0 to v_{25}. The velocity of the bullet at a distance of 25 m is calculated using author's program

SR Sinterfire BiCu Bi100_7.62

Figure 4. Experimental cartridges.

Table 3. Values of coefficients of approximated Eqn (2)

Bullet	*a*	*b*	α
SR	110.73	-0.00106	1.3079
Sinterfire	157.10	-0.008609	0.9231
BiCu	1057.80	-0.90	0.285
BiCu Sinter	3762.50	-1.47	0.2359
Bi100_7.62	131.46	-0.013	1.122

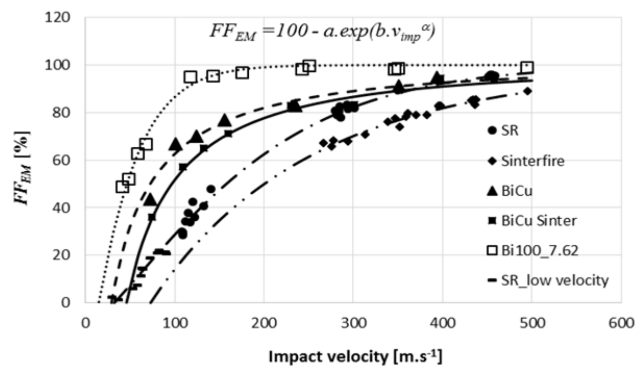

Figure 5. Dependences of frangibility factor on impact velocity for various types of frangible bullet.

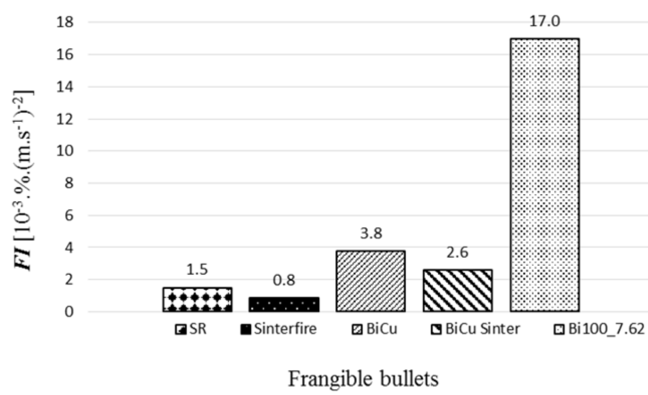

Figure 6. Frangibility index for various types of frangible bullet.

Table 2. Properties of the experimental bullet

Bullet	SR	Sinterfire	BiCu	BiCu Sinter	Bi100_7.62
Material of bullet	50 % Fe + 50 % Sn	-	50 % Bi + 50 % Cu	50 % Bi + 50 % Cu	100 % Bi
Mass (g)	5.16	6.48	7	7	4
Density (kg/m^3)	6650	7440	8670	8670	9550
Compressive strength (Mpa)	69.1	319	118.9	123.5	67.2
Production process	Cold compaction	Commercial frangible bullet	Cold compaction	Cold compaction and sintered at 220 °C for 60 minutes	Cold compaction
Compaction pressure (Mpa)	472		472	472	439

of external ballistics. The ballistic coefficients (drag law 1943) of bullets SR, Sinterfire, BiCu (BiCu Sinter) and Bi100_7.62 are 28.7 (m^2/kg), 21.2 (m^2/kg), 23.6 (m^2/kg) and 103 (m^2/kg), respectively. These ballistic coefficients are derived from the decrease of bullet's velocity on the trajectory when shooting into the target at a distance of 5 m from the barrel muzzle. In Table 4, the calculation of the frangibility index in the range of interest of the impact velocity for selected bullets is shown. The table shows that the *SF* value for Bi100_7.62 bullet is the highest. The Sinterfire bullet has the lowest *SF* value. The BiCu bullet has a lower *SF* value than SR bullet. The Sinterfire bullet has higher impact velocities than the BiCu bullet; however, its *SF* value is still lower.

The mean value FF_{EMS} and the arithmetic average FF'_{EMS} are slightly different; the value of FF_{EMS} is more objective. For example, the FF'_{EMS} values for SR bullet and BiCu Sinter bullet are almost the same, but the FF_{EMS} values of these bullets are different (94.4 % and 90.6 %).

In addition, the *SF* values of various types of bullet are also calculated in the same range of impact velocity of 200 - 400 m/s (namely $SF_{200-400}$). In this case, the frangibility order of the bullet is the same as the frangibility index *FI*.

Figure 6 and Table 4 show that the sort order of frangibility for various types of frangible bullets is different depending on the evaluation criteria. The sort order of frangibility according to the *FI* and the $SF_{200-400}$ for experimental bullets is the same. The sort order of frangibility according to the *SF* and the FF_{EMS} is the same. According to all of the criteria, the Bi100_7.62 bullet has the highest frangibility, and the Sinterfire bullet has the lowest frangibility. On the other hand, the sort order of frangibility according to the *FI* and the $SF_{200-400}$ consists of the sort order of compressive strength of bullets. For example, the frangibility of Sinterfire bullet (compressive strength of 319 MPa) is lower than the frangibility of BiCu bullet (compressive strength of 118.9 MPa), though the impact velocity of Sinterfire bullet is higher than the BiCu bullet (Table 4).

Table 4. Calculation of the frangibility index in the interested range of impact velocities

Bullet	SR	Sinterfire	BiCu	BiCu Sinter	Bi100_7.62
v_0 (m/s)	466	439	406	406	494
v_{25} (m/s)	406	399	361	361	313
SF (%.m/s)	5666	3348	4149	4075	18099
FF_{EMS} (%)	94.4	83.7	92.2	90.6	100.0
FF'_{EMS} (%)	92.1	83.6	91.1	92.2	100.0
$SF_{200-400}$ (%.m/s)	16157	13781	17718	17215	19968
FI (10^{-3}.%.(m/s)$^{-2}$)	1.5	0.8	3.8	2.6	17.0

5. CONCLUSION

Assessing the frangibility has a crucial meaning in researching and developing the frangible bullet. Frangibility can be quantified using the Frangibility Factor FF_{EM} and its derivation, which were proposed in this article - the frangibility index (*FI* and *SF*).

The proposed methods can be used to test the frangible bullet and to compare various types of frangible bullets.

In five experimental bullets, the bullet Bi100_7.62 has the highest frangibility, and the bullet Sinterfire has the lowest frangibility. The sort order of frangibility for various types of frangible bullets is different depending on the evaluation criteria. The evaluation method using Frangibility Index *FI* is more suitable for evaluating the frangibility of a frangible bullet.

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CONTRIBUTORS

Dr Xuan Son Bui obtained his PhD in specialisation Weapons and ammunition at Military academy in Brno, Czech Republic, in 2017. He works at the department of Munition at Le Quy Don technical university, Ha Noi, Viet Nam, as the lecturer and researcher. His areas of interest are ammunition, ammunition design, and mechanical fuze.
In this study, he did propose the evaluation method of frangibility of frangible bullet, testing, and evaluation frangibility of bullets.

Prof. Jan Komenda works as a associate professor at the Department of Weapons and Ammunition at University of Defence, Brno, Czech Republic, as the senior lecturer and researcher. His area of interest is ballistics, ammunition, and weapon.
He has extended supervision to the main author for the analysis, the outline of the research work and analysis of the results.

Dr Roman Vitek obtained his PhD in specialisation Weapons and ammunition at Military academy in Brno, Czech Republic, in 2000. He works at the department of Weapons and Ammunition at University of Defence, Brno, Czech Republic, as the senior lecturer and researcher. His area of research includes ballistic testing and measurement, digital signal and image processing, and software application development.
He is responsible for the preparation, carrying out, and evaluation of the experiments.