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Original article

The problem and analysis of vibrations appearing in N10 and N11 groups military vehicles with manually-operated armament modules

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INFORMATION

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ABSTRACT

This article is a continuation of work aimed to identify vibrations. It contains the results of tests, calculations, and analyses in the field of vibrations occurring on the elements of equipment of the N10 group tracked vehicle and the N11 group armored wheeled vehicle (classification according to NO-06-A103:2005) equipped with manually operated weapon systems. A detailed description of the analyses carried out, and the results of the research on the N10 group vehicle are contained in the article: "The Problem and Analysis of Vibrations Appearing in an N10 Group Military Vehicle Fitted with a Manually-Operated Armament Module" published in the quarterly Problems of Mechatronics Armament, Aviation, Safety Engineering. This study thoroughly presents the test results and their analysis for the N11 group vehicle and only recalls the results of similar tests and analyses for the N10 group vehicle for comparison. The research aimed to get acquainted with the characteristics of vibrations occurring in stabilized turret systems (weapon system) and devices supplying turret systems in terms of amplitudes, practical values, and their energy for various operating conditions. The analyses were carried out concerning the requirements of the Polish defense standard NO-06-A103:2005 and MIL-STD-810F regarding the correctness of their application.

KEYWORDS

vibrations, military vehicles, turret system

Introduction

The article presents a continuation of the author's work on vibrations appearing on equipment elements of N10 and N11 groups vehicles (Fig. 1). Detailed results of tests, calculations, and analyses concerning the N10 vehicle are included in the study [1]. The following article provides information on two vehicle groups, with an emphasis on the N11 vehicle group.

Vibrations are one of the most critical negative phenomena generated by systems and means of transport. They are undesirable since they have a significant impact on the level of safety

Fig. 1. Selected N10 and N11 groups vehicles
Source: Own study.

and technical environment degradation [2]. The assessment of the level of vibrations affecting the human body is one of the most crucial indicators that prove the comfort of travel [3]. The paper [4] presents an assessment of the comfort conditions for passenger transport in selected special-purpose vehicles. Failure to meet the criteria for the human body's exposure to vibrations resulting from vehicle motion may lead to severe disturbances of perception, making it difficult for the crew to perform operational activities. In turn, work [5] addresses the optimization of spring elements of the suspension system, adopting the criterion of minimizing vertical accelerations of the driver's seat in relation to the eight-hour exposure to vibrations. The conditions of comfort, optimization of chair elements, analysis of adverse effects affecting the human body described in the works [2-5] are essential, but one should also remember about the operational readiness index [6] as loss of combat readiness caused by too high vibrations can damage one of the main elements responsible for fire values, i.e., the turret system or its equipment.

The conducted research aimed to identify vibration levels occurring on stabilized turret systems (weapons systems) and devices supplying these systems (APU – Auxiliary Power Unit) integrated with military wheeled and tracked vehicles, Therefore, in accordance with NO-06-A103:2005, these were vehicles belonging to N10 (applies to devices installed in tanks and objects built on their base) and N11 (applies to devices intended for installation in light tanks, infantry fighting vehicles, wheeled armored personnel carriers and objects built on their basis) groups. The Polish defense standard requirements are very restrictive, and the research method proposed therein is mismatched in terms of the real conditions to which the test objects are subjected [1]. The research results presented in the article [1] for the object from the N10 group confirm that thesis, however, to prove it, a series of tests should be carried out on other objects from N10 and N11 groups. Therefore, the following article is a continuation of the author's works, the objective of collecting data in the aspect of vibrations appearing on elements of vehicle equipment of the groups mentioned above. The results contained in the article [1] showed that the revision of not only the requirements and expectations of modern armaments [6] but also the requirements contained in the normative documents is necessary.

The main subject of research and analysis were vibrations occurring on stabilized weapon systems, as it is a key module on a military vehicle used for combat. The effectiveness of stabilized turret systems depends mainly on the operating parameters of the stabilization system [8], whose task is to maintain the aiming line set by the target operator [9]. The stabilization system includes the main part of the tower system equipment, which is exposed to vibrations [1], however, all elements of the equipment of the tower system shown in Figure 2 are essential equipment for the performance of the fire task.

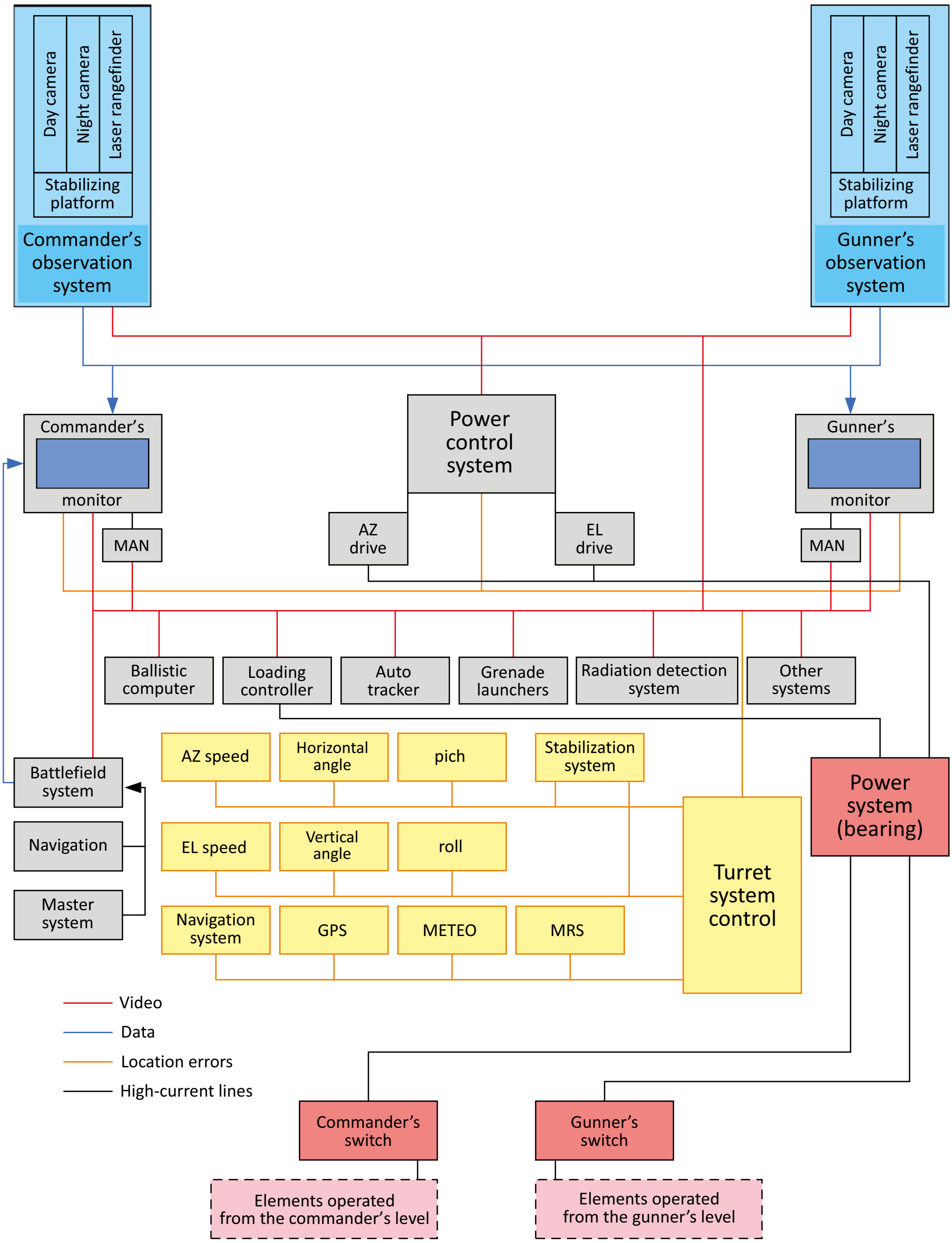
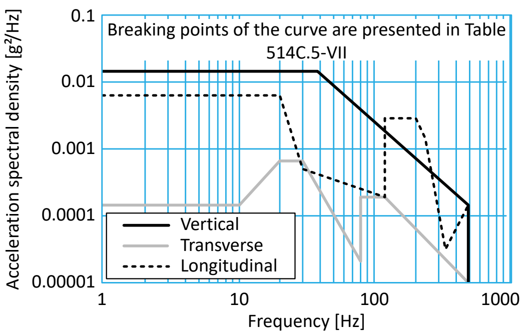


Fig. 2. Block diagram of the exemplary turret system construction
Source: [1].

An additional subject of research and analysis were vibrations occurring on auxiliary power units. APUs exposed to vibrations are subject to random damage resulting from an accidental change of the value of at least one of the basic parameters of the product beyond the acceptable tolerance limits and is the cause of failure [3]. Taking into account the demand for energy necessary for the stabilized weapon system operation that, depending on the caliber of the weapon (also related to the weight), ranges from 7.2 kW (for stabilized turret systems with a 30 mm gun in extreme operating conditions) to even 24 kW (for stabilized turret systems with a 120 mm gun in extreme operating conditions) and in case of failure, limits the further use of the key equipment element, i.e., armament.

1. Requirements of Polish and foreign standards

The requirements of MIL-STD-810F in accordance with procedure 514.5 contain detailed information and sinusoidal vibration values for testing devices intended for installation in military vehicles (Fig. 3).



Exposure values					
Vertical		Transverse		Longitudinal	
Hz	g²/Hz	Hz	g²/Hz	Hz	g²/Hz
10	0.01500	10	0.00013	10	0.00650
40	0.01500	20	0.00064	20	0.00650
500	0.00015	30	0.00065	120	0.00020
1.04 g rms		78	0.00002	121	0.00300
		79	0.00019	200	0.00300
		120	0.00019	240	0.00150
		500	0.00001	340	0.00003
		0.204 g rms		500	0.00015
				0.740 g rms	

Fig. 3. Vibration exposure for wheeled vehicles
Source: (METHOD 514.5, MIL-STD-810F) [10].

The requirements of the Polish defense standard NO-06-A103:2005 contain general information and values of sinusoidal vibrations to which devices intended for installation in N10 and N11 groups military vehicles should be subjected, and they differ in relation to the requirements of MIL-STD-810F. Vibration amplitude during tests of N10 and N11 devices according to the above-mentioned defensive standard in the entire frequency range from 5 Hz to 500 Hz should be 60 m/s² (6.12 g). A derogation is also allowed for the devices of the mentioned groups intended for installation in the turret (armament system), upon agreement with the customer, sinusoidal vibrations may occur in the 1-500 Hz frequency range with an acceleration amplitude of 30 m/s² (3.06 g). For devices planned for installation in the engine and transmission compartment and at the bottom of the vehicle, sinusoidal vibrations should be in the 1-500 Hz frequency range with an acceleration amplitude of 100 m/s² (10.2 g) [11].

2. Theoretical analyses

The durability of vehicle equipment elements in aspect of mechanical vibrations is the ability of these elements to transfer mechanical loads. The article will specify the minimum and maximum values (vibration amplitudes) and the effective values of accelerations to which the elements of the N10 group vehicles are exposed. Besides, spectral analyses of the recorded signals will be carried out.

The minimum and maximum vibration values define the peak exposure values to which items of equipment are subjected.

The effective values of vibration acceleration (the root mean square of the instantaneous vibration values) is a measure of the vibration amplitude. It characterizes the vibration taking account of the vibration time history and contains information about the amplitude value.

$$A_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)dt} \quad (1)$$

Spectral analysis is a key tool to study vibration signals [12]. It is based on the systematic vibration signal analysis for the presence of vibrational images of all defects that may affect the considered installation [13-17]. The work focuses on the analysis of vibrations occurring in the points shown in Figures 8 and 9. Each signal lasts in time and is built of a certain number of harmonics with an appropriate amplitude and initial phase. The number of harmonics, their amplitude, and the initial phase depends on the form of the signal. Since the signal can be broken down into harmonics, it has a frequency representation [18]. Periodic signals can be presented in the form of the complex (2) or trigonometric Fourier series (4).

$$x(t) = \sum_{-\infty}^{\infty} \underline{X_n} \cdot e^{jn\omega_1 t} \quad (2)$$

where:

X_n – coefficients of the complex Fourier series.

$$\underline{X_n} = \frac{1}{T}\int_{t_0}^{t_0+T} x(t) \cdot e^{-jn\omega_1 t} \cdot dt = |X_n| \cdot e^{-j\varphi_n} \quad (3)$$

where:

$|X_n|$ – signal amplitude spectrum,

φ_n – signal phase spectrum.

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cdot \cos n\omega_1 t + b_n + \sin n\omega_1 t] \quad (4)$$

where:

a_0, a_n, b_n – coefficients of signal distribution with period T,

ω_1 – basic signal pulsation.

$$a_0 = \frac{1}{T}\int_{t_0}^{t_0+T} x(t) \cdot dt \quad (5)$$

$$a_n = \frac{2}{T}\int_{t_0}^{t_0+T} x(t) \cdot \cos(n\omega_1 t)\, dt \quad (6)$$

$$b_n = \frac{2}{T}\int_{t_0}^{t_0+T} x(t) \cdot \sin(n\omega_1 t) dt \quad (7)$$

In dependencies: 5, 6 and 7:

t_0 – beginning of the signal period,

t_0+T – end of signal period,

n – consecutive number of the signal harmonics,

$\frac{2\pi}{T}$ – frequency of the fundamental signal harmonics.

The spectral analysis of the recorded vibration signal was preceded by the signal analysis in terms of meeting Dirichlet conditions. The selected signals (functions) for analysis were absolutely integrable for any period (8), for any time interval they had a finite number of extremes and for any time interval they had a finite number of continuous points [19].

$$\int_{-\infty}^{\infty} |x(t)| dt < \infty \quad (8)$$

3. Results of experimental research and analysis

Identical measurement conditions were assumed for objects from N10 and N11 groups, the places of sensor installation were as close as possible, and analogous calculations were made.

3.1. Test conditions, objects, and method

The test objects were a heavy tank from the N10 group and a wheeled APC from the N11 group. The tests were carried out on two types of ground, a military range path (Fig. 4) and cobblestones (Fig. 4) – these are the terrain conditions in which military vehicles operate. The tests were carried out for two different travel speeds, approximately 10 km/h and approximately 20 km/h, and, additionally, for speeds of approximately 30 km/h and approximately 20 km/h for the tank. The selected speeds of 10 km/h and 20 km/h are not accidental but result from tests conducted in the 1990s, which assessed the impact of vehicle speed on the probability of hitting the target [20].

Fig. 4. Path section: military range on the left, cobblestones on the right
Source: Own study.

Vibration measurements used three three-axis PCB 356A16 sensors with a 50 g range (Fig. 5) and a data acquisition station with the NI cDAQ-9172 module and three NI9233 (2 pcs.) and NI9234 (1 pc.) measurement cards (Fig. 6). The NI SignalExpress 2015 software with an algorithm developed for the test purposes was used for communication and data recording (Fig. 7).

Fig. 5. A set of PCB sensors
Source: Own study.

Fig. 6. Data acquisition station
Source: Own study.

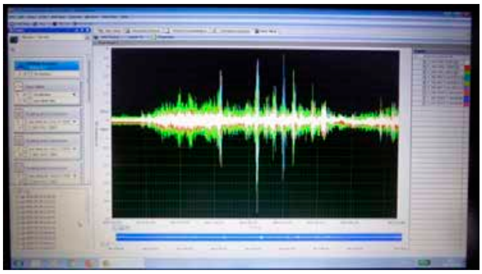


Fig. 7. NI SignalExpress 2015 software
Source: Own study.

Three-axis vibration sensors were placed on the test objects according to the adopted XYZ coordinate system shown in the figures below (Figs. 8 and 9).

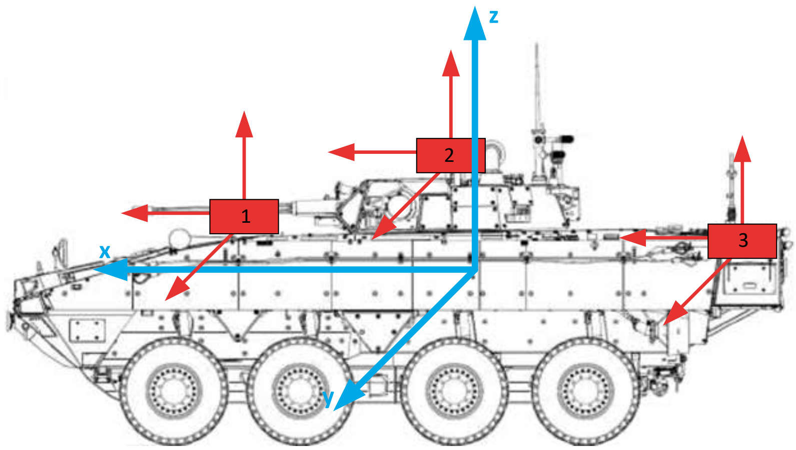


Fig. 8. Overview sketch of the wheeled APC (N11 group)
and the location of vibration sensors (1 – Hull, 2 – Sight, 3 – APU)
(according to MIL-STD-810F: Longitudinal – X, Traverse – Y, Vertical – Z)
Source: Own study.

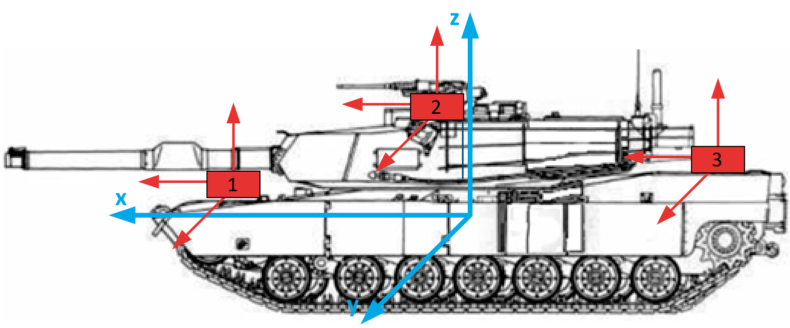


Fig. 9. Overview sketch of a tracked vehicle (N10 group)
and locations of vibration sensors (1 – Hull, 2 – Sight, 3 – APU)
(according to MIL-STD-810F: Longitudinal – X, Traverse – Y, Vertical – Z)
Source: Own study.

3.2. Analysis of maximum and minimum vibration values

The maximum acceleration values for the performed tests did not exceed 2.4 g (26.5 m/s² upwards) and 2.7 g (26.5 m/s² downwards). Figures 10-12 display the maximum and minimum acceleration values as a function of the object speed recorded on the N11 group vehicle while driving on the military range path and cobblestones. Based on the analysis of the presented data, it can be unequivocally stated that in none of the selected sensor installation locations values higher than those required in NO-06-A103:2005 on the tested object were recorded.

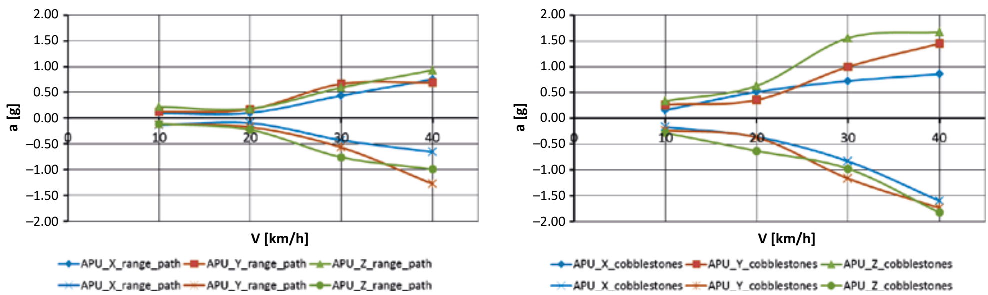


Fig. 10. Maximum and minimum acceleration values recorded based on the N10 vehicle APU for various speeds (driving on the military range path and cobblestones)
Source: Own study.

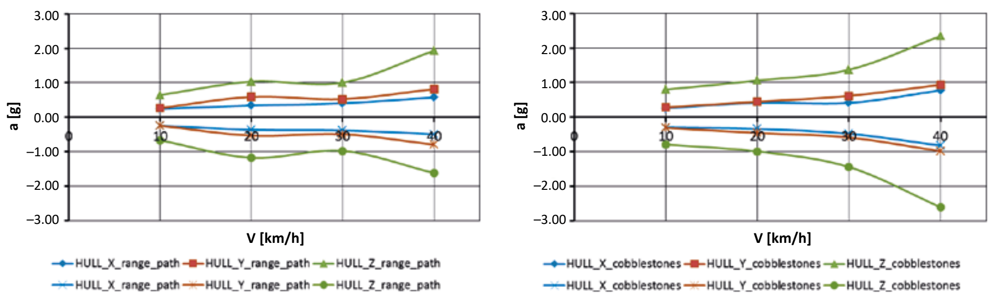


Fig. 11. Maximum and minimum acceleration values recorded on the upper plate of the N10 vehicle hull for various speeds (driving on the military range path and cobblestones)
Source: Own study.

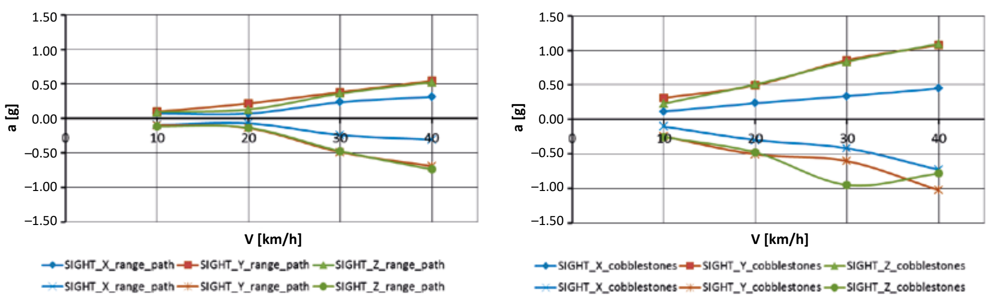


Fig. 12. Maximum and minimum acceleration values recorded based on the N10 vehicle observation device for various speeds (driving on the military range path and cobblestones)
Source: Own study.

Comparing the maximum and minimum acceleration values for the N10 object, it can be concluded that the maximum acceleration values for the speed of approximately 20 km/h in the Z axis exceeded those required in NO-06-A103:2005 and were higher than 6.12 g (60.0 m/s²), both while driving on the military range track and cobblestones [1]. The highest amplitudes were recorded on the vehicle top plate in the Z axis at the speed of approximately 20 km/h on the military range track and were –7.47 g (75.9 m/s²) and 7.90 g (77.5 m/s²). Thus, they were about three times higher than for the N11 object.

3.3. Analysis of effective vibration values

The effective vibration value (RMS) is the optimal indicator characterizing vibrations as it takes into considerations both the time history of the course and information about the amplitude value. The highest effective vibration value for the N11 group object was also recorded on the hull upper plate along the Z axis but it did not exceed the value of 0.3 g (2.9 m/s²) and occurred during the driving on the cobblestones. Figures 13, 14 and 15 display the effective acceleration values recorded in the places where the N11 vehicle sensors were mounted for different travel speeds (driving on the military range track and cobblestones).

Comparing the effective vibration values for the group N10 object, which were recorded on the upper plate of the hull in the Z axis while driving not on cobblestones but along the military range path, it can be concluded that they were ten times higher than for the N11 group object and exceeded the value of 3 g (29.4 m/s²) [1].

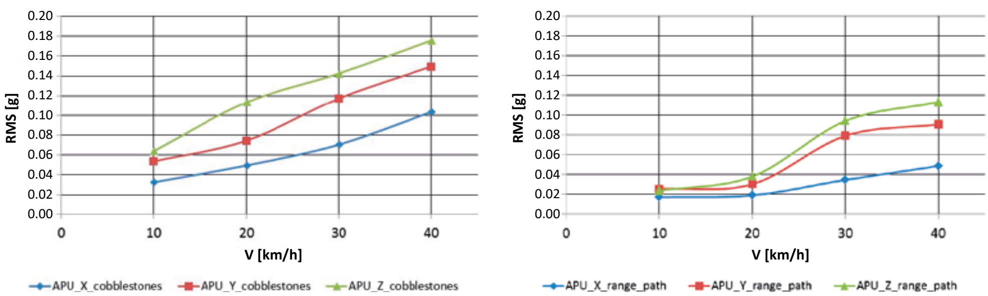


Fig. 13. RMS values recorded based on the N11 vehicle APU for various speeds (driving on the military range path and cobblestones)
Source: Own study.

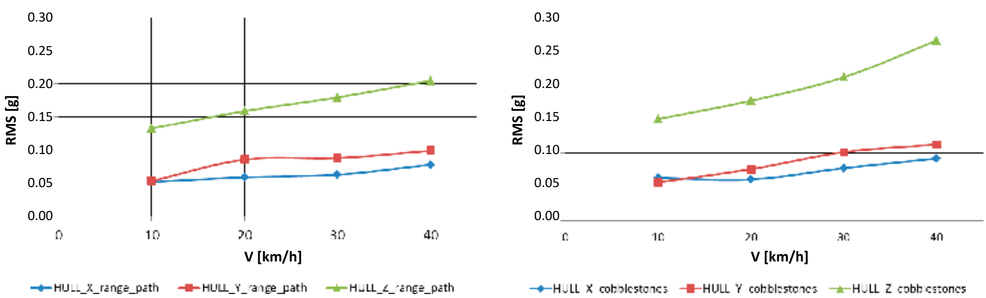


Fig. 14. RMS values recorded on the upper plate of the N11 vehicle hull for various speeds (driving on the military range path and cobblestones)
Source: Own study.

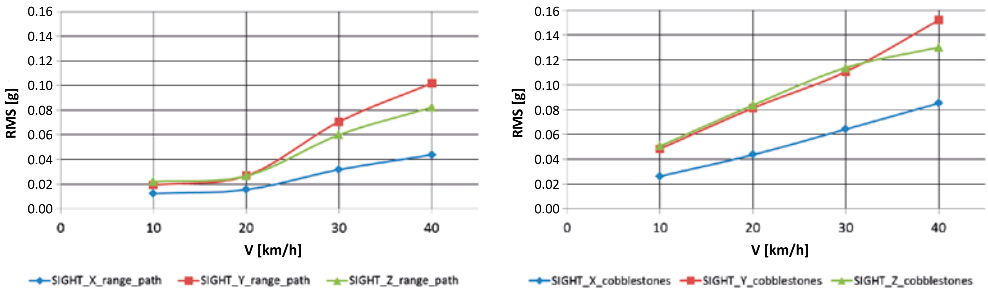


Fig. 15. RMS values recorded based on the N11 vehicle observation device for various speeds (driving on the military range path and cobblestones)
Source: Own study.

3.4. Power Spectral Density (PSD) analysis

The research subject and objective were to obtain data for the calculation and analysis of the acceleration values occurring on the turret system elements, the APU, and the top plate, however the limitations of the article size make it impossible to present all the results of calculations and analyses in detail. Thus, the article will present only selective calculations and analyzes concerning the N11 group object, in which the vibration values exceeded those required in the standards mentioned. The article [1] gives details about the N10 object.

For the required frequency range in accordance with MIL-STD-810F, for a vehicle classified to the N11 group, it can be concluded after calculations and analyses that the content of frequency components is exceeded, which is shown in Tables 1-3 and, for example, selected diagrams of power spectral density (PSD) for the assumed test conditions. Tables 1 to 3 show the observed exceedances of the energy values (NO) and the not exceeded energy values (OK) for the assumed measurement conditions, while driving along the military range path and the cobblestones for four various speeds for the N11 group vehicle.

Due to the large number of PSD diagrams obtained for the object N11, the number of which is 72, the article will only present selected ones, in which the required energy values were exceeded.

Figure 16 shows the spectrum of accelerations in the Y and Z axes recorded on the upper plate of the N11 hull, in the 5-500 Hz frequency range for driving on cobblestones at speeds of approximately 30 km/h and approximately 40 km/h.

Table 1. Value exceedance of the required energy on the APU

	APU_cobblestones				APU_range_path			
Axis	Speed [km/h]				Speed [km/h]			
	10	20	30	40	10	20	30	40
X	OK	OK	OK	OK	OK	OK	OK	OK
Y	OK	OK	NO	NO	OK	OK	OK	OK
Z	OK	OK	NO	NO	OK	OK	NO	OK

Source: Own study.

Table 2. Value exceedance of the required energy on the top plate

HULL_cobblestones					HULL_range_path			
Axis	Speed [km/h]				Speed [km/h]			
	10	20	30	40	10	20	30	40
X	OK	OK	OK	OK	OK	OK	OK	OK
Y	OK	OK	NO[1]	NO[1]	OK	OK	NO	NO
Z	OK	OK	NO[1]	NO[1]	OK	OK	OK	OK

[1] – the result of calculations and analyses is presented in Figure 10

Source: Own study.

Table 3. Value exceedance of the required energy based on the observation device

SIGHT_cobblestones					SIGHT_range_path			
Axis	Speed [km/h]				Speed [km/h]			
	10	20	30	40	10	20	30	40
X	OK	OK	OK	OK	OK	OK	OK	OK
Y	NO[2]	NO[2]	NO[2]	NO[2]	OK	OK	NO	NO
Z	OK	OK	OK	NO	OK	OK	OK	OK

[2] – the result of calculations and analyses is presented in Figure 11

Source: Own study.

From the presented Figure 16, one can observe the exceedances for driving at a speed of approximately 30 km/h by an order of magnitude in the Y axis for the requirements in accordance with MIL-STD-810F, and slight exceedances in the Z axis. For the driving speed of approximately 40 km/h, there are also exceedances in the Y axis by an order of magnitude, and slight exceedances in the Z axis. For all cases, the exceedances occur in the low frequency range.

Figure 17 shows the spectrum of accelerations along the Y axis, recorded based on the observation device installed on the N11 object. Data were also recorded in the 5-500 Hz frequency range for driving on cobblestones at speeds of approximately 10, 20, 30 and approximately 40 km/h.

On the presented Figure 17, it is possible to observe the exceedances during the data recording for all the assumed speeds. They increase in the same frequency range as the speed of the test object increases. It can be clearly stated that under all presented conditions, they exceed the requirements for the tests to which the objects assembled on the N11 group objects are subjected in accordance with MIL-STD-810F.

Compared to the N10 object, it can be clearly stated that the energy exceedances mainly occur in the low frequency range. Also, the exceedance values are slightly higher than the values to which the devices intended for mounting on the N10 group objects are subjected, which cannot be stated for the N11 group object. The energy exceeds also appear in the low frequency range (30-40 Hz), but they are much higher. The recorded and presented energy values in article [1] are two or even three orders higher than the required values according to MIL-STD-810F.

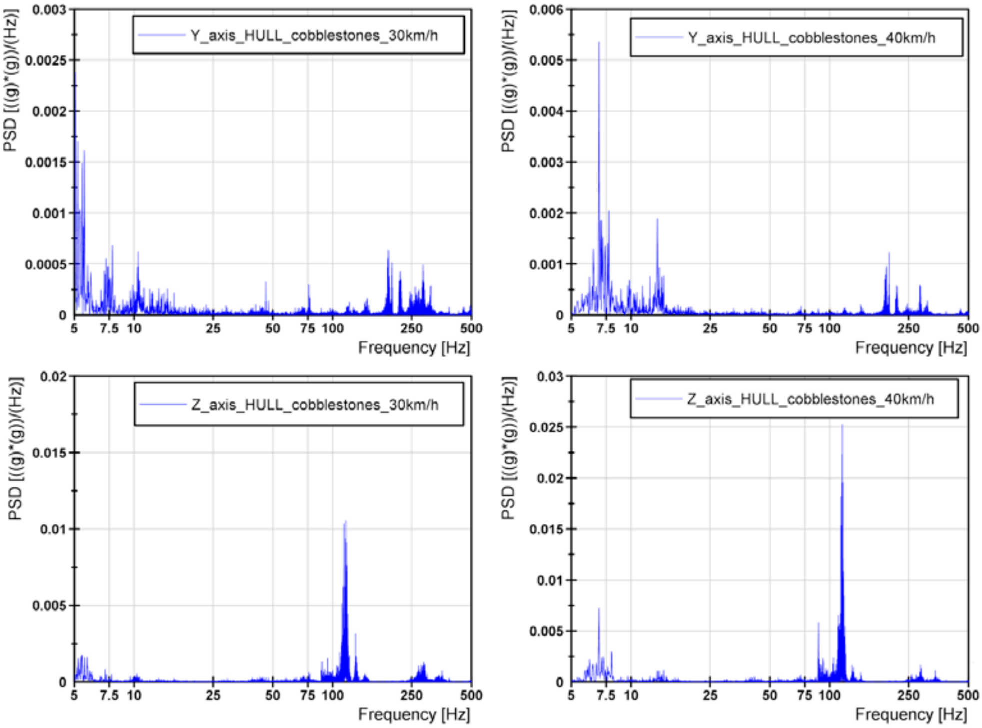


Fig. 16. The spectrum of accelerations in the Y and Z axes on the hull plate in the 5-500 Hz frequency range for driving on cobblestones at speeds of approximately 30 km/h and approximately 40 km/h
Source: Own study.

In the high frequency range from 5 Hz to 4 kHz for the N11 group object no significant harmonics were found, for the N10 group object the frequency components were found in the mentioned range. They exceeded the required energy values ranging from 5 to 500 Hz in the X, Y and Z axes for speeds of about 10 and 20 km/h. Selected results are presented in the article [1].

Conclusions

The conducted tests and the analysis of the maximum and minimum (negative) values of vibrations occurring in the tested objects in the 5-500 Hz frequency range showed exceeding the ranges for the N10 group object regarding the defense standard NO-06-A103:2005. Exceedances of the maximum and minimum vibration values were not registered for the N11 group object.

The determination of the statistical measure of the vibration value through specifying the effective vibration value made it possible to estimate the time history of the vibration course considering the information on the amplitude. For the N10 group object in the Z axis, the RMS values of vibrations were ten times higher than for the N11 group object.

By analyzing the spectral distributions of the acceleration values in the 5-500 Hz frequency range for the N10 group object, it can be concluded that significant exceedances were

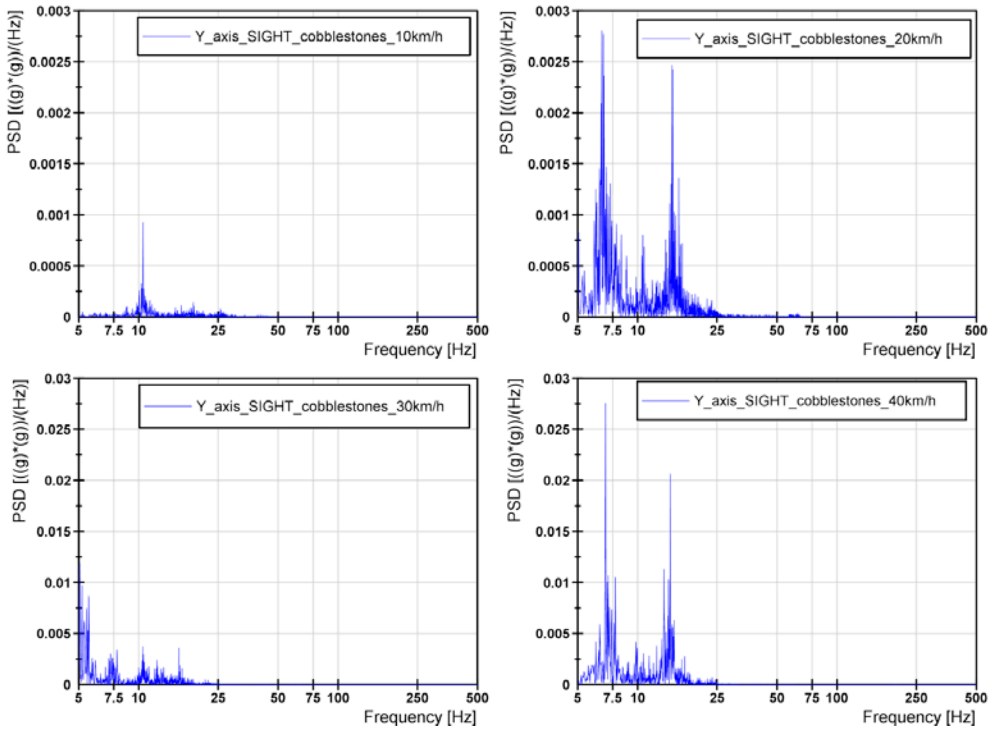


Fig. 17. The spectrum of accelerations in the Y axis on the hull plate in the 5-500 Hz frequency range for driving on cobblestones at speeds of approximately 10, 20, 30 and 40 km/h
Source: Own study.

recorded in virtually all measurement points. For the N11 group object, energy exceedances were also recorded, however, they are insignificant and occur in the low frequency range, which proves the necessity to conduct additional tests for this type of object. The tests also showed the occurrence of vibrations for the N10 group object with frequency components in the range above 500 Hz and the energy value, which is given for the range of 5-500 Hz in the document MIL-STD-810F. No significant components above 500 Hz were registered for the N11 group object.

The conducted tests showed that the values of permissible vibrations in the operating conditions of military vehicles were exceeded beyond the required ranges to which the elements of equipment are subjected during laboratory tests. These exceedances may lead to their malfunction, and in extreme cases to damage or failure. Therefore, the problem of determining the actual vibrations appearing on N10 and N11 groups objects is of key importance and should be known. The presented work contains only information on the actual vibration values for the two selected objects and cannot be, from the statistical point of view, the result of changes made in normative documents.

It seems indispensable to continue exploratory work to collect as much data for analysis as possible to get to know the vibration values in detail and confirm the correctness of the obtained results and the validity of the adopted thesis.

At the moment, it can be clearly stated that the requirement NO-06-A103:2005 that requires carrying out laboratory tests in the 5-500 Hz frequency range and with an amplitude of 60 m/s^2 (6.12 g) is inadequate to the actual operating conditions. The linear characteristic of frequency changes for the constant amplitude of vibrations in the Polish standard can take place only during laboratory tests; the adoption of a random change in MIL-STD-810F seems to be a more correct approach, reflecting the actual exposure to which the objects are subjected. NO-06-A103:2005 and MIL-STD-810F contain exposure ranges and values, which turned out to be a subset of the vibration values recorded during the tests.

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Conflict of interests

All authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

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Analiza i problem drgań występujących w pojazdach wojskowych grup N10 i N11 z zainstalowanymi ręcznie sterowanymi modułami uzbrojenia

STRESZCZENIE Artykuł to kontynuacja prac, celem których jest poznanie rzeczywistych wibracji. Zawiera wyniki przeprowadzonych badań, obliczeń i analiz w zakresie wibracji występujących na elementach wyposażenia pojazdu gąsienicowego z grupy N10 oraz opancerzonego pojazdu kołowego z grupy N11 (klasyfikacje wg NO-06-A103:2005) wyposażonych w ręcznie sterowane systemy uzbrojenia. Szczegółowy opis przeprowadzonych analiz oraz wyniki badań w zakresie pojazdu grupy N10 zawarte są w artykule: „The Problem and Analysis of Vibrations Appearing in an N10 Group Military Vehicle Fitted with a Manually-Operated Armament Module" opublikowanym w kwartalniku Problems of Mechatronics Armament, Aviation, Safety Engineering. Niniejszy artykuł gruntownie prezentuje wyniki badań oraz ich analizy dla pojazdu grupy N11 i przywołuje jedynie wyniki analogicznych badań i analiz dla pojazdu grupy N10 w celu ich porównania. Przeprowadzone badania miały na celu zapoznanie się z charakterystyką drgań występujących na stabilizowanych systemach wieżowych (systemie uzbrojenia) oraz urządzeniach zasilających systemy wieżowe w aspekcie amplitud, wartości skutecznych oraz ich energii dla różnych warunków eksploatacji. Analizy przeprowadzono w odniesieniu do wymagań polskiej normy obronnej NO-06-A103:2005 oraz MIL-STD--810F w aspekcie słuszności ich stosowania.

SŁOWA KLUCZOWE drgania, wibracje, pojazdy wojskowe, systemy wieżowe

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