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Analysis and Parameter Identification of Automatic Cannon Carriages

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ABSTRACT

Experimental procedures for the research of vibrations in automatic weapons mounted on combat vehicles is introduced. Experiment preparation procedures, experience and examples of evaluation of measured results in direct fire from a tracked combat vehicle are explained on BMP-2 IFV example. The result is the movements of the turret and the hull of a combat vehicle in single shot firing, and short and long burst firing. In addition to time domain analysis, methods of correlation and spectral analysis are used. Live firing experiments are complemented by laboratory experiments and are used to determine model parameters for calculations such as stiffness and damping in the suspensions of the hull, elevation parts, clearance in the elevating gear, and the natural vibration frequency of the hull and elevation parts.

Keywords: Automatic cannon; Combat vehicle; Weapon mounting; Turret; Elevating parts; Cradle; Correlation function; Spectrum analysis

1. INTRODUCTION

One of problems that need to be solved when automatic weapons fire, is an elimination of the undesirable effects of carriage and basic structure vibrations. Vibrations influence the stable position of the weapon when firing. The important characteristic is the firing stability of the weapon. The weapon is stable if maintains the set (aimed) position of the barrel muzzle at the moment the projectile leaves the barrel[1-2]. The changes of the aiming angle reduce the hit probability mainly in the case of firing bursts[3-4]. The aiming errors achieve, according to the fire power, values from several milliradians (light machine guns and automatic weapons on vehicles) to tens of milliradian (automatic grenade launcher)[3-4]. The calculations lead into the make-up of the discrete models having inertial, elastic and damping properties mainly as lumped parameters and the continuum characteristics are considered less (FEM)[1-6]. The research of weapon vibrations can be done purely experimentally or in combination with accompanying calculations, but rarely in a computational way. The article presents the possibilities of determination of some dynamic characteristics of the hull, turret, and elevation parts of small calibre cannon carriage. The characteristics were selected from the point of view of the necessary inputs for the calculation of the part of weapon system oscillation and the evaluation of the influence of the vibrations of the individual parts on the firing stability.

2. FIRING STABILITY OF AUTOMATIC WEAPONS MOUNTED ON TRIPODS

The experimental way of tripod mounted small arms firing stability included designing a special frame with the displacement gauges fixed on it, and the weapon could move[3]. The gauges measured the linear vertical displacements in the front and rear part of the weapon (y_F, y_R). The change of elevation angle was set according to the Eqn. (1):

$$\alpha = a\tan\left(\frac{y_F - y_R}{l_{FR}}\right) \tag{1}$$

where l_{FR} - distance between both sensors.

This method was used for investigation of the 7.62 mm M59 machine gun, and 30 mm AGS-17 grenade launcher[3]. The measuring method was improved by changing the inductive sensors with contactless laser displacement sensors. Their advantage was their quick preparation.

Similarly, contactless method with using of two high-speed cameras has been used on same M59 machine gun[3].

These optical methods allow one to determine the kinematic parameters of the barrel movement without interfering with the construction of the weapon. In the small-calibre automatic weapons shooting in laboratory firing ranges satisfactory results were achieved, while not in open terrain. Their use on other weapon parts, such as turrets and hulls requires improving procedures during experiment preparations with respect to environmental conditions. Contrast and reflectivity are the main parameters that need to be taken into account before the experiment. The method on the open firing range is affected by offset voltage and the degrading influence of background sunlight[3,4,7-9].

More difficult experiments have been associated with firing experiments from combat vehicles with turret-mounted automatic cannons.

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3. FIRING STABILITY OF AUTOMATIC CANNONS

3.1 Measuring Chain

A possible way of how to determine the movement of the hull and turret when an automatic cannon is turret-mounted and burst fires is discussed. Experience gained from small calibre arms was suitably employed for the analysis of operation of higher calibre weapons, particularly including automatic cannons mounted on vehicles. Balla[7], *et al.* described the twin anti-aircraft weapon system where the pendulum sensor was used for hull vibration recording. The record of the vibrations of the hull proved to be unsuitable for the purpose due to the higher time constant. No reliable data on vehicle hull vibrations has been obtained[7]. The other parameters investigated, such as the relative moves of the turret with respect to the combat vehicle body, cradle acceleration, recoil of both barrels, and the forces transferred to the cradle were successfully recorded.

To eliminate problems with the recording of hull vibrations, further experiments are described. In addition, it was necessary to determine the behaviour of the weapon system not only at 0° bearing, but also at other angles, especially at 90°.

Experiments were performed on a BMP-2 infantry fighting vehicle with a turret-mounted 30 mm automatic gas operated and recoiling barrel cannon. 300 HE projectiles were shot in single shooting mode, lower rate of fire of 250 shots per minute, and higher rate of fire of 550 shots per minute in a near-zero elevating angle at 0°. The turret bearings were 0° and 90°. The turret movement was measured with respect to the hull, and the hull movement was considered absolute to the terrain.

HBM (Hottinger Baldwin Messtechnik) inductive and strain gauge transducers measured the linear displacements (output values are in mm), and time when projectile leaves the barrel (output value is µm/m) as indicated in Fig. 1 and in Table 1.

Table 1. Measured parameters

Channel	Parameter	Value
t_E	Exit time of projectile from barrel	µm/m
y_{VP}	Linear displacement of the turret front with respect to the hull	mm
y_{VZ}	Linear displacement of the turret rear with respect to the hull	mm
y_{KOP}	Linear displacement of the front hull	mm
y_{KOZ}	Linear displacement of the rear hull	mm

The γ_t angular rotation of the turret, and the ψ_h angular rotation of the hull at 90° bearing were calculated using similar relations as in the Eqn. (1):

$$\gamma_t = a\tan\left(\frac{y_{vp} - y_{vz}}{l_v}\right), \quad \psi_h = a\tan\left(\frac{y_{kop} - y_{koz}}{l_{ko}}\right) \qquad (2)$$

where the numerators are measured linear displacement in the front and the rear part of the turret and the hull. The distances in the denominators of individual sensors are labelled l_v, l_{ko} according to the given bearing. The subscript index *t* belongs to the turret, and the other *h* to the hull.

The position of the 90° weapon bearing is evident from Fig. 1. Here l_v = 2000 mm, l_{ko} = 1940 mm. For 0° bearing, distances l_v, l_{ko} were changed to l_v = 2120 mm, and l_{ko} = 4500 mm. Similarly, the ψ_h angle of the hull is changed to θ_h.

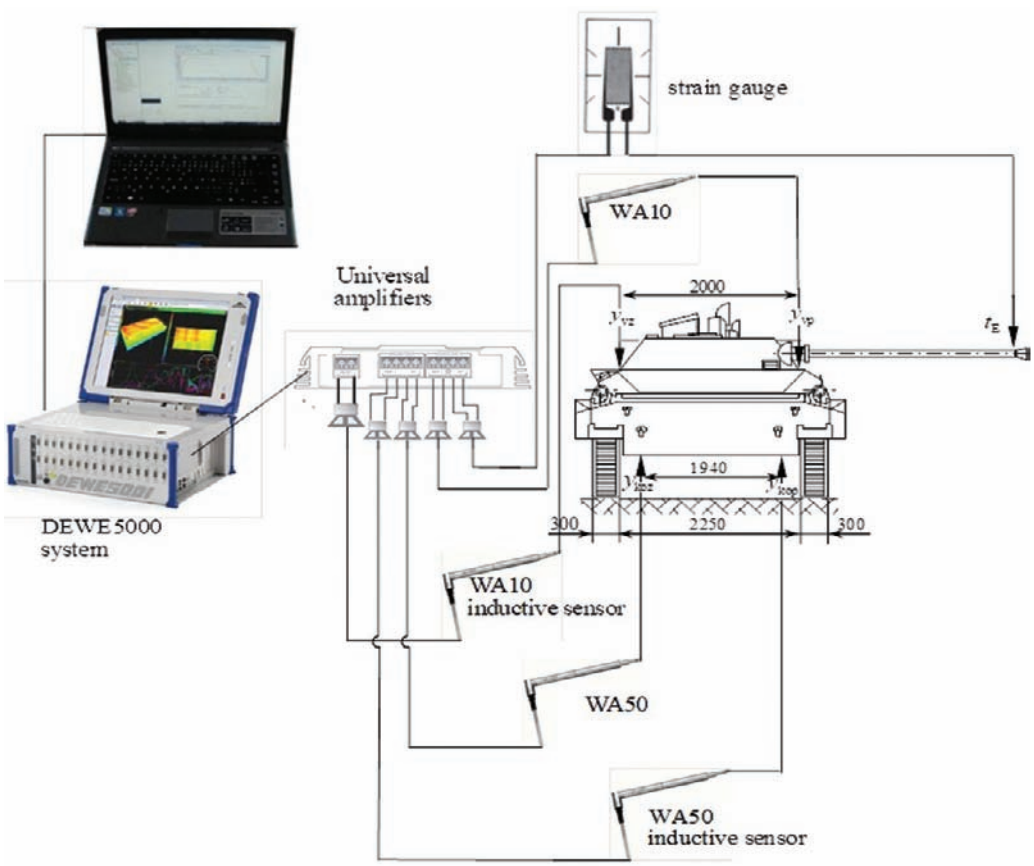

Figure 1. Five-channel measuring system scheme – bearing 90°.

The angular displacements of the turret and the hull are calculated from the individual displacements and distances between the sensors as shown in Fig. 1. The LY116/350 HBM strain gauge on the barrel muzzle set the time when projectiles exit the barrel. This moment in time is critical in terms of barrel positioning and mainly affects the aiming accuracy.

The five-channel measuring system scheme is as displayed in Fig. 1 (bearing is 90°). A similar configuration was used when the system fires with 0° bearing[8]. The individual signals are amplified and transmitted to the DEWE 5000 data logger. After transfer into ASCII code, the signals were processed by conventional software means such as Microsoft Excel®, MATLAB®, and Next View® software. The sample rate of 20 kHz has been chosen with a view to accurately determination when the projectile leaves the barrel. The reason was that the duration of the projectile movement in the barrel is a matter of a few milliseconds[9-11].

Pure signals had been pre-processed via high and low pass filters. The channels t_E, y_{VP}, y_{VZ} were filtered by 1 Hz through a high pass filter. The linear trends were removed. Low frequency filters of 100 Hz and 25 Hz filtered the channels recording turret and hull motion[12-15].

Analysis of the measurement records took place in the time domain also using the correlation functions and in the frequency domain for the determination of the spectra of the selected characteristics.

The significant characteristics of the signal are hidden in the correlation function enabling detection of the periodic signal component, or determination of the delay between the two signals[12]. The unbiased correlation function was calculated using the formula

$$R_{xx}(\tau) = \frac{1}{N - |m|} \sum_{n=1}^{N-m+1} x(n)x(n+m-1) \quad (3)$$

where

N – number of samples,

$m = 1, 2, \ldots, M+1$,

M – number of delay.

The spectral properties were determined by the standard procedures of Fourier transform as the spectral density is

$$G_{XX}(f) = \frac{2}{T} \cdot \left|X_T(jf)\right|^2 \quad (4)$$

where

$X_T(jf)$– Fourier transform of given signal x_T,

T – finite measurement time, f – frequency, j – imaginary unit.

3.2 Fire with 0° Bearing

Examples of measured results obtained from technical experiments follow in the next figures.

Hull and turret movements during 9 shots with a higher rate of fire (550 rds/min) are as shown in Fig. 2. This case is typical for the floating mount of weapons, where the hull (θ_h black line) does not return to its basic position during the shooting, and movement is stabilised at a new equilibrium position. In this case, the system even exhibits a tendency towards an unstable state. The reason is that for a low rate of fire the system can be returned to its basic position between shots. With higher rates of fire there is insufficient time to do so. Therefore, the floating mount is used in which subsequent shots are fired while the hull is still moving forward during fire, and until 0.5 s the θ_h angle rises to 2 mrad. After 0.4 s the hull is in the new basic position. The firing frequency is about 9 Hz (it corresponds to 550 rds/min), and the natural angular frequency of the hull is approximately 0.8 Hz. On the other hand the natural frequency of the turret is greater than 10 Hz, it is therefore able to follow changes in the excitation force.

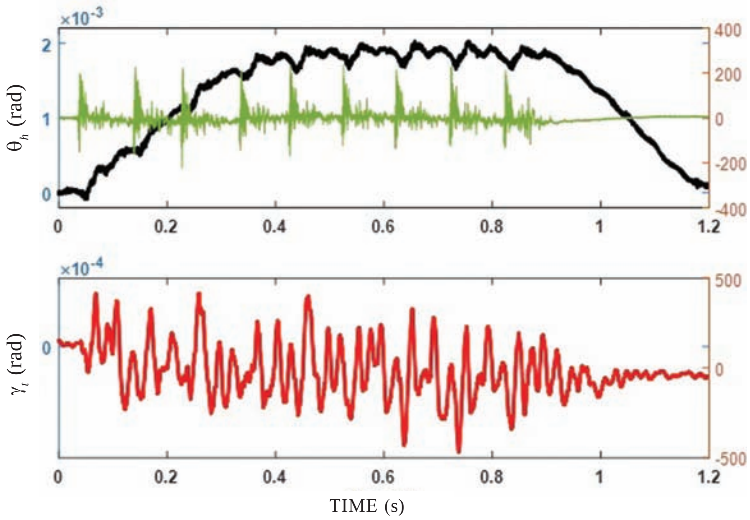

Figure 2. Hull (black) with strain gauge signal (green) and turret angular displacement (red) during nine burst shots.

The spectrum of the hull vibration confirmed the fact that the hull behaves as a low frequency filter[4]. This filter evenly passes the signals up to the limit frequency f_m. This range is called the bandwidth. The range is known as a band pass where for the limit frequency is[1]:

$$f_m = \frac{1}{2T_n} \quad (5)$$

where T_n is the rise time given with the tangent line in the point where the output (hull angular displacement) achieves half of the steady state value. In this case this is approximately 1.25 Hz (hull natural frequency f_θ is 0.8 Hz). The natural frequency 0.8 Hz of the hull was confirmed by the experiment in the next section of the article.

The γ_t turret movement displayed in Fig. 2 has a typical disordered movement. Hidden patterns can be detected by using spectral analysis and correlation functions, see Fig. 3. Significant frequencies are around 9.7 Hz and 30 Hz, which correspond to the shooting frequency and the natural frequency of the turret vibrations. Peaks in the correlation function represent individual shots in a burst, and the rate of fire of the weapon can also be determined from the shift between them. The first peak belongs to the first shot, and the lag between the second peak multiplied by the sample rate gives one shot cycle. These values correlate with the calculation of the spectrum density in Fig. 3 and the shooting frequency around 9.7 Hz is therefore confirmed.

3.3 Fire with 90° Bearing

Fire with a 90° bearing is less used in real conditions. Experimental results of the behaviour of parts of combat vehicles, in particular the hull and turret, have not yet been published. Records from the strain gauge sensor at the time when the projectile leaves the barrel were not recorded due to damage to the supply cables caused by a high barrel surface temperature after fire at 0° bearing. Figure 4 shows the hull (black line), and the turret (red line) angular displacements. In the figure the numbers of shots fired at a lower rate of fire is clearly recognisable. This example belongs to 250 rds/min rate of fire. It corresponds approximately to 4 Hz frequency of fire.

The situation corresponding to the bearing of 90° corresponds to the position of the combat vehicle according to Fig. 1 with the ψ angle of rotation of the hull. The system is characterised by a lower mass moment of inertia of the sprung parts compared to firing at 0° bearing. It is expected that the system will react faster than in 0° bearing. Frequency spectrum calculations have shown that the 3.4 Hz frequency is the instantaneous value of the rate of fire, which may, as in the previous case, differ from table cadence values[1,4,11]. The hull follows the changes of excitation forces due also to the dwell between each shot, when the breechblock carrier is caught in the rear position through an electromagnetic trigger mechanism.

The higher rate of fire when the bearing is 90° takes effect similarly as was mentioned previously in Fig. 2. The lower angles of the hull are caused due to a higher value of the natural frequency of the hull given with a higher value of suspension stiffness. Figure 5 shows the hull displacement (red line), and the turret displacement (green line).

4. PARAMETER IDENTIFICATION WITHOUT LIVE FIRING

Parameters were set without firing tests, especially those dealing with hull parameters. These are the natural frequency of the hull, damping characteristics and the parameters of the elevating parts such as: hull stiffness in the case of firing with 0° and 90° bearing, the hull linear damping coefficient, stiffness and clearance in the elevating gear.

4.1 Hull Parameters

The resistance of the whole suspension was determined by means of a jack and inductive displacement sensors as is as shown in Fig. 6. The angular displacement and the force exerted with the jack give the course of torque depending on the angle of the hull. The reduced angular stiffness of the hull mount on the flexible suspension calculated in the work[4] was confirmed as $k_\theta = 1.24\times10^6$ Nm/rad. The reduced rigidity of one flexible hinge wheel is 76 x 10^3 N/m. The configuration in the case of 90° bearing was similar.

For determination of the b_θ linear damping coefficient of the hull angular vibration and the f_θ natural frequency of the angular vibration of the hull vehicle was braked at a velocity of 20 km/h. From the dying hull oscillations

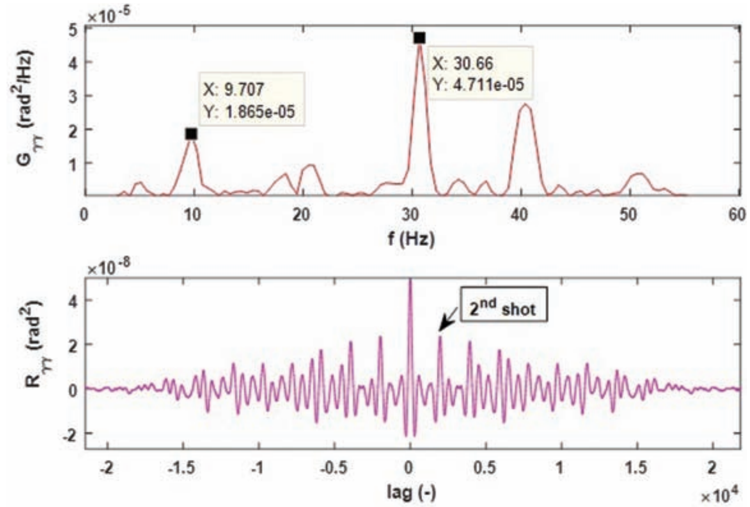

Figure 3. Spectral density and correlation function of turret vibration.

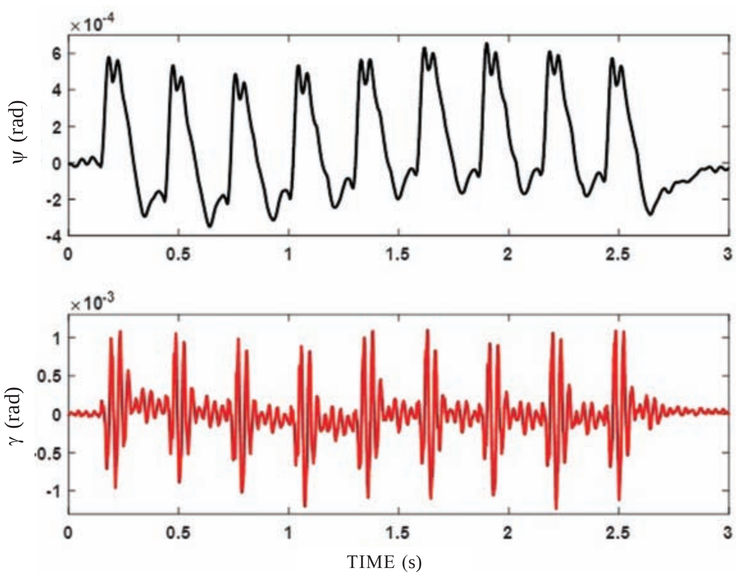

Figure 4. Hull and turret displacement after firing nine shots.

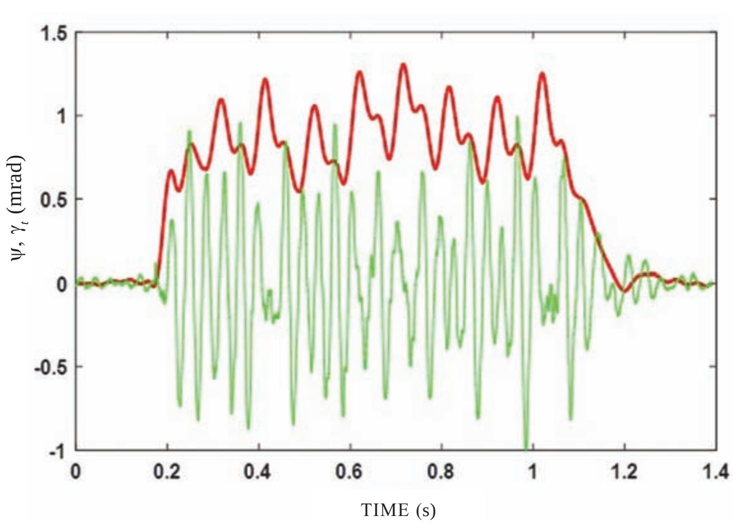

Figure 5. Hull and turret angular displacement.

the b_θ coefficient was set by means of two B1 Seika Kempten accelerometers, located on the hull as a_1, a_2, as shown in Fig. 6.

Signals from the accelerometers were twice integrated and after rearrangements, the result is as shown in Fig. 7.

The angular damped vibration frequency is as follows

$$f_\theta = \frac{1}{T_\theta} = \frac{1}{1.67 - 0.42} = 0.8 \text{ Hz.} \quad (6)$$

The logarithmic decrement[9,15]:

$$\Lambda = \ln\left(\frac{\theta^i_{yko}}{\theta^{i+1}_{yko}}\right) = \ln\left(\frac{0.0997}{0.0449}\right) = 0.797\,. \quad (7)$$

The damping ratio[9,15]:

$$\varsigma = \frac{\Lambda}{\sqrt{(2\pi)^2 + \Lambda^2}} = \frac{0.797}{\sqrt{(2\times\pi)^2 + 0.797^2}} = 0.125 \quad (8)$$

The natural angular frequency of undamped vibrations is

$$\omega_n = \frac{2\pi f_\theta}{\sqrt{1-\varsigma^2}} = \frac{2\times\pi\times 0.8}{\sqrt{1-0.125^2}} = 5.06\ rad/s \quad (9)$$

If we know k_θ, it is possible to determine the mass moment of inertia of the sprung parts with respect to the transverse axis

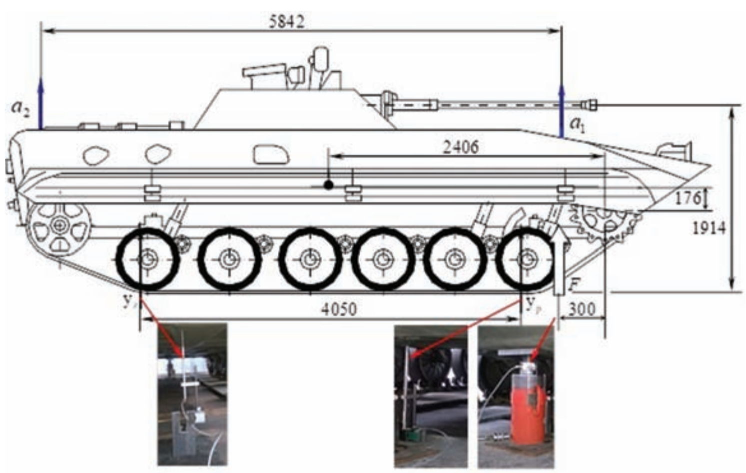

Figure 6. Hull measuring system configuration.

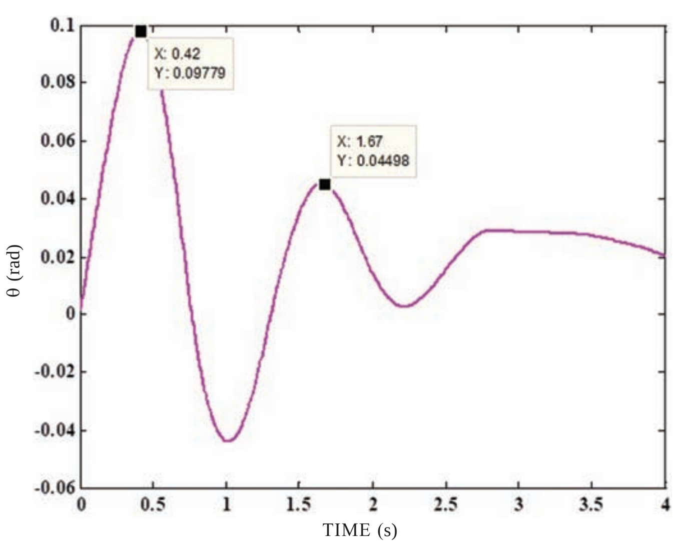

Figure 7. Free-decay record of vibration of the hull.

passing through their centre of gravity[9,15]:

$$I_\theta = \frac{k_\theta}{\omega_n^2} = \frac{1.24\times 10^6}{5.06^2} = 48\,430 \text{ kg}\cdot\text{m}^2 \quad (10)$$

The b_K critical and b_θ linearised damping coefficients[9,15] after substitution of numerical values are

$$b_K = 2\sqrt{k_\theta I_S} = 2\sqrt{1.24\times 10^6 \times 48430} = 490115 \quad (11)$$

$$b_\theta = 2\varsigma I_\theta \omega_\theta = 2\times 0.125\times 48430\times 5.03 = 60900 \quad (12)$$

The b_θ damping coefficient (N·m·s/rad) is used in a simplified differential equation of angular vibration of the combat vehicle body[2,11]

$$I_\theta\ddot{\theta} + b_\theta\dot{\theta} + k_\theta\theta = M_F \quad (13)$$

where M_F is exiting force moment of fire.

4.2 Elevating Parts Parameters

The elevating parts play an important role in the vibration of the combat vehicle together with the hull and the turret. The significant dynamic parameters are the stiffness of the elevating gear, design damping, mass moment of inertia and trunnion clearance. The elevating gears of tanks and infantry fighting vehicles have rigid mounting only in the case of going on roads or off-road without firing. In the case of battle the elevating gears cannot be caught stiff. This leads to the fact that in this displacement torques of the inertia forces are of considerable magnitude and wringing and winding of the gears and twisting of the shafts can occur. Similarly, as in the previous case on the hull, the logarithmic decrement and the damping ratio for the elevating parts were determined. Figure 8 shows the configuration for the experimental set of the k_{EG} elevating gear stiffness. The angular clearance in the elevating gear was similarly determined. Determination of the elevating gear stiffness consists of measuring the α_E rotation of the elevating parts from the M_E known torque attached statically.

The stiffness formula between the torque and the angle is

$$k_{EG} = \frac{M_E}{\alpha_E} = \frac{F\cdot l_F}{\frac{w_1}{l_T}} \quad (14)$$

The linearised value $k_{EG} = 724\ 000$ N·m/rad enables to determine the elevating parts mass moment of inertia with respect to the trunnion according to the formula

$$I_E = \frac{k_{EG}}{\omega_E^2} = \frac{724\,000}{(2\pi f_E)^2} = 279\ kg\cdot m^2 \quad (15)$$

The frequency of the damping vibration of the elevating parts is as given according to Fig. 9, and the following equation

$$f_E = \frac{1}{T_E} = \frac{1}{0.15 - 0.025} = 8 \text{ (Hz)} \quad (16)$$

The logarithmic decrement of the elevating parts

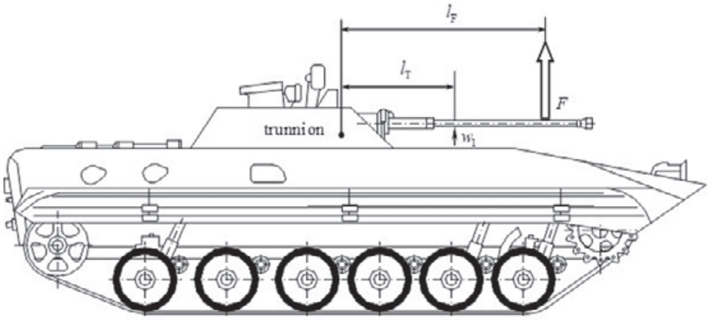

Figure 8. Elevating gear stiffness measuring configuration.

$$\Lambda_E = \ln\left(\frac{\alpha^i}{\alpha^{i+1}}\right) = \ln\left(\frac{0.001187}{0.0004129}\right) = 1.05 \tag{17}$$

The damping ratio of the elevating parts

$$\varsigma_E = \frac{\Lambda_E}{\sqrt{(2\pi)^2 + \Lambda_E^2}} = \frac{1.05}{\sqrt{(2\times\pi)^2 + 1.05^2}} = 0.164 \tag{18}$$

The natural angular frequency of natural vibrations is

$$\omega_{En} = \frac{2\pi f_E}{\sqrt{1-\varsigma_E^2}} = \frac{2\times\pi\times 8}{\sqrt{1-0.164^2}} = 50.9\ rad/s \tag{19}$$

The elevating parts parameters were put together with the hull parameters in Table 2.

Table 2. Parameters of automatic cannon carriage

f_{low}	Lower rate of fire	250 rds/min
f_{high}	Higher rate of fire	550 rds/min
f_Θ	Frequency of angular longitudinal vibration of the hull	0.8 Hz
f_ψ	Frequency of angular transversal vibration of the hull	1.2 Hz
f_t	Frequency of angular vibration of the turret	30 Hz
f_E	Frequency of angular vibration of the elevating parts	8 Hz
Λ_Θ	Logarithmic decrement of the hull	0.797
Λ_E	Logarithmic decrement of the elevating parts	1.05
I_Θ	Mass moment of inertia of the hull with respect to the lateral axis through the centre of gravity	48430 kg·m^2
I_ψ	Mass moment of inertia of the hull with respect to the longitudinal axis through the centre of gravity	15450 kg·m^2
I_E	Mass moment of inertia of the elevating parts with respect to the lateral axis through the trunnion	279 kg·m^2
k_{EG}	Elevating gear stiffness	724000 N·m/rad

5. CONCLUSIONS

The issues described in this paper are on the basis of the theory and the experimental work solving the dynamics of automatic weapon mounts and carriages.

Le[4] published one of the possible uses of the results published here. The dynamic model has 14 degrees of freedom, as shown in Fig. 10. The input data from this article were used in the calculations.

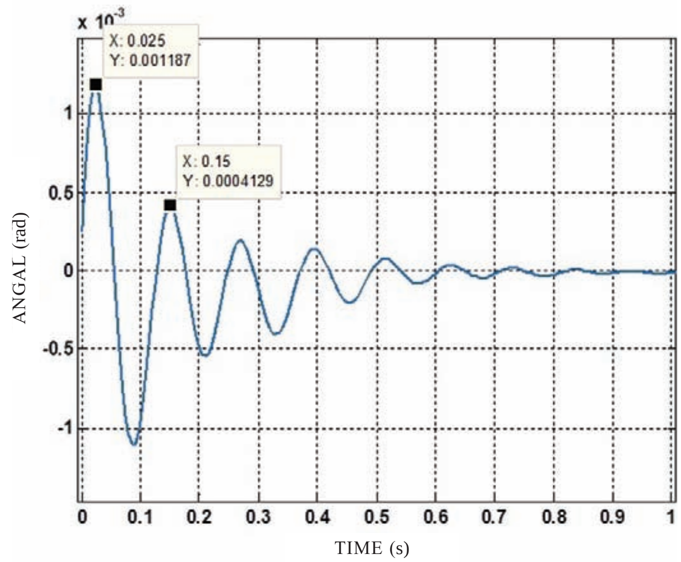

Figure 9. Natural vibration of elevating parts.

Control and comparative calculations showed compliance with the measurement up to 15 per cent. The oscillation processes depend not only on the precise values of the dynamic parameters, but also with the production tolerances of the ammunition, the technical condition of the weapon and, finally, the meteorological conditions at that moment. During preliminary testing of the weapon systems with automatic cannon, we must be careful of broader generalisations on other systems. This paper is one of the contributions into this area, and it requires further comprehensive theoretical and experimental work.

For a particular type of BMP-2 combat vehicle, it can be noted that aiming errors due to the body and turret vibrations reach up to 2 mrad in all firing modes without driving to ground targets. The question is what the impact of shooting is while driving with the simultaneous movement of the target.

We strongly recommend focusing attention on improving measurement with high-speed cameras in sunlight in open terrain, and protecting the cables from the excessive temperature from the heated parts of the barrel. Attention should be paid to the determination of the clearances and stiffness for model calculations of the vibration of the turret by its static loading and the measurement of deformations in the turret mounting.

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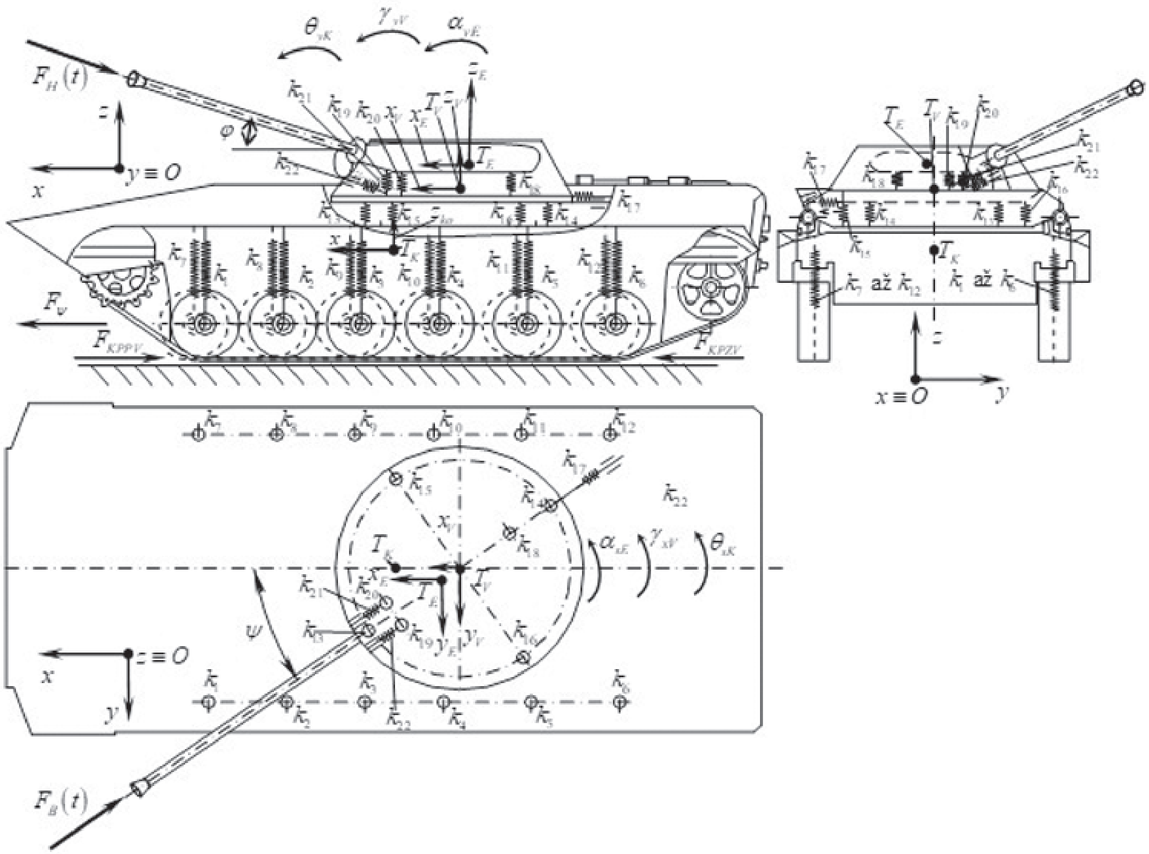

Figure 10. Dynamic model with 14 degrees of freedom.

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