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Dynamics Analysis of Hull Vibration for Tank Firing on the Move

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***Abstract*—Aiming at the low firing accuracy problem of tank on the move caused by hull vibration under the condition of high-speed and uneven surface road, using the muzzle vibration to characterize firing accuracy, a dynamic model for tank firing on the move was established based on multi-body system dynamics, vehicle-terramechanics and gun launch dynamics. The three-dimensional road surface spectrum file considering the left and right track unevenness coherence was written by means of the sinusoid superposition method. Through the dynamics analysis of the hull vibration, some of the proposals for reducing the influence of hull vibration were presented. The results show that the hull vibration can be divided into linear vibration and angular vibration. The linear vibration is very sensitive to the changes of speed and road surface level and can be effectively reduced by integrating the control device into the suspension. The angular vibration is more sensitive to the changes of the pavement level than the speed. Through the optimization design of fire system and introducing modern control theory into the current stabilizer, angular vibration effect can be effectively reduced. The result provides a certain reference to understand the muzzle vibration rule and improve the firing accuracy of on-the-move tank.**

***Keyword*—tank; firing on the move; hull vibration; multi-body system dynamics**

I. INTRODUCTION

Tank is a kind of comprehensive weapon with firepower, maneuverability and protection ability. As the backbone of rapid penetration in modern ground war, it is important for tank to have extremely high firing accuracy on the move. There are many factors that affect the firing accuracy of on-the-move tank[1-3], but the biggest difference between the on-the-move tank and other stationary turret is that the vehicle weapon system inevitably vibrates with the hull because of the stimulation caused by the roughness of the road. A large number of facts and studies have shown[4-6] that hull vibration is an important factor affecting the firing accuracy of on-the-move tank. The hull vibration includes linear vibration and angular vibration. Literature [4] has comprehensively analyzed the influence mechanism of chassis linear vibration on firing accuracy in real vehicle experiment. It includes three aspects, respectively, affecting the cross velocity of the projectile easily when out of the muzzle, reducing the imaging quality of aiming system, affecting the observation and aiming efficiency of the crew. Literature [5] makes a comprehensive analysis of the gun firing deviation caused by chassis angular vibration within the firing delay time, and finds that the main factor for the limitation of the speed of firing on-the-move tank is that the fire angle deviation increases as the vehicle speed increases. Literature [6] combined the hull vibration with the motion of gun under the effect of stabilizer by dynamics analysis of the interaction process of the ground-tank-gun system, so as to more comprehensively and objectively reflect the working mechanism of moving gun.

In this paper, the influence levels of linear vibration and angular vibration are comprehensively analyzed by establishing the dynamic model of the tank firing on the move and calculating the hull vibration response under multiple driving conditions. In addition, some suggestions on restraining the influence of hull vibration are put forward in this paper, so as to better grasp the muzzle vibration law and provide some references for improving the firing accuracy of on-the-move tank.

II. DYNAMICS MODELING OF THE FIRING ON-THE-MOVE TANK

A. *Path of Vibration Transmission*

Nowadays, static firing is used in most towed guns. To improve the firing accuracy, spade is generally used to improve the overall stability of the gun. Similarly, in order to improve the firing accuracy of on-the-move tank, the stability of the hull should be ensured as much as possible. However, due to the incentive from the road, it will inevitably produce random vibration which is not conducive to the firing accuracy. In addition, due to the influence of the suspension, the elasticity of metal parts and the gap between parts, the random vibration of tank is actually a complex motion composed of rigid motion and elastic motion. Therefore, the muzzle vibration characteristics are very complex.

Path of vibration transmission of the on-the-move tank studied in this paper is shown in Figure 1. In the process of driving, the incentive from the road to the left and right track is transmitted to the hull after the suspension absorbed, then to the turret through the saddle ring, and to the gun body through the trunnion at last, resulting in vibration of the recoil element. Therefore, the projectile motion will be influenced and the firing accuracy will be decreased.

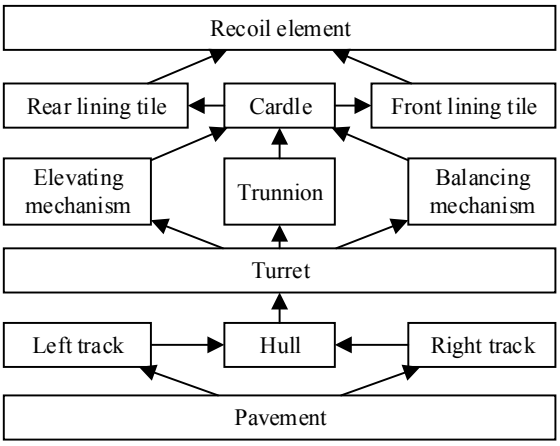


FIGURE I. PATH OF VIBRATION TRANSMISSION OF THE ON-THE-MOVE TANK

B. *Three-dimensional Model of Road*

Road roughness represents the deviation level of a certain road surface from the known ideal reference plane. It is easy to find that the main factor of causing the hull vibration of the tank firing on the move is road roughness through the analysis of the vibration transmission path, so the key point of modeling is to accurately reconstruct the road roughness. This paper is based on mathematical tool Mathematica to write the pavement spectrum program by means of sinusoid superposition method.

The pavement spatial frequency $f\,(f_1 < f < f_2)$ is divided into N intervals, and the power spectral density value $G_q(f_i)$ corresponding to the center frequency $f_i\,(i = 1, 2, \ldots\ldots, N)$ of each interval is taken to approximately replace the value of the entire interval Δf, then the random process of road roughness can be expressed as[7-8]

$$q(x) = \sum_{i=1}^{N} \sqrt{2} A_i \cdot \sin[2\pi(n_i x + \alpha)] \quad , \tag{1}$$

where x is the displacement of the pavement in the X direction, α is the random number uniformly distributed in $[0,1]$, and A_i is the vibration amplitude of the harmonic corresponding to the center frequency f_i, expressed as

$$A_i = \sqrt{G_q(f_i)\Delta f} \quad . \tag{2}$$

In addition, the left and right track are stimulated differently from the road in the real driving process. The coherence of the wheels on both sides stimulated from the road can be expressed as

$$\gamma(n) = \begin{cases} e^{-\rho n d_v} & n \in (n_1, n_2) \\ 0 & n \notin (n_1, n_2) \end{cases} , \tag{3}$$

where d_v is the wheel base, ρ is empirical constant, n_1 and n_2 are respectively the upper and lower limits of pavement spatial frequency.

Since the random phase angle α in the road roughness function is the main factor causing the difference in incentive between left and right track, the random process of 3D road roughness can be expressed as

$$q(xy) = \sum_{i=1}^{N} \sqrt{2} A_i \sin[2\pi(n_i y + \alpha_x)] \quad , \tag{4}$$

where α_x is the random phase of road roughness incentive in the X direction, expressed as

$$\alpha_x = \frac{e^{-2\pi x n^{1.5}} \alpha_1 + \sqrt{1 - e^{-2\pi x n^{1.5}} \alpha_n}}{\sqrt{1 - e^{-2\pi x n^{1.5}}} + e^{-2\pi x n^{1.5}}} \quad , \tag{5}$$

and α_n is the newly random number in $[0,1]$.

3D pavement spectral program can be written according to the above formula, then 3D pavement roughness model of class D and class F with a length of 100*m* and a width of 5*m* can also be reconstructed, and readable pavement file is legally generated by method of node stitching.

C. *Topology Structure of Multi-body System for the Tank*

The connection between parts within a tank is complex, and there are a lot of contact collisions. The high degree of nonlinearity has a great impact on the calculation. These contact connections must be properly handled. The tank model mainly includes chassis and fire parts, connected by the ball race contact simulated by the revolving joint and the torsion spring. The chassis is mainly composed of the hull, the road wheel, the support wheel, the idle wheel, the drive wheel and the track shoe. The road wheel through torsion bar suspension, the idle wheel through the stretching device, and support wheel and drive wheel through the rotary joint are respectively connected with the hull. The mass and inertia of other parts are loaded onto the hull by equivalent calculation. The track shoe is in rigid contact with the ground.

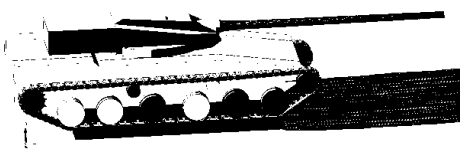


FIGURE II. MULTI-BODY SYSTEM DYNAMIC MODEL OF THE FIRING ON-THE-MOVE TANK

The fire part is mainly composed of the recoil parts, cradle parts and turret parts. The turret and the hull are respectively fixedly connected with the upper and lower saddle ring. The trunnion and bearing are respectively fixedly connected with the cradle and turret. The rotational relationship between the cradle and the turret is defined by defining the contact collision between the trunnion and the bearing. The contact collisions between the gear and tooth arc are equivalent to torsion spring by calculating. The barrel is modal flexibility, which is fixedly connected with the breech ring through the nodes on the after end interface. The rigid and soft contact collision between the barrel and the front and rear lining tile are established respectively. As shown in Figure 2, the whole gun contains 260 rigid bodies, 1 elastic body, 3 translational joint constraints, 39 revolving joint constraints, 22 fixed joint constraints and 8 contacts. There are 1335 degrees of freedom in the whole system.

III. Analysis of the Influence of Hull Vibration on Firing Accuracy

In order to analyze the influence of hull vibration on the firing accuracy of on-the-move tank, the multi-body system dynamic model of the tank firing on the move is established based on above. The hull vibration of the tank driving on the class D and class F pavement under the conditions of 15*km/h*, 30*km/h* and 40*km/h* are respectively calculated. The vibration of the mass center is selected to characterize the hull vibration, and the muzzle vibration is selected to characterize firing accuracy. The setting of driving condition parameters is shown in Table 1.

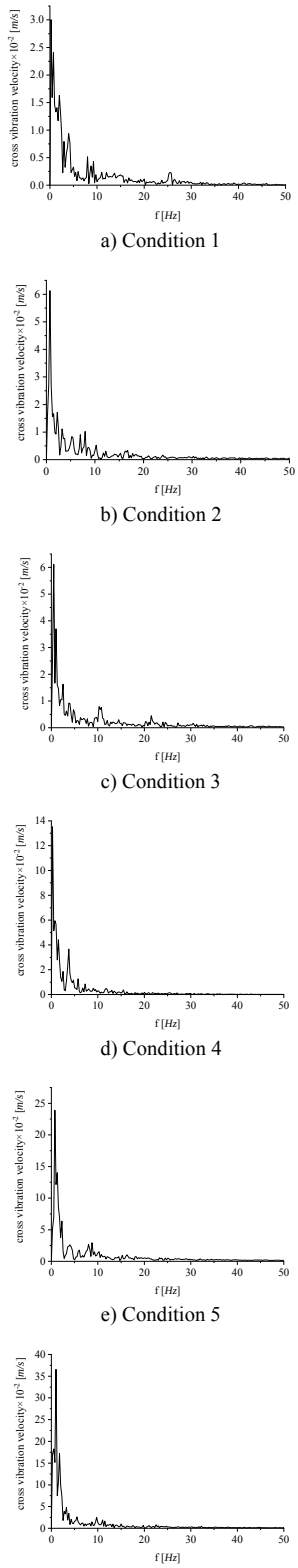
TABLE I. SETTING OF DRIVING CONDITION PARAMETERS

Condition	1	2	3	4	5	6
Vehicle speed [*km/h*]	15	30	40	15	30	40
Road surface level	D	D	D	F	F	F

The calculation time was set at 6*s*. After many trial calculations, it was found that the tank was in the stage of static balance and acceleration in the first 2*s*, and the hull did not enter the rough pavement completely. Therefore, the data within the after 4*s* was taken in the analysis only. The hull longitudinal vibration which has a great impact on the muzzle vibration is mainly analyzed.

A. *Influence of the Linear Hull Vibration*

The tracks are stimulated by the pavement as the tank moves. The hull vibration will be caused randomly due to the elasticity of the antivibration device. The power spectral density of the linear hull vibration acceleration can be obtained by fast Fourier transform. Figure 3 shows the frequency spectrum of the linear hull longitudinal vibration velocity under different driving conditions.



a) Condition 1
b) Condition 2
c) Condition 3
d) Condition 4
e) Condition 5
f) Condition 6

FIGURE III. FREQUENCY SPECTRUM OF THE LINEAR HULL LONGITUDINAL VIBRATION VELOCITY UNDER DIFFERENT DRIVING CONDITIONS

It can be seen from the figure that there are obvious differences in hull vibration under different driving conditions. Under condition 1, the main peak value of the linear hull longitudinal vibration velocity is 0.03*m/s* and the frequency is 0.25*Hz*. Under condition 6, the main peak value of the linear hull longitudinal vibration velocity increases to 0.365*m/s* and the frequency increases to 1.0*Hz*. The main peak value under different conditions is between 0.3*m/s* and 0.365*m/s*, and its corresponding frequency is between 0.25*Hz* and 1.0*Hz*. This is a wide range of variation, which indicates that the velocity and frequency response of the linear hull longitudinal vibration is very sensitive to the change of driving conditions. That is, the linear hull vibration is more greatly affected by the pavement and vehicle speed.

TABLE II. LINEAR VIBRATION STATISTICS OF THE POSITION OF THE MASS CENTER OF THE HULL

Statistics	Direction	Condition					
		1	2	3	4	5	6
RMS value of vibration velocity [*m/s*]	Longitudinal	0.0432	0.0649	0.0631	0.1381	0.2563	0.3883
	Cross	0.0497	0.0468	0.0556	0.0776	0.1661	0.1888
RMS value of vibration acceleration [*m/s*]	Longitudinal	1.088	1.4010	1.5652	1.6898	3.3313	4.4861
	Cross	0.8513	0.7329	0.6531	1.4256	2.6135	3.6654

Because the gun is installed on the turret by the trunnion, the effect of linear hull vibration on the firing accuracy of on-the-move tank is mainly transmitted to the gun through the turret, resulting the gun axis vibrates up and down. It will result in the cross velocity of the projectile when out of muzzle. The statistics of the linear vibration of the mass center position under different driving conditions are shown in Table 2. The linear hull vibration has a significant increasing trend with the increase of vehicle speed and the decrease of road surface level according to the analysis of Table 2 combined with Figure 3. This is due to the incentive from the road acting on the left and right track become more intense. However, it can be found that the RMS value of the maximum vibration velocity listed in the table is only 0.3883*m/s*, which is very small compared with the projectile flight velocity[4], so the effect of linear hull vibration on gun firing deviation can be nearly ignored.

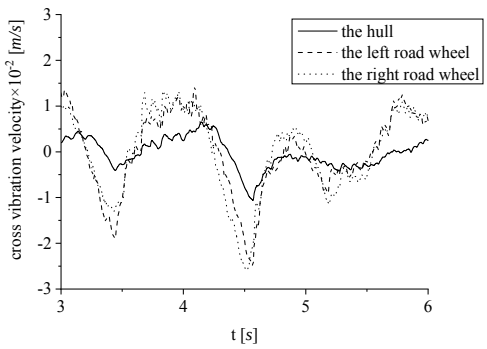
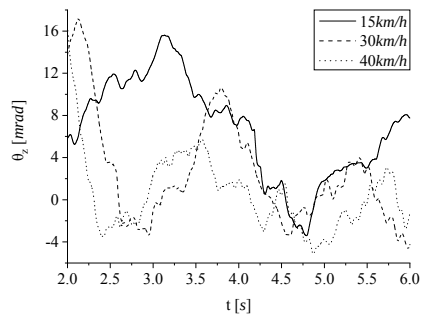


FIGURE IV. COMPARISON OF THE LONGITUDINAL VIBRATION VELOCITY BETWEEN THE ROAD WHEEL AND THE HULL

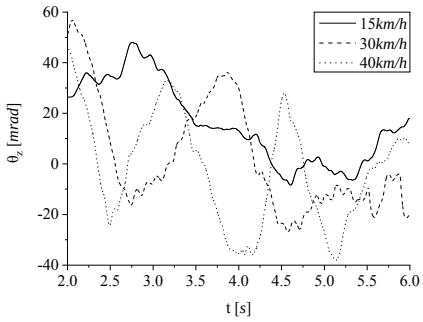
Although the linear hull vibration has little influence on the firing accuracy, the comfort of the crews and the smoothness of operating and aiming will be affected. Therefore, the inhibition of the linear hull vibration cannot be ignored. The linear vibration velocity curve of the first road wheel of the left and right track under the 6th driving condition where the firing accuracy is seriously reduced is shown in Figure 4. It can be found that the longitudinal vibration velocity variation trend of the first road wheel of the left and right track is similar by comparison. This is because the left and right road wheel work on the same level of road surface, but the vibration speed is also different due to the difference in real-time incentive. It can also be found that the vibration degree at the mass center of the hull is significantly lower than that at the position of the road wheel. The suspension plays an important role in antivibration. Therefore, the linear hull vibration can be effectively controlled by adding active control to the suspension system in future studies[9].

B. *Influence of the Angular Hull Vibration*

Not only linear vibration, but also angular vibration will be produced to the hull due to the height of the ground resulting from the large span of the front and rear road wheel of the track when the tank is on the move. The elevation angle displacement diagrams of the angular hull vibration under different driving conditions are shown in Figure 5.



a) class D pavement



b) class F pavement

FIGURE V. ELEVATION ANGLE DISPLACEMENT DIAGRAM OF THE ANGULAR HULL VIBRATION

It can be seen from the figure that the numerical span of the elevation angle displacement increases with the increase of the vehicle speed and the decrease of road surface level. This is

because the lower the road surface level is, the larger the change range of ground elevation in the same length will be, and the higher the vehicle speed is, the longer the hang time of the tank will be. The RMS values of the angular displacement of the mass center of the tank are shown in Table 2. Combined with Figure 5, it can be found that the numerical span of the elevation angle displacement changes little and the RMS value of the angular displacement is also small when the velocity changes. The numerical span and RMS value of the elevation angle displacement both change exponentially when the road surface level changes. The analysis above indicates that the sensitivity of the elevation angle displacement to the road surface level is obviously greater than that to the vehicle speed.

TABLE III. STATISTICS OF THE RMS VALUE OF THE ELEVATION ANGLE DISPLACEMENT OF THE MASS CENTER OF THE HULL

Condition	1	2	3	4	5	6
Elevation angle [*mrad*]	8.2592	5.7874	3.5356	22.6237	22.2244	21.7048
Drift angle [*mrad*]	21.8135	21.8140	21.0593	56.3288	61.7652	62.2286

The angular hull vibration will be transmitted to the cradle through the trunnion, directly resulting in the deviation of the firing angle. It can cause the target distance deviation to be 3 times to 5 times of the deviation which is caused by the cross velocity of projectile [5]. The elevation angle displacement of the muzzle increases obviously as the angular hull vibration increases, so the angular hull vibration will lead to a sharply decline in the firing accuracy when the road surface level decreases. In order to ensure the firing accuracy, it is necessary to reduce the influence of the angular hull vibration. The variation curve of the elevation angle displacement of the muzzle under condition 6 where the firing accuracy is seriously reduced is shown in Figure 6.

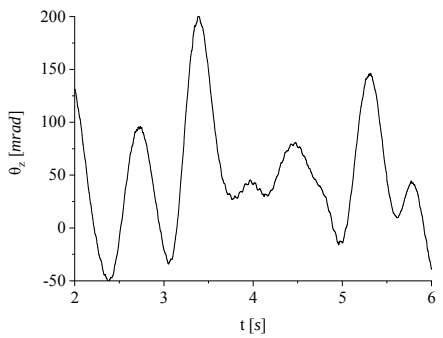


FIGURE VI. VARIATION CURVE OF THE ELEVATION ANGLE DISPLACEMENT OF THE MUZZLE UNDER CONDITION 6

Combined with Figure 5, it can be found that the elevation angle displacement of the muzzle is greater than that of the hull on the whole, which is caused by the contact collisions between various mechanisms in the fire system and flexibility of the barrel. It is suggested that the muzzle vibration can be effectively controlled by optimizing the design and selecting appropriate overall parameters[10]. In addition, the existing gun stabilization device can also reduce the influence of angular hull vibration to a certain extent[11]. However, the conventional gun control system is designed according to the classical control theory. It cannot compensate the nonlinearity of the system and achieve a satisfactory performance. It is necessary to redesign the gun stabilization device with superior performance according to modern intelligent control theory. This will be focused in the future work.

IV. SUMMARY

In this paper, the hull vibration of the tank firing on the move was analyzed through establishing the multi-body system dynamics and writing the 3D pavement spectrum program considering the left and right track unevenness coherence. The hull vibration can be divided into linear vibration and angular vibration. The linear vibration is very sensitive to the changes of vehicle speed and road surface level, but it has little influence on the firing accuracy. It can be effectively reduced by joining the control device into the suspension. The angular vibration is more sensitive to the changes of the pavement level than the vehicle speed, which has a great influence on the firing accuracy. The mechanism collision and the flexibility of barrel can inhibit the angular vibration transferring to a certain extent. The muzzle vibration can be effectively controlled by optimizing the design and selecting appropriate overall parameters. The modern control theory can be introduced into the existing stabilization device to inhibit the rotation of the cradle with the hull. The firing accuracy can be effectively improved. However, the influence of the suspension and stabilization device on the firing accuracy has not been studied in this paper. The gaps and omissions will be gradually completed in the future work.

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