

Time-domain Response Simulation Research on a Certain Type of Ammunition Transport Vehicle

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Abstract. A 1/2 seven degree-of-freedom vehicle dynamic model was built for exploring the excitation that was obtained from a certain type of ammunition transport vehicle, which running on standard highway at the speed of 20m/s. According to the power spectral density function advised by national standard, the harmony superposition method (HSM) and pseudo white noise method (PWNM) were both used for simulating the road roughness. And the roughness of generated by these two methods was analysed and compared by MATLAB. Moreover, the vertical acceleration responses spectrum of grade A; B; C road were calculated. The numerical results reflect that the HSM is better than PWNM in road roughness simulation with the same time step size, and the root mean square value (RMS) of car centre of mass will grow largely with the decrease of road grade, the calculation results show the RMS of grade C road is above 300% than that of A.

1. Introduction

A better ride comfort of military automobile, particularly of a certain type of ammunition transport vehicle, is vital to guarantee the routine training and ammo delivery safe and timely. An ammunition transport vehicle would ride on complicated road conditions under some certain circumstances, which included standard level road, rural road and field road et al. Because of road roughness affection, the automotive vibration, with stochastic, stationary, and ergodic properties, was generated[1]. The energy of vibration would reduce the service lifespan of vehicle, and lower the handling stability of drivers. On the other hand, transmitted vibration that through suspension would undermining the structural integrity of ammo, that is, the combat effect might fall short of a requirement, and more severely, it could cause dangerous accidents[2-3]. The dynamic response of ammo carried by vehicle could be the criteria to predict its service life. The research of dynamic response of ammo, of course, became the hotspots.

The road transportation of ammo was a multiple degree-of-freedom (DOF), nonlinear system that contained vehicle, package and ammo. A precise dynamic model of vehicle was the foundation of analysing and assessing the response, and had direct effect on the credibility of numerical results. In a large number of investigations of analysing dynamic response, a typical 1/4 nonlinear two-DOF model was developed to discuss the influence of different parameters[4]. And a more complex 13-DOF dynamic model, with the consideration of suspension systems and tires, was used to evaluate the corresponding parameters affections on the dynamic interaction[5]. But a linear two-DOF suspension has been proved could not be described the vibration performance of vehicle on different road conditions, commendably[6]. The practicability of five freedom half vehicle system was confirmed by absorbed power method in a recent study[7]. In addition, the simulation results of a specific heavy vehicle based on 15 kinds of roads provided basic references on improving the ride comfort



performance[3]. And a chaotic response has been found in a full-vehicle model[8]. Overall, the more detailed of the dynamic model, the more accurate of the acquired simulation results, yet the computational complexity would grow excessively.

The reasonably simplified 1/2 seven DOF vehicle dynamic model was built in this paper, and the road roughness of grade C was modelled by the harmony superposition method (HSM) and pseudo white noise method (PWNM), respectively. Subsequently, the dynamic response of carriage was computed by an improved four-order precise Runge-Kutta integration, which achieved by MATLAB[9]. Compared with the of the root mean square value of field tests, the HSM proved to be more effective and feasible than the PWNM with the same time-step. Moreover, it also revealed the simulation adopted by nonlinear dynamic model was available, and the excitation obtained from numerical calculation could be used for the structural integrity assessment of the ammo.

2. 1/2 Seven DOF vehicle dynamic model

Measuring the dynamic response by accelerometers in field tests did provide some reliable results for calculating the distribution of stress and strain in ammo. However, this method was tremendously limited by the huge cost, long experimental period, and poor repeatability[10-11]. Reference[12] suggested that excitations of carriage but without ammo under different road conditions collected by several accelerometers could be used in ambient shaking table tests. This method will no doubt be universal and safer. While, drawing support from refined mathematical models of road roughness and improved numerical simulation methods, combining with the relative parameters of transport vehicle, more practical results could be obtained by simulating on MATLAB. By means of this way, the deficiencies of field tests would be made up for.

On the basis of relevant parameters of ammo transport vehicle, and with reasonable simplifications[13], Figure.1 shows a 1/2 seven degree-of-freedom vehicle dynamic model. The vehicle body is represented by a rigid bar with mass m_0 , which considered heave motions x_0 and roll motions, were masses, dampers elements and spring equivalent stiffness of sprung, respectively. were dampers elements and spring equivalent stiffness of tires. The road roughness excitations of different tires were defined as $s_1 \dots s_5$, and $l_1 \dots l_5$ were the lengths between the sprung to and the centre of gravity of vehicle mass.

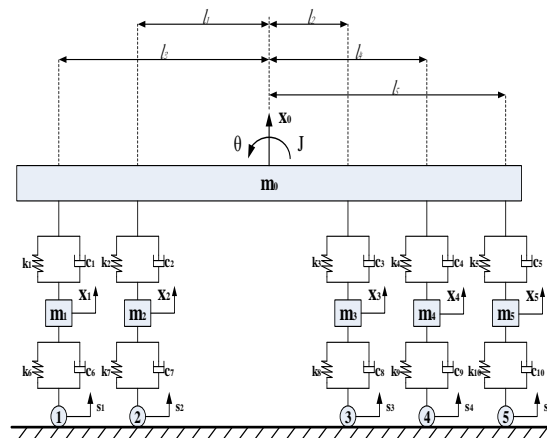


Figure 1. 1/2 seven-degree dynamic model of ammo transport vehicle.

To make it easier to compute the dynamic response, several basic postulates are listed as follows:

- (1) The vehicle was symmetrical to the middle plane that cross the centre of mass, its body, car frame and their connections were rigid.
- (2) The vehicle kept uniform motion in a straight line, only micro-amplitude vibration happened on equilibrium position. And tires always kept the point contact with road.
- (3) The road roughness was random, there were time differences among the excitation of tires.

(4) Only heave and roll motion of vehicle were considered, the vibrations caused by other factors were ignored.

3. Models of road roughness

Road roughness was the shifting over ideal reference plane, and was determined by the displacement of power spectrum density, the general form was revealed as follows[14]:

$$G_s(n) = G_s(n_0) \left(\frac{n}{n_0} \right)^{-w} \quad (1)$$

Where n the spatial frequency, m^{-1} , n_0 is the reference spatial frequency, usually is $0.1m^{-1}$, and $G_s(n_0)$ is the power spectrum density value at the reference spatial frequency, changed with the road condition, also defined as the road irregularity coefficient. w is the frequency index, affects the structure of road spectrum, usually is 2.

The frequency-domain model was usually adopted to describe the road surface roughness, however, this analysis method is not applicable to the realistic nonlinear vehicle system[15]. That is, time-domain model was much more suitable for calculating the vertical displacements of vehicle that changed with time. Simultaneously, the accumulative damage and service life prediction became easier. Then, it is necessary to employ the time-domain model to solve the dynamic response of nonlinear vehicle system. Translating spatial frequency into time frequency is the key to carry out the time-domain analysis, transformation relationship as below, where f is the time frequency, and v is the transport speed.

$$f = vn \quad (2)$$

The random road roughness in time-domain was generated by HSM and PWNM, respectively. The time-domain excitation expressions of these two methods were listed as below:

HSM[16]:

$$\dot{s}(t) + 2\pi f_1 s(t) = 2\pi n_0 \sqrt{G_s(n_0)} w(t) \quad (3)$$

PWNM[17]:

$$s(t) = \sum_{i=1}^m \sqrt{2G_s(f_{mid-i})\Delta f_i} \sin(2\pi f_{mid-i}t + \theta_i) \quad (4)$$

Where f_1 is the lower cut-off frequency, $w(t)$ is the standard Gauss white noise sequence, m is the interval number of f , $m=5000$, f_{mid-i} is the centre frequency of the i th interval, and θ_i is the random number of $[0, 2\pi]$ that satisfies normal distribution.

4. Kinetic equations of transport vehicle

The kinetic equations of the seven DOF ammo model are put forward in equations (5) - (11) using Lagrange method.

Heave kinetic equation of carriage

$$-m_0\ddot{x}_0 + k_1(x_0 - x_1 - l_1\theta) + c_1(\dot{x}_0 - \dot{x}_1 - l_1\dot{\theta}) + k_2(x_0 - x_2 - l_2\theta) + c_2(\dot{x}_0 - \dot{x}_2 - l_2\dot{\theta}) + k_3(x_0 - x_3 + l_3\theta) + c_3(\dot{x}_0 - \dot{x}_3 + l_3\dot{\theta}) + k_4(x_0 - x_4 + l_4\theta) + c_4(\dot{x}_0 - \dot{x}_4 + l_4\dot{\theta}) + k_5(x_0 - x_5 + l_5\theta) + c_5(\dot{x}_0 - \dot{x}_5 + l_5\dot{\theta}) = 0 \quad (5)$$

Roll kinetic equation of carriage

$$J\ddot{\theta} - k_1l_1(x_0 - x_1 - l_1\theta) - c_1l_1(\dot{x}_0 - \dot{x}_1 - l_1\dot{\theta}) - k_2l_2(x_0 - x_2 - l_2\theta) - c_2l_2(\dot{x}_0 - \dot{x}_2 - l_2\dot{\theta}) + k_3l_3(x_0 - x_3 + l_3\theta) + c_3l_3(\dot{x}_0 - \dot{x}_3 + l_3\dot{\theta}) + k_4l_4(x_0 - x_4 + l_4\theta) + c_4l_4(\dot{x}_0 - \dot{x}_4 + l_4\dot{\theta}) + k_5l_5(x_0 - x_5 + l_5\theta) + c_5l_5(\dot{x}_0 - \dot{x}_5 + l_5\dot{\theta}) = 0 \quad (6)$$

Heave kinetic equation of tire 1

$$m_1\ddot{x}_1 - k_1(x_0 - x_1 - l_1\theta) - c_1(\dot{x}_0 - \dot{x}_1 - l_1\dot{\theta}) + k_6(x_1 - S_1) + c_6(\dot{x}_1 - \dot{S}_1) = 0 \quad (7)$$

Heave kinetic equation of tire 2

$$m_2 \ddot{x}_2 - k_2(x_0 - x_2 - l_2\theta) - c_2(\dot{x}_0 - \dot{x}_2 - l_2\dot{\theta}) + k_7(x_2 - S_2) + c_7(\dot{x}_2 - \dot{S}_2) = 0 \quad (8)$$

Heave kinetic equation of tire 3

$$m_3 \ddot{x}_3 - k_3(x_0 - x_3 + l_3\theta) - c_3(\dot{x}_0 - \dot{x}_3 + l_3\dot{\theta}) + k_8(x_3 - S_3) + c_8(\dot{x}_3 - \dot{S}_3) = 0 \quad (9)$$

Heave kinetic equation of tire 4

$$m_4 \ddot{x}_4 - k_4(x_0 - x_4 + l_4\theta) - c_4(\dot{x}_0 - \dot{x}_4 + l_4\dot{\theta}) + k_9(x_4 - S_4) + c_9(\dot{x}_4 - \dot{S}_4) = 0 \quad (10)$$

Heave kinetic equation of tire 5

$$m_5 \ddot{x}_5 - k_5(x_0 - x_5 + l_5\theta) - c_5(\dot{x}_0 - \dot{x}_5 + l_5\dot{\theta}) + k_{10}(x_5 - S_5) + c_{10}(\dot{x}_5 - \dot{S}_5) = 0 \quad (11)$$

In summary, the kinetic model of the ammo transport vehicle could be defined as the following equations.

$$[\mathbf{M}]\{\ddot{\mathbf{x}}\} + [\mathbf{C}]\{\dot{\mathbf{x}}\} + [\mathbf{K}]\{\mathbf{x}\} = \{\mathbf{F}(\mathbf{t})\} \quad (12)$$

Where $[\mathbf{M}] = [m_0 \quad J \quad m_1 \quad m_2 \quad m_3 \quad m_4 \quad m_5]$ is the inertial matrix, $[\mathbf{C}] = \begin{bmatrix} C_1 & C_2 \\ C_3 & C_4 \end{bmatrix}$ is the damping matrix, and

$$[\mathbf{C}_1] = \begin{bmatrix} c_1 + c_2 + c_3 + c_4 + c_5 & -l_1c_1 - l_2c_2 + l_3c_3 + l_4c_4 + l_5c_5 \\ -l_1c_1 - l_2c_2 + l_3c_3 + l_4c_4 + l_5c_5 & l_1^2c_1 + l_2^2c_2 + l_3^2c_3 + l_4^2c_4 + l_5^2c_5 \end{bmatrix}, [\mathbf{C}_2] = \begin{bmatrix} -c_1 & -c_2 & -c_3 & -c_4 & -c_5 \\ l_1c_1 & l_2c_2 & -l_3c_3 & -l_4c_4 & -l_5c_5 \end{bmatrix},$$

$$[\mathbf{C}_3] = \begin{bmatrix} -c_1 & l_1c_1 \\ -c_2 & l_2c_2 \\ -c_3 & -l_3c_3 \\ -c_4 & -l_4c_4 \\ -c_5 & -l_5c_5 \end{bmatrix}, [\mathbf{C}_4] = \begin{bmatrix} c_1 + c_6 & 0 & 0 & 0 & 0 \\ 0 & c_2 + c_7 & 0 & 0 & 0 \\ 0 & 0 & c_3 + c_8 & 0 & 0 \\ 0 & 0 & 0 & c_4 + c_9 & 0 \\ 0 & 0 & 0 & 0 & c_5 + c_{10} \end{bmatrix},$$

$[\mathbf{K}] = \begin{bmatrix} \mathbf{K}_1 & \mathbf{K}_2 \\ \mathbf{K}_3 & \mathbf{K}_4 \end{bmatrix}$ is the stiffness matrix, and

$$[\mathbf{K}_1] = \begin{bmatrix} k_1 + k_2 + k_3 + k_4 + k_5 & -l_1k_1 - l_2k_2 + l_3k_3 + l_4k_4 + l_5k_5 \\ -l_1k_1 - l_2k_2 + l_3k_3 + l_4k_4 + l_5k_5 & l_1^2k_1 + l_2^2k_2 + l_3^2k_3 + l_4^2k_4 + l_5^2k_5 \end{bmatrix}, [\mathbf{K}_2] = \begin{bmatrix} -k_1 & -k_2 & -k_3 & -k_4 & -k_5 \\ l_1k_1 & l_2k_2 & -l_3k_3 & -l_4k_4 & -l_5k_5 \end{bmatrix},$$

$$[\mathbf{K}_3] = \begin{bmatrix} -k_1 & l_1k_1 \\ -k_2 & l_2k_2 \\ -k_3 & -l_3k_3 \\ -k_4 & -l_4k_4 \\ -k_5 & -l_5k_5 \end{bmatrix}, [\mathbf{K}_4] = \begin{bmatrix} k_1 + k_6 & 0 & 0 & 0 & 0 \\ 0 & k_2 + k_7 & 0 & 0 & 0 \\ 0 & 0 & k_3 + k_8 & 0 & 0 \\ 0 & 0 & 0 & k_4 + k_9 & 0 \\ 0 & 0 & 0 & 0 & k_5 + k_{10} \end{bmatrix},$$

And the matrix of road roughness excitation is $\{\mathbf{F}(\mathbf{t})\} = \{\mathbf{F}_K(\mathbf{t})\} + \{\mathbf{F}_C(\mathbf{t})\}$.

Where the damper force that generated by road roughness is

$$\{\mathbf{F}_C(\mathbf{t})\} = [0 \quad 0 \quad c_6\dot{q}_1 \quad c_7\dot{q}_2 \quad c_8\dot{q}_3 \quad c_9\dot{q}_4 \quad c_{10}\dot{q}_5]^T,$$

and the sprung force that generated by road roughness is

$$\{\mathbf{F}_K(\mathbf{t})\} = [0 \quad 0 \quad k_6q_1 \quad k_7q_2 \quad k_8q_3 \quad k_9q_4 \quad k_{10}q_5]^T,$$

the matrix of displacements response is $\{\mathbf{x}\} = [x_0 \quad x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5]^T$,

the matrix of speeds response is $\{\dot{\mathbf{x}}\} = [\dot{x}_0 \quad \dot{x}_1 \quad \dot{x}_2 \quad \dot{x}_3 \quad \dot{x}_4 \quad \dot{x}_5]^T$,

the matrix of accelerations response is $\{\ddot{\mathbf{x}}\} = [\ddot{x}_0 \quad \ddot{x}_1 \quad \ddot{x}_2 \quad \ddot{x}_3 \quad \ddot{x}_4 \quad \ddot{x}_5]^T$.

The compute time starts from tire 5, and the excitation of tire 4 could be derived from equation (13), and the others could be deducted in the same way.

$$s_4(t) = s_5(t + \frac{l_5 - l_4}{v}) \quad (13)$$

The state space formulation of equation (12) was built for effective use of the improved four-order precise Runge-Kutta integration solving dynamic response.

$$\{\dot{\mathbf{u}}\} = [\mathbf{H}]\{\mathbf{u}\} + \{\mathbf{P}(t)\} \quad (14)$$

$$\text{And } \{\mathbf{u}\} = \{x \dot{x}\}^T, \{\mathbf{P}(t)\} = \{0 \ \mathbf{M}^{-1}\mathbf{F}(t)\}^T, [\mathbf{H}] = \begin{bmatrix} 0 & I \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}.$$

5. Numerical simulation and results analysis

The feasibility study of HSM and PWNM adopted in this paper has been verified[18-19]. The displacement and acceleration response of the carriage barycentre on grade A; B; C road were calculated utilizing MATLAB. The road irregularity coefficients of grade A; B; C road are 16、64、256 $\text{mm}^2/\text{m}^{-1}$, respectively. And the range of spatial frequency is 0.011~2.830 m^{-1} . The corresponding range of time frequency was calculated by equation (2), and that range could totally overlap the natural frequency of the vehicle body and tires^[14].

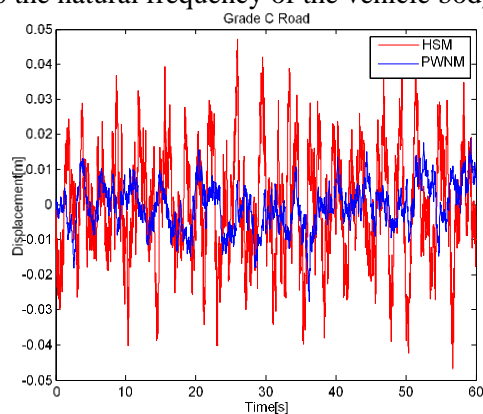


Figure 2. Comparison results of grade C road surface roughness simulated by HSM and PWNM.

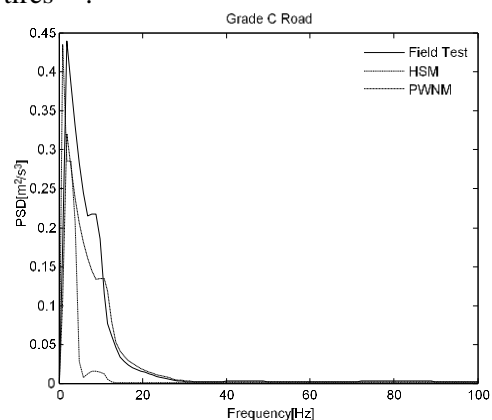


Figure 3. Acceleration response of carriage barycentre on grade C road simulated by HSM and PWNM.

Figure 2 shows the comparison results of grade C road surface roughness simulated by HSM and PWNM, and figure 3 gives the acceleration power spectrum density of carriage barycentre on grade C road, which also provides the comparison result combined with field test. It is not hard to catch sight of that the road roughness simulated by HSM is closer to the field test than PWNM under the same time-step. There are still some deviations in several parts frequency band that attribute to the moment of forces generated by different road roughness on tires of both sides, and the discrepancies between the analogue and complex actual signals. However, the peak of main frequency band simulated by HSM is essentially in agreement with the field test, which could reflect the vibration characteristics, and also illustrates the rationality of the vehicle dynamic model. The following discussion, therefore, is based on the results that simulated by HSM.

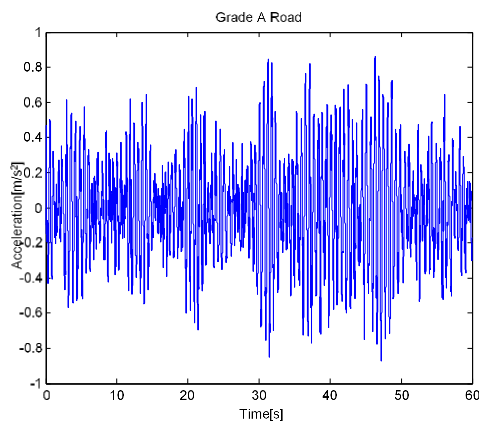


Figure 4. Acceleration response of carriage barycentre on grade A road simulated by HSM.

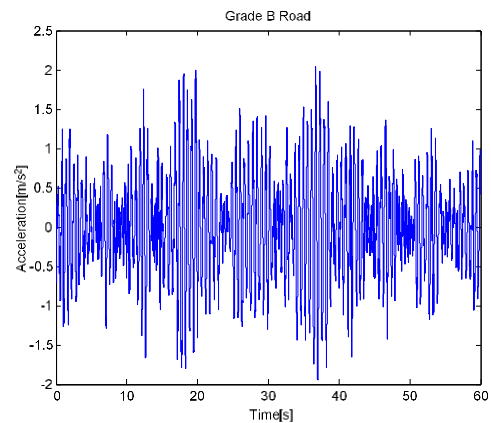


Figure 5. Acceleration response of carriage barycentre on grade B road simulated by HSM.

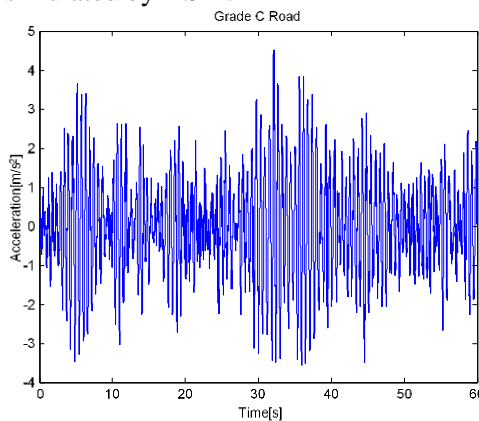


Figure 6. Acceleration response of carriage barycentre on grade C road simulated by HSM.

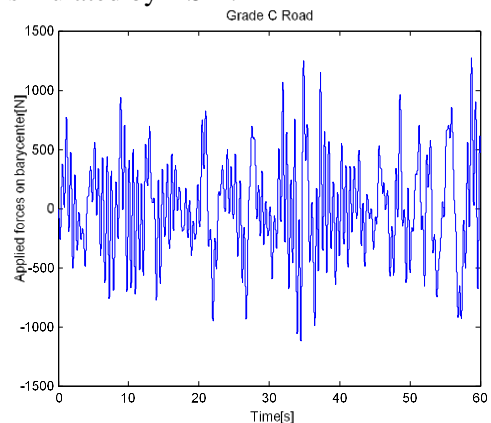


Figure 7. Applied force of carriage barycentre on grade C road simulated by HSM.

The simulation results from figure 4 to 6 indicated that the heave acceleration response of carriage barycentre changes with the road condition, and gets higher when road grades become worse, which accords with the facts. And root mean square (RMS) increased from 0.3177 m/s^2 of grade A to 0.7493 m/s^2 grade B, finally to 1.3005 m/s^2 of grade C. The forces applied on the barycentre showing in figure 7 indicates that the indispensable research on the destructiveness of ammo road transportation, particularly the accumulative damage of ammo caused by long-distance transportation.

6. Conclusion

Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure. This paper presents a reasonably simplified half seven DOF nonlinear dynamic model, according to the propositional expression of road roughness coefficients, and mainly using the HSM to simulate the road roughness with different grades. The displacement and acceleration response of dynamic model under different road excitations were calculated by an improved four-order precise Runge-Kutta integration, and also obtained the applied forces of carriage barycentre on grid C road changed with time.

The deviations of carriage barycentre response under the road roughness simulated by HSM, which compared with that under the field test, strongly indicates that there is a necessity to build a full-vehicle model. The numerical results also reveal that the applied forces on ammo could not cause the strength failure, but the accumulative damage could not be neglected in the next study.

In the research, we can conclude that the method of generate road roughness and the vehicle dynamic model need to be improved, particularly a full-vehicle model that considers pitch motions should be built. Moreover, the applied forces could be taken as the excitations of the vehicle on the ammo model, and the simulation that analyses the affections on the structural integrity of ammo could be carried on.

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