Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.12785/amis/092L38

Dynamic Virtual Prototyping Modeling and Simulation of Special Vehicle

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Received: 6 Aug. 2014, Revised: 7 Nov. 2014, Accepted: 8 Nov. 2014

Abstract: Taking Special Vehicle as an example, the research is made on dynamic virtual prototyping modeling and simulation of complex mechanical, electrical and hydraulic integrated system. Based on hydro-pneumatic spring model, ”magic formula” tire model, road spectrum model, flexible body model of key components, and vehicle control-hydraulic model, a mechanical, electrical and hydraulic coupling dynamic virtual prototyping model of Special Vehicle is built capitalizing on dynamic simulation analytical software ADAMS and control system simulation analytical software MATLAB/Simulink, and the virtual prototyping model is validated and verified by the physical test data. On the basis of the built prototyping model, the virtual tests are carried out in various typical working conditions, which include vehicle driving stability, vehicle unfolding and folding stability, etc. The complete data are obtained from virtual tests and the performance indexes achievability and adaptability to the environment of Special Vehicle are evaluated. The correlation of the main design parameters and the performance indexes is established, which provides basic technical support for optimizing its overall design parameters. The research results have important significance for the simulation and optimization of complicated mechanical, electrical and hydraulic integrated system.

Keywords: Special Vehicle, Dynamic Virtual Prototyping, Modeling, Co-simulation

1 Introduction

Special Vehicle is one of the most important equipment in the weapon system, the main function of which is to transport, erect and launch another important equipment to ensure its stable work.

Special Vehicle, a kind of typical complicated mechanical, electrical and hydraulic system, integrates a mechanical subsystem, a control subsystem and a hydraulic subsystem, etc. The research and development of each subsystem and the integration and test of the entire system have a decisive impact on realization of performance indexes of Special Vehicle. The traditional design of Special Vehicle is a process of iterative design which can be described as follows: each subsystem is designed independently and integrated into the whole system which is evaluated, and then subsystems are redesigned and reintegrated based on the evaluation results. Because the coupling relationship between the various subsystems is not considered in the process of the independent design, it is difficult to quickly find a fully coordinated overall design concept between the various subsystems, and may even lead to the unbalance of the development risk between the various subsystems, which will affect the development process of Special Vehicle. The application of virtual prototyping technology provides an effective way to solve the above technical problems. Virtual prototyping technology is a high-tech solution to the traditional design defects from the angle of analyzing and solving the product’s overall performance and related problems, which enables designers to simulate real working state of the product in a variety of virtual environments, and even can conduct those tests which are difficult or impossible for physical prototype [1].

In order to solve the technical problems in the Special Vehicle’s development process, this paper presents the application of virtual prototyping technology to Special Vehicle for system-level and multi-domain coupling modeling and simulation. Based on hydro-pneumatic spring model, ”magic formula” tire model, road spectrum model, flexible body model of key components and vehicle control-hydraulic model, the mechanical,

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electrical and hydraulic coupling dynamic virtual prototyping model of Special Vehicle is built using ADAMS——a mechanical system dynamic simulation analytical software and MATLAB/Simulink——a control system simulation analytical software. Through the virtual simulation tests under all kinds of typical working conditions, more complete virtual test data are obtained and the evaluation on Special Vehicle's capability to achieve the performance indexes and ability to adapt to the environment is made. The correlation established between the main design parameters and the performance indexes provides basic technical support for optimization of the overall design parameters of Special Vehicle.

2 Dynamic Virtual Prototyping Platform of Special Vehicle

With the application of existing commercial software, the dynamic virtual prototyping platform of Special Vehicle is built, which integrates a number of CAE simulation software and can achieve the co-simulation between multi-domains such as the mechanical system, the control system, the hydraulic system, etc[2,3,4,5,6]. Its block diagram of framework is shown in Figure 1.

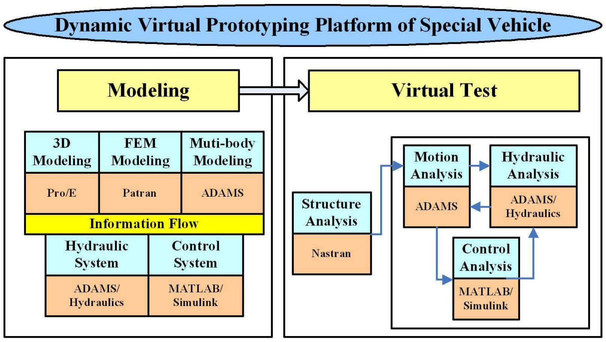

Fig. 1: Dynamic virtual prototyping platform of Special Vehicle

The dynamic virtual prototyping platform of Special Vehicle is quite systematic because it fully considers the interaction between multi-domains such as mechanical, control and hydraulic systems to achieve their concurrent design and integrated simulation analysis; this platform is also technically advanced because it capitalizes on high-quality common commercial software integration through its own interface or secondary development, with full consideration of current advanced and sustainable developing technology in related domains.

3 Virtual Prototyping Modeling of Special Vehicle

The virtual prototyping model of Special Vehicle contains two main parts: the mechanical subsystem and the vehicle control-hydraulic subsystem. The mechanical structure, as the framework support, is an important visual part of the virtual prototyping model; the vehicle control system as the controller and the hydraulic system as the executor are interdependent and inseparable, so they are generally called vehicle control-hydraulic system.

3.1 Mechanical dynamic modeling

The 3D solid model of Special Vehicle is built using Pro/E software with powerful 3D modelling function, and then is imported into ADAMS simulation platform by means of the seamless interface program Mechanism/Pro, and finally the mechanical dynamic model of Special Vehicle is built by defining a variety of constraints and applied force in ADAMS.

All the data of the components' mass, center-of-mass and moment of inertia in the mechanical dynamic model of Special Vehicle can be calculated automatically by Pro/E software according to the 3D geometry model offered by the designer. The built multi-rigid body dynamic virtual prototyping model of Special Vehicle has 28 Degrees of Freedom (DOF). The mechanical dynamic model of Special Vehicle includes the following relatively important models-hydro-pneumatic spring model, tire model, road spectrum model and flexible body model of key components.

3.1.1 Hydro-pneumatic spring modeling

The suspension of Special Vehicle is that of hydro-pneumatic spring. The model of hydro-pneumatic spring is a kind of nonlinear spring-damping model and its schematic diagram is shown in figure 2. With the several assumptions of the hydro-pneumatic spring theoretical model [7], the relational expressions between pressures can be obtained based on thin-walled pinhole model, pipe flow model and local pressure loss model due to variable diameter of pipelines. Meanwhile, with the gas state equation of the energy accumulator, the mathematical model of hydro-pneumatic spring can be expressed as:

$$\begin{cases} p_2 - p_1 = \frac{1}{2}\rho_2\left\{\frac{A_2\dot{x}}{[C_{d1}S_1+C_{d2}S_2(1-\mathrm{sign}(\dot{x}))/2]}\right\}^2 \mathrm{sign}(\dot{x}) \\ p_3 - p_1 = \frac{1}{2}(\rho_1\zeta_1 + 2\rho_1\zeta_{21})\left\{\frac{\rho_1A_1-\rho_2A_2}{\rho_1S_4}\dot{x}\right\}^2 \mathrm{sign}(\dot{x}) \\ p_4 - p_3 = (\lambda\frac{l}{d} + \zeta_{22}) \times (\rho_3+\rho_4)[\frac{(\rho_1A_1-\rho_2A_2)}{(\rho_3+\rho_4)S_3}\dot{x}]^2 \mathrm{sign}(\dot{x}) \\ p_5 - p_4 = \frac{1}{2}\rho_5\zeta_3\left\{\frac{\rho_1A_1-\rho_2A_2}{\rho_5S_3}\dot{x}\right\}^2 \mathrm{sign}(\dot{x}) \\ p_5[V_{g0} + (V_{h0} - \frac{\rho_0V_{h0}-(\rho_1A_1-\rho_2A_2)x}{\rho_5})]^r = p_{g0}V_{g0}^r \end{cases} \tag{1}$$

Where $p_i(i=1,\cdots,5)$ is pressure; $\rho_i(i=1,\cdots,5)$ is density; A_1 is inner cavity area of hydraulic cylinder; A_2 is ring cavity area of hydraulic cylinder; S_1 is orifice area; S_2 is check valve area; S_3 is pipeline area; S_4 is cross-sectional area of the junction between hydraulic pipeline and hydro-pneumatic spring cavity; l is the length of pipeline; d is the diameter of pipeline; V_{g0} is gas volume in the energy accumulator; p_{g0} is gas pressure in the energy accumulator; ρ_0 is the density of hydraulic oil; V_{k0} is oil volume in the energy accumulator; C_{d1} and C_{d2} are flux coefficient of thin-walled pinhole; ζ_1, ζ_{21}, ζ_{22} and ζ_3 are local resistance coefficient; λ is frictional resistant coefficient; r is gas exponent; x and $\dot{x}$ are position and velocity of piston of hydro-pneumatic spring hydraulic cylinder respectively.

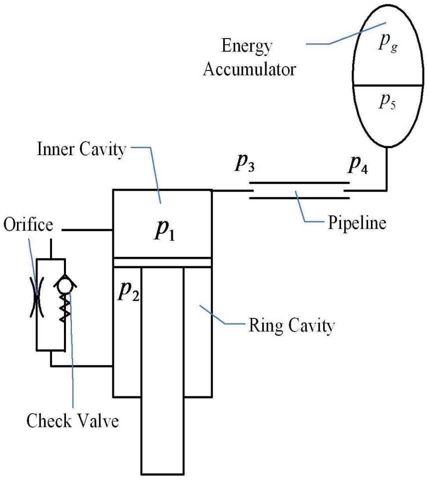

Fig. 2: Schematic diagram of hydro-pneumatic spring

Under the Integrated Development Environment VC++, capitalizing on the above built hydro-pneumatic spring mathematical model and the user-defined interface program SFOSUB [8] provided by ADAMS/solver, the user subroutine of the hydro-pneumatic spring can be built, compiled and linked to generate Dynamic Link Library (DLL) which can be used in ADAMS to define the 12 hydro-pneumatic springs of the independent suspension in Special Vehicle.

3.1.2 Tire modeling

The tire model of dynamic virtual prototyping of Special Vehicle is built based on the ”magic formula” tire model[9] which is in the form of sine-arctangent combination to fit tire test data and obtain a set of tire models which can simultaneously express the longitudinal force, the lateral force and the aligning torque. The mathematical expression of ”magic formula” tire model is shown as follows:

$$Y(x) = D\sin\{Carctg[Bx - E(Bx - arctgBx)]\} \tag{2}$$

Where Y is the longitudinal force, the lateral force or the aligning torque; x is independent variable, which can be used to express lateral angle or longitudinal slip rate of tire in different conditions; D is called the peak factor, which determines the peak of the tire's characteristic curve; C is called the shape factor, which determines the used part of the sine and, therefore, mainly influences the shape of the tire curve; B is called stiffness factor, which stretches the tire curve; E is called curvature factor, which can modify the characteristic around the peak of the tire curve.

The 6 tire models of Special Vehicle are established making use of PAC2002 tire template in the ADAMS/Tire template library in the modeling process. Tire coefficient B, C, D and E are obtained from the fitting results of test data via the tool provided by ADAMS.

3.1.3 Road spectrum modeling

Road model is an important part of the driving state simulation study, and the road roughness is mainly expressed via road power spectrum density. In 1984 International Standard Organization (ISO) issued the standard draft of road roughness representation in the file TC108/SC2N67, and in 1986 China also issued a national standard (GB7031-86)——”vehicle vibration input——the standard of road roughness representation”. For the road power spectrum density , both documents have suggested the fitting expression as [10]:

$$G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \tag{3}$$

Where n is spatial frequency, which is the reciprocal of the wavelength, its unit is m^{-1}; n_0 is spatial reference frequency n_0=0.1m^{-1}; $G_q(n_0)$ is called road roughness coefficient, which is power spectrum density under the spatial reference frequency n_0, its unit is m^3; ω is called frequency exponent, which is oblique line slope under the double logarithmic coordinates and determines frequency structure of road power spectrum density.

According to the standards or tests, different corresponding level values can be chosen for $G_q(n)$. The road roughness is divided into eight classes in the national standard GB7031-86 according to road power spectral density. This paper selects the road roughness of class 2 as per the design requirements for Special Vehicle and adopts software MATLAB to generate the required random road spectrum model file based on the white noise method [11].

3.1.4 Flexible body modeling

In order to build a more accurate virtual prototyping model and simulate the performance of Special Vehicle more realistically, it is required to build the flexible body model for the key components like the vehicle frame, erecting arm, and rack container etc.

The building process of the flexible body model is: through components grid discretization and a series of relevant definitions in the finite element modeling software Patran, the finite element model input files (*.bdf) are generated, which are submitted to the finite element solver Nastran for mode calculation to automatically generate the required MNF modal neutral file which is finally read to define the flexible body model via ADAMS/Flex interface in ADAMS.

The expression method of flexile body in ADAMS is the modal synthesis method, which is a particularly effective method to reduce DOF. The linear elastic structure's vibration deformation can be approximated as a linear combination of mode shapes whenever in free or forced vibration, that is:

$$u = \Phi q \tag{4}$$

Where the column matrix u is the vector of linear physical nodal deformation; the modal shape matrix Φ is the transformation from the smaller set of modal coordinates to the larger set of physical coordinates; the column matrix q is the vector of modal coordinates.

The modal synthesis method has a variety of theories and calculation methods. ADAMS takes the Craig-Bampton method [12] which builds the structure Ritz-basis from kinematics views. The structure is divided into several substructures of which any interior node's displacement can be expressed as follows:

$$u = \begin{bmatrix} u_B \\ u_I \end{bmatrix} = \begin{bmatrix} I & 0 \\ \Phi_{IC} & \Phi_{IN} \end{bmatrix} \begin{bmatrix} q_C \\ q_N \end{bmatrix} = \Phi q \tag{5}$$

Where u_B is the boundary DOF; u_I is the interior DOF; I and 0 are identity and zero matrices respectively; Φ_{IC} is the physical displacements of the interior DOF in the constraint modes; Φ_{IN} is the physical displacements of the interior DOF in the normal modes; q_C is the modal coordinates of the constraint modes; q_N is the modal coordinates of the fixed-boundary normal modes.

The generalized mass and stiffness matrices corresponding to the Craig-Bampton basis are obtained via a modal transformation. The two matrices are shown in the following expression:

$$\overline{M} = \Phi^T M \Phi = \Phi^T \begin{bmatrix} M_{BB} & M_{BI} \\ M_{IB} & M_{II} \end{bmatrix} \Phi = \begin{bmatrix} \overline{M}_{CC} & \overline{M}_{NC} \\ \overline{M}_{CN} & \overline{M}_{NN} \end{bmatrix} \tag{6}$$

$$\overline{K} = \Phi^T K \Phi = \Phi^T \begin{bmatrix} K_{BB} & K_{BI} \\ K_{IB} & K_{II} \end{bmatrix} \Phi = \begin{bmatrix} \overline{K}_{CC} & 0 \\ 0 & \overline{K}_{NN} \end{bmatrix} \tag{7}$$

where $\overline{M}$ and $\overline{K}$ are generalized mass matrices and generalized stiffness matrices respectively; M and K are mass matrices and stiffness matrices of finite element for the flexible component; the subscripts I , B , N , and C denote internal DOF, boundary DOF, normal mode and constraint mode respectively.

The equation of motion of flexible body, in terms of the mode coordinates is:

$$\overline{M}\ddot{q} + \overline{K}q = \begin{bmatrix} \overline{M}_{CC} & \overline{M}_{NC} \\ \overline{M}_{CN} & \overline{M}_{NN} \end{bmatrix} \begin{bmatrix} \ddot{q}_B \\ \ddot{q}_I \end{bmatrix} + \begin{bmatrix} \overline{K}_{CC} & 0 \\ 0 & \overline{K}_{NN} \end{bmatrix} \begin{bmatrix} q_B \\ q_I \end{bmatrix} = \begin{bmatrix} \overline{F}_B \\ \overline{F}_I \end{bmatrix} = f \tag{8}$$

where f is the mode load vector, which is the projection of the nodal force vector on the model coordinates. Its expression is shown as:

$$f = \Phi^T F \tag{9}$$

where F is the force vector in the physical coordinates.

According to Craig-Bampton methodology, the built vehicle frame and erecting arm flexible body models in ADAMS are shown in figure 3.

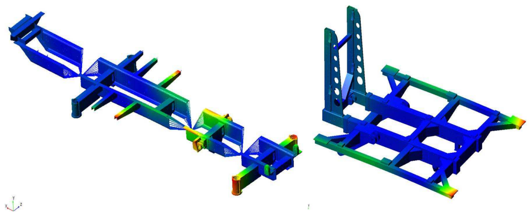

Fig. 3: Flexible body of the vehicle frame and erecting arm

3.2 Vehicle control-hydraulic system modeling

The vehicle control system of Special Vehicle appears "independent" relative to the hydraulic system., It identifies the working progress status of the hydraulic circuit by reading the feedback signals on the pre-sensor of Special Vehicle, obtains output control parameter values by solving pre-set control strategies, and achieves control of the hydraulic system by adjusting the spool position of electromagnetic hydraulic valves. The hydraulic system completes Special Vehicle body leveling and rack container erecting under the command of vehicle control system. In the virtual prototyping model of Special Vehicle, the integrated modeling of vehicle control-hydraulic system utilizes the two systems' highly interdependent relationship.

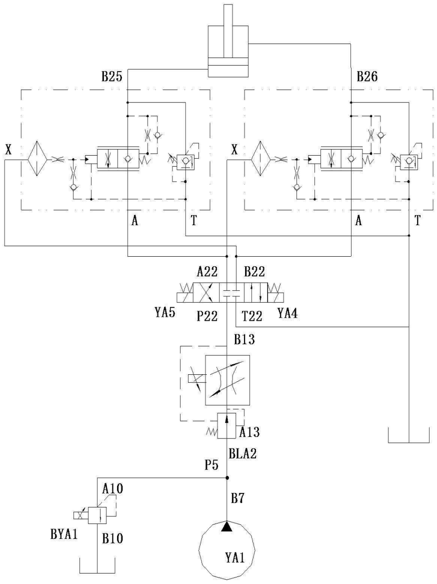

Fig. 4: The hydraulic schematic diagram of erecting circuit

Vehicle control-hydraulic system simulation adopts "co-simulation", in which the vehicle control system model is built by MATLAB/Simulink, the hydraulic system model is built by ADAMS/Hydraulics, and their software interface is realized by ADAMS/Controls. According to the schematic diagram of hydraulic system of Special Vehicle, hydraulic system circuit model of Special Vehicle is established by revising the hydraulic component parameters in the block diagram modeler provided by ADAMS/Hydraulics. Per the control circuit flow chart of Special Vehicle, the vehicle control system model can be built in MATLAB/Simulink through designing control block diagram and corresponding control programs. The hydraulic schematic diagram and the control flow chart of erecting circuit are shown in figure 4 and figure 5 respectively.

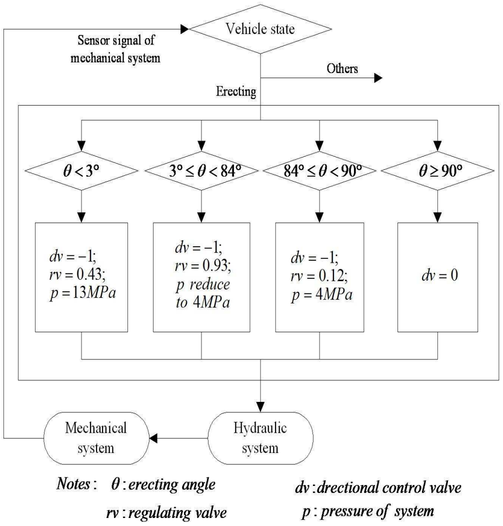

Fig. 5: The control flow chat of erecting circuit

3.3 Mechanical, electrical and hydraulic integrated virtual prototyping model of Special Vehicle

Based on the mechanical system modeling and vehicle control-hydraulic system modeling, the mechanical electrical and hydraulic integrated virtual prototyping model of Special Vehicle is built in MATLAB/Simulink, importing the nonlinear mechanical system model and hydraulic model Adams_sub into MATLAB via seamless interface program ADAMS/Controls and combining the vehicle control model. The mechanical dynamic virtual prototyping model built in ADMAS is shown in figure 6. The block diagram of the mechanical, electrical and hydraulic integrated virtual prototyping model is shown in figure 7. The relationship between input and output interface of Adams_sub model is shown figure 8.

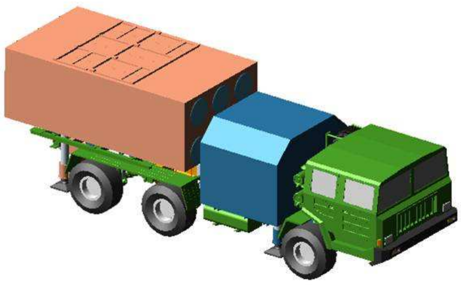

Fig. 6: Mechanical dynamic virtual prototyping model of Special Vehicle

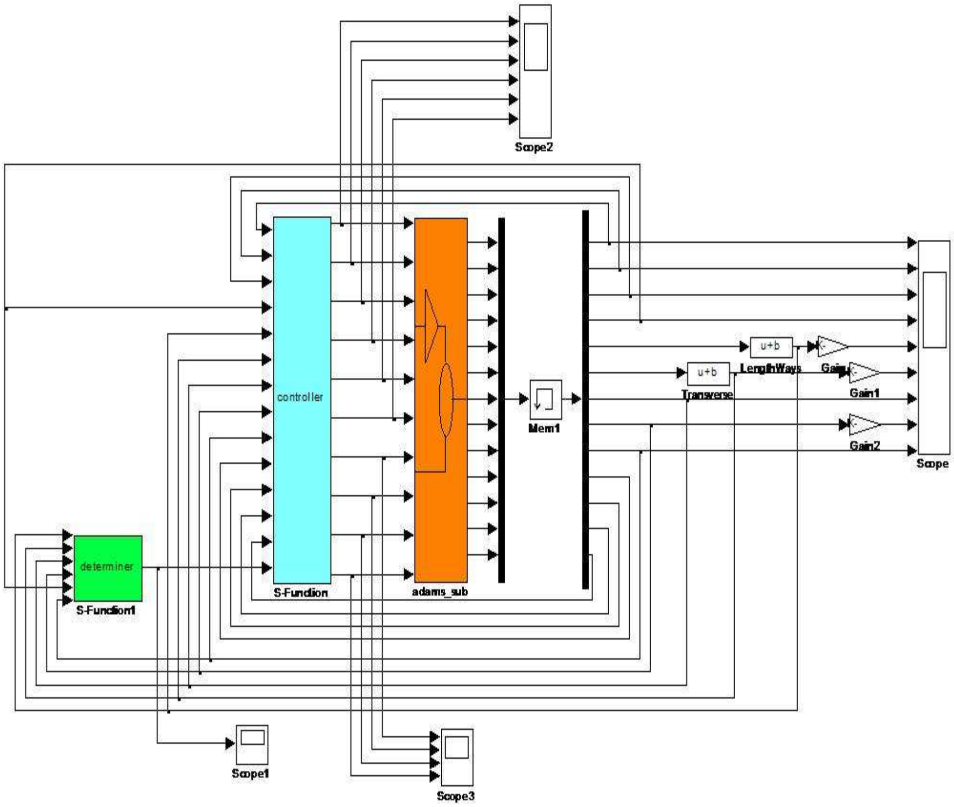

Fig. 7: Diagram of integrated mechanical, electrical and hydraulic virtual prototyping model of Special Vehicle

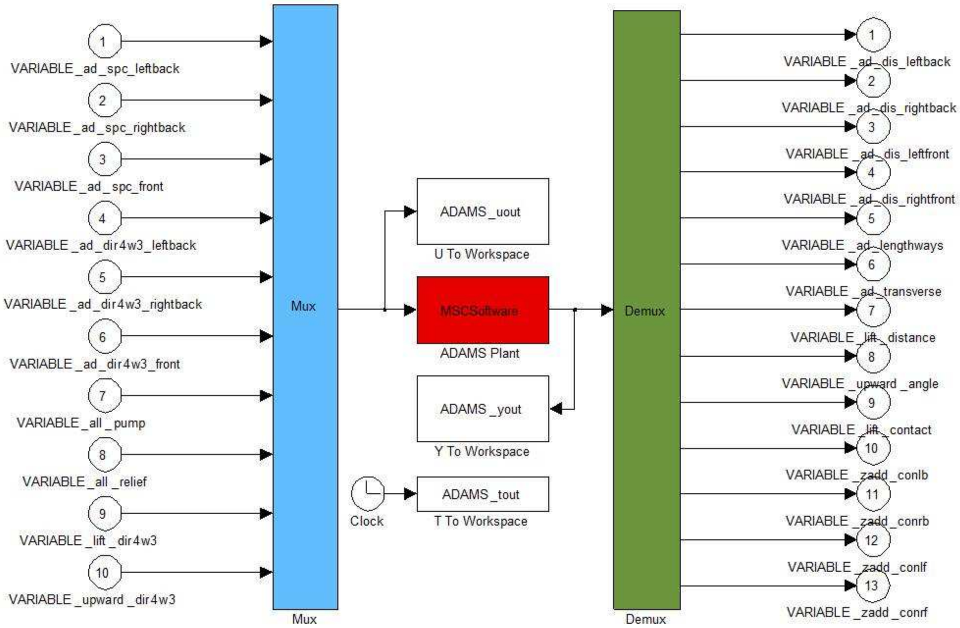

Fig. 8: Relationship between input and output interface of Adams_sub model

4 Model Verification of Special Vehicle

To accurately predict the performance of Special Vehicle under various typical working conditions, the built virtual prototyping model of Special Vehicle is required to validate and verify. The verification method is that parameters of the dynamic virtual prototyping model of Special Vehicle are repeatedly adjusted to enable the multi-group performance indexes of virtual test results to conform to the physical test results.

4.1 Static verification of the model

Under static conditions, the axle-load distribution of Special Vehicle is one of the most important design specifications. The simulation result of dynamic virtual prototyping model of Special Vehicle indicates that Special Vehicle's axle-load ratio is 29:71, which meets the design requirements.

4.2 Dynamic verification of the model

At the speed of $40km/h$ and under the class-2 road roughness condition, both time domain and frequency domain methods are taken to compare the virtual test results with the physical ones. . Figure 9 is the contrast curves of acceleration time history of virtual tests and physical tests measured in the mass center of important equipment. Figure 10 is the contrast curves of acceleration frequency spectrum density. From figure 9 and figure 10 it can be concluded: whatever the time domain or frequency domain, the data consistency of virtual test results and physical test results is good enough to effectively prove the modeling accuracy of the virtual prototyping model of Special Vehicle.

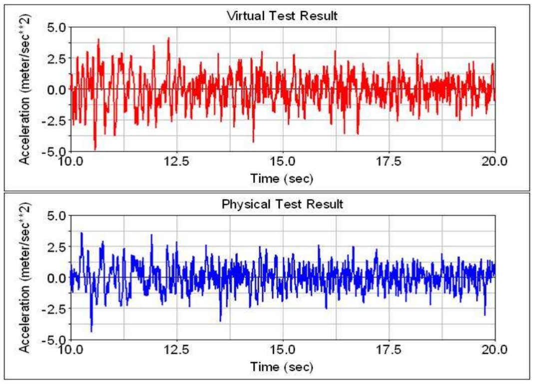

Fig. 9: Contrast of time history curves of virtual test and physical test

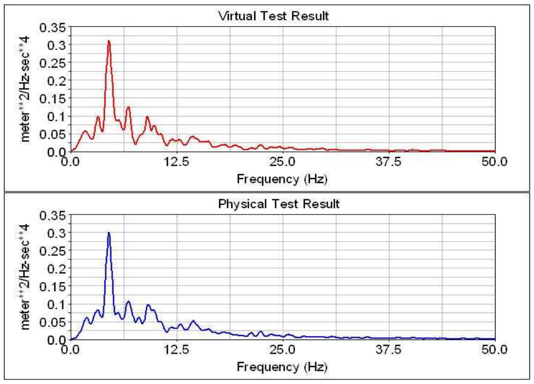

Fig. 10: Contrast of frequency spectrum density of virtual and physical test

5 Virtual Tests of Special Vehicle

5.1 Virtual tests of driving stability

The virtual tests of driving stability include the stability of quick start-up, high-speed driving and braking and the stability of low-speed across trench and low-speed over obstacle, and so on. Virtual tests of driving stability can be easily achieved by defining different driving motions on the driving shaft of Special Vehicle.

5.1.1 Virtual tests of quick start-up, high-speed driving and braking stability

Special Vehicle frequently accelerates and decelerates in the driving state. Under the extreme conditions, it assumes that the Special Vehicle accelerates at 0.4 m/s^2 from rest to start, 6 seconds later, and accelerates at 2 m/s^2 until velocity of Special Vehicle reaches $22.4m/s$ (about 80 km/h), and drives at a steady speed of 22.4 m/s for 30 seconds, and then decelerates to 8.4 m/s (about 30 km/h) at -1.6 m/s^2 in 10 seconds, and finally comes to brake test at acceleration of -2.9 m/s^2 until a complete stop.

Figure 11 shows the response curve of vertical vibration acceleration in the mass center of important equipment at a period of time, which indicates: when Special Vehicle is at the state of start-up, acceleration, high-speed driving and braking, the vertical acceleration of the mass center of important equipment is less than $5m/s^2$ in the whole process, therefore, Special Vehicle meets the corresponding dynamic environment requirements under the class-2 road roughness driving conditions.

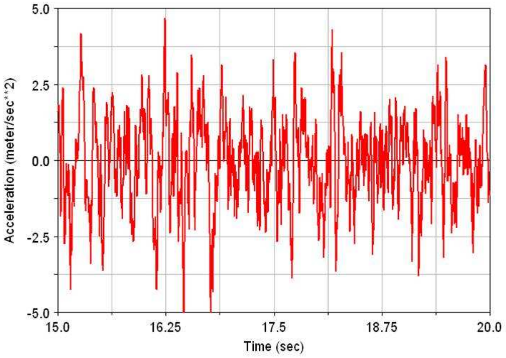

Fig. 11: Response curve of vertical vibration acceleration in the mass center of important equipment

5.1.2 Virtual tests of low speed across trench and over obstacle

Special Vehicle is driven at 15km/h on the flat road. When the vehicle comes to a certain position, it crosses over a 0.7m-wide and 1m-deep trench, after that, it returns to flat road. Figure 12 shows the virtual test results of low speed across trench.

Fig. 12: Virtual test of low speed across trench

Special Vehicle is driven at 3km/h on the flat road. When the vehicle comes to a certain position, it climbs over a 0.6m-high vertical obstacle, after that, it returns to flat road. Figure 13 shows the virtual test results of low speed over obstacle.

Both virtual test results indicate that the vertical acceleration of the mass center of important equipment is less than 15m/s^2 when Special Vehicle is driven at low speed across the trench or over the vertical obstacle. Therefore, excessive impact acceleration is not generated on the important equipment which meets the corresponding dynamic environment requirements.

Fig. 13: Virtual test of low speed over obstacle

5.2 Virtual tests of vehicle unfolding and folding

The hydraulic executive system of Special Vehicle carries out vehicle unfolding and folding under the command of vehicle control system. In this vehicle unfolding and folding process, the dynamic topology of Special Vehicle has significant changes; ending state of vehicle unfolding as the beginning state of the important equipment working state undoubtedly has a significant impact on normal operation of vehicle equipment. The virtual tests of vehicle unfolding and folding are important tools to verify the design quality of the control and hydraulic system and the operation platform of design improving. The total time of vehicle unfolding and folding is about 300 seconds. Figure 14 shows the virtual test results of vehicle unfolding and folding. From figure 14 it can be concluded that the change of the support leg force is stable in the whole process.

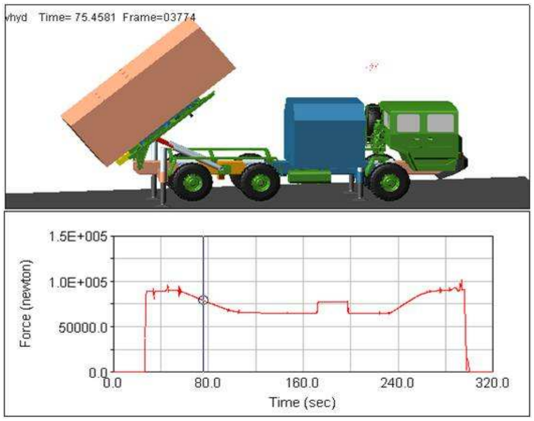

Fig. 14: Virtual test of unfolding and folding vehicle

The virtual tests of unfolding and folding processes indicate that at each process, the vehicle body is very stable and has no instability phenomenon, and the hydraulic system has no excessive jitter, seizure or oscillation phenomenon. Therefore, Special Vehicle meets the corresponding dynamic environment requirements.

6 Conclusion

Taking Special Vehicle as the prototype, this paper carries out research on dynamic virtual prototyping modeling and virtual tests of the complex mechanical, electrical and hydraulic system. In the modeling process, the visible mechanical system and the vehicle control-hydraulic system are elaborated, and the mechanical, electrical and hydraulic integrated virtual prototyping model of Special Vehicle is built. Based on the model, the dynamic characteristics of the large dynamic system composed of Special Vehicle and relative dynamic environment is studied. The correlation established between the main design parameters and the performance indexes lays the foundation for optimizing its overall design parameters. The comprehensive virtual simulation tests of Special Vehicle are carried out. The results of virtual tests quantitatively evaluate the ability to achieve performance indexes and ability to adapt to the dynamic environment of the important equipment in various typical conditions, meanwhile estimate the overall design of Special Vehicle fully and systematically. The research results have important significance for the simulation and optimization of complicated mechanical electrical, and hydraulic integrated system.

References

[1] Xiong Guangleng, Guo Bin, Chen Xiaobo. Co-simulation and Virtual Prototyping Technology (Tsinghua Publishing House, Beijing, China, 2004).

[2] ZHAN Jinchun, GUO Xiaosong, YANG Yanni. New Multi-software Environment for Collaborative Modeling and Simulation of Mechatronic Systems. Journal of System Simulation, **21**, (2008), 5816-5828.

[3] ZHU Dalin, QIN Jinyi, ZHANG Yi, ZHANG Hu, XIA Minmin. Research on Co-simulation Using ADAMS and MATLAB for Active Vibration Isolation System. The 3th International Conference on Intelligent Computation Technology and Automation, (2010) May 11-12, 1126-1129; Changsha, China.

[4] SUN Guangxu, YUAN Duancai. Dynamics Simulation of Scissors Elevating Platform Dynamics Simulation of Scissors Elevating Platform. Journal of System Simulation, **11**, (2010), 2650-2653.

[5] XIONG Haiguo, HUANG Qitao, MA Jianming, HAN Junwei. Research on Co-modeling Virtual Prototype of Motion System of Flight Simulator. Proceedings of the 2009 IEEE, International Conference on Mechatronics and Automation, (2009) August 9-12, Changchun, China, 2260-2264.

[6] Ma Changlin, Li Feng, Hao Lin, Zhang Zhili. Modeling and simulation for Electro-hydraulic systems based on multi-software collaboration. 2008 Asia Simulation Conference-7th International conference on system simulation and scientific computing, (2008) November 17-19, Chengdu, China, 110-113.

[7] Zhuang De-Jun, Liu Jiang, Yu Fan, Lin Yi. The Nonlinear Mathematical Model and Characteristics of Hydro-Pneumatic Spring. Journal of Shanghai Jiao Tong University, **9**, (2005), 1441-1444.

[8] Zheng Jianrong. ADAMS-Introduction and Improvement of Virtual Prototyping Technology (China Machine Press, Beijing, China, 2002).

[9] Lin Yi, Li Sheng. Study on The Bifurcation Character of Steering Wheel Self-excited Shimmy of Motor Vehicle With Dependent Suspension. Chinese Journal of Mechanical Engineering, **12**, (2004), 187-191.

[10] Zhou Yunbo, Yan Qingdong, Li Hongcai. Road Roughness Research of Tracked Vehicle Compliance Simulation Experiment. Journal of System Simulation, **2**, (2006), 95-100.

[11] Chen Jieping, Chen Wuwei, Zhu Hui, Zhu Maofei. Modeling and Simulation on Stochastic Road Surface Irregularity Based on MATLAB/Simulink. Transactions of the Chinese Society for Agricultural Machinery, **3**, (2010), 11-15.

[12] Craig Wood. Integrated Durability Analysis a Vehicle Through Virtual Simulation (Windsor University Publishers, Canada, 2003), 52-67.

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