Dynamic coupling analysis of rocket propelled sled using multibody-finite element method

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Abstract

Rocket propelled sled is a most important testing tool in aerospace and aviation industries flying along the rails on the ground. It is very difficult to simulate the operating conditions in the computer using numerical analysis method. In consideration of this fact, the dynamics analysis and simulation of the rocket propelled sled were done based on Multibody System Dynamics and Finite Element Analysis theory in this paper. The most difficult work during the analysis was establishing the boundary conditions of the rocket propelled sled. This paper made this kind of attempt. Then the relevant post processing figures and data were obtained, thereby providing the designer and manufacturer with detailed and reliable data. The conclusion is the combination of finite element analysis and multisystem theory is more effective than those before and the boundary conditions are correct and acceptable. The results of it can be important references of structure designers.

Keywords: Rocket propelled sled, Finite Element Analysis, Multibody Dynamic Analysis (MDA), Multibody-Finite-Element Method, Rail Irregularity

1 Introduction

As the increase of R&D projects of large civil aircraft, weapon system and aviation life-saving equipments, the demand for deferent types of rocket-propelled sled is growing quickly. Rocket propelled sled [1-4], as its name implies, is a specifically made sled flying along specially made tracks, which propelled by one or more rocket engines. Rocket propelled sled is a most important testing tool flying along the rails on the ground. It is extensively applied in the design of many fields such as the testing of advanced weapons especially the long-range missiles, the detection of aeronautic and astronautic devices and the examination of equipments in aircraft's escape systems etc. Meanwhile such aeronautical ground facilities must be upgraded to match the increased size and performance of future aircraft, so the importance of designing of rocket propelled sled with hypervelocity and high reliability becomes apparent. It can be equipped with the test specimen and fly in extra high speed, often several times the speed of sound. Due to the high cost of the test equipments, it is very difficult to design. Therefore, how to secure the security of the vehicle and the expensive equipments is very difficult. But the test failure have occurred from time to time and the loss is very huge, so how to secure the vehicle's structural design as reasonable as possible, in addition to experiences, computer simulation and optimization is also very important.

Rocket propelled sled's flying environment is very abominable, such as high velocity, high acceleration, strong vibration etc. Traditionally, in order to ensure the recycling of rocket propelled sled and the valuable equipment on it, the designers placed much emphasis on previous practical experience and chose a large safety factor. The design like this makes rocket propelled sled cumbersome and poorly stabilized. In addition, the heavy weight of rocket propelled sled not only increases the cost of test (need more propellant, more number of rocket engines), but also increases the uncertainty of the flight. Although the departments concerned are now able to do some numerical simulations, they are only restricted to the simple finite element analysis of a single part in rocket propelled sled testing system. The new theories and methods, especially the way of building boundary conditions must be developed for rocket-propelled sled's high acceleration, extremely adverse testing environment. Most important of all, the rocket-propelled sled must be researched as a whole system. Therefore, this paper uses the method of coupling mechanical system simulation (ADAMS) and finite element analysis (ANSYS) technologies [5, 6] to model and simulate the flight of rocket propelled sled. And the rocket propelled sled testing system's response for the coupled case and the function of the external force are offered. This methods based on theories of dynamics of multibody system and finite element method [7, 8]. At last, the integrated and accurate data are obtained for the designers of rocket propelled sled.

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2 The algorithm of multibody system mechanics and Finite Element Method

To derive the basic equation of the multibody finite element theory [9], we assume that the continuum is linear elastic and small internal deformation. Then we mesh these continuums respectively, a transient kinetic equation at time will be derived from the Lagrange Dynamics Equation [10] like the below:

$$\sum_{i=1}^{N}(M_i\ddot{u}_{t+\tau}+C_i\dot{u}_{t+\tau}+K_iu_{t+\tau})=\sum_{i=1}^{N}(F_{t+\tau}^{i}+G_{t+\tau}^{i}\lambda_{t+\tau}^{i}),\quad(1)$$

where, M_i, C_i, K_i are Mass matrix, Damping Matrix, stiffness Matrix respectively. $F_{t+\tau}^{i}$ is a vector of a given load. $G_{t+\tau}^{i}$ is a matrix of coordinate conversion, $\lambda_{t+\tau}^{i}$ is a coupling unknown load vector.

A simple form of this equation is:

$$M\ddot{u}_{t+\tau}+C\dot{u}_{t+\tau}+Ku_{t+\tau}=F_{t+\tau}+G\lambda_{t+\tau}. \quad (2)$$

We use equation (3) like blow to get the value of $\ddot{u}_{t+\tau}, \dot{u}_{t+\tau}, u_{t+\tau}, \lambda_{t+\tau}$, which is a expression including the known variables $\ddot{u}_t$, $\dot{u}_t$ and u_t.

$$\begin{cases}\dot{u}_{t+\tau}=u_{t+\tau}[(1-a)\ddot{u}_t+a\ddot{u}_{t+\tau}]\\ u_{t+\tau}=u_t+\tau\dot{u}_t+\frac{1}{2}\tau^2[(1-b)\ddot{u}_t+b\ddot{u}_{t+\tau}]\end{cases}, \quad (3)$$

where a, b, τ are the formatting parameters. Substituting equation (3) into equation (2), we will get:

$$\bar{K}_{t+\tau}u_{u+t}=\bar{F}_{t+\tau}+G_{t+\tau}\lambda_{t+\tau}, \quad (4)$$

where, $\bar{K}$ is effective stiffness matrix, $\bar{F}$ is equivalent load vector. As a rule, we also give the simplified form like the below:

$$\bar{K}u=\bar{F}+G\lambda. \quad (5)$$

Then, consulting equation (5), we can construct a functional equation as is equation (6) shown:

$$J(u,\lambda)=\frac{1}{2}\lambda^T\bar{K}u-u^T\bar{F}-u^TG\lambda. \quad (6)$$

The another form of equation (5) is as equation (7) describes:

$$u=\bar{K}^{-1}(\bar{F}+G\lambda). \quad (7)$$

Substituting equation (7) into equation (6):

$$J(\lambda)=-\frac{1}{2}\lambda^TG^T\bar{K}^{-1}G^{-1}\lambda-\lambda^TG^TK^{-1}F-\frac{1}{2}\bar{F}^T\bar{K}^{-1}\bar{F}. \quad (8)$$

This functional's minimum can be deduced equation (9):

$$K_\lambda\lambda=F_\lambda. \quad (9)$$

Therefore, the main work of the multibody finite element theory is to solve the equations like below:

$$\begin{cases}K_\lambda\lambda=F_\lambda\\ \bar{K}u=\bar{F}+G\lambda\end{cases}. \quad (10)$$

From these equations, we can see the possibility of the joint about these two theories, which implementation is the combination of ANSYS and ADAMS, as the upcoming section discusses.

3 Method of combined use of ANSYS and ADAMS

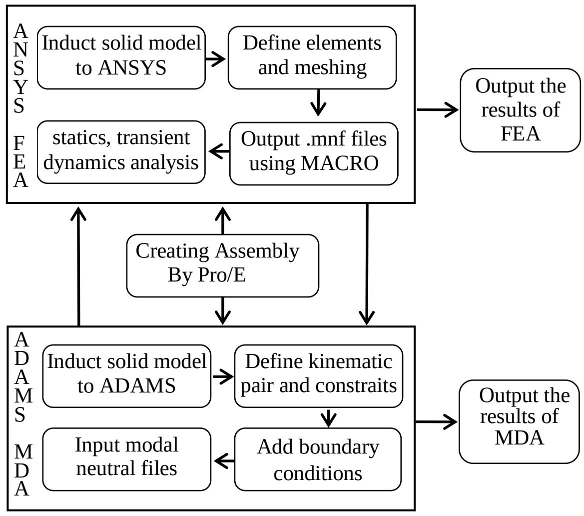


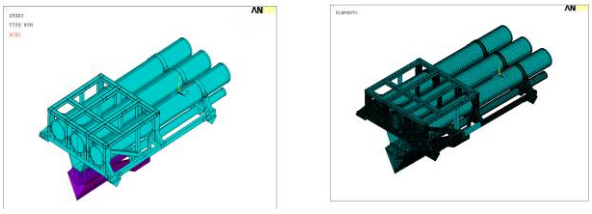
FIGURE 1 Procedure of the joint simulation

In a complex mechanical system, the flexible body will have a major impact on movement of the whole system, without which, Kinematic and Dynamic Analysis on the rigid-flexible coupling model (RFCM) will result in large errors. The movement of the whole system in turn determines the status of the force and motion state of each component. Only phasing in flexible technology can we get the accurate distribution of each part's stress and strain. In other words, only the key parts of sled are dealt with flexible bodies, can accurate dynamic simulation results be got correctly. In essence, at theory, the stress and strain analysis of flexible bodies models(FBM) need the union of the multibody dynamics and finite element method8, while in practice, the joint use of ANSYS and ADAMS (see FIGURE 1) can make the simulation results more accurate. ANSYS program automatically generates the finite element model of flexible body parts, then using the macro command "ADAMS.MAC", we can easily output model neutral file (jobname.mnf), which is required by ADAMS, this file contains all the information in the flexible body. After defined the constraint of sled's kinematic pair and the boundary conditions, ADAMS can do dynamics simulation reasonably

4 Creating Rigid-Flexible Coupling Model

4.1 THE NECESSARY ASSUMPTIONS TO SIMPLIFY THE MODEL

The following assumptions should be made when simulating on the rocket-propelled sled's Rigid-Flexible Coupling Model (RFCM) [11, 12], as is shown in Figure 2:



1) Entity Mode 2) RFCM
FIGURE 2 Entity model and RFCM of rocket sled

1) Rocket propelled sled flies along a straight line and the sled body moves in parallel to the ground;
2) 1/2 model can simulate the whole sled exactly, because the sled is right-left symmetrical;
3) In addition to the elastic component we focus on, the other parts are thought as rigid bodies, which not considered those deformations.

Proewildfire4.0's global Cartesian coordinate system, which origin placed in the midpoint of the two back slippers, X-axis pointing to flight direction, Y-axis pointing to the left direction, Z-axis pointing vertically.

4.2 THE COORDINATE SYSTEM OF THE MODEL

During the establishment of multibody model, the choice of coordinate system concerns the complexity and difficulty of solving mathematical model's equations [13-15]. In this paper, the use of the ISO coordinate system makes this problem simpler. Rocket propelled sled models reference for the coordinates system in Pro/E.

4.3 DEFINITION OF KINEMATIC PAIRS

The principle of defining Kinematic pairs is that they must reflect the physical prototype's true working status as far as possible, meanwhile neglecting the unnecessary ones. Table 1 defines the deferent types of Kinematic pairs in the model, and S is the abbreviation of slipper; P represents the product sled; D is on behalf of driver sled; T, on behalf of three-dimensional NC turntable; LF is the representative of the left-front position; LB, representative of the left-back position; RF, on behalf of right-front position; RB is the representative of right-front position.

TABLE 1 Types of kinematic pairs of RFCM

Index	Type	Definition in ADAMS
1	Contact pair	Contact (.RocketSled. Product-sled. Stop&. RocketSled.Ground. Spring-damper)
2	Revolute pair	Revolute (.RocketSled. Product Driver-sled &. RocketSled. Pin)
3	Cylindrical pair	Cylindrical (.RocketSled. Pin &. RocketSled. Slider)
4	Contact pair	Contact(.RocketSled. Slider & .RocketSled. Ground. Rail)
5	Fixed pair	Fixed (.RocketSled. Product-sled&. RocketSled. Turntable)
6	Contact pair	Contact (.RocketSled. Product-sled. Contactor &.RocketSled. Driver-sled. Contactor)
7	Fixed pair	Fixed (.RocketSled. Driver-sled &. RocketSled. Rocket)

Given name of rocketsled, the model's every part is automatically added the prefix '.rocketsled'. Driver sled and product sled are connected with the rails by pins and sliders. The sliders clench the rails firmly so as to ensure the sled cannot get away from the rails during the flight at ultra high speed. The connection of sled and pin is revolve pair, which have two groups, that is, driver sled and four pins, product sled and four pins respectively. The two contact pairs are between driver sled and product sled, and two or three groups of fixed pairs ensure that there is no relative sliding between rocket engine and driver sled. At last, we will get the rigid-flexible coupling model of the rocket-propelled sled testing system in ADAMS2005. The types of kinematic pairs are shown in Table 1 and Table 2.

5 Boundary Conditions During Flight of Sled

5.1 THE CALCULATION OF WIND LOAD

The applied wind pressure of the flying rocket Propelled sled can be equivalent to the wind loads. The way of getting the wind load is as follows: If rocket propelled sled is flying at high-speed of 300m/s, it is equivalent that there is the same high-speed wind of 300m/s blowing to the rocket propelled sled. The mechanics model of rocket propelled sled is shown in Figure 3.

TABLE 2 Detailed definition of joint type

Joint style	Joint name	First rigid body	Second rigid body
Revolute	*.Rocketsled.D-Pin-LF*	*.Rocketsled.Driver-sled*	*.Rocketsled.Pin-_D-LF*
Revolute	*.Rocketsled.D-Pin-LB*	*.Rocketsled.Driver-sled*	*.Rocketsled.Pin-_D-LB*
Revolute	*.Rocketsled.D-Pin-RF*	*.Rocketsled.Driver-sled*	*.Rocketsled.Pin-_D-RF*
Revolute	*.Rocketsled.D-Pin-RB*	*.Rocketsled.Driver-sled*	*.Rocketsled.Pin-_D-RB*
Revolute	*.Rocketsled.P-Pin-LF*	*.Rocketsled.Product-sled*	*Rocketsled.Pin-_P-LF*
Revolute	*.Rocketsled.P_-pin-_LB*	*.Rocketsled.Product-sled*	*.Rocketsled.Pin-_P-LB*
Revolute	*.Rocketsled.P_-pin-_RF*	*.Rocketsled.Product-sled*	*.Rocketsled.Pin-_P-RF*
Cylindrical	*.Rocketsled.P_-pin-_RB*	*.Rocketsled.Product-sled*	*.Rocketsled.Pin-_P-RB*
Cylindrical	*.Rocketsled.Pin-_S_D_LF*	*.Rocketsled.Pin-_D-LF*	*.Rocketsled.Slider-D-LF*
Cylindrical	*.Rocketsled.Pin-_S_D_LB*	*.Rocketsled.Pin-_D-LB*	*.Rocketsled.Slider-D-LB*
Cylindrical	*.Rocketsled.Pin-_S_D_RF*	*.Rocketsled.Pin-_D-RF*	*.Rocketsled.Slider-D-RF*
Cylindrical	*.Rocketsled.Pin-_S_D_RB*	*.Rocketsled.Pin-_D-RB*	*Rocketsled.Slider-D-RB*
Cylindrical	*.Rocketsled.Pin-_S_P_LF*	*.Rocketsled.Pin-_P-LF*	*.Rocketsled.Slider-P-LF*
Cylindrical	*.Rocketsled.Pin-_S_P_LB*	*.Rocketsled.Pin-_P-LB*	*.Rocketsled.Slider-P-LB*
Cylindrical	*.Rocketsled.Pin-S-P-RF*	*.Rocketsled.Pin-_P-RF*	*.Rocketsled.Slider-P-RF*
Cylindrical	*.Rocketsled.Pin-S-P-RB*	*.Rocketsled.Pin-_P-RB*	*.Rocketsled.Slider-P-RB*
Planar	*.Rocketsled. S-D-LF/B*	*.Rocketsled.Slider-D-LF/B*	*Rocketsled.Ground.L-rail*
Planar	*.Rocketsled. S-D-RF/B*	*.Rocketsled.Slider-D-RF/B*	*.Rocketsled.Ground.R-rail*
Planar	*.Rocketsled. S-P-LF*	*Rocketsled.Slider-P-LF*	*.Rocketsled.Ground.L-rail*
Planar	*.Rocketsled. S-P-LB*	*.Rocketsled.Slider-P-LB*	*.Rocketsled.Ground.L-rail*
Planar	*.Rocketsled. S-P-RF*	*.Rocketsled.Slider_P_RF*	*.Rocketsled.Ground.R-rail*
Planar	*.Rocketsled. S-P-RB*	*.Rocketsled.Slider_P_RB*	*.Rocketsled.Ground.R-rail*
Contact	*.Rocketsled.Damper-L*	*.Rocketsled.Driver-sled. Damper_L*	*.Rocketsled.Product-sled. Damper-L*
Contact	*.Rocketsled.Damper-R*	*.Rocketsled.Driver-sled. Damper-R*	*.Rocketsled.Product-sled. amper-R*
Fixed	*.Rocketsled.Fixed-P-T*	*.Rocketsled.Product-sled.*	*.Rocketsled.Turntable*
Fixed	*.Rocketsled.Fixed-D-R*	*.Rocketsled.Driver-sled.*	*.Rocketsled.Rocket*

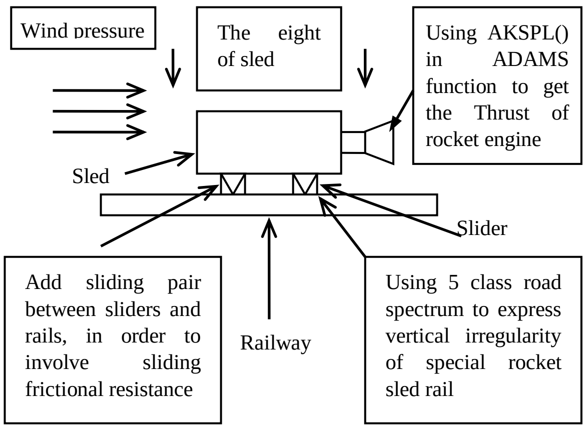


FIGURE3 Mechanics model of sled

The strength of the wind is usually expressed by wind pressure. It is question in the domain of fluid mechanics. The Bernoulli equation can give us the exact wind pressure, as is shown in the following expression:

$$w=\frac{1}{2}\rho v^2=\frac{1}{2}\frac{\gamma}{g}v^2(kN/m^2), \qquad (10)$$

where ρ is the density of the air (t/m^3), v is the speed of wind (m/s).

If the air pressure is the standard atmosphere pressure, $1/2(r/g)$ is about 1/1630. It is various in deferent part of the world, in china we can use 1/1600 according to china's concerned specifics.

Then, $w=1/1600\times300\times300=56.25\text{KN}$.

5.2 VERTICAL IRREGULARITY OF SPECIAL ROCKET PROPELLED SLED RAIL

As previously mentioned, the sled, either driver sled or product sled, is sliding along the rails, in other words, it is the slider that enables the sled flying in the railway and keep the sliding frictional contact between this two components. The cross-section of rail is choose the GB (national standard) size. The rails' distance is 1.2 meters, and the sleepers' space are all 0.5m. To calculate the vibrations from rails, we choose some kind of actual 5 class spectral density to simulate the vertical irregularity of the special rocket propelled sled rail, as is shown in Figure 4.

(a) The approach to take about the rail spectral density's expression in ADAMS is as below, namely, choosing about 20 sampling points in the road spectral curve, then using the spline curve function, which is in the ADAMS Function Builder to fit those 20 points, and finally simulating by Motion in the software.

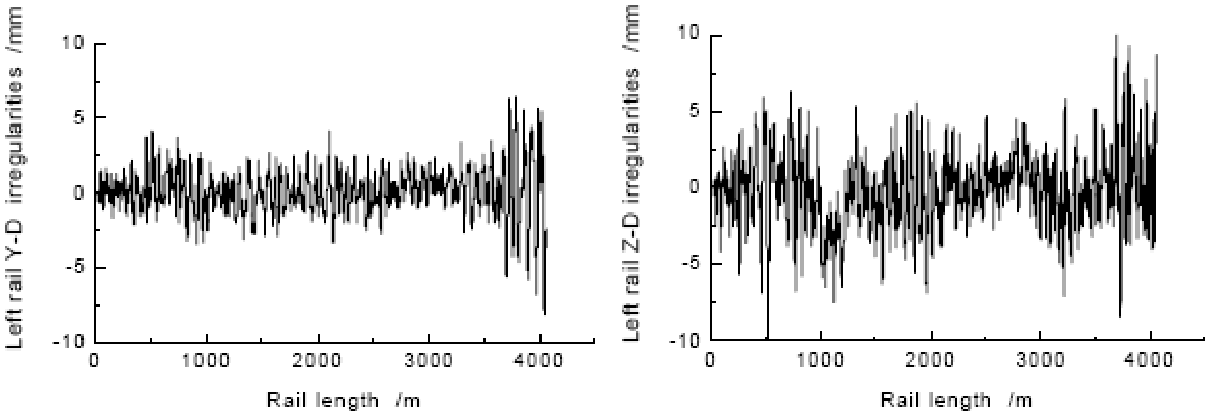


FIGURE 4 Some Actual 5 Class Spectral Density

5.3 THE THRUST OF THE ROCKET ENGINE

The rocket propelled sled's thrust on driver sled is also fit with spline curve function AKISPL() in ADAMS Function Builder. As shown below: AKISPL(Time, .Rocketsled. Driver_time, .Rocketsled. Spline_n,0) where, Time is the simulation current time, .Rocketsled.Driver_time is the time of rocket engine ignition time, .Rocketsled.Spline_n is the curve of rocket engine's thrust, which is fit by spline function in ADAMS. We can select a group of rocket engine performance thrust curve according to the needs then, and verify the performance of different rocket engines' thrust curve and its influence on the system, in order that we can select the most appropriate physical prototype testing engine models. The other useful friction parameters is: Stiffness=1.0E+008, Force Exponent=2.2, Damping= 1.0E+004， dynamic friction coefficient Dynamics=0.3, static friction coefficient Static＝0.5.

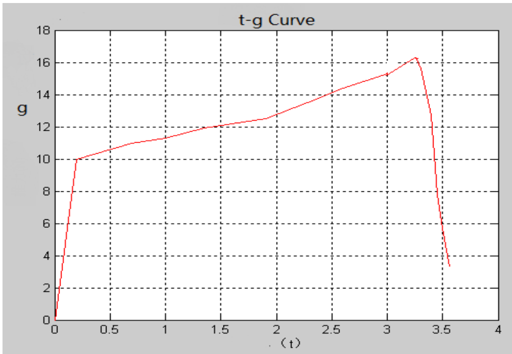


FIGURE 5 The front-back direction’s acceleration

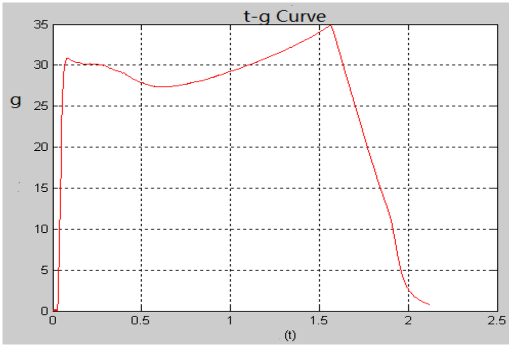


FIGURE 6 The up-down direction's acceleration

6 Some simulation results

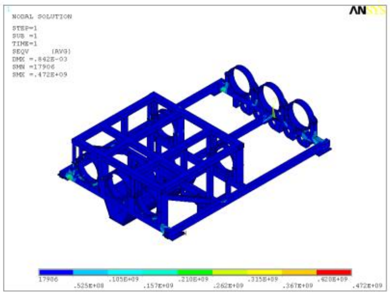
6.1 RESPONSE OF ROCKET PROPELLED SLED ACCELERATION

Through the calculation of ADAMS, we can get the acceleration curve of three directions along three axes in Cartesian coordinate system, as shown in Figures 5 and 6.

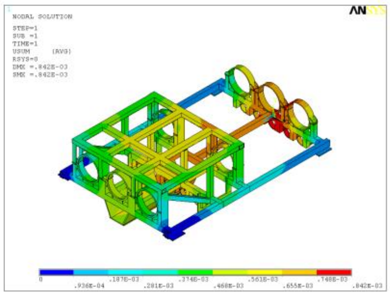
It can be seen from the following three figures: The up-down direction's acceleration is about 35g, the front-back direction (flight direction) one is 16g. Compared with the actual test, the gap between those data is permitted, what verifies the reliability of the simulation theory and method, especially the definition of Boundary Conditions in this paper. (In a actual flight test, we used the accelerometer to measure two directions’ acceleration were 15g, 36g).

6.2 INPUT THE LOAD FILE GOTTEN IN ADAMS TO ANSYS

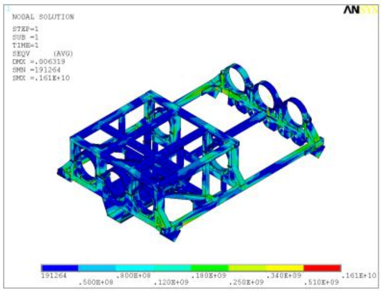
After getting the modal neutral file of the part we concerned, we establish the whole sled's rigid-flexible coupling mechanical system in ADAMS, with driver sled as flexible body. In this model, we establish the connecting way of rigid boy and flexible body, and do the dynamics analysis after defined the loads and boundary conditions. At the end of the analysis, we get output load files (.lod), which required by ANSYS. This file contains movement status at different time points and other load information (such as force, acceleration and so on). Because the load suffered by slippers is transferred to sled body through the pins, we add this equivalent load to sled body directly. Then we choose 4 time points and wait for ANSYS's calculation, at last get the driver sled's deformations in Figure 7.



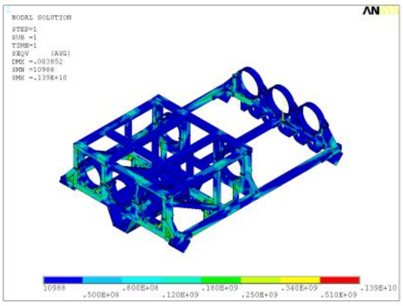
1st deformation



2nd deformation



3rd deformation



4th deformation

FIGURE7 The Deformation of 4 time points

7 Conclusions

It is an effective way that we carry out the rocket-propelled sled testing system's simulation analysis by building a reasonable dynamics-simulating model. Through this attempt, we can overcome the difficulty of the restriction of flight test actual condition, as well as the critical lack of research funds, the shortage of real testing device. Most of all, we can do this test through a much safer way, that is, computer virtual simulation. Of cause, we finally get the integrated data and the mechanical structure's effect on the real test, which should be the necessary and critical instructions of the design of various rocket propelled sled-testing system. Moreover, there is no large difference between data of the virtual simulation analysis and those of actual test of physical prototype. Through the comparative analysis, we think that the method and the definition of boundary conditions this paper constructed is reliable and faithful.

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