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REAL-TIME SIMULATION OF A HIGH SPEED MULTIBODY TRACKED VEHICLE

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ABSTRACT−Development of a real-time simulation model for high-speed and multibody tracked vehicles is difficult because they involve hundreds of highly nonlinear equations. In the development of a reliable tracked vehicle model for real-time simulation, it is helpful to use an off-line tracked vehicle model developed by considering all the degrees of freedom of each element. This paper presents a step-by-step procedure for the development of a real-time simulation model based on the off-line tracked vehicle model. The road input data, Profile IV, is used for the real time simulation and simulation results are compared with vehicle test results obtained in the military test field. It is noted that the simulation results are quite close to the test results.

KEY WORDS : Real-time simulation, Off-line simulation, Multibody tracked vehicle, Road input, Chassis subsystem, Track subsystem, Sprocket, Road wheel, Idler wheel, Supporter roller, Tension adjuster

1. INTRODUCTION

Simulation software allows engineers to change system parameters without doing expensive experiments to predict and control the system performance in advance. On- and off-line simulation technologies replace system hardware with a computer simulation based on mathematical modeling. Off-line simulation allows more precise analysis of the system than on-line simulation. When the system is identified through off-line simulation, real-time simulation can be achieved based on off-line simulation (Hanselmann and Smith, 1996; Kim *et al.*, 2003).

Accurate models of actual multibody tracked vehicle can be used for off-line simulation and more correct information can be obtained. However, PC-based real-time simulation of multibody tracked vehicles is almost impossible because the vehicle model is complicated and composed of hundreds of elements. Therefore, the system model should be simplified for real-time simulation in order to decrease the simulation time and control the design parameters.

In this paper, four real-time simulation models for the multibody tracked vehicle are proposed based on an off-line tracked vehicle model (Shabana, 1994; Shin *et al.*, 1998; Kim and Yi, 2001) consisting of two kinematically decoupled subsystems, i.e., the chassis subsystem and track subsystem. The chassis subsystem includes the chassis frame, sprocket, six road wheels, six road wheel arms, idler wheel, idler wheel arm, three supporter rollers, and tension adjuster, while the track subsystem is represented as a closed kinematic chain consisting of 76 rigid track links interconnected by revolute joints.

This off-line tracked vehicle model with 96 bodies is simplified for real-time simulation. The first proposed model has just five elements, the chassis frame, idler wheel, idler wheel arm, road wheel and road wheel arm, to show the basic behavior of the tracked vehicle. The second proposed vehicle model is composed of the chassis frame, idler wheel and six road wheels. The third proposed model combines the first and second models, and so is more complicated than both. This vehicle model includes the chassis frame, idler wheel, idler wheel arm, six road wheels and road wheel arm. In the fourth model, a simple tension adjuster and track subsystem are added to the third model. This real-time tracked vehicle model will be used for HIL (hardware-in-the-loop) simulation to develop a real-time controller of the tension adjuster in future work.

MATLAB SIMULINK was used to simulate the proposed real-time models. The S-function in MATLAB SIMULINK was used to decrease the simulation time for real-time simulation. This S-function was used to solve the dynamic algebraic equations of the tracked vehicle model. Use of the S-function improves computational efficiency, and stabilizes the system more than the use of the SIMULINK block alone does (Mat94, 1994; dSPACE95,

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1995).

Real-time simulation was performed on a Pentium IV 1.4GHz PC, and simulation results for the four proposed tracked vehicle models were compared to vehicle field test results. Simulation results agreed well with the experimental results, while satisfying given simulation time.

2. MODELING FOR REAL-TIME SIMULATION

The planar model consisting of 96 rigid bodies for off-line simulation of the high-speed multibody tracked vehicle is shown in Figure 1. This off-line tracked vehicle model consists of two kinematically decoupled subsystems, i.e. the chassis subsystem and the track subsystem. The chassis subsystem includes the chassis frame, sprocket, road wheels, idler wheel, road wheel arms, idler wheel arm, supporter rollers, and tension adjuster, while the track subsystem is a closed kinematic chain consisting of seventy-six rigid track links interconnected by revolute joints. The sprocket, road wheel arms, idler wheel arms, supporter rollers, and tension adjuster are connected to the chassis subsystems by revolute joints. The road wheels are connected to the road wheel arms by revolute joints. The idler wheel arm and tension adjuster are also connected to the idler wheel by revolute joints.

This kind of complete model can be used for off-line simulation and to obtain more realistic information (Kim and Yi, 2001). However, this off-line simulation model should be simplified for real-time simulation to decrease the simulation time and control the design parameters such as hydraulic pressure of the tension adjuster. The off-line tracked vehicle simulation model, consisting of the 96 rigid bodies, has 249 degrees of freedom and is composed of a 57 × 21 matrix in the chassis subsystem and a 228 × 78 matrix in the track subsystem, which cannot be handled in real-time simulation. In this section, the simplified models substituting the off-line tracked vehicle model shown in Figure 1 are proposed and modeled for real-time simulation.

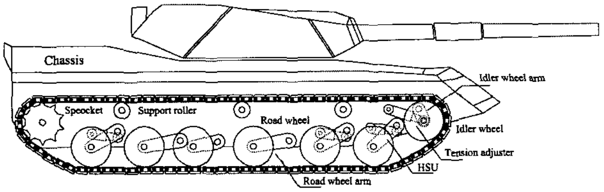

Figure 1. Off-line planar multibody tracked vehicle model.

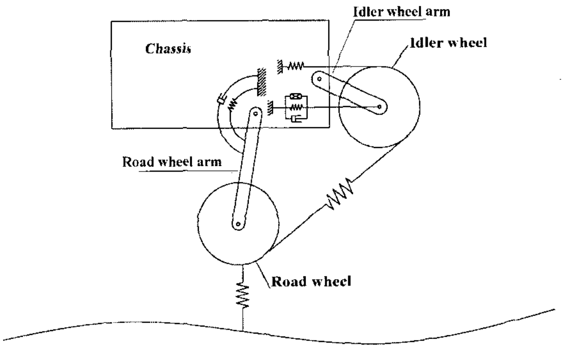

Figure 2. The first proposed tracked vehicle model.

2.1. Chassis Frame-Idler Wheel-Road Wheel Subsystem Model

The first proposed model shown in Figure 2 for real-time simulation is composed of basic elements, the chassis frame, idler wheel, idler wheel arm, road wheel and road wheel arm. The vehicle components are connected to the chassis by revolute joints,springs, and dampers. The 76 track links, three upper rollers, five road wheels, five road wheel arms and tension adjuster are not considered in this model.

2.2. Chassis Frame-Idler Wheel-Six Road Wheels Subsystem Model

The second proposed model shown in Figure 3 is composed of the chassis frame, idler wheel and six road wheels. To decrease simulation time, the 76 tracks, three upper rollers, six road wheel arms, one idler arm and the tension adjuster are not considered in the second model. Springs and dampers connect the vehicle components to the chassis. Compared with the first proposed tracked vehicle model, five more road wheels are added and the road wheel and idler arms are removed.

This second model is different from the first in the degrees of freedom of each element. The six road wheels are only allowed to move in the y direction and idler wheel is only allowed to move in the x direction while chassis is allowed to move in the y and θ directions. The

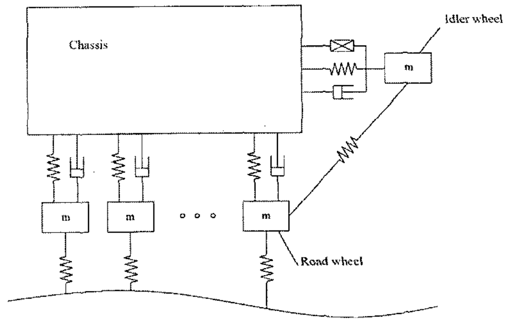

Figure 3. The second proposed tracked vehicle model.

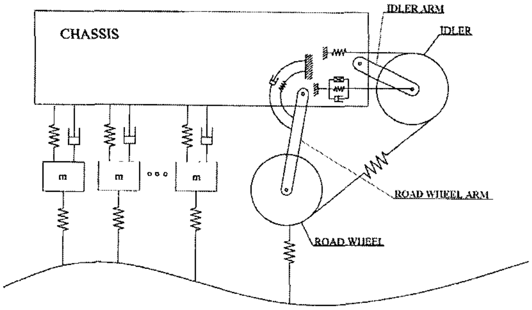

Figure 4. The third proposed tracked vehicle model.

unconstrained motion of each element in the second model has only one degree of freedom except the chassis. In this second system, the total number of elements is increased, but the degrees of freedom are decreased.

2.3. Subsystem Model III

The third proposed model is more complicated than the first and second models, combining the two previous models as shown in Figure 4. This vehicle model includes the chassis frame, idler wheel, idler wheel arm, six road wheels and road wheel arm. The vehicle components are connected to the chassis by revolute joints, springs, and dampers.

2.4. Real-Time Tracked Vehicle Model

The tracked vehicle model will become off-line if the track subsystem is fully considered, because the off-line track subsystem model is represented as a closed kinematic chain, consisting of 76 rigid track links interconnected by revolute joints. Therefore, part of the track subsystem should be used to decrease the simulation time. The last proposed real-time tracked vehicle model shown in Figure 5 is composed of the chassis frame, idler wheel, idler wheel arm, six road wheels, six road wheel arms, tension adjuster and track subsystem.

In this model, the chassis subsystem is considered first and track subsystem is partially added when the track passes the sprocket and idler wheel, while checking the positions of the tracks moved in the driving direction along the track subsystem during simulation. Compared with the third model, this real-time vehicle model is more similar to the high-speed, multibody tracked vehicle model.

In the high-speed tracked vehicle, the tension adjuster shown in Figure 6 plays an important role. It is a kind of hydraulic actuator controlling the position of the idler wheel. One end of the tension adjuster is fixed at the lower part of the chassis and the other end at the idler wheel arm. The center of the idler wheel and idler wheel arm are pin-connected. The idler wheel arm mounting on the idler wheel acts as a supporting arm, unlike a HSU (hydro-pneumatic suspension unit) or road wheel arm, which has stiffness and damping characteristics and constrains the motion of idler wheel. In this way, the tension adjuster controls the track tension by changing the position of idler wheel. The track tension prevents track separation, distributes pressure on the terrain, and affects vibration, noise, and life of the track chain. When the tracked vehicle moves, the track tension depends mainly on the pre-tension, velocity, shape and property of terrain, friction, rotational velocity of the sprocket and so forth. Therefore, it is difficult to predict the track tension. In this study, the hydraulic characteristics of tension adjuster are neglected to decrease the simulation time.

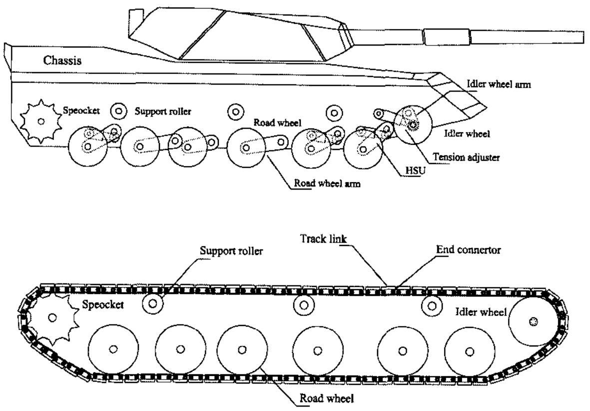

Figure 5. Chassis and track subsystems of the real-time tracked vehicle model.

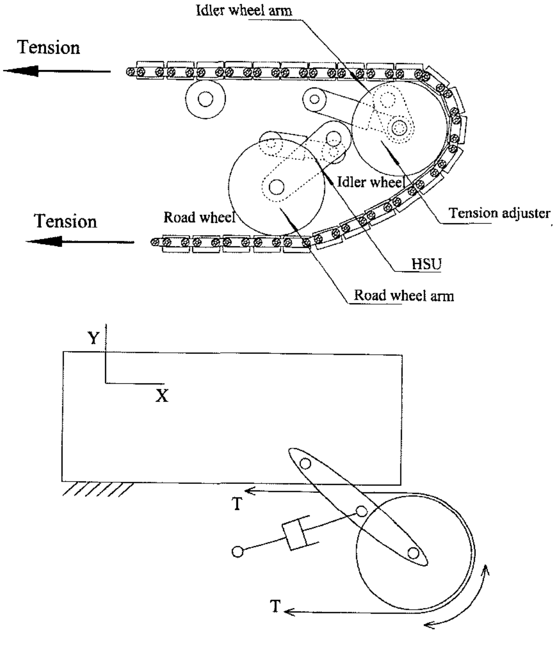

Figure 6. Dynamic model of a tension adjuster.

3. SIMULATION AND RESULTS

The tracked vehicle model with 96 bodies for off-line simulation shown in Figure 1 is simplified for real time simulation. The first proposed model has just five vehicle components, i.e., chassis frame, road wheel, idler wheel, road wheel arm, and idler wheel arm. The track subsystem is not considered and road input is not used. In the second proposed model, road input is also not used. The second proposed vehicle model is composed of the chassis frame, idler wheel and six road wheels. The third proposed model incorporates the chassis frame, idler wheel, idler wheel arm, six road wheels and road wheel arm. In the third model, road input, Profile IV is used. The last model is composed of the chassis subsystem and part of the track subsystem. In this model, road input, Profile IV, is also used. Simulations were conducted using an IBM-PC equipped with 1.4 GHz CPU.

3.1. Road Input (Profile IV)

Profile IV shown in Figure 7 represents a symmetric road profile which can be used as road input for two-dimensional tracked vehicle models. Profile IV shows the road height along the distances. The dark rectangles on profile IV show the low rough bumps. When the tracked vehicle moves on these bumps, higher frequencies can be observed due to the impact forces between bumps and tracks. Profile IV is not used for the first and second proposed tracked vehicle models but is used for the third and last tracked vehicle models.

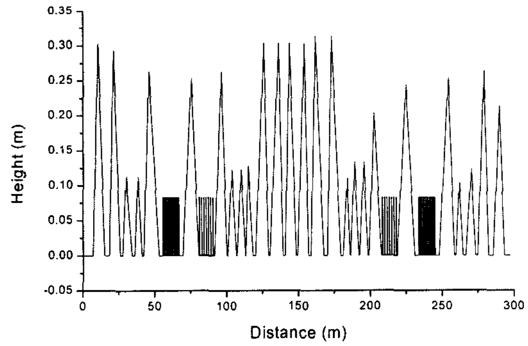

Figure 7. Profile IV.

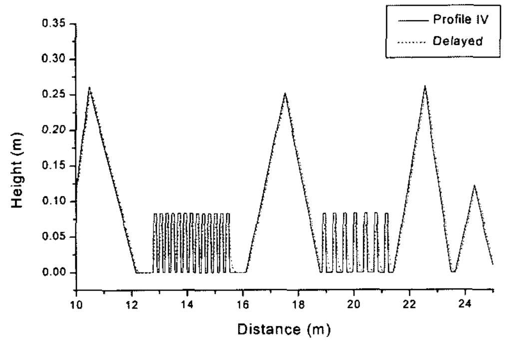

Figure 8. Delayed profile IV.

Figure 8 shows the road input used for real-time simulation in this study. The track cannot follow the paths exactly because there are sudden changes in the road shape and the time delay should be considered for actual path simulation as shown in Figure 8. The delayed road input is similar to the actual path where the tracks of the vehicle pass by.

3.2. Simulation Results for the Real-Time Tracked Vehicle Model

Computer simulations for the four proposed real-time simulation tracked vehicle models were conducted for 35 seconds, which is enough time for the track to move one and half cycles of the track subsystem to develop the real-time tracked vehicle model. In this paper, the simulation results of the last model are presented and compared to the experimental measurements. The experiment was conducted in a military test driving field. Data measurements began 15 seconds after the experiment began because of the equipment's time delay.

The simulation results of the first and second subsystem models do not exactly follow the off-line simulation or experimental results but show similar trends because only several vehicle components out of 96 are included. The 35-second simulation for these two models was finished within 2 seconds, which means more complex models can be used for real-time simulation. The third proposed model combined the two previous subsystem models with the road input, delayed Profile IV. The last proposed real-time tracked vehicle model composed of chassis and track subsystems as shown in Figure 5 also used the road input.

When the tracked vehicle moves, the tracks can contact the terrain, sprocket, road wheels, idler, and support rollers. However, the tracks were assumed to contact with only the sprocket and idler in order to decrease the simulation time for this model. Table 1 shows the off-line and real-time simulation time for 35 seconds with 0.0005-second timesteps. Actual computation time for this last proposed model was about 28 seconds, 7 seconds less than simulation time. Therefore, the last proposed model could be the most promising real-time simulation tracked vehicle model that shows the

Table 1. Simulation time for off-line and real-time models.

	Simulation time (sec)
Off-line	35,649.113
Real-time	27.328

characteristics of the tracked vehicle. This real-time simulation tracked vehicle model can be used for HIL (hardware-in-the-loop) simulation to develop the real-time controller of the tension adjuster in future work.

The running test of the tracked vehicle used in this study was conducted in a military test field. Thirteen channels were used to obtain the data. These data gathered from sensors were stored using a PC through dSPACE AUTOBOX. A gyro was installed on the turret to measure the roll and pitch angles and the yaw rate of the chassis. The three-dimensional accelerometer was installed at the center of the chassis. The one-dimensional accelerometers were installed on the first and third road wheel arms. The pressure sensors were installed on the tension adjusters. The other sensors are also installed at the appropriate places.

The simulation and experimental results are shown in Figures 9–18. The velocities of the tracked vehicle in simulation and experiment were kept constant at 15 km/h. The pitch angles of chassis in simulation and experiment are shown in Figures 9 and 10, respectively.

Simulation results show trends similar to the experimental ones. These figures clearly show the pitch movement of the large (approximately 50 tons) tracked vehicle during the constant velocity motion. When the tracked vehicle moved on the flat surfaces, regular fluctuations of the pitch angles were observed. As the tracked vehicle ran over the rough bumps, the repeated short interval frequencies that were due to the high impulsive contact forces were observed. When the tracked vehicle moved on the bumps, more fluctuations were observed approximately 15 and 21 seconds after the simulation began and 30 and 36 seconds after the experiment began.

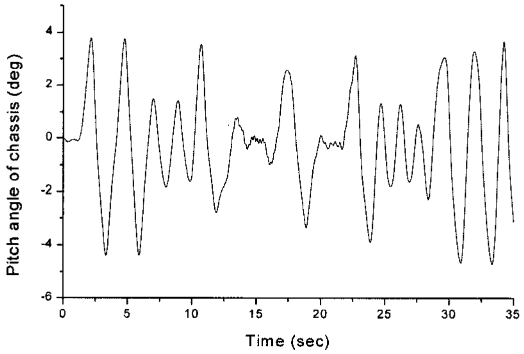

Figure 9. Pitch angle of a chassis (simulation).

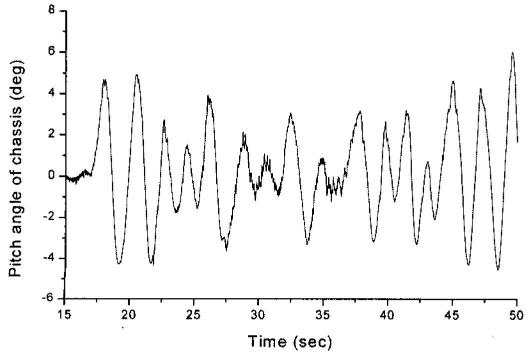

Figure 10. Pitch angle of a chassis (experiment).

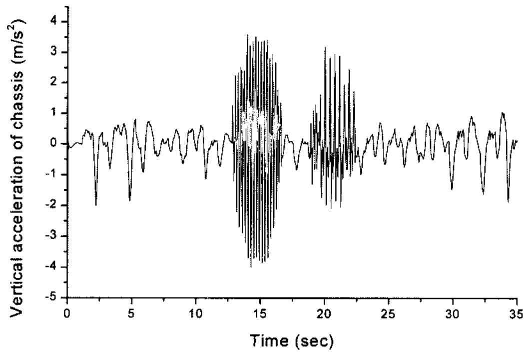

Figure 11. Vertical acceleration of a chassis (simulation).

Figures 11 and 12 show the vertical accelerations of chassis in the simulation and experiment, respectively. They show the vibrations due to the contact between tacked vehicle and terrain. Simulation results show trends similar to the experimental results. The test results show more vibrations than the simulation, because the driver could not keep a constant speed on Profile IV, while the simulation could. The repeated shorter interval higher frequencies were observed when the tracked vehicle ran over the rough bumps, due to the high impulsive contact forces. When the tracked vehicle moved on the bumps, more fluctuations were observed around 15 and 21 seconds after the simulation began and 30 and 36 seconds after the experiment began.

Figures 13 and 14 shows the vertical accelerations of road wheel arm 1 in the simulation and experiment, respectively. The test result also shows more vibrations

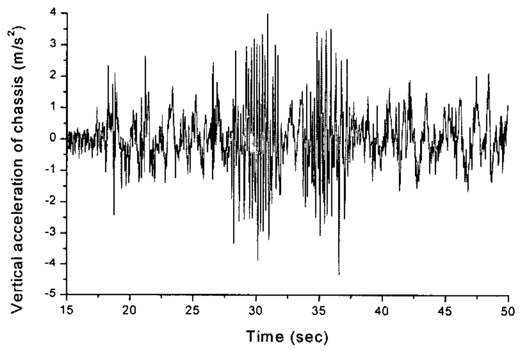

Figure 12. Vertical acceleration of a chassis (experiment).

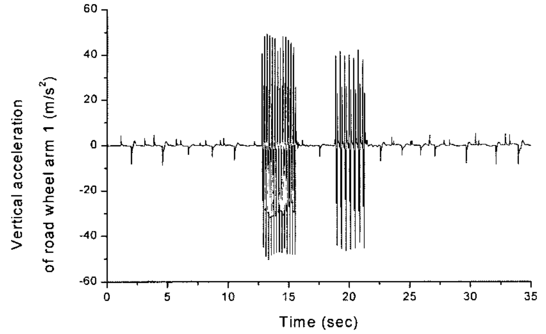

Figure 13. Vertical acceleration of road wheel arm 1 (simulation).

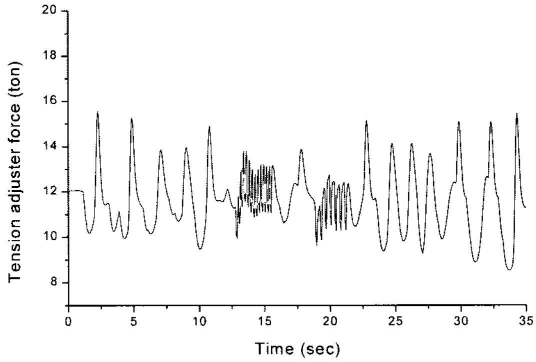

Figure 15. Tension adjuster force (simulation).

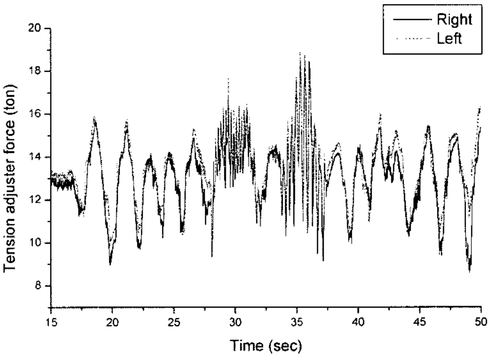

Figure 16. Tension adjuster force (experiment).

than simulation because the driver could not maintain a constant speed on Profile IV, whereas the simulation could. Simulation results exhibit higher frequencies than those found in the experimental ones, because road wheel arms are simply modeled with springs and dampers without considering hydraulic characteristics.

The tracked vehicle is designed to move over rough, off-road terrain. The mobility of off-road vehicles is limited by the soft ground performance of the tracked vehicle. The ground pressure exerted on the terrain, generally used in estimating the sinkage, motion resistance and tractive effort, greatly influences the soft ground performance of a tracked vehicle. A tracked vehicle moving over a terrain causes an interaction between the track and the terrain.

The vertical and horizontal pressures and shear stresses at the contact point of the track represent this interaction. All major vehicle and terrain parameters that may influence the track-terrain interaction should be taken into account. This interaction can be presented in the form of, among other things, track tension. The dive (forward pitch) during braking and squat (rearward pitch) during acceleration also influence the track tension. Therefore, the track tension should be controlled for the maximum tractive force and the prevention of track separation from the chassis.

Figures 15 and 16 show the tension adjuster force in the simulation and experiment, respectively. Simulation results also show trends similar to the observed values. When the tracked vehicle moved on the flat surfaces, regular fluctuations of the tension adjuster forces were observed. When the tracked vehicle ran over the rough bumps, the repeated short interval frequencies were observed due to the high impulsive contact forces. When

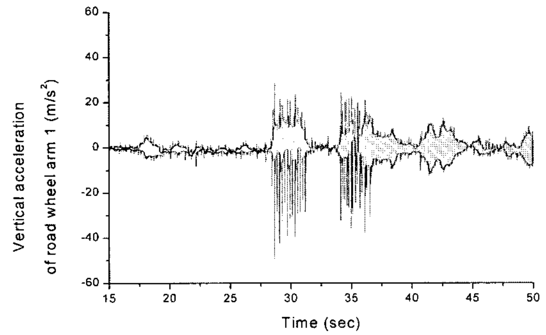

Figure 14. Vertical acceleration of road wheel arm 1 (experiment).

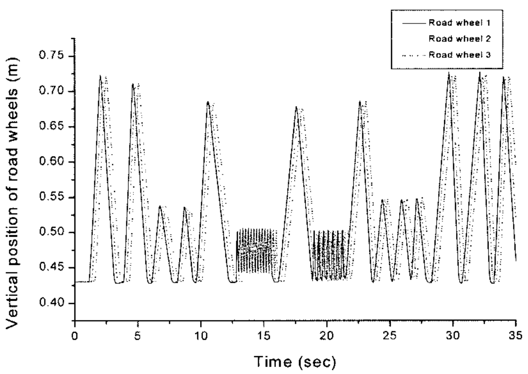

Figure 17. Vertical position of road wheels (1, 2, 3).

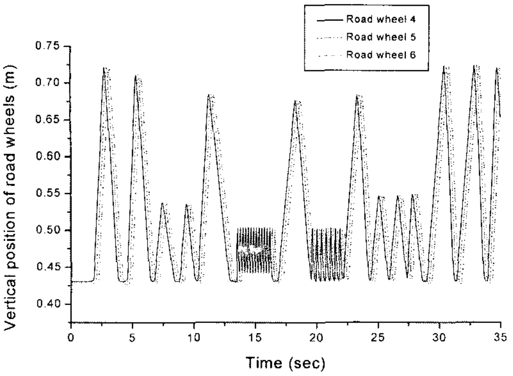

Figure 18. Vertical position of road wheels (4, 5, 6).

the tracked vehicle initially moves, the track tension is significantly decreased because 10 percent of the tracked vehicle weight is usually used as pre-tension not to separate the tracks from chassis. These data can be used to control the tension of the track.

Figures 17 and 18 show the simulation results of the vertical positions of the six road wheels. They show that the vertical positions follow the Profile IV road input data well, consecutively passing the same spot as expected.

4. CONCLUSION

We presented a step-by-step procedure for the development of a real-time simulation tracked vehicle model based on the off-line tracked vehicle model. The proposed model consisting of the sprocket, idler wheel, idler wheel arm, six road wheels, six road wheel arms, tension adjuster and track subsystem is very similar to the high-speed multibody tracked vehicle model. During the simulation, the chassis subsystem is considered first and the track subsystem is partially added to decrease the computation time. MATLAB SIMULINK was used to simulate these models and the S-function was used to decrease the computation time. The road input data, delayed Profile IV, was used for the real-time simulation. The time-domain computer simulation results of the last proposed real-time simulation model were compared with field test data and they are quite close to the test results. This real-time simulation tracked vehicle model can be used for HIL (hardware-in-the-loop) simulation to develop the real-time controller of the tension adjuster in future work.

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