The influence of the temperature of hydro-pneumatic spring into the state of tracked vehicle

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Abstract. Based on the multi-body dynamics model, the influence of the temperature of the hydro-pneumatic spring on the state of a lighted tracked vehicle under several driving conditions is studied. A multi-body dynamics model of chassis and body of a tracked vehicle is established, and verified with simulation and experimental results in the relevant literatures. Typical driving conditions are studied including running on a flat road with constant velocity, passing a semi-round obstacle with the radius of 200 mm, and running on a sinusoidal surface with wavelength of 2 m and amplitude of 100 mm. Some responses of the vehicle are compared and analyzed, so as to obtain the influence of the temperature of hydro-pneumatic spring. The numerical analysis results show that the temperature of hydro-pneumatic spring has a significant effect on the vehicle’s responses including height of centroid, vertical acceleration of centroid, pitch angle, track tension and gas pressure of the springs.

1. Introduction
When tracked vehicle is running on flat road surface, the stroke of the road-wheel is small, and small stiffness of the suspension can improve the ride comfort. While running on rough road surface, the stroke of the road-wheel is large, and large stiffness of the suspension is required to increase the vibration absorption ability. The stiffness of hydro-pneumatic increases as the piston stroke increases, and this characteristic is very suitable for such driving requirements of tracked vehicles. The hydro-pneumatic spring provides elastic force by compressing the high pressure gas in the closed container. The state equation of the ideal gas shows that the pressure of gas in the chamber is related to its volume and temperature. Due to long-term work of the hydro-pneumatic spring or changes in the ambient temperature, the gas temperature will change greatly, then the stiffness will change, which will eventually affect the state of the tracked vehicle.

When the oil passes through the orifice at high speed, the internal friction between its molecules will occur, then the temperature of the oil increases. This is the heat generation mechanism of the hydro-pneumatic spring. Then the heat is transferred to the gas chamber through the floating piston to make the gas temperature increases [1, 2]. Chen Yijie et al. [3] studied the law of temperature rise of hydro-pneumatic spring under the excitation of E and F level roads, but did not pay attention to the influence of temperature rise on vehicle state. Chen Yijie et al. [4] studied the influence of viscous heat of hydro-pneumatic spring on its damping force, the law of temperature rise when running on the C, D, E level roads at a constant speed, and optimize the factors affecting temperature rise. Els P. S. et al. [5] studied the effect of heat transfer on the temperature of hydro-pneumatic springs. It is mentioned that temperature has a significant influence on the stiffness of hydro-pneumatic springs. It is also pointed out that the heat source is affected by road roughness, vehicle speed and damping force.

Many researches in the literature are about the heat generation mechanism of hydro-pneumatic springs, the way of heat dissipation, the factors that affect the temperature rise, and the effect of...
temperature on the stiffness and damping characteristics. Temperature changes affect the stiffness of the hydro-pneumatic springs, which in turn affects the state of the vehicle, however there are few studies on this topic.

In this paper the multi-body dynamics model of a high-speed and high-mobility tracked vehicle with hydro-pneumatic spring suspension is established. This paper studies the influence of gas temperature on the vehicle state when running on several typical road surfaces, in order to reveal the importance of controlling the temperature rise of the hydro-pneumatic spring to the stability of tracked vehicles.

2. Establish and validation of the dynamic model

2.1. Multi-body dynamics model of a tracked vehicle

The research object of this paper is a high-mobility tracked vehicle. The multi-body dynamics model of the vehicle is built based on the dynamic software RecurDyn, as shown in figure 1.

This model has 1038 degrees of freedom and 265 rigid bodies, among which every track link is a rigid body. Each track subsystem shown in figure 2 has a sprocket, six road wheels, six road arms, three rollers, 83 track links, a crank-link mechanism of the hydro-pneumatic spring, and a track tensioner mechanism at the idler. The sprockets, rollers, idlers and road arms are connected to vehicle body through revolute joints. The road wheels are connected with road arms by revolute joints. The link for hydro-pneumatic spring is connected to crank and main piston by revolute joint, while the crank and the road arm are connected by a fixed joint. Translational joint is added between main piston and vehicle body, also between idler and one tensioner link. Double-pin type of track link is used, and contact is defined between track link and idler, sprocket, roller, road wheel, and the ground. The vehicle model is driven by applying angular velocity to sprockets, since no engine and transmission system model have been established.

Before performing dynamic simulation, it is necessary to determine the initial equilibrium state of the vehicle. All the suspensions of the tracked vehicle studied in this paper use hydro-pneumatic springs, so the stiffness is greatly affected by temperature. Here the temperature is set to be 30 °C. Elastic tensioners are used at the idlers. Some parameters of the initial equilibrium state are shown in table 1 and table 2.

![Figure 1. Multi-body dynamic model of a tracked vehicle](image)

![Figure 2. Track subsystem](image)

**Table 1. Parameters of the initial equilibrium state**

| Pitch angle/deg | Stiffness of tensioner (N/mm) | Compression of tensioner (mm) | Track tension around the idler/N |
|-----------------|-------------------------------|-------------------------------|--------------------------------|
| 0.021           | 208.5                         | 313                           | 34024.4                        |

**Table 2. Parameters of the initial equilibrium state-continued**

| No. of road-wheel | Gas pressure/MPa | Incline angle of road-arm/deg | Contact of track and ground under road-wheel/N |
|-------------------|-------------------|-------------------------------|-----------------------------------------------|
| 1                 | 14.2              | 24.5                          | 10658.2                                       |
| 2                 | 15.8              | 25.8                          | 31317.9                                       |
| 3                 | 17.0              | 25.8                          | 33154.2                                       |
| 4                 | 18.7              | 25.9                          | 37374.5                                       |
2.2. Gas chamber model of hydro-pneumatic spring

Figure 3 shows the structure of the gas chamber, in which \( H_b \) is the depth of the floating piston chamber, \( d_u \) is the diameter of the floating piston chamber, \( d \) is the diameter of gas chamber, and \( l_g \) is the effective length of the gas chamber.

![Gas chamber of a hydro-pneumatic spring](image)

Figure 3. Gas chamber of a hydro-pneumatic spring

The oil and gas cylinder have the same inner diameter and their cross-sectional area is

\[
A = \pi(d/2)^2.
\]

The volume of the floating piston inner chamber is

\[
V_u = \pi\left(d_u/2\right)^2 \cdot H_u,
\]

and all the volume of gas is

\[
V = V_u + A \cdot l_g.
\]

According to state equation of the ideal gas that is

\[
pV/T = \text{const.},
\]

the relationship between the gas pressure and the displacement of the piston and also the temperature can be obtained by

\[
p = p_0 \frac{(V_u + l_{g0} \cdot A) \cdot T}{(V_u + l_g \cdot A) \cdot T_0}.
\]  
(1)

Where \( p_0 \) is the initial gas pressure, \( l_{g0} \) is the initial length of the gas chamber; when the gas temperature is changed to \( T \) the gas chamber length is

\[
l_g = l_{g0} - \Delta x
\]

and gas pressure is \( p \), where \( \Delta x \) is the displacement of the floating piston.

After obtaining the gas pressure, the force of the high pressure gas on the floating piston can be obtained as

\[
F_g = p \cdot A.
\]  
(2)

In the multi-body dynamics model, the elastic force of the hydro-pneumatic spring is built as the axial force acting on the piston, which is calculated by the equations (1) and (2). The multi-body dynamics model of the vehicle is simulated under different scenarios, and by modifying the temperature \( T \) in the equations, the influence of gas temperature on the vehicle state can be studied.

2.3. Validation of multi-body dynamics model

The multi-body dynamics model established in this paper has not been verified by field experiments due to some limited conditions. However, some literature has carried out similar modeling and experimental validation of high-mobility tracked vehicles. This section reproduces the same scenarios in the literature, and compares the same responses, in order to validate the rationality of the model indirectly.

In [6], the FFT amplitude spectrum of the vertical acceleration of the centroid is carried out when the vehicle is running on flat road at a constant speed of 10 km/h. Figure 4(a) shows the simulation and experimental results in the literature and figure 4(b) shows the simulation results of this paper. It can be seen that the curve shape is similar. The peak frequency in the literature is about 15 Hz, that of this paper is about 17.5 Hz, and the acceleration amplitude at the peak frequency is consistent in magnitude. The difference of amplitude values is due to the difference in vehicle parameters.
In [7], the vehicle is simulated on a flat road at a constant speed of 50km/h. This paper carries out the same scenario. Figure 5 shows the vertical displacement of a track link in literature [7] and this paper. It can be seen that the curve shape is quite similar.

Through analysis of these results, the rationality of the multi-body dynamics model of the tracked vehicle built in this paper is validated indirectly.

3. Analysis of the simulation results

3.1. Driving on flat road

Changes in the ambient temperature of the vehicle or continuous driving for a long time will cause the temperature of all the hydro-pneumatic springs to change, and the magnitude of the change for each spring can be considered approximately the same. In this scenario, the temperature of all hydro-pneumatic springs is -45, -30, -15, 0, 30, 60, 90, 120, 140, 160 °C, and some responses are analyzed when driving on flat road at a constant speed. The input torque of the sprocket is a constant value of 8500 N•m.

Figure 6 shows the curves of several responses varying with the gas temperature. Figure 6(a) is the curve of the centroid driving velocity. During the steady driving phase, the velocity of the centroid decreases with the increase of gas temperature, and the fluctuation range is from 43.1 to 39.4 km/h. Figure 6(b) is a graph showing the height change of the vehicle centroid relative to normal temperature of 30 °C. The height of centroid increases with the increase of gas temperature. After the temperature is higher than 120 °C, the height remains almost unchanged.

Figure 6(c) shows the pitch angle of the vehicle body varying with the gas temperature. In this
paper, the pitch angle of the vehicle body is positive when the tail of the car is low, and vice versa. The pitch angle of the vehicle body is positive at each temperature and decreases with the increase of gas temperature. The pitch angle decreases to 0° when the temperature reaches higher than 120 °C. Figure 6 (d) is a plot of the average value of the track tension. The average track tension is defined as the mean value of the track tension of all track links at the given time. It increases from 5.1×10^4 N to 6.5×10^4 N as the gas temperature increases. Figure 6(e) is the curve of the gas pressure of each hydro-pneumatic spring. All the gas pressure increases with the increase of temperature and the gas pressure of the 1st spring is always the lowest.

![Figure 6. Responses of vehicle running on flat road with constant velocity](image)

After the temperature is higher than 120 °C, the velocity of the vehicle body, height of the centroid, pitch angle and average track tension remain almost unchanged, because all the road-arms have hit
their lower limiters, and this situation is undesired for tracked vehicle.

3.2. Driving through a single semi-round obstacle of radius 200 mm
When the gas temperature is -45, -30, -15, 0, 30, 60, 90, 120, 140, 160 °C, the vehicle drives through a single semi-round obstacle of radius 200 mm with constant input torque to the sprocket of 8500 N•m.

Some responses are analyzed of this scenario as shown in Figure 7. Figure 7(a) shows the variation curve about the range of the centroid height. As the temperature increases, the height variation range shows a decreasing trend. When the temperature is lower than 30 °C, the speed of the decrease is faster; while the temperature is higher than 30 °C, the speed gets slower.

Figure 7(b) shows the time history of the vertical acceleration of vehicle centroid when passing the obstacle. The analysis is carried out at a normal temperature of 30 °C and a typical high temperature of 120 °C together with a low temperature of -30 °C. At the temperature of -30 °C, the vertical acceleration of vehicle centroid has a significant impact peak, which is due to the phenomenon that some road-arm hits its upper limiter. This situation is undesired for ride comfort. Figure 7(c) is the curve of the pitch angle displacement of the body. As the temperature increases, the maximum value decreases, the minimum value changes little, and the range decreases. Figure 7(d) is the curve of all the gas pressure range. As the temperature increases, the pressure range increases firstly and then decreases.

![Figure 7](image_url)

Figure 7. Responses of vehicle when passing a semi-round obstacle

3.3. Driving on a sinusoidal surface with the wavelength of 2 m and amplitude of 100 mm
When the temperature of all hydro-pneumatic springs is -45, -30, -15, 0, 30, 60, 90, 120, 140, 160 °C, the vehicle drives on a sinusoidal surface with the wavelength of 2 m and amplitude of 100 mm at a constant speed. The maximum, minimum, and range values of each response are statistical results of the stable driving phase on the sinusoidal road surface. The input torque of the sprocket is also a
constant value of 8500 N•m just like the two scenarios above.

Figure 8 shows the typical responses varying with gas temperature under this scenario. Figure 8(a) shows the height variation of the vehicle centroid. With the increase of temperature, the maximum and minimum values increase, while the range of the height does not change much, from 4 mm to 14.5 mm. Figure 8(b) is the curve of the pitch angle displacement of the body. As the temperature increases, the maximum and minimum values of the pitch angle increase first and then decrease, and the turning point is 30 °C; the range of the pitch angle gradually increases. Figure 8(c) is the curve of all the gas pressure range. As the temperature increases, the range of gas pressure decreases. The pressure range of the 1st spring is the smallest at each temperature, while its change value with temperature is the largest.

![Graphs showing vehicle responses](image)

**Figure 8.** Responses of vehicle when running on sin wave road

4. Conclusions

Based on the dynamic model of a tracked vehicle, this paper studies the influence of the gas temperature on the state of the vehicle body. The typical driving scenarios include running on flat road at a constant speed and passing through a semi-round obstacle with radius of 200 mm, running on a sinusoidal road surface with wavelength of 2 m and magnitude of 100 mm. The responses indicating the running state of the vehicle include the height of the vehicle centroid, vertical acceleration of the centroid, pitch angle, gas pressure of the hydro-pneumatic springs, the track tension. The main conclusions drawn are as follows:

1. The height of the vehicle centroid increases with the increase of gas temperature; when the temperature is higher than 120 °C, each road-arm will hit the lower limiter, which is undesired for tracked vehicle; in the low temperature environment such as -30 °C when passing the semi-round obstacle the centroid acceleration is large due to the impact of road-arm and its upper limit. In general the state of the vehicle body changes a lot with the change of gas temperature in all the three scenarios.
displayed in this paper.

(2) Good heat dissipation performance of the hydro-pneumatic spring is very important, which can ensure that the gas temperature changes within a small range. Thus its working reliability can be increased, and the vehicle body posture and the driving stability can be maintained.

5. References

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