Adaptive Control and Simulation Research on Dynamic Tensioning Force for Tracked Vehicle

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***Abstract*—Tracked vehicles have been widely used in transportation and military fields, and track tension mainly affects track reliability. Stable track tension can extend the service life of the track and improve the off-road performance of tracked vehicles. In order to maintain stable track tension during vehicle operation, we established a theoretical estimation model for track tension. The dynamic analysis of various components of the track tension device was conducted, and the theoretical calculation formula for track tension was derived. The theoretical calculation results were compared with the results of multi body dynamics simulation, verifying their consistency. On this basis, an active control system for track tension was designed based on fuzzy PID (proportional - integral-derivative) control theory, using a co-simulation mode of RecurDyn and Matlab. It was found that the control system can quickly and accurately achieve the desired track tension. Compared with traditional track tensioning methods, the fuzzy PID control system can effectively reduce the dynamic track tension of the track in the contact area, and has a significant effect on suppressing the vibration of the vehicle body and the impact load of the track on the supporting roller, improving the stability of the tracked vehicle during driving.**

***Keywords*—track tension, mathematical model, fuzzy PID, dynamic analysis, co-simulation**

I. INTRODUCTION

Tracked vehicles play an important role in the battlefield, mainly due to their good trafficability and strong maneuverability, greatly improving the combat effectiveness and survival rate of combatants. The track action system determines the driving performance of tracked vehicles. The track mainly provides a stable railway for the road wheel system [1,2], enabling it to overcome walking obstacles and ensure that the vehicle passes smoothly at high speed on rough terrain [3,4,5]. The track tension has a significant impact on the dynamic performance of the track installation [6,7].

During the operation of tracked vehicles, frequent contact and collision occur between the tracks, road wheels, and the ground, resulting in significant changes in track tension [8]. The track pre-tension is usually adjusted by moving the position of the idler wheel before the vehicle starts. This adjustment method requires the tensioner to be locked, and the idler wheel is fixed relative to the chassis, thereby the ability of the track tensioner to adjust the track tension in real-time is limited. Excessive tension and track stiffness can reduce the cushioning effect of the track[9], increase friction between the track and chassis components, generate frictional heat, and may cause belt breakage in severe cases; If the tension is too small, the track becomes loose, which can easily cause detachment, rake teeth, and even cause track failure, resulting in paralysis of the vehicle's driving system. Therefore, many scholars have conducted research on the adjustment strategy of track tension.

Fan Beibei [10] established a theoretical estimation model for track tension, including the sprocket, idler wheel, road wheel, support rollers, and track shoe, and verified the accuracy of the mathematical model through simulation. Bian Meihui [11] analyzed the impact of track pre-tension on vehicle smoothness and found that the track pre tensioning force, which is about 10% of the vehicle weight, is optimal for vehicle smoothness. After obtaining the theoretical formula for track tension, Wang Yaxiang [12] used the orthogonal experimental method to study the significance of the influence of multiple parameters in the formula on tension, and obtained the structural parameters for optimizing track tension. Wang [13] designed a track tension control system, which consists of a self-tuning PID (proportional -integral-derivative) controller based on radial basis function neural network, an electro-hydraulic servo system, and a steering arm. The track tension was adjusted through the steering arm. After simulation, it was found that the system can modify parameters online and has strong anti-interference ability, but the response speed and accuracy of the control system need to be improved. Ketting M [14] added an elastic connection device between the idler wheel and the chassis, which can stabilize the track tension by changing the spring stiffness, but this device cannot achieve real-time control of the track tension.

Our research group proposes a dynamic tension control system for track based on fuzzy PID control. Firstly, the geometric relationship and force situation of the idler wheel, idler wheel curved arm, road wheel, support rollers, and hydraulic tensioner of tracked vehicles were analyzed, and a theoretical calculation model for track tension was obtained. And based on the structural dimensions of a certain type of main battle high-speed tracked vehicle, a multi body dynamic simulation model was established in RecurDyn. Theoretical calculations and fuzzy PID control system simulation analysis were used to verify each other, and the impact of the dynamic tension control system on the track tension and vehicle driving stability and reliability was analyzed and summarized.

II. THEORETICAL CALCULATIONS

The tension of the track is usually adjusted by moving the position of the idler wheel before the vehicle starts, mainly from the initial static tension. In order to more accurately evaluate the tension of the track, a calculation model was established as shown in Fig. 1.

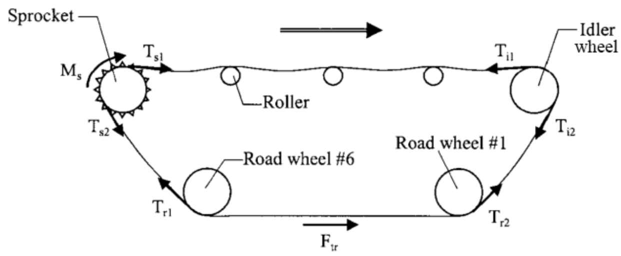


Fig. 1.Distribution of tension on the track ring

A. *Force analysis of the upper support section*

During the driving process of tracked vehicles, the friction force at each wheel bearing and the inertia moment of each wheel have little impact on the tension around each wheel, so it can be ignored. And there can be the following relationships:

$$T_{s1} \approx T_{s2} + M_s/r_s \tag{1}$$

$$T_{i1} \approx T_{i2} \tag{2}$$

B. *Force analysis of the sprocket section*

It can be considered that the tension of the track spanning between the sprocket and the idler wheel is approximately equal everywhere. And the track tension at both ends of the inclined support section around the sprocket and idler wheel is approximately equal, which is:

$$T_{s1} \approx T_{i1} \tag{3}$$

$$T_{s2} \approx T_{r1} \tag{4}$$

C. *Force analysis of the lower support section*

In the lower section of the track, due to the magnitude of the contact friction between the track and the soil, as well as the friction between the road wheel and the track, which is much smaller than the traction force F_{tr} of the entire vehicle system, so it can be ignored. Therefore, for the tension force of the lower section of the track, there are:

$$T_{i2} \approx T_{r2} \tag{5}$$

$$F_{tr} \approx T_{r1} - T_{r2} \tag{6}$$

The above formula characterizes the distribution of track tension on the entire track ring. In order to achieve real-time control of track tension and maintain it within a good range, we mainly calculate the track tension around the idler wheel and adjust the magnitude of track tension in real-time by changing the relative position of the idler wheel through the hydraulic system.

D. *Force analysis of the idler wheel section*

The track tension device is shown in Fig. 2. When the track tension increases, the hydraulic tensioner can cause the idler wheel to move backwards, making the track tensioned; On the contrary, the hydraulic tensioner can cause the curved arm and idler wheel to move forward, reducing the tension.

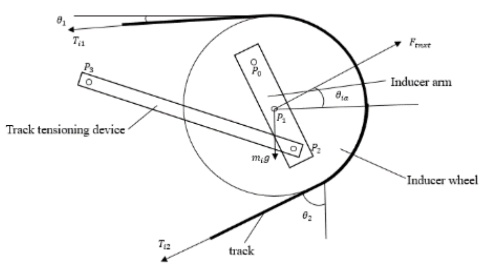


Fig. 2.Dynamic model of idler wheel

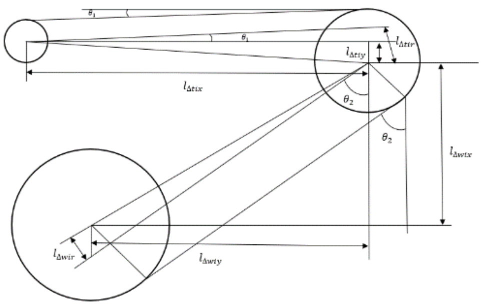
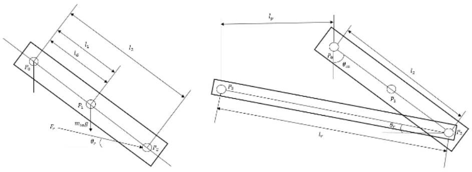


Fig. 3.The geometric relationship between the idler wheel and its nearby road wheels



(a) (b)

Fig. 4.Dynamic model of idler arm and track tensioning device (a) idler arm (b)track tensioning device

The tension between the upper support section and the inclined support section of the track can be simplified as the following relationship:

$$\hat{T}_{i1} \approx \hat{T}_{i2} \approx \frac{[F_r l_2 \cos(\theta_r+\theta_{ia}) - m_{ia} g l_G \sin\theta_{ia}]/l_1 + F_{tnxt} - m_i g \sin\theta_{ia}}{\cos(\theta_{ia}-\theta_1)+\sin(\theta_{ia}+\theta_2)} \tag{7}$$

III. Establishing a Simulation Model Based on RecurDyn

The estimated tension force of the track around the idler wheel was calculated by analyzing the dynamic model of the idler wheel and tensioning mechanism. Compared with theoretical models, the RecurDyn model of tracked vehicles considers factors such as track shoe structure, meshing between the track and the sprocket, as well as contact between the track and the road wheels, which is closer to the actual tension of tracked vehicles[15]. Therefore, we compared the theoretical calculation results under different operating conditions with the dynamic simulation results of a multi body system by using multi-body dynamics simulation software RecurDyn to verify the correctness of the theoretical model for estimating track tension.

As shown in Fig. 5, this model is based on the design data of a certain type of armored vehicle and its 3D solid model. A dynamic 3D simulation model of the track and the entire vehicle was established in the multi lift dynamic simulation analysis software RecurDyn. The vehicle body system included a body system, a track tension system, and two track subsystems. The vehicle body system consisted of the vehicle body, sprockets, idler wheels, support rollers, road wheels, balance elbows, elastic and damping components, etc. The track tension system used three rods to replace the idler wheel arm, hydraulic cylinder, and hydraulic tension rod. The track ring system on both sides was a circular structure composed of multiple track shoes through track connectors, which established corresponding constraint relationships based on the actual driving conditions of tracked vehicles.

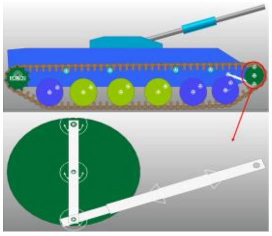


Fig. 5.Tracked vehicle and hydraulic tensioning system model

A. Comparison and Analysis of Multibody Dynamics Simulation Results and Theoretical Calculation Results

By analyzing the force acting on the idler wheel and track tension device, a theoretical calculation model for the track tension around the idler wheel was obtained, as shown in equation (7). The simulation results of track tension can be used to verify the correctness of the theoretical calculation results. When conducting theoretical calculations, output RecurDyn θ_r、θ_{ia}、θ_1、θ_2、ω_i substitute the values of parameters into equation (7) to obtain the theoretical calculation value of the tension force. When calculating the results of multi body dynamics simulation, the Analysis result in RecurDyn is used to directly extract the liner force between any adjacent track shoes around the idler wheel, and the simulation value of tension force is obtained.

1) *Comparison of simulation and theoretical results of vehicles under stationary conditions*

Before starting the vehicle, a certain track pre-tension should be set to tension the track. According to the theoretical model, different hydraulic driving forces will result in different pre-tension of the track. In order to verify the correctness of the theoretical model under the stationary condition of tracked vehicles, we selected hydraulic driving forces of 20kN, 30kN, 40kN, 50kN, and 60kN respectively to keep the vehicle stationary on a flat road surface until the tension of the track ring reached a stable state. The comparison results between theoretical and simulation results are shown in Table I.

TABLE I. COMPARISON OF THEORY AND SIMULATION UNDER STATIC OPERATING CONDITIONS

Hydraulic driving force(kN)	**20**	**30**	**40**	**50**	**60**
Theoretical model results(kN)	17.429	25.056	32.465	39.562	46.146
RecurDyn Simulation results(kN)	17.703	25.118	32.546	39.704	46.258
Relative Error	1.5%	0.24%	0.25%	0.35%	0.242%

From the above Table, we can observe that under static working conditions, the theoretical calculation value of track tension is basically consistent with the simulation results of RecurDyn, with all deviations within 2%. As the hydraulic driving force increases, the track tension also gradually increases.

2) *Comparison of simulation and theoretical results of vehicles under off-road conditions*

In order to prove the correctness of the theoretical model, we selected a relatively flat C-level surface and an E-level surface relative to the crushed stone surface. Import road roughness data into RecurDyn to generate C and E level road models. During the simulation process, the tracked vehicle was in the static balance stage from 0 to 8 seconds, and the acceleration stage was from 9 to 10 seconds, accelerating from 0 km/h to 57 km/h, and then driving at this constant speed. Throughout the entire process, the RecurDyn model outputted the variables required for calculating the tension force of the theoretical model, which can calculate the track tension force around the idler wheel and compare it with the simulation analysis results, as shown in Fig. 6 and 7.

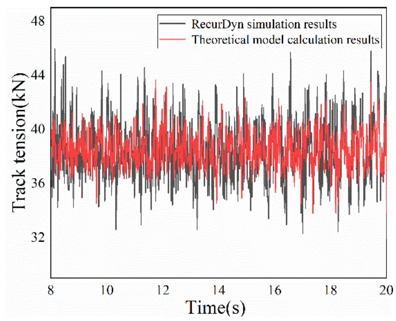


Fig. 6.Comparison of C-level pavement theory and simulation

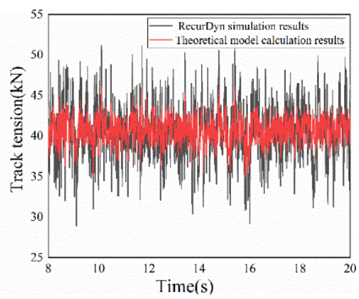


Fig. 7.Comparison of E-level pavement theory and simulation

By comparing the simulation results of multi body dynamics with the calculation results of the theoretical model, it can be found that there is a certain deviation between the simulation results and the theoretical simulation results. This is mainly because the multi body dynamics model considers factors such as the structure of the track shoe, the meshing polygon effect between the track and the sprocket, the contact between the track and the support rollers, the road wheel, and the nonlinearity between the track shoe. So the simulation results will be slightly larger than the theoretical model calculation results. However, from an overall perspective, the trend of changes between the two is similar. Although there is a certain amount of error or time lag within a certain time period, the impact on simulating the actual track tension state of the vehicle is relatively small. By comparing the simulation results of the above two working conditions, it is shown that the proposed theoretical model calculation method can reflect the changes in track tension around the idler wheel, and also verifies the effectiveness of the theoretical model calculation formula.

IV. SIMULATION MODEL FOR ADAPTIVE CONTROL OF TRACK TENSION

A. *Design and simulation model construction of adaptive control strategy for track tension adjustment*

The track tension control system can adjust the track tension appropriately and maintain its stability, which helps to improve the track life cycle, reliability, maintainability, and reduce the power loss of the entire track ring. The parameters of ordinary PID controllers are fixed, which cannot meet the requirements of real-time track tension system to maintain relatively stable track tension. Fuzzy control has a strong adaptive ability, which can effectively control complex nonlinear systems. Our research work is based on the fuzzy PID control strategy to achieve adaptive adjustment control of track tension.

The block diagram of the track tension control system is shown in Fig. 8. In the figure, Tˆ is the reference track tension required for tracked vehicles during operation, e_T is the difference between real-time track tension and reference tension, $\triangle K_P$ is the proportional coefficient correction of the track tension adjustment PID controller, $\triangle K_I$ is the integral coefficient correction of the track tension adjustment PID controller, and F is the track tension adjustment required for the vehicle's mechanical system, θ_r、θ_{ia}、θ_1、θ_2 ω_i is the parameter variable required for the theoretical calculation model of track tension, and T * is the real-time track tension of the tracked vehicle system. The fuzzy PID controller utilizes fuzzy logic algorithms to optimize PID parameters in real-time based on certain fuzzy rules, achieving ideal control results. Compare the real-time track tension with the reference track tension, and perform fuzzy inference based on the deviation and change rate of the deviation between the real-time track tension and the reference track tension to obtain the correction amount of P and I parameters, and then obtain the compensation amount of track tension, thereby achieving the function of real-time adjusting the track tension. In order to achieve good control effect, the self-tuning rules of the fuzzy PID parameters K_P and K_I are as follows:

(1) When there is a significant deviation between the track tension and the reference track tension, in order to quickly reach the reference value of the track tension, reduce the response time of the controller, and avoid overshoot, the K_P value can be appropriately increased and K_I can be set to 0; When the deviation between the track tension and the reference track tension is small, in order to further reduce the deviation and prevent overshoot, oscillation, and stability deterioration, the K_P value can be appropriately reduced, and the K_I value can be taken as the median; When the deviation between the track tension and the reference value is very small, to further eliminate the steady-state error between the track tension and the reference value and ensure that the system does not overshoot, the K_P value can be continuously reduced and the K_I value can be maintained at the original level or slightly increased.

(2) When the deviation and rate of change between the track tension and the reference track tension are of the same sign, it indicates that the difference between the current track tension and the reference track tension is increasing. In order to eliminate the tension deviation as soon as possible, the K_P value should be taken as the maximum; When the deviation of track tension and the rate of change of deviation are different, the K_P value should gradually decrease with the decrease of deviation.

Based on the functions of the PID parameters mentioned above, a fuzzy control table for the correction of proportional coefficient and integral coefficient was provided, as shown in Tables II and III. In Tables II and III, NB, NM, NS, Z, PS, PM, PB represent respectively the fuzzy states of variables as negative large, negative medium, negative small, zero, positive small, positive medium, and positive large.

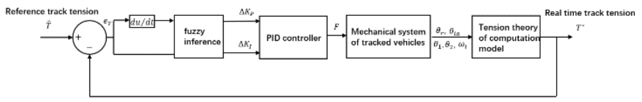


Fig. 8.Block diagram of adaptive control system for track tension

TABLE II. PROPORTIONAL COEFFICIENT CORRECTION △KP FUZZY CONTROL TABLE

e_T	de_T/dt						
	NB	***NM***	***NS***	***Z***	***PS***	***PM***	***PB***
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

TABLE III. INTEGRAL COEFFICIENT CORRECTION △KI FUZZY CONTROL TABLE

e_T	de_T/dt						
	NB	***NM***	***NS***	***Z***	***PS***	***PM***	***PB***
NB	PB	PB	PB	PB	PB	PB	PB
NM	PB	PB	PB	PS	PS	PS	PS
NS	PB	PS	PS	Z	NS	NS	NB
Z	PB	PS	Z	Z	Z	PS	PB
PS	NB	NS	NS	Z	PB	PB	PB
PM	Z	PS	PS	PS	PB	PB	PB
PB	PB	PB	PB	PB	PB	PB	PB

A track tension control model based on fuzzy PID had been established by using Matlab/Simulink software, and a co-simulation model had been established through Co-simulation with the multi body dynamics software RecurDyn. The co-simulation model is shown in Fig. 9. The theoretical calculation model of track tension had been written in the S-function, as shown in the computation module in the figure. And RecurDyn can input real-time θ_r, θ_{ia}, θ_1, θ_2, ω_i into this module. And this module can be used to calculate the dynamic tension of the track around the idler wheel section during the driving process of tracked vehicles in real time.

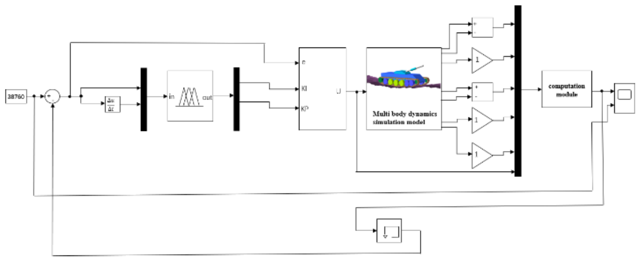


Fig. 9.Matlab and RecurDyn/HM co-simulation model

B. *Analysis of Track Tensioning Control Effect*

The track tension control system maintains the tension of the track ring within the range of 8% of the vehicle weight at all times. The vehicle accelerated from 0 to 38km/h within 5-8 seconds from a stationary state, and then traveled at a constant speed on an E-level road. Fig. 10 shows the comparison of real-time track tension around the idler wheel and reference track tension when using a track tension control system. The results show that during the off-road process of tracked vehicles, there is a significant fluctuation in track tension under ordinary PI control. Compared to ordinary PI algorithms, the fuzzy PID algorithm can not only quickly reach the preset reference track tension value, but also the track tension value is closer to the preset reference track tension value. This indicates that the track tension control system can maintain a relatively stable dynamic tension under driving conditions, and make it maintain a relatively small range of fluctuations as much as possible, proving the effectiveness of this control system.

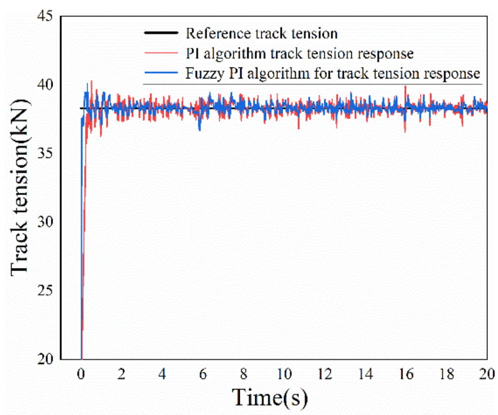


Fig. 10.Comparison results of real-time track tension and reference track tension under fuzzy PID control

Under off-road conditions, the tension of the track in the contact area changes more severely, resulting in frequent changes in the circumference of the track. The track is repeatedly stretched, affecting the service life of its rubber sleeve components. Fig.11 shows the dynamic tension change of the track in the contact area. It can be seen from the figure that under the control of fuzzy PID, the amplitude and fluctuation of the dynamic tension of the track in the contact area can be effectively reduced. Reducing the amplitude of dynamic tension on the track can improve the lifespan of the track [16]. This indicates that the control system is beneficial for the lifespan of the track ring system.

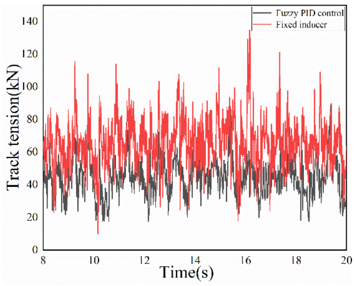


Fig. 11.Dynamic tension of track in contact area

C. *Analysis of the influence of track tension control on vehicle vibration characteristics*

Fig. 12 and Fig. 13 show the analysis of the influence of the track tension control system on the vehicle body smoothness when the tracked vehicle is running at 38km/h on the level of 8% of the vehicle weight under the E-level road surface, mainly including the vertical displacement acceleration, pitch angular acceleration curves and frequency domain analysis curves. Table IV shows the root mean square (RMS) and standard deviation (SD) of displacement acceleration and angular acceleration respectively.

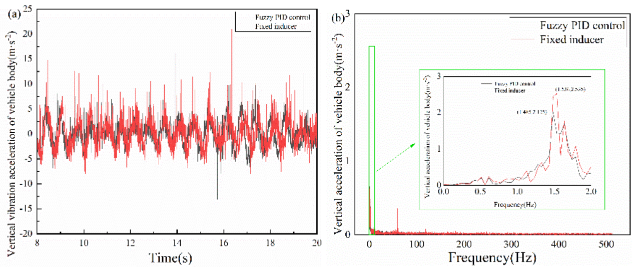


Fig. 12.Vehicle vertical acceleration curve and frequency domain analysis curve (a) vertical vibration acceleration of vehicle body (b) vertical acceleration of vehicle body

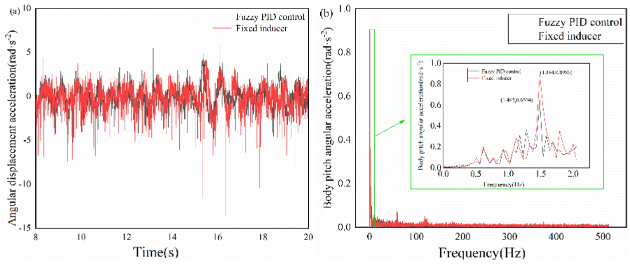


Fig. 13.Car body angular acceleration curve and frequency domain analysis curve (a) angular displacement acceleration (b) body pitch angular acceleration

TABLE IV. ROOT MEAN SQUARE (RMS) AND STANDARD DEVIATION (SD) OF DISPLACEMENT ACCELERATION AND ANGULAR ACCELERATION

Mode	RMS	RMS	SD	SD
	Displacement acceleration ($m\cdot s^{-2}$)	***Angular displacement acceleration ($rad\cdot s^{-2}$)***	***Displacement acceleration ($m\cdot s^{-2}$)***	***Angular displacement acceleration ($rad\cdot s^{-2}$)***
Fuzzy PID	2.3082	1.0847	2.1082	1.0847
Fixed idler wheel	2.6199	1.2401	2.6199	1.2401

From Table IV, we can observe that under the same driving conditions, the root mean square value of the vertical vibration acceleration of the vehicle body based on the fuzzy PID track tension control system decreases from 2.6199 $m\cdot s^{-2}$ to 2.3682 $m\cdot s^{-2}$ compared to the fixed idler wheel, with a decrease of over 8%. The pitching angular acceleration of the car body decreases from 1.2401 $rad\cdot s^{-2}$ to 1.0847 $rad\cdot s^{-2}$, with a decrease of more than 12%. From the above table, it can also be seen that the variation range of vehicle vibration acceleration has also decreased. Therefore, the track tension control system has a certain positive effect on improving the smoothness of tracked vehicles.

Fig. 14 shows the variation of the impact load on the four supporting rollers of the tracked vehicle. From the figure, it can be seen that compared with the traditional fixing method of the idler wheel, the impact load on the track of all four supporting rollers under the fuzzy PID control system is reduced. It indicates that this control system can improve the phenomenon of fatigue cracks at the connection between the support roller and the vehicle body caused by the impact of the track on the support roller, and enhance the reliability of tracked vehicles.

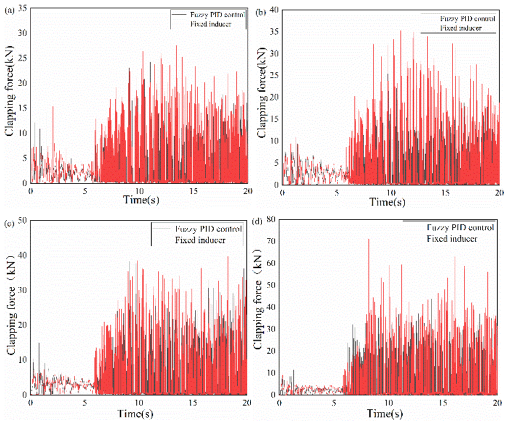


Fig. 14.Impact load on the supporting pulley (a) clapping force 0-35kN (b) clapping force 0-40kN (c) clapping force 0-50kN (d) clapping force 0-80kN

V. Conclusions

A simulation model was established based on RecurDyn and found that the error is within 2%, verifying the effectiveness of the theoretical model. The following conclusions are obtained through simulation and comparative research.

Firstly compared with ordinary PI algorithms, the fuzzy PID algorithm can quickly reach the preset reference track tension value, and the track tension value is closer to the preset reference track tension value, reducing the dynamic peak of track tension, decreasing tension fluctuation, and improving the service life of the track.

Secondly the control system can improve the smoothness of the vehicle system, and the impact load of the four carrier pulleys is also reduced, improving the reliability of the tracked vehicle.

Acknowledgment

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References

[1] J. Y. Wong, W. Huang. An investigation into the effects of initial track tension on soft ground mobility of tracked vehicles using an advanced computer simulation model[J]. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2006, 220(6) : 695-711.

[2] M. Wallin, A. K. Aboubakr, P. Jayakumar, et al. A comparative study of joint formulations: application to multibody system tracked vehicles[J]. Nonlinear Dynamics, 2013, 74(3) : 783-800.

[3] Z. Y. Zhao, H. O. Liu, H. Y. Chen, J. M. Hu, H. M. Guo. Kinematics-aware model predictive control for autonomous high-speed tracked vehicles under the off-road conditions[J]. Mechanical Systems and Signal Processing, 2019, 123 : 333-350.

[4] T. Liu, X. Hu. A bi-level control for energy efficiency improvement of a hybrid tracked vehicle[J]. IEEE T IND INFORM. 14 (4) (2018) 1616–1625.

[5] H. Peng, Y. Zou, X. S. Hu, F. C. Sun, L. Guzzella. Combined optimal sizing and control for a hybrid tracked vehicle[J]. Energies, 2012, 5(11) : 4697-4710.

[6] J.Y. Wong, W. Huang. Approaches to improving the mobility of military tracked vehicles on soft terrain[J]. Int. J. of Heavy Vehicle Systems, 2008, 15(2/3/4) : 127-151.

[7] J.Y. Wong, W. Huang. Evaluation of the effects of design features on tracked vehicle mobility using an advanced computer simulation model[J]. Int. J. of Heavy Vehicle Syst. 12 (2005) 344–3.

[8] T. Fukushima, E. Inoue, M. Mitsuoka, K. Sato, T. Oguri. A simple rubber crawler model for studying fluctuation in crawler tension[J]. Engineering in Agriculture, Environment and Food, 2018, 11(3) : 122-126.

[9] K. Huh, J. Kim, D. Hong, Estimation of dynamic track tension utilizing a simplified tracked vehicle model[J]. In: Proceedings of the American Control Conference, Arlington, 2001, pp. 3335–3.

[10] B. B. Fan , N.X. Liao. Establishment and simulation of a mathematical model for track tension [J] Measurement and Testing Technology,2021,48(07):25-27+31.(in Chinese)

[11] M. H. Bian, Y. Zhang, Z. Q. Du. The influence and simulation of pre tensioning force on smoothness of tracked vehicles [J] Vehicle and Power Technology,2019,(01):34-37. (in Chinese)

[12] Y. X. Wang, J. J. Zhang. Optimization of the tension of tracked robots based on orthogonal experiments [J] Journal of Southwest University of Science and Technology,2018,33(04):98-102. (in Chinese)

[13] P. X. Wang, X. T. Rui, H. L. Yu, G. P. Wang, D. Y. Chen. Adaptive control of track tension estimation using radial basis function neural network[J]. Defence Technology,2020.

[14] M. Ketting. Structural design of tension units for tracked vehicles, especially construction machines under the aspect of safety requirements[J]. Journal of Terramechanics, 1997, 34(3) : 155-163.

[15] Y. C. Qin, C. F. Wei, X. L. Tang, N. Zhang, M. M. Dong, C. Hu. A novel nonlinear road profile classification approach for controllable suspension system: Simulation and experimental validation[J]. Mechanical Systems and Signal Processing, 2019, 125 : 79-98.

[16] P. X. Wang, X. T. Rui, H. L. Yu. Study on dynamic track tension control for high-speed tracked vehicles[J]. Mechanical Systems and Signal Processing, 2019 ,132 : 277-292.