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Tracked walking mechanism for large hydraulic excavators

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ABSTRACT

The conventional design methods for tracked walking systems of large hydraulic excavators based on empirical formulas, does not take into account the dynamic load of the track. As such, a safety margin factor has to be adopted to ensure adequate working strength. However, the machine weight will be increased, and the hydraulic system will be overmatched. To address this design issue, an electromechanical–hydraulic design approach based on co-simulation is proposed in this study. The proposed design approach consists of four parts, namely, 1) a terramechanics model of the track that considers the pressure–sinkage relationship and soil shear stress of the individual tracked plate, 2) a tracked multibody dynamics (MBD) model that considers the intermittent transmission between the sprocket and the tracks, 3) the hydraulic systems model, and 4) the data communication interface. To demonstrate the proposed approach, it was used to design a large hydraulic excavator with a bucket capacity of 15 m^3. Experimental results from the prototype showed that the proposed design principle can accurately reflect the impact load and periodic torque fluctuations on the track. The maximum error between the simulated and experimental results is 5.4% in forward walking and 12.7% in backward walking, thus demonstrating the effectiveness and accuracy of the proposed design approach.

1. Introduction

Large hydraulic excavators are extensively used in opencast mining and large infrastructure projects. In order to work reliably in the harsh ground environments, this machine generally uses tracked walking systems with low ground pressure and high ground adhesion. The complete track is an assembly of many individual tracked plates, which results in the polygon effect in the sprocket. In addition, it causes an unstable dynamical transmission and complicated loading states. Consequently, it is difficult to conduct a comprehensive analysis on the dynamic force and transmission characteristics, especially when the tonnage and load increase. Owing to calculation difficulties, the design of the tracked walking system of the large hydraulic excavators mainly relies on the static empirical formula. In these formulas, the intermittent transmission and dynamic load are ignored. The empirical formulas also fail to consider the interaction between the hydraulic system and the mechanical structure. This insufficiency must be offset by the increase of safety factors which lead to an overweight machine and an unmatched hydraulic system. The optimization of safety factors requires a long-term accumulation of the experimental data, but the safety factor alone cannot accurately reflect the actual load in the empirical formulas.

The accurate mechanical structural model of the track is important to obtain reliable dynamic loads, so it was investigated by many researchers. The tracked system is composed of a large number of separate tracked plates and wheels, which are connected by hinges. The tracked plates and wheels are restrained by contact forces. As a result, the dynamic model has an increased number of degrees-of-freedom (DOFs) and a tremendous computational cost. To solve this problem, a set of parts is usually simplified as a super-element in the modeling process. Dhir et al. built a tracked vehicle model with 2 + N DOFs, where N is the number of road wheels [1]. In this model, the entire tracked vehicle was simplified to a two-DOFs model. Ferretti et al. developed the program MOSES to analyze the vehicle kinetic characteristic [2]. In this program, the single-side tracked assembly, which includes track link, the sprocket, idler wheel, road wheels, and suspension, is considered as a super-element. Each part was computed by a simplified analytical model, and entire vehicle consisted of the chassis, left tracked super-element, and right tracked super-element. These methods increase the computational speed of the model by reducing the DOFs of the tracked model. Moreover, the same methods allow the partial quantification of the dynamic characteristics of the mechanical structure of the track.

In the mechanical structural model of the track, the interaction between the track and ground is a key factor that affects the computational accuracy of the dynamic load. Bekker established the classical

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Nomenclature

B	width of the tracked contact area
B_m	damping coefficient of the walking hydraulic motor
b	shorter length of the contact patch rectangle
c_n	damping of the Hertzian contact force
c_s	cohesion of the internal shearing resistance of terramechanics
D_m	displacement of the walking hydraulic motor
D_p	displacement of the main pump
e_1, e_2	nonlinear factors of Hertzian contact force
e_3	exponent of the indentation damping effect
F_c	Hertzian contact force between the rollers and track link
F_{cx}, F_{cy}, F_{cz}	component of Hertzian contact force
F_f	friction of terramechanics
F_r	resistance force of the entire machine
F_{rg}	grade resistance
F_{ri}	inner resistance
F_{rm}	inertial resistance
F_{rs}	soil resistance
F_t	tension force of the tracked system
f_L	load frequency of the tracked system
g	gravitational acceleration
$\mathbf{I}_o$	moment of inertia matrix of the upper carriage
i_m	transmission ratio of the walking hydraulic motor gearbox
J_m	equivalent rotating inertia of hydraulic motor
K_s	shear modulus of shear stress of terramechanics
k_c, k_ϕ, n	pressure–sinkage parameters which are obtained from tests
k_{lp}	total leakage coefficient of the hydraulic circuit
k_t	correction coefficient related to the number of return rollers
k_n	stiffness of Hertzian contact force
L	length of the tracked contact area
l	distance between the two return rollers
M_o	mass coordinate of the upper carriage
m	mass of the entire machine
n_m	rotational speed of the walking hydraulic motor
n_p	rotational speed of the main pump
n_s	rotational speed of the sprocket
P_m	power consumption of the walking hydraulic motor
P_{max}	maximum power limit of the main pump
P_{mh}	power consumption of the walking hydraulic motor at high speeds
P_{ml}	power consumption of the walking hydraulic motor at low speeds
p_A	pressure of the walking hydraulic motor inlet
p_B	pressure of the walking hydraulic motor outlet
p_{pump}	real-time pressure of the main pump outlet
p_z	contact pressure of terramechanics
Q_m	flow of the walking hydraulic motor
Q_p	output flow of the main pump
q	quality of tracked plates per unit length
q_{input}	input pump displacement
q_{max}	maximum pump displacement
q_{min}	minimum pump displacement
q_{pump}	real-time pump displacement
R_s	radius of the sprocket pitch circle
S_t	displacement of the tension cylinder
s	shear displacement terramechanics
s_{max}	maximum sag of upper tracks
T_d	driving torque of the sprocket
T_{dmax}	maximum driving torque of the sprocket
T_L	load torque of the walking hydraulic motor
T_p	input torque of the main pump
V_A	volume of the chamber of the walking hydraulic motor inlet
V_m	displacement of the walking hydraulic motor
z	sinkage depth of the terrain pressure
z_s	number of the sprocket teeth
α	climbing angle of the tracked system
β	bulk modulus of the hydraulic system
β_{rt}	coefficient related to ground pressure
Δp_m	differential pressure of the walking hydraulic motor
ζ_n	damping ratio of the hydraulic system transfer function
δ	penetration between Hertzian contact coupling
η_{Vp}	volume efficiency of the main pump
η_{Vs}	volume efficiency of the hydraulic system
η_{mp}	mechanical efficiency of the main pump
η_{ms}	mechanical efficiency of the hydraulic system
θ_d	rotational angle of the sprocket
λ_s	soil resistance coefficient
μ	friction coefficient of terramechanics
ϕ	angle between the two teeth of the sprocket
φ	angle of internal shearing resistance of terramechanics
ω_{ls}	corner frequency of the load–motor dynamic stiffness
ω_n	natural frequency of the hydraulic system's transfer function
τ	angle between the fulcrums of the upper tracks and the horizontal direction
τ_s	shear stress of terramechanics

theory of terramechanics by taking into account the pressure–sinkage relationship between the track and the ground to analyze this interaction [3]. Paoluzzi et al. established the tracked model of the entire vehicle with the pressure–sinkage relationship model. It was used to analyze the interaction between the tracked vehicle and the ground [4]. Wong developed Bekker's theory and two programs for modeling and analysis of high-speed and low-speed tracked vehicles [5]. Wong's model was supported by a large number of experiments and has been successfully applied in the industrial and military fields [6]. Wong improved a variety of pressure–sinkage relationship models for different ground conditions. His work proved that the ground model had a great impact on the calculation of dynamic load.

By reducing the complexity of the model, the dynamic characteristics of the tracked mechanical structure are partially obtained. With the development of computer technology, the mechanical structural model of the track, including all its parts, can be established by the multibody dynamics (MBD) method. Huh et al. developed a 3D tracked vehicle MBD model where all the rotating parts were connected with track link based on contact forces [7,8]. In addition, Rubinstein developed the software package REKEM [9]. This program built the MBD model based on the Lagrangian equation, and solved the model with the Runge–Kutta method. The contact force between the tracked plates and ground was also considered. Using the commercial software LMS–DADS, Rubinstein et al. built a high–speed tracked vehicle MBD model [10]. Furthermore, by adding the grousers, they established an MBD model for low-speed tracked vehicles [11]. They analyzed the performance of the chassis and track link in terms of velocity and acceleration. Zhou et al. analyzed the barrier properties and the climbing performance of a high-speed military vehicle using the commercial software ADAMS/ATV [12]. Mężyk et al. established a high-speed, heavy–load military vehicle model in Virtual Lab and its dynamic characteristics and ride comfort was analyzed [13]. Kim et al. built a heavy tank model using the RecurDyn Track–HM toolkit to optimize the suspension system. The chassis vibration was reduced and the ride