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Research Paper

Investigation of dynamic heat generation and transfer behavior and energy dissipation for nonlinear synchronous belt transmission

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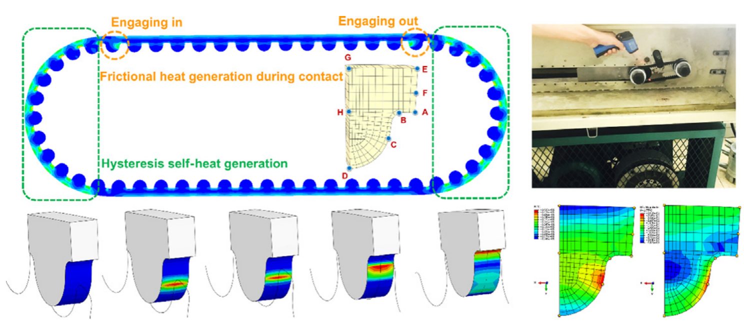
HIGHLIGHTS

- Temperature rise and transmission efficiency of synchronous belt was predicted by thermo-mechanical simulation.
- Viscoelastic hysteresis and nonlinear meshing friction behaviors were fully taken into consideration.
- Heat generation ratios in two forms and temperature change tendency under different conditions were investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

Study on energy dissipation and temperature distribution of synchronous belt transmission is of great importance in industrial engineering field, which is highly related to transmission efficiency estimation, thermal fatigue life prediction, and product design. However, the complex behaviors of viscoelastic hysteresis and meshing friction make it much more difficult to investigate heat generation and transfer mechanism of synchronous belt than other products. To accurately predict temperature and energy dissipation, a thermo-mechanical coupling model was developed through combining experiment and finite element analysis method, in which material nonlinearity of rubber hyper-viscoelasticity, and contact nonlinearity of meshing interference were comprehensively considered. Meanwhile, the friction heat flux partition coefficient and convective heat transfer coefficient were theoretically computed and corrected. As a result, the temperature distribution, hysteresis and friction energy dissipation of synchronous belt could be computed accurately, the transmission efficiency was estimated as well. The simulation temperatures of various operating conditions were confirmed by testing results. The presented methodology can completely predict energy dissipation and temperature distribution of synchronous belt transmission, which has far-reaching consequences in the engineering application filed.

1. Introduction

High torque drives (HTD) synchronous belts with circle-arc teeth are specially designed for high torque, high revolving speed working conditions and widely used in machining tools, automobile, metallurgy and so on [1]. It transmits power through teeth meshing between belt and pulleys, with accurate driving performance and lower noise [2]. Analysis of energy dissipation and temperature simulation of

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Nomenclature

W_{loop}	hysteresis energy dissipation of each cycle
$\hat{\sigma}$,$\hat{\varepsilon}$	peak value of stress and strain
$\bar{\sigma}$,$\bar{\varepsilon}$	equivalent stress and strain
sinδ	sine value of hysteretic angle
$\dot{\xi}$	nodal hysteresis energy dissipation rate
G_s,G_l	storage and loss modulus of rubber
f	frequency of synchronous belt transmission
μ	friction coefficient
t_j	contacting time increment
$\overline{F_j}$,$\overline{P_j}$	average friction force and positive pressure at t_j
S_j	accumulated slippage at t_j
$\dot{H}$	surface friction heat generation rate
q_{rubber},q_{steel}	friction heat flux transferring into belt tooth and pulley tooth
α	friction heat flux partition coefficient
λ,ρ,C	thermal conductivity, density and specific heat capacity
Re,Nu,Pr	Reynolds number, Nusselt number and Prandtl number
h_p,h_b	convective heat transfer coefficient of pulley and belt
W_h,W_{fb}	total thermal loading of hysteresis or friction in a half belt tooth
η	belt transmission efficiency

synchronous belt is always an important hotspot issue in industrial engineering. On the one hand, energy dissipation which can be used to estimate transmission efficiency plays a key role in evaluating the comprehensive performance of synchronous belt [3]. On the other hand, temperature distribution must be fully taken into consideration in fatigue failure analysis to ascertain appropriate testing conditions, obtaining accurate predicted results [4,5]. However, the complex behaviors of viscoelastic hysteresis and nonlinear meshing friction make it much more difficult to investigate heat generation and transfer mechanism of synchronous belt than other products.

In the past decade, large numbers of pioneer studies on energy dissipation or temperature prediction of rubber products which include driving belts have been conducted. Fredo and Silva et al. [6,7] respectively developed analytical models for predicting power losses of V-belt continuously variable transmission (CVT) and poly-V-belt, in which material hysteresis and friction sliding losses were considered. However, the material property and contact deformation were simplified. More importantly, V-belt segments were tested to obtain hysteresis loss factors, which indicated that energy dissipation of V-belt couldn't be completely predicted unless finished products were produced previously. In comparison with V-belt, the dynamic behaviors of synchronous belt are much more complex, especially the nonlinear contact pressure, slippage, and large deformation during meshing interference, which makes it difficult to calculate energy dissipation through an analytical model, let alone temperature rise prediction. Merghache et al. [8] observed that the temperature of belt tooth was a little higher than belt back surface when study temperature distribution of AT10 synchronous belt. Hence, an analytical model based on Fourier heat transfer equation was proposed with a hypothesis that heat flux in belt tooth transferred uniaxially. Although it presented a preliminary acquaintance of temperature distribution of synchronous belt, energy dissipation and temperature distribution were not able to be predicted. With the development of finite element analysis (FEA) technic, thermal-mechanical coupling approach was widely used in accurate temperature prediction of various rubber products. Zhang et al. [9] performed the heat build-up analysis of a simple rubber specimen under sinusoidal compressive loading by FEA. The predicted temperature provided a good match with experiment result. Felicelli et al. [10] developed a FEA approach to computationally evaluate the temperature filed of a pneumatic tire, which included body-ply composite structure modeled by REBAR element. But the un-harmonic characteristic of mechanical deformation, and friction sliding were neglected which inevitably led to a decrease in prediction accuracy. Han et al. [11,12] successively studied the heat generation and temperature distribution of a rubber bushing which operated under harmonic loading or actual working condition through FEA model. To exactly compute heat generation rate of the latter, the random spectrum of actual loading was decomposed by Fourier transform. By contrast, several important and difficult issues should be focused on when establishing thermal-mechanical coupling model of synchronous belt which was rarely reported. Firstly, Fourier transform should be employed since the stress and strain changed unharmonically; secondly, the friction heat generation caused by nonlinear meshing must be taken into consideration, however it was always neglected in thermal analysis of other products; thirdly, the friction heat flux partition and surface convective heat transfer should also be considered comprehensively. There are a lot of cutting-edge researches concerning on complicated convective heat transfer problem, especial theoretical calculation of nonlinear thermal boundary condition [13–15]. Hence, it plays a key role to ascertain an appropriate convection heat coefficient.

In this work, to further investigate heat generation and transfer behavior of synchronous belt, a sequential thermal-mechanical coupling model was developed using the commercial software ABAQUS (It's not appropriate to use direct coupling method because of the huge operand). A steady-state belt transmission model was established previously to extract nonlinear stress, strain, contact pressure, and slippage in each period. Meanwhile, the hysteretic angle which reflects energy loss performance of rubber material was measured by DMA. Therefore, the hysteresis and friction energy loss rate could be calculated respectively based on hysteresis energy dissipation theory and integral-summation methodology. Then a thermal analysis model was established to simulate heat generation and transfer behavior of synchronous belt. Thermal loading and boundary conditions computed theoretically were applied in model and corrected by inversion method. At last, the energy dissipation and temperature distribution were accurately predicted and verified by conducted measurements. The presented model is helpful for engineers to design synchronous belts and evaluate durable properties, which effectively improves the modern design theory of synchronous belts and has important value in engineering application field.

2. Parameters and FEA mechanical model of synchronous belt

2.1. Parameters of synchronous belt and test setup

The small pitch belts (such as 3M, 5M) apply to small space requirement, and large pitch belts (such as 14M) which need to be assembled big pulleys apply to ultrahigh torque condition. Therefore, 8M belt which is most widely used and has the best comprehensive performance was modeled in this work. Its teeth profile and structure were designed strictly according to Chinese machinery industry standard JB/T 7512 (as shown in Table 1). Side view and transverse section of 8M synchronous belt have been shown in Fig. 1a which indicated that the structure primarily included backside layer, reinforcing layer and belt teeth. In order to comprehensively considerate the rubber-glass fiber composite structure, the rubber material of backside layer and teeth were simulated by Mooney-Rivlin hyperelastic constitutive equation [16], and glass fiber cords were modeled by REBAR element. The defined modulus, sectional area, orientation, and cords interval were given in Table 2. The dynamic test setup for synchronous belt transmission was shown in Fig. 1b. An 8M synchronous belt was mounted between two pulleys. The driving pulley which was connected with the drive motor was fixed while the driven pulley could be moved for