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Mechanics model and its equation of wire rope based on elastic thin rod theory

Weiguo Wu*, Xin Cao

Humanoid and Gorilla Robot & Its Intelligent Motion Control Lab, School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

In view of the lack of general mechanics model and theoretical formula for force-deformation calculation of wire rope, a novel modeling method for wire rope mechanics model is presented. The mathematical model of wire rope's secondary helix is established using the Frenet frame and differential geometry. On the basis of that geometrical parameters of secondary helical line is derived from the necessary assumptions and geometrical relationship, using elastic thin rod theory of Love to establish an equivalent mechanics model of wire rope, and the equivalent elastic modulus and equivalent shear modulus calculation formulas are deduced. The deformation and elongation of wire rope under known tension can be calculated by the formulas. The force-deformation calculation of actual wire rope is carried out, and the results show that the maximum deviation of elongation is less than 8% compared with the finite element simulation and experimental measurement. Therefore, the correctness and generality of the model are verified, and it has theoretical and practical significance for the application and analysis of wire rope.

1. Introduction

Wire rope is a kind of metal product with space helix layered structure. The main production process of wire rope includes: wire drawing, twisting into strand and twisting into rope. As shown in Fig. 1, a strand is twisted by several wires, and a rope is twisted by several strands. Therefore, side wire in side strand is a special helical line around a helical line. In this paper, the special helical line is defined as secondary helical line. Because of the high strength, good softness and high stability, wire rope is widely applied in various fields including machinery, construction, mining marine, aerospace and so on. In the literatures, the geometry structure of wire rope is studied by analytic method, and applying numerical method and simulation software to research the relationship between load and deformation, contact stress and deformation, abrasion, fatigue and fracture (Wang et al., 2013). Firstly, summarizing the research situation of wire rope modeling below. At present, there are mainly three types of wire rope model. The first type is to establish the wire rope model through experimental study, the second is to establish numerical calculation model by theoretical deduction, and the third is to establish the simulation model by using the finite element analysis softwares or other dynamic analysis softwares.

The first type includes: In 2003, Zhang et al. researched on the wire rope friction caused by fatigue and fracture, through a series of wire rope fretting friction experiments (Zhang et al., 2003); In 2012, Tan and Zuo proposed a method of estimating the breaking force of wire rope, through the analysis of a large number of wire rope breaking experimental data (Tan and Hang, 2012). The second type includes: In 2004, Elata et al. of Israel Institute researched on mechanical characteristic of the independent wire rope (Elata et al., 2004). A mathematical model of independent wire rope was established, the numerical calculation was carried out by using Maple. The experimental results showed that the error of the wire rope stiffness between numerical calculation and measurement is less than 20%; The French scholar Berlioz carried out the dynamic modeling of the state of cable-stayed wire rope with the boundary condition in 2005 (Berlioz and Lamarque, 2005), using a multi scale method to predict nonlinear characteristics of wire rope; Zhang and Agrawal (2006) based on the premise that the axial velocity is unknown, derived a dynamic model of flexible variable length wire rope transmission system by the Hamilton principle. The model can obtain the longitudinal vibration response of wire rope and be used to design the Lyapunov controller; A nonlinear model of wire rope under natural wind load was proposed by Nicola in Italy in 2011 (Impollonia et al., 2011), the natural wind load was defined by the continuous method, simplifying the vertical inertial force and effectively reducing the amount of calculation using orthogonal method to numerically solve; Argatov established an asymptotic model for wire rope strand in 2011 (Argatov, 2011). Poisson

* Corresponding author.
E-mail address: wuwg@hit.edu.cn (W. Wu).

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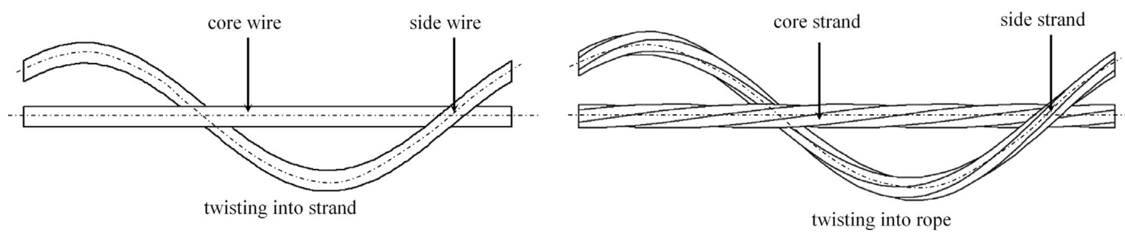

Fig. 1. twisting process of wire rope.

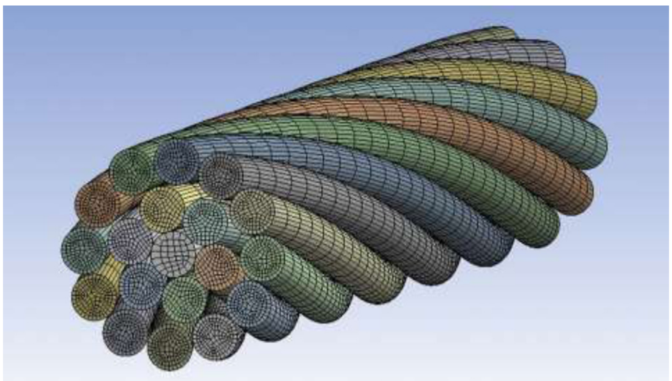

Fig. 2. Finite element model of wire rope (Páczelt and Beleznai, 2011).

ratio was considered and local contact deformations were studied in detail in this literature. The constructed asymptotic model allows for obtaining local contact stresses which are very important in a design process and in a preliminary step to study the strand strength and its wear resistance; Choi established a wire rope model using the spectral element method in 2014 (Choi and Inman, 2014). The numerical results of the model can be used to predict the elastic deformation of wire rope accurately. However, the ability of this method to simulate the heterogeneous or 2D and 3D structure is weak, and general property needs to be improved; The semi-continuous approach, in which each wire layer is replaced by a transversely isotropic continuous layer, has been developed by Blouin and Cardou (1989), and recently extended by Crossley et al. (2003); A new continuum model for multilayered fibrous structures was developed by Ghoreishi et al. (2007). The third type includes: Imanishi et al. carried on the dynamic simulation of the hydraulic system including drum and wire rope by finite element method in 2009 (Imanishi et al., 2009); Ma et al. established the finite element model of wire rope by ANSYS (Ma et al., 2009, 2012). The load distribution of steel wire in rope core and the stress distribution among the steel wires were respectively analyzed in 2009 and 2012. Páczelt et al. used finite element method to analyze the nonlinear contact theory of wire rope in 2011 (Páczelt and Beleznai, 2011). Wang et al. solved dynamic characteristics of wire rope in 2012 (Wang et al., 2012), through the combination of ADAMS and MATLAB/Simulink simulation, and secondary development function of ADAMS was applied. In 2013, Kastratovi and Vidanović analyzed wire rope for aircraft using finite element software (Kastratović and Vidanović, 2013). The mechanical behavior of wire rope in the lifting process can be predicted well, but experimental verification wasn't carried out.Wu calculated the stress and deformation distribution of wire rope with ANSYS in 2014 (Wu et al., 2014). Zhao analyzed the change of impact load of wire rope in 2015 (Zhao, 2015), under the conditions of lifting load dropping at different heights, with ANSYS. In addition, Wu et al. designed a modular flexible driven unit for joint of robot (Wu and Hou, 2011, 2014), Dynamics model was deduced based on constitutive equation of viscoelasticity, and a novel method of building wire rope-pulley system was provided using 3D relative variable polyline. By simulation and experimental verification, this method is suitable for the modeling of the flexible driven unit modeling. In order to improve the accuracy of unit control, further improve the unit structure, optimize the performance index, need to establish a more accurate wire rope model.

It is worth mentioning that the present work is different from that of Usabiaga and Pagalday (2008). First, the radial contraction of wire due to Poisson's effect is neglected in their work. And the kinematics in their work are based on the assumption that wires are un-lubricated, therefore, no relative sliding between adjacent wires happens. However, the friction among steel wires is ignored is this paper. What's more, they didn't compare the results with experiments. In this paper, we compare the results with experiments and FEM simulation. The work of Costello is so classical and comprehensive that almost all the theoretical researches of wire rope use Costello's work for reference. In this paper, further research is carried out on the basis of previous studies. The deformation and equivalent elastic modulus of wire rope are focus in our research. The difference from the work of Costello (1990) and Phillips and Costello (1985) is that secondary helical line is considered in present work. In addition, the improved constitutive relation of Ramsey is applied in present work when the mechanics model is established.

Most of the existing calculation models of wire rope, only suit a single type of wire rope, lack of universality. Taking finite element simulation as an example, when the wire rope structure changes, it's necessary to re-modeling analysis. In this paper, a new mechanics model of wire rope will be established, which is simple, accurate, easy to use, and can be used without the aid of finite element analysis and numerical calculation softwares. In this paper, the research method of literature Argatov (2011) was referenced. However, the research object in literature Argatov (2011) is simple, just a strand; the model proposed in this paper is more general. In addition, the significant difference is that wire rope side strand is a key research object in this paper. And the secondary helix has not been mentioned in literature Argatov (2011). Section 2 mainly introduces wire rope geometric modeling process and prepares for stress analysis. In Section 3, stress analysis of wire rope is carried out, from steel wire to strand and rope. The mechanics model of wire rope is established, and calculation formula of the equivalent elastic modulus and elongation of wire rope is obtained. In Section 4, compared with results of the existing simulation or tensile experiment, the correctness of the model is verified.

2. Establishment of geometric model of wire rope

2.1. Derivation of secondary helical line

Helical line widely exists in the life body, which is determined by its excellent properties, including: helical line can play a role in saving energy consumption, like a spring with certain elasticity and so on. These properties make the living body occupy the advantage in the struggle for existence, directly or indirectly.