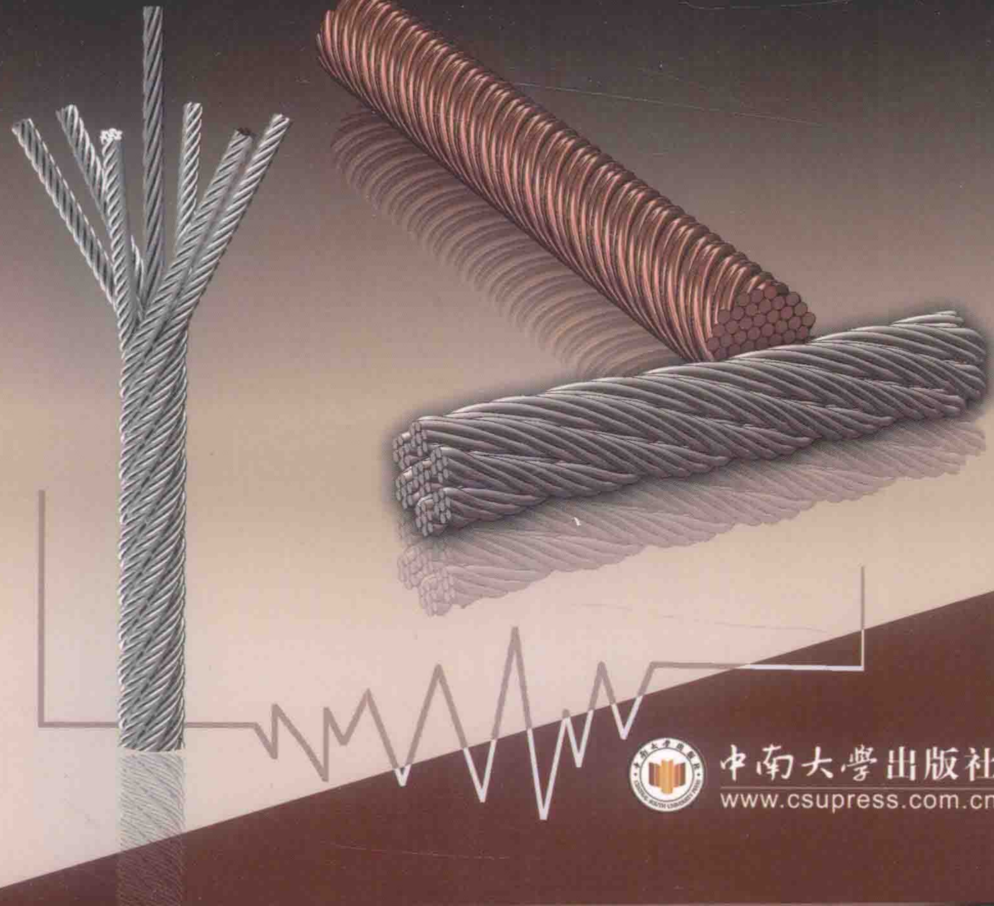
提升钢丝绳力学建模与微动疲劳损伤行为研究

TISHENG GANGSISHENG LIXUE JIANMO YU WEIDONG PILAO SUNSHANG XINGWEI YANJIU

◎ 王大刚 著



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作者简介

王大刚，1984 年 5 月生，博士。2010 年至 2012 年曾留学德国 Wuppertal 大学工程力学系做联培博士；2012 年 12 月毕业于中国矿业大学机械设计及理论专业，获工学博士学位；2013 年至今为深部岩土力学与地下工程国家重点实验室在站博士后；2015 年 7 月至 10 月到比利时 Ghent 大学应用力学系做访问学者。2013 年 4 月进入中国矿业大学机电工程学院机械设计系工作。

一直从事微动磨损、微动疲劳、微动腐蚀疲劳、提升动力学和数值仿真方面的研究。在提升钢丝绳微动损伤失效方面，已发表 SCI、EI 检索论文分别为 18 篇和 9 篇，参加国内外学术会议 12 次，已授权、公开国家发明专利分别为 4 项和 12 项。主持国家自然科学基金项目 1 项、中国博士后科学基金项目(一等)1 项、国家重点实验室开放基金 2 项、中央高校基本科研业务费专项资金资助项目 1 项、中国矿业大学人才类项目 3 项、企业横向课题项目 2 项；作为指导教师正在指导国家、江苏省大学生创新训练计划项目各 1 项；正在开展江苏省产学研合作项目 1 项；正在参与国家自然科学基金项目 2 项。荣获 2014 年度江苏省优秀博士学位论文、2014 年中国机械工业科学技术奖科技进步奖二等奖。

序 1

It is a great pleasure for me to write this preface for the book of Dr Dagang Wang, who has made a substantial contribution to the knowledge of fretting fatigue, fretting wear phenomena and their applications to steel wires during the last few years.

The topic of this book is dynamics and fretting damage of steel wire rope and deals with the different aspects required to analyze and predict damage in steel wires. The analysis of fretting fatigue and fretting wear is quit complex because it requires knowledge of several theories, such as Contact Mechanics, Continuum Damage Mechanics, Fracture Mechanics and Tribology. The contact between the two bodies is studied using Contact Mechanics, fretting fatigue leads to crack initiation, studied by Continuum Damage Mechanics, followed by crack propagation, studied by Fracture Mechanics, and fretting wear is studied by Tribology. Therefore, special considerations should be exercised in the experimental as well as in the numerical techniques used for this kind of problems. Moreover, when considering the application to steel wire ropes used in mining the dynamics of the system and the inertia forces play a very important role in the loading conditions acting between the steel wires.

In his book, Dr Dagang Wang considers all these complex aspects in analyzing damage in steel wires, namely dynamics, fretting fatigue crack initiation, fretting fatigue crack propagation, fretting wear and the interaction between these different phenomena. Regarding dynamic analysis, he investigates the effect of hoisting parameters, such as maximum speed, acceleration and deceleration and terminal mass, on the tensile force in the rope at the sheave tangent point during different stages of the lifting cycle. The link between dynamics and fretting fatigue is established by Dr Wang through mathematical expressions that relate fretting fatigue parameters of wires to tensile force in the rope during lifting cycle. He further presents the effects of hoisting parameters on fretting fatigue of the steel wires.

Moreover, Dr Wang uses Finite Element Analysis to model the contact between the steel wires assuming both elastic and elasto - plastic material behaviors. He provides details about contact stress analysis of straight and spiral strands and studies the effect of different parameters on the stress distributions. Furthermore, comparisons between the results obtained using linear elastic material properties and those obtained using elasto -

plastic material properties are presented and discussed.

Dr Wang presents also a study of fretting wear of wires, its interaction with fatigue fracture at contact surface and its effect on rope failure. The effects of crossing angle and contact load on contact width and pressure are investigated using Hertzian contact theory and Archard's wear model. To determine fretting damage experimentally, he develops a homemade wire fretting fatigue apparatus that can record fretting parameters, such as tangential force between contacting wires and relative displacement amplitude. Some interesting results are found using this apparatus.

Dr Wang further reports his research concerned with fretting fatigue crack initiation and crackpropagation, and lifetime prediction using both experimental and numerical techniques. Valuable results on crack initiation on the contact surface of tensile wire and lifetime estimation are reported.

To conclude, I highly recommend this book to all researchers involved with fretting fatigue, fretting wear and their applications to steel wires.

Prof. dr. ir. Magd Abdel Wahab
Professor of Applied Mechanics
Ghent University, Belgium
06/06/2015

序 2

This book addresses the problem of fretting fatigue in mine ropes. Fretting fatigue is one of most complex types of problems that may threat the structural integrity of mechanical components. The term fretting is associated to relative displacements of low amplitude between points on a contact interface. While fretting between the contact surfaces provokes some level of material loss and a localized stress concentration, which will encourage crack initiation, a remote fatigue load may drive this crack to dangerous lengths eventually leading to complete failure of the component. The occurrence of fretting fatigue in wire ropes involves an additional level of complexity due to their complicated geometry and because of the enormous challenge involved in estimating the appropriate loading in the critical crack initiation zones. As the failure of a rope can cause great economic losses and impose serious safety risks for mine workers, it must be avoided by all means. In this setting, this book constitutes a key reference for engineers and scientists interested in the design and maintenance of these mechanical elements against fretting fatigue. The book brings together an important set of research work produced by Professor Wang in this subject in the last 8 years. He has published a significant amount of scientific papers on the modeling, testing and numerical simulation of the fretting fatigue problem in wire hopes in some of the most prestigious journals available. This work was now possible to be presented in a greater level of detail.

In summary, the book describes a methodology to correlate mine hoisting parameters with stress history, fretting wear evolution, and fretting fatigue life estimation of steel wires. Hoisting dynamicsand numerical simulations are essential points in the analysis, which were also properly addressed. Most of the case studies were conducted considering a 6 × 19 + IWS rope. More specifically, the book is organized as follows. Load – carrying conditions of hoisting rope at the sheave tangent point at the start and end of a lifting cycle were calculated. Afterwards, the oreticalrelation shipsbetween rope tensionsand fretting fatigue parameters, and corresponding Simulink simulation models were established. Moreover, the stresses and deformations of 6 × 19 + IWS rope and the three – layered strand under axial extension were explored employing the finite element method. Then contact widths and maximum contact pressure between wires, and evolutions of fretting wear depths of wires crossed at different angles during fretting wear were explored. Meanwhile, the fretting fatigue behavior of steel wires in low cycle fatigue was investigated employing a homemade fretting fatigue test apparatus. Finally, the crack initiation and the stress distribution of wires without damage and with wear gaps were investigated using the finite element method. A correlation between fatigue lives of wires and fretting parameters was established. To conclude, I highly recommend this book to all researchers and engineers involved with hoisting dynamics, fretting wear, fretting fatigueand their applications to steel wire rope.

Prof. José Alexander Araújo
Professor of Engineering Mechanics
University of Brasilia
Brasília, 29th of May 2015

前　言

本书是在博士论文的基础上整编而成，并得到了国家自然科学基金青年科学基金项目(51405489)、国家自然科学基金面上项目(51375479)、中国博士后科学基金面上项目(2013M540474)、中央高校基本科研业务费专项资金资助项目(2014QNA42)、清华大学摩擦学国家重点实验室开放基金资助项目(SKLTKF13A04)、固体润滑国家重点实验室开放课题(LSL－1305)、江苏省高校优势学科建设工程资助项目(PAPD)、中国矿业大学青年教师启航计划第九批中国矿业大学优秀青年骨干教师等项目的资助。

本书是在中国矿业大学导师张德坤教授和德国伍珀塔尔大学导师袁荒教授悉心指导下完成的，他们渊博的学识、敏锐的学术洞察力、严谨的科研作风以及无私奉献的精神，一直激励着我勇于进取和善于探索，在此谨向两位导师致以最崇高的敬意和衷心的感谢！衷心感谢科学技术研究院朱真才院长在出国研修、科研和就业等方面给予的热情帮助和细致指导！感谢所有关心、支持、帮助过我的各级领导、老师、同事和朋友们！感谢江苏省矿山机电装备重点实验室(中国矿业大学)、清华大学摩擦学国家重点实验室、固体润滑国家重点实验室和摩擦学与可靠性工程研究所提供的优良科研实验环境！感谢多年来父母、妻子和姐姐给予我深深的理解和全力支持！

受中国矿业大学机电学院委托，南京航空航天大学周飞教授、青岛理工大学郭峰教授、中国矿业大学肖兴明教授、曹希传教授和沈承金教授详细审阅了本书，并提出了许多宝贵的意见。另外，国外微动疲劳领域知名专家——巴西的巴西利亚大学 José Alexander Araújo 教授和比利时根特大学 Magd Abdel Wahab 对该书给予很高的评价，并为本书作序。出版社的编辑人员为本书的出版和提高质量投入了大量的劳动。在此一并致以衷心的感谢。

限于编者的水平和编写时间的仓促，书中难免有不当之处，请读者不吝批评指正。来信请寄江苏省徐州市大学路1号中国矿业大学机电学院(邮编：221116)，或发电子邮件至 wangdg@cumt.edu.cn。

编　者
2015年6月于徐州

内容提要

矿井提升过程中，提升钢丝绳内部股与股、丝与丝之间存在微动磨损和微动疲劳，将加速钢丝绳的疲劳断丝，导致钢丝绳承载能力的降低，影响了钢丝绳的使用可靠性以及煤矿的安全生产。因此，研究钢丝的微动损伤行为和微动疲劳寿命预测对延长钢丝绳服役寿命和提高钢丝绳的使用可靠性具有重要的意义。

本书以 6×19+IWS 钢丝绳为研究对象，通过静力学分析考察了矿井提升机上提容器始、末钢丝绳的承载状况及其受终端质量的影响。基于上提容器过程中钢丝绳张力的动力学模型建立了 Simulink 仿真模型，分析了最大提升速度、提升加(减)速度和终端质量对钢丝绳所受峰值张力和张力幅值的影响。仿真结果表明，在上提容器始、末阶段，过渡段钢丝绳张力的总范围分别为 2102.1 ~ 18762.1 N 和 191.1 ~ 16851.1 N。在上提容器过程中，最大峰值张力、最大张力幅值、最小峰值张力和最小张力幅值的总变化范围分别为 9793.3 ~ 19896.9 N、176 ~ 4817.6 N、1240 ~ 19821.3 N 和 39.5 ~ 2366 N。

依据钢丝绳静力学理论和接触力学知识，建立钢丝绳所受张力和张力幅值与钢丝微动疲劳参数间的数学关系模型并建立 Simulink 仿真模型，探讨了上提容器整个过程中矿井提升参数对微动疲劳参数的影响。结果表明，在整个上提容器过程中，各微动疲劳参数的总范围几乎均随着矿井提升参数的增大而呈扩大或上升扩大的趋势，整个上提容器过程中绳内钢丝的拉力范围是 1.5 ~ 175.6 N，相对位移范围是 0.2 ~ 99.6 μm，接触载荷的范围是 0.2 ~ 452.1 N。

应用有限元法分析了 6×19+IWS 钢丝绳的应力和变形状况，运用精确的边界条件和子模型技术对受拉三层直股进行细致分析，探讨了摩擦系数和材料模型对应力分布和径向变形的影响。结果表明，钢丝表面的应力和变形均呈空间二次曲线状分布，钢丝绳轴向中间位置的截面上各应力均呈对称分布，直股和螺旋股中钢丝截面上的应力均分别沿径向向外降低，相邻螺旋股接触钢丝的变形差值最大。三层直股中，摩擦系数、材料模型和股轴向应变的变化均导致各丝的应力水平、相邻丝层钢丝接触区的应力突变和径向变形的不同。

运用三维赫兹接触理论分析了交叉角度和接触载荷对交叉接触钢丝的接触尺寸和最大接触应力的影响，建立了微动磨损过程中以不同角度交叉接触钢丝的磨损深度的演化模型以及磨损深度与微动参数间的关联模型。结果表明，不同的接触载荷和交叉角度会导致接触尺寸和最大接触应力的差异。比较钢丝交叉角度分别为 90°和 18°时不同微动参数下钢丝试样的微动磨损深度实验值和演化模型预

测，发现两者吻合较好。

运用自制钢丝微动疲劳试验机开展了低周疲劳下钢丝的微动疲劳实验，探讨了微动振幅、应变幅值和接触载荷对钢丝微动疲劳行为的影响。结果表明，不同微动疲劳参数下实验过程中摩擦系数、微动运行区域、磨损机理、微动疲劳寿命以及裂纹萌生和扩展特性均有所差异，而这些微动疲劳行为要素是相互作用的。

采用有限元法研究了垂直交叉接触钢丝（无损伤和带磨损缺口）的微动疲劳行为，探讨了微动疲劳参数对微动运行区域和接触面应力分布的影响，运用多轴疲劳准则考察了微动疲劳初期疲劳钢丝微动面的裂纹萌生特性及其受微动参数的影响，运用线弹性断裂力学理论和幂函数拟合法建立了循环应力参数、接触载荷和微动振幅与钢丝微动疲劳寿命间的定量关系。结果表明，在两种情况下，不同微动疲劳参数均导致不同的微动运行区域、应力分布和接触边缘的应力突变。随着接触载荷和微动振幅的增大，疲劳钢丝接触面上裂纹萌生分别变得困难和容易，与应力分析结果一致。通过理论预测法和拟合法得到的寿命值与实验值吻合较好，验证了理论模型的正确性。

Abstract

Fretting wear and fretting fatigue occurs among neighboring strands andamong contacting wires in hoisting rope during lifting in coal mine, which accelerates the fatigue fracture of steel wires, thereby reduces the endurance strength of the rope, and thus affects the rope reliability and production safety in coal mine. Therefore, studies on fretting damage behavior and fretting fatigue life estimation of steel wires are significant to prolong the rope service life and to enhance the rope reliability.

6 × 19 + IWS rope is taken as the objective of study in this thesis. Load - carrying conditions of hoisting rope at the sheave tangent point at the start and end of a lifting cycle are explored by static analysis. Simulink simulation models are built based on dynamic models of the rope tension during the lifting cycle. The roles of maximum hoisting velocity, hoisting acceleration (deceleration), and terminal load on peak tensions and tension amplitudes of the rope during the lifting cycle are investigated. Simulation results show that overall ranges of the rope tension vary from 2102.1 ~ 18762.1 N and from 191.1 ~ 16851.1 N at the start and end of the lifting cycle, respectively. During lifting, overall ranges of maximum peak tension, maximum tension amplitude, minimum peak tension and minimum tension amplitude are 9793.3 ~ 19896.9 N, 176 ~ 4817.6 N, 1240 ~ 19821.3 N, and 39.5 ~ 2366 N, respectively.

Mathematical relationships between tensions and tension amplitudes of the rope and fretting fatigue parameters of steel wires, and corresponding Simulink simulation models are established employing the rope theory and contact mechanics. The effects of hoisting parameters on fretting fatigue parameters during the whole lifting cycle are discussed. Simulation results show overall ranges of various fretting fatigue parameters almost all present the expanding or upward expanding trends with increasing hoisting parameters during the whole lifting cycle. Overall ranges of wire tension, contact load and relative displacement between wires change from 1.5 ~ 175.6 N, from 0.2 ~ 452.1 N and from 0.2 ~ 99.6 μm, respectively.

The stresses and deformations of 6 × 19 + IWS rope are explored employing the finite element method. Detailed analysis of the three - layered strand under axial extension is carried out using concise boundary conditions and sub - modeling technique. Effects of friction of coefficient and material model on stress distributions and radial deformations are analyzed. The results show that stresses along wire surfaces and wire deformations both present distributions of quadratic curves. Various stresses on the cross - section of rope in the axially middle location all exhibit symmetric distributions. The stresses on cross - sections of the straight strand and spiral strand both decrease along the radially outward direction, respectively. Neighboring spiral strands exhibit the largest difference in deformations of contacting wires. Variations of coefficient of friction, material model and strand axial extension strain all cause distinct stress levels of various wires, abrupt changes of stress near contact zones of contacting wires of adjacent wire layers, and radial deformations.

Three - dimensional Hertzian contact theory is introduced to investigate the effects of crossing angle and contact load on the contact widths and maximum contact pressure. The evolution of fretting wear depth of wires crossed at different angles during fretting wear and the correlation model between fretting wear depth and fretting parameters are established. The results demonstrate that different crossing angles and contact loads both cause distinct contact widths and maximum contact pressure. Experimental values of wear depths of steel wires crossed at angles of 90° and 18° in tests with different fretting parameters show good agreement with corresponding predicted values, which validates the fretting wear evolution model.

The roles of fretting amplitude, strain amplitude and contact load on fretting fatigue behaviors of steel wires in low cycle fatigue are investigated employing the homemade fretting fatigue test apparatus. The results show that different fretting fatigue parameters induces distinct coefficients of friction, fretting regimes, wear mechanisms, fretting fatigue lives, crack initiation and propagation characteristics during the fretting fatigue tests. Those elements of fretting fatigue behaviors interact with each other.

Fretting fatigue behaviors of perpendicularly crossed steel wires without damage and with wear gaps are studied using finite element method. The effects of fretting fatigue parameters on fretting regimes and stress distributions on contact surfaces are explored. Multiaxial fatigue criteria are employed to investigate roles of fretting parameters on crack initiation characteristics on the tensile wire surface during the initial fretting stage. The linear elastic fracture mechanics and method for a power function curve fitting are used to establish quantitative relationships between fretting fatigue lives of tensile wire and cyclic stress, contact load and fretting amplitude, respectively. The results show that different fretting fatigue parameters induce distinct fretting regimes, stress distributions and abrupt changes of stresses near trailing edges in two cases. Crack initiation on the contact surface of tensile wire becomes more difficult and easier with increasing contact load and increasing fretting amplitude, respectively. Predicted fatigue lives are in good agreement with experimental values, which validates the theoretical model.

变量注释表

F_R	钢丝绳最大工作静张力（过渡段钢丝绳张力）
A_S	钢丝总断面积
K_R	钢丝绳捻制折减系数
σ_b	钢丝的公称抗拉强度
n_R	安全系数
H	提升行程
M_t	终端质量
m_R	悬垂钢丝绳质量
ε_R	提升钢丝绳的应变
a_1	提升加速度
a_2	提升减速度
E_R	钢丝绳的杨氏模量
$L_\zeta(t)$	第 ζ 提升阶段终端质量与天轮间悬垂钢丝绳长度
m	终端质量
t	提升时间
t_1	加速阶段末对应的提升时间
t_2	匀速阶段末对应的提升时间
u_0	钢丝绳初始伸长量
v_m	最大提升速度
ρ	钢丝绳每米质量
V_0	激励作用下钢丝绳内纵向波传播速度
σ_0	激励前钢丝绳的拉伸应力
$a(\zeta)$	第 ζ 提升阶段对应的加速度
$t(\zeta)$	第 ζ 提升阶段对应的提升时间
$v(\zeta)$	第 ζ 提升阶段对应的提升速度
K	悬垂钢丝绳等效刚度

ω	钢丝绳振动频率
F_{g}	惯性载荷
$F_{0\max}$	最大峰值张力
$F_{\min}$	最小峰值张力
$\Delta F_{\max}$	最大张力幅值
$\Delta F_{\min}$	最小张力幅值
i	绳股的钢丝层
F_i	绳股中第 i 钢丝层单根钢丝的拉力
S_i	F_i沿绳股轴向的分量
U_i	F_i沿绳股周向的分量
n	绳股中钢丝层数
z_i	第 i 钢丝层的钢丝数
l_{S}	绳股的长度
l_{i}	钢丝长度
Δl_{i}	钢丝伸长量
E_i	钢丝的弹性模量
A_i	第 i 钢丝层钢丝的横截面积
u_{i}	缠绕周长
Δu_{i}	缠绕周长的收缩量
k	绳股某丝层
S_{t}	绳股的拉力
F_k	第 k 钢丝层单根钢丝的拉力
j	钢丝绳的股层数
l	钢丝绳某股层
S	钢丝绳张力
F_{ij}	钢丝绳中第 j 股第 i 丝层单根钢丝的拉力
F_{kl}	钢丝绳中第 l 股第 k 丝层单根钢丝的拉力
ΔD_{ij}	因第 j 股第 i 丝层钢丝的拉伸变形引起的它与相邻钢丝间的错动位移量
ΔF_{ij}	钢丝绳中第 j 股第 i 丝层单根钢丝的张力差
P_{ij}	钢丝绳中第 j 股第 i 丝层相邻钢丝间的接触载荷

$P_{i(i+1)}$	螺旋股中相邻钢丝层相邻钢丝间的接触载荷
$P_{j(j+1)}$	外层股与芯股的钢丝间接触载荷
P_j	相邻外层股的钢丝间接触载荷
$F_{ij\max}$	每个提升阶段开始时刻对应的最大钢丝绳张力
$F_{ij\min}$	每个提升阶段开始时刻对应的最小钢丝绳张力
$\Delta F_{ij\max}$	每个提升阶段开始时对应的最大钢丝张力差
$\Delta F_{ij\min}$	每个提升阶段结束时对应的最小钢丝张力差
p_i	螺旋钢丝的捻距
r_i	第 i 层单螺旋钢丝的螺旋半径
e_Z	绳股轴
α_i	第 i 层单螺旋钢丝的螺旋捻角
θ_i	单螺旋相角和第 i 层钢丝中心线沿股轴 e_Z 对 e_X 的旋转角之和
X_{OCW}、Y_{OCW}、Z_{OCW}	单螺旋芯丝的位置坐标
r_{oj}	外层螺旋股中第 j 层双螺旋钢丝绕单螺旋芯丝的螺旋半径
θ_{OCW}	单螺旋芯丝中心线沿绳轴 e_Z 对 e_X 的旋转角
α_{oj}	第 j 层双螺旋钢丝的螺旋捻角
ΔU_1、ΔU_2、U_3	坐标系中前横截面上节点 n 的位移分量
$\Delta U'_1$、$\Delta U'_2$、U'_3	坐标系中与节点 n 相对应的后横截面上节点 n' 的位移分量
U_P	1/6 直股长度
ε_S	直股轴向应变
θ	两钢丝柱体交叉接触角度
F	交叉钢丝间的接触载荷
a、b	交叉接触钢丝椭圆形接触区的半长轴长和半短轴长
C_F、C_σ	与应力相关的系数
C_a、C_b	与接触体形状及尺寸相关的常数
γ	等效弹性模量的倒数
E_1、E_2	圆柱实体 1 和 2 的弹性模量
ν_1、ν_2	圆柱实体 1 和 2 的泊松比
k_r	椭圆形接触区半短轴与半长轴之比
σ_c	接触区最大压应力