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钢丝绳探伤的永磁励磁器设计*

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钢丝绳探伤的电磁法中, 损伤信号由磁敏元件捕获因损伤引起的钢丝绳表面磁场变化而产生, 实现探伤的前提与基础就是要将钢丝绳磁化, 磁化的方法和效果直接决定了损伤信号的可靠性与准确性, 又决定了励磁器的结构和体积。本文将对励磁器的设计及参数确定进行详细的分析。

1 磁化回路的分析

随着永久磁铁的性能不断提高, 使用永磁作为磁源可以用很小的体积和重量满足钢丝绳磁化的要求, 并且克服了传统的直流励磁方法结构复杂、需要外接电源和具有发热损耗的缺点。对钢丝绳进行磁化, 首先要使被检测段达到一定的磁感应强度, 并且在被检测段中部产生一定长度的均匀磁化段以保证损伤信号的强度和准确性; 其次要求励磁器尽可能轻、小, 以满足现场检测的需要。综合以上考虑, 作者在钢丝绳探伤研究中采用了永久磁铁周向均匀励磁的励磁器, 其结构如图1所示, 永磁沿钢丝绳周向均匀分布形成极靴, 衔铁做成管状, 最大限度地减少了漏磁。等效的简化磁路见图2。

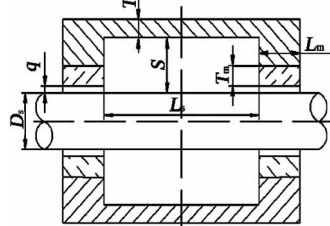


图1 励磁器结构

与一般的工程应用中的磁路不同, 本磁路不是要求气隙中的磁场强度, 而是要将磁通量尽可能地引入到钢丝绳中, 且在钢丝绳中达到一定的均匀的磁感应强度, 属于已知磁通量, 求磁动势的问题。由磁路基尔霍夫第二定律列出方程组如下

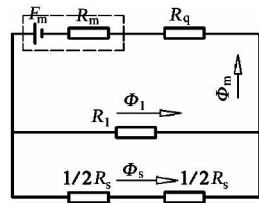


图2 等效简化磁路

为便于计算引入了磁导 G 的概念

$$\begin{cases} F_m = R_q F_m + R_l F_l \\ R_l F_l = \frac{1}{2} (R_s + R_x) F_s \end{cases}$$

为便于计算引入了磁导 G 的概念

$$G = \frac{1}{R} \frac{mS}{L}$$

式中 G —— 材料导磁性能的量度
 m —— 磁导率
 S —— 磁路段的截面积
 L —— 磁路段长度

下面是用解析法计算确定的各磁路段磁导公式。
 钢丝绳的磁导

$$G_s = m_s \delta D_s^2 / [4(L_s + 2L_m)]$$

衔铁的磁导

$$G_x = m_x \delta (D_s + 2S + T_x) T_x / (L_s + 2L_m)$$

衔铁内外端面与钢丝绳表面间漏磁通的磁导

$$G_l = 4m_l \left[D_s + \sqrt{(q+T_m)S} \ln \left(\frac{S}{q+T_m} \right) + \sqrt{(q+T_m)(S+T_x)} \ln \left(\frac{S+T_x}{q+T_m} \right) \right]$$

磁铁内侧与钢丝绳表面间的气隙磁导

$$G_q = 2\delta m_q L_m / \ln(1+q/R_s)$$

式中 D_s —— 钢丝绳公称直径
 L_s —— 两极靴内侧间距
 L_m —— 永磁沿钢丝绳轴向的长度
 T_m —— 永磁沿钢丝绳径向的厚度
 S —— 钢丝绳表面到衔铁内侧的距离
 T_x —— 衔铁沿钢丝绳径向的厚度
 q —— 永磁与钢丝绳表面的气隙

2 磁化回路参数的确定与计算

结合磁场理论与实验验证, 磁路中各参数的计算与确定说明如下。

L_s 要满足在中间部位轴向形成一均匀磁化段 L_0 , 考虑到放置探伤传感器的需要, 其长度应不小于钢丝绳的两个股间距 L_g 。由于漏磁通的存在, 从两极靴端面到中间, 钢丝绳表面径向的磁场强度由最大值逐渐减小到零, 形成非均匀的过渡磁化段 L_t 。笔者用图3所示的实验装置对距离钢丝绳表面3mm处漏磁通强度的径向分量 B_r 进行了测量

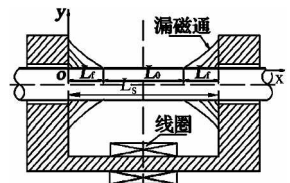


图3 过渡磁化段长度测量实验装置

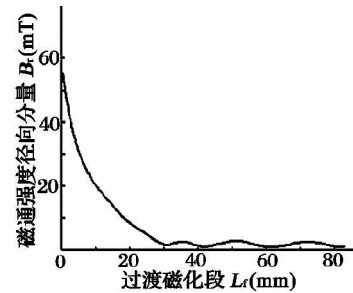


图4 过渡磁化段长度测量实验数据 ($q=5$ mm), 结果见图4。

钢丝绳表面至衔铁内侧的空间需要满足放置探伤传感器的需要, S 的大小由探伤传感器的尺寸及布置形式确定。

铁磁性材料的磁导率是空气的数千倍, 由磁路的欧姆定律 $F_m = RF = L/mS$ 可以看出, 气隙是磁路中影响磁势降的主要因素。以磁化 $\text{f}30$ 的 6×19 钢丝绳为例, 在其他参数不变的情况下, 不同气隙条件所需的磁动势, 见表1。

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表1 不同气隙条件下磁化钢丝绳所需的磁动势

气隙 q (mm)	2	4	6	8	10	12
磁动势 F_m (A)	486.90	630.76	897.73	1 141.23	1 363.61	1 596.97
气隙 q (mm)	14	16	18	20	22	24
磁动势 F_m (A)	1 759.66	1 938.00	2 104.67	2 261.92	2 410.37	2 550.60
气隙 q (mm)	26	28	30	32		
磁动势 F_m (A)	2 684.38	2 811.12	2 932.58	3 048.73		

从表 1 可以看出,在其他参数不变的情况下, q 每增加 2 mm, 磁动势 F_m 增加 150 A 左右, 而 f 30 钢丝绳的磁势降为 129.51A, 随着 q 的增加, 磁化效率会严重下降。采用钕铁硼永磁材料, 其最佳工作点的磁场强度 H_d 为 1 200 kA/m, 由表 1 的数据可知, 当气隙 q 超过 10 mm 时, 将不能满足磁化钢丝绳的要求(其他参数见表 2)。考虑到钢丝绳的可通过性, q 不能小于钢丝绳直径的 1/10。

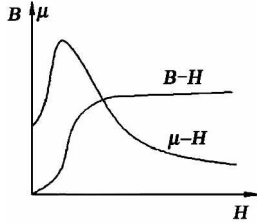


图5 铁磁性材料的磁化曲线

永磁应尽量靠近钢绳表面以提高励磁效果。考虑到磁通分布的特性, 极靴的径向长度要大于钢丝绳的一个段间距 L_g 。本研究取 $L_m = L_g + 5$ mm。

铁磁性材料的磁导率 m 随 B 呈非线性变化, 如图 5 所示。首先应根据具体的磁化曲线确定各磁路段的工作点, 进而确定各磁路段的磁参数。

图 6 是典型的 6×19 的钢丝绳磁化特性曲线。在初始饱和区, 曲线较为平稳, 钢丝绳的磁感应强度不易受到外界干扰的影响。在初始饱和区右侧的深度饱和区, 磁感应强度变化不大, 而磁动势的消耗不断增加, 所以为达到稳定、经济的磁化效果, 钢丝绳的工作点应选在初始饱和区。

衔铁由矫顽力小、饱和磁感应强度高的软磁材料构成, 其作用是连接磁源形成磁回路, 并且将磁通最大限度地引入到衔铁中以减少漏磁, 提高磁化效率。在常用的软磁材料中, 工业纯铁具有很高的饱和磁感应强度和很大的磁导率及良好的机械加工性能, 是理想的导磁材料, 其磁化曲线见图 7, 工作点应该在最大磁导率附近。

各段的工作点确定后, 即可由方程组求出所需的磁动势 F_m 和磁通量 F_m , 并由此确定永磁的工作点。永磁的性能参数有剩磁 B_r 、矫顽力 H_c 和最大磁能积 $(B_H)_{max}$ 。在开路状态下工作的永磁, 其磁

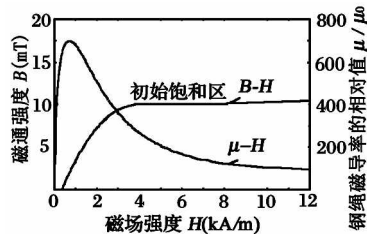


图7 工业纯铁的磁化曲线

感应强度并不是在 B_r 点上, 而是在比 B_r 低的位于第二象限的退磁曲线上的一点 D , 称为永磁的工作点, 如图 8 所示。对于一定型号的永磁, 其工作点主要决定于永磁自身的形状和磁路的结构。最大磁能积 $(B_H)_{max}$ 是衡量永磁能量密度大小的参数, 工作点在 $(B_H)_{max}$ 点附近, 可以充分利用永磁的能量。本磁路的设计主要是保证稳定的磁感应强度, 在此前提下, 应选取矫顽力 H_c 较大的永磁材料, 以提高磁路的稳定性。

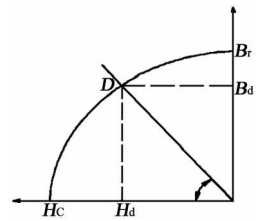


图8 永久磁铁的工作点

作者在钢丝绳探伤研究中采用工业纯铁 DT3 和钕铁硼永磁, 对直径 10 ~ 60 mm 的 6 股钢丝绳励磁回路进行了设计计算, 结果见表 2。

目前性能最高的钕铁硼永磁材料, 最佳工作点处的磁感应强度 B_d 为 1 000 mT, 磁场强度 H_d 为 1 200 kA/m。从表 2 的结果可以看出, 在钢丝绳探伤中使用永久磁铁周向均匀励磁的励磁器, 可以很好地满足磁化钢丝绳的要求, 而且具有稳定性好, 结构简单, 体积小, 重量轻, 无需外接电源的优点。

表2 磁路参数

磁路结构参数							钢丝绳磁参数			气隙		磁铁磁参数		励磁器
D_s (mm)	L_s (mm)	L_m (mm)	T_m (mm)	S (mm)	T_x (mm)	q (mm)	B_s (mm)	磁通 (%)	磁势降 (A)	磁势降 (A)	B_m (mT)	H_m (kA/m)	重量 (g)	
10	73	15	10	30	0.30	2	1	86.4	93.37	258.23	138	35.16	897.33	
20	86	25	10	30	1.03	2	1	93.7	111.43	307.13	178	41.86	1 916.64	
30	99	35	10	30	2.04	2	1	95.9	129.51	486.90	186	73.70	3 319.97	
40	112	45	10	30	3.23	2	1	96.7	147.59	506.78	200	129.93	5 262.64	
50	125	55	10	30	3.89	2	1	96.5	165.70	857.60	196	203.28	10 654.78	
60	138	65	10	40	5.17	2	1	97.0	183.72	881.66	205	291.48	14 588.21	

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shows that this reducer could satisfies the small size and the strength requirement of load-bearing work condition, which lead to successful spread for semi-coal rock stumpy cantilever tunneler. **【Descriptors】** Semi-coal rock Cantilever tunneler Cutting reducer Heat treatment

Loaders & Haulers

Current Status and Development of Mining Info Technology.....

.....GAO MengXiong et al.(37-44)
According to the info from MINExpo 2004 INTERNATIONAL(a global mining expos)and the others, the paper briefly narrates the application of the info technology in mining industry and its development. **【Descriptors】** Info technology Sensor technology Communication technology Computertechnology

Application of the DTC Variable Frequency Velocity Regulating Device on Cableway-Poled Trolley in Shaft.....

.....FENG HePing et al.(44-46)
The paper analyses the cableway-poled trolley in shaft about its current employment status and existing problem, introduces the control strategy and spot application status of the DTC variable frequency velocity regulation device, puts forward the necessity of innovating the DC driving system of traditional mine-used cableway-poled trolley by DTC variable frequency velocity regulating technique. **【Descriptors】** Transducer Direct torque control Trolley

Design and Study of the Buffering Spring of Arrestor on Trolley Line.....

.....JIANG Mei(47-49)
The paper analyses the stress circumstance of the arrestor on trolley line, provides the design method to optimize buffering spring, gets better effect in engineering application. **【Descriptors】** Tramcar Trolley Dynamic analysis Buffering spring Arrestor

Study to Semi-Active Control for Tramcar Suspension System Based on Electro-rheological Damper.....

.....HU WanHua(51-52)
The paper analyses the characteristic of the electro-rheological fluid and damper, establishes the dynamic model according to the performance of passive suspension, active suspension and semi-active suspension system, offers the schematic diagram of control system of electro-rheological damper. Simulation result shows that the active suspension system has better buffering effect than the semi-active one which is improved effectively compared with the passive suspension system. **【Descriptors】** Tramcar suspension Semi-active control Electro-rheological damper

Hoists & Winches

Design to Permanent Magnetic Exciter for Detecting Steel Wire.....

.....TIAN Jun et al.(60-61)
To detect steel wire by electromagnetic approach, steel wire should be magnetized firstly. According to the magnetization requirement of steel wire, the paper analyses the steel wire magnetization circuit that uniformly excites around the permanent magnet, and offers the method to determine the parameters of magnetic path and the structure of exciter. **【Descriptors】** Detection for steel wire Magnetization curve Permanent magnet Operation point

A New Kind of Digital Trigger and Its Application.....

.....DOU ZhenLan et al.(64-66)
Aiming at twelve pulse variable current circuit, the paper designs the circuit of a new kind of high performance fully-controlled digital trigger on basis of 80C196KC, gives concrete narration to the design scheme for the hardware and the software of digital trigger and its application in velocity regulation system of mine hoists. **【Descriptors】** Digital trigger Single-chip processor High velocity output port Twelve pulse variable current Non-circumfluence logic control

Continuous Conveyers

Development on Study to Solid-Liquid Pump.....

.....NI FuSheng et al.(67-69)
The paper gives brief description to the domestic and foreign development on study to solid-liquid pump and the test study for the

slurry pump used in lake dredging engineering, indicates several matters of solid-liquid pump need to further study. **【Descriptors】** Solid-liquid pump Dredge Development on study

Development and Application of Flameproof and Antistatic Plastic Tube Material Used in Coal Mine.....

.....LI Huai et al.(70-71)
On basis of the analysis to the producing mechanism of static on the surface of flameproof and antistatic plastic tube, the paper selects the basic material for plastic tube, and develops the mine-used flameproof and antistatic PVC tube material to replace the each kind steel tube in underground coal mine. **【Descriptors】** Flameproof and antistatic Mine-used plastic tube material Coal mine

Line Friction and Multi-Position Driven Belt Conveyor with Steel Wire as Core.....

.....HU DengEn(72-73)
The paper introduces this belt conveyer about its main technical parameters, working principle, advantage, structure, characteristic on design, innovation content and employment circumstance etc. **【Descriptors】** Line friction multi-position driven Belt conveyer with steel wire as core Characteristic

Application of the Remote Coordination Design Technique on the Design for Belt Conveyor.....

.....MA Qi et al.(73-75)
The paper mainly introduces a system that design and discuss the belt conveyer based on the coordination of computer, and founds dynamic database to select the model of belt transportation of conveyer and makes strength calculation. **【Descriptors】** Remote coordination design Belt conveyer Dynamic database

Common Techniques

Application of Ultrasonic Velocity Detecting Technique on Flux Monitor.....

.....WANG BingRen et al.(77-79)
The paper concludes each flux monitoring method based on ultrasonic detection technique, systematically narrates the detecting principle about radiating velocity difference method and Doppler method, offers suggestion to correct selection and installation. In addition, applying example of ultrasonic flowmeter in industrial spot is introduced. **【Descriptors】** Ultrasonic flowmeter Doppler method Flux monitor Application

Realization of 103 Stipulation and DeviceNet Communication Approach.....

.....ZHANG Li et al.(79-81)
For it is difficult for DeviceNet to collect relaying protection info in monitoring system of transformer station in coal mine, the paper design a kind of communication approach between 103 stipulation and DeviceNet spot bus, which realizes the communication between them. **【Descriptors】** Equipment network IEC60870-5-103 stipulation Protocol conversion

Application and Enlightenment of Stability Theory and Chaos Recognition in Prewarning Maintenance for Equipment.....

.....FANG YeXiang et al.(83-85)
Stability theory of Differential Equation is applied to judge instability condition of equipment during operation, probes the method to control instability, and discusses stability of non-linear system. According to the stability, bifurcation and chaos belonging to equipment inherent character that behave during operation, the paper provides the method theory to make preventive maintenance for equipment from essences, guarantees the safety operation for equipment by establishing corresponding prewarning and closed loop feedback system etc. **【Descriptors】** Stability Bifurcation Chaos Kelmogorov entropy Equipment maintenance

Application of MasterCAM Lathe on Programming for Parts Manufacture.....

.....DAI Ming et al.(86-88)
The paper introduces the application of MasterCAM Lathe on programming for parts manufacture by an example. Rough of parts is determined by outline drawing, the tool route and each manufacturing parameter are setup, tool route and manufacture is simulated. Finally, NC program code used for numerical control manufacture is directly produced. **【Descriptors】** MasterCam Lathe NC program Tool route