

西安交通大学航天航空学院  
School of Aerospace, Xi'an Jiaotong University

# 电磁机械力学

—Electromagnetic Mechanics

• 李勇

5/26/2011 Electromagnetic Mechanics

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## 第十一章：电磁无损检测



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## 问题1

无损检测概要，基本原理？



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联合航空232坠毁事件

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联合航空232坠毁事件 (前篇)

Sioux City, Iowa, July 19, 1989...

联合航空232号班机在因引擎破坏导致全机失控，于美国苏城迫降时坠毁，111人死亡，185人获救。（即“苏城空难”）

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联合航空232坠毁事件 (后篇)

在飞机日常维护检修中，对飞机发动机叶片内缺陷的漏检，是造成坠毁事件的主要原因。

尾部发动机叶片发生疲劳断裂导致发动机解体，液压系统失灵。

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**列车脱轨**

1911年美国纽约州列车脱轨

2000年英国Hatfield列车脱轨

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**桥梁坍塌**

2007年美国明尼苏达州桥梁坍塌

1967年美国俄亥俄州桥梁坍塌

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**无损检测的重要性**

- 确保设备安全运行，保障生命财产安全
  - 发现和确认装置安全运行隐患，防止事故发生（特别是对大型设备：核反应堆、飞机、铁路、管道等）
- 评估设备安全使用寿命
  - 根据早期缺陷及其发展程度，确定损伤方位、尺寸、取向和性质
- 改进生产工艺，提高产品质量，降低成本，提高效益
  - 质量控制（材料冶金质量、加工工艺质量、组织状态、涂镀层厚度等）
  - 质量鉴定（铸造、锻压、焊接、热处理、切削加工）

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**无损检测必要性**



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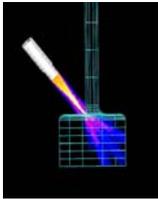
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**什么是无损检测?**

**“Nondestructive testing (NDT&E) are noninvasive techniques to determine the integrity of a material, component or structure or quantitatively measure some characteristic of an object.”**  
 ——摘自 NDT Wiki

在不破坏 (Nondestructive) 被  
 查工件、不影响 (Noninvasive) 其用  
 途的前提下检查工件中的裂纹、腐蚀  
 或其他缺陷 (Defects)，推知缺陷的  
 类型、大小、位置等信息，或者测量  
 工件的材料 (Materials) 特性。



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**要点**



- 不破坏被检工件
- 不影响用途
- 完整性评估, 缺陷评估
- 材料特性检测与评估



- 不损伤人体
- 无副作用
- 健康程度评估, 病患部位评估
- 血液等检验

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### 无损检测特点

- 非破坏性
- 全程性：适用于原材料、半成品、成品及在役设备的检测
- 应用领域广
- 检测方法众多，各有适用范围和优缺点
- 多学科交叉
- 历史悠久，不断发展

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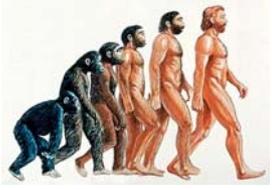
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### 无损检测的发展

无损探伤  
Nondestructive Inspection

无损检测  
Nondestructive Testing

无损评估  
Nondestructive Evaluation



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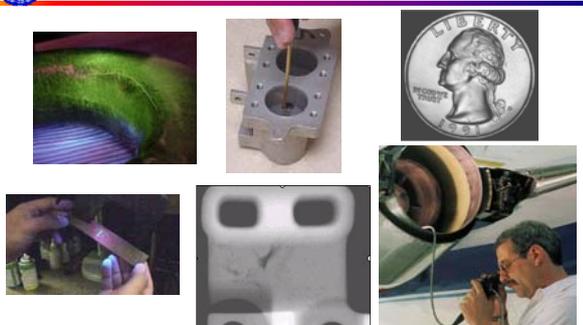
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### 无损检测方法



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### 无损检测方法

目视 Visual  
微波 Microwave  
热成像 Thermography  
X射线 X-ray  
磁粉 Magnetic Particle  
声学显微 Acoustic Microscopy  
声发射 Acoustic Emission  
磁测量 Magnetic Measurements  
超声 Ultrasonic  
复制 Replication  
渗透 Liquid Penetrant  
漏磁 Flux Leakage  
激光全息干涉 Laser Interferometry  
涡流 Eddy Current

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### 无损检测应用

- 缺陷检测与评估
- 渗漏定位
- 位置确定
- 多维测量
- 结构及微观结构的识别
- 机械和物理属性的评估
- 应力及动态响应测量
- 材料识别和化学成分测定
- 等等



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### 初级产品检测

- 锻造
- 铸造
- 挤压成型
- 等等



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### 再加工产品检测

- 切削加工
- 焊接
- 磨削加工
- 热处理
- 电镀
- 等等



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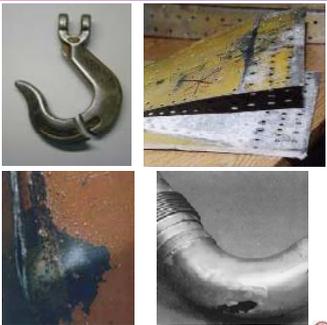
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### 服役工件检测

- 裂纹
- 腐蚀
- 冲蚀
- 热损伤
- 应力集中
- 等等



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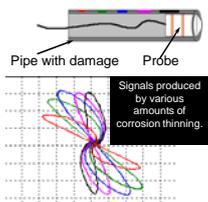
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### (核) 电站检测

电站周期性停机进行无损检测。  
检测人员通常采用涡流检测方法，  
将涡流检测放置于换热器管道内，  
以实现管道内出现的腐蚀进行检测和评估。



Pipe with damage    Probe

Signals produced by various amounts of corrosion thinning.

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### 承载缆绳检测

电磁检测法与目视法相结合，对承载缆绳出现的断线及其他损伤进行检测和评估，确保索道、电梯、吊车等设备的正常运行。

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### 储油罐检测

集成超声检测法的机械攀爬设备对地上储油罐进行罐壁减薄（由腐蚀造成）检测和评估。

装载有微型照相机/录像机的智能机械手臂可用于地下储油罐的缺陷检测和评估。

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### 飞机发动机检测

- 飞机发动机在服役一段时间后需进行大修。
- 发动机各个部件将被拆卸，逐一进行清洗、无损检测，在确保发动机运行安全的条件下，对发动机进行重新组装。
- 通常采用荧光渗透法对多数发动机部件进行无损检测。

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### 压力容器检测

压力容器的损伤将导致大量能源的流失。鉴于此，射线检测法和超声检测法通常应用于压力容器的无损检测中。



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### 铁轨检测

对铁轨内出现的可导致机车脱轨的缺陷，采用集成无损检测手段的特种设备（机车、手推车等）对其进行检测和评估。



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### 桥梁检测

- 针对桥梁内部的腐蚀、裂纹及其他缺陷进行无损检测，避免坍塌的严重后果。
- 目前，每两年对服役中的桥梁进行目视检测。
- 当前，越来越多的桥梁在建造期间就已经装配有声发射传感器，实现在桥梁服役期间对缺陷生长所产生的声音进行‘监听’。



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**(输油) 管道检测**

无损检测广泛应用于管道检测中，避免管道出现漏洞而导致的环境污染。对于管道检测，通常采用目视检测法、射线检测法和漏磁检测法。



管道漏磁检测设备



Photo: Courtesy of Insitu  
远程目视机器人



Photo © 管道焊缝的射线检测

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**特种设备检测**

来自佛罗里达州的技术员采用无损检测方法对独立钟进行无损检测以及评估。他们采用涡流检测法对独立钟的电鍍材料（铜）电导率进行测量，以实现独立钟完整性的评估。




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**问题2**

涡流检测方法，新进展？



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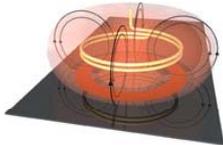
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**什么是涡流检测？**

利用电磁感应原理，通过测定被检工件内感生涡流的变化来无损地评定导电材料及其工件的某些性能，或发现缺陷的无损检测方法。



“Eddy current inspection is one of several methods that use the principal of ‘ELECTROMAGNETISM’ as the basis for conducting examinations. Several other methods such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise also use this principle.”

---NDT Wiki

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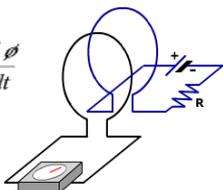
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**电磁感应原理 (Electromagnetism)**

法拉第电磁感应定律 (Faraday's law of electromagnetic induction)：穿过线圈的磁通量发生变化时，在线圈里产生感应电动势 ( $V_L$ )， $V_L$ 的大小与磁通量 ( $\phi$ ) 对时间 ( $t$ ) 的变化率的负值成正比。

$$V_L = -\frac{d\phi}{dt}$$



Michael Faraday (1791 - 1867)

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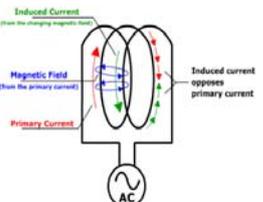
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**楞次定律**

楞次定律 (Lenz's law): 变化的磁场在闭合回路中产生的感应电流有确定的方向, 它总是企图使自己产生的通过回路面积的磁通量去抵偿 (反抗) 引起感应电流的磁通量的改变




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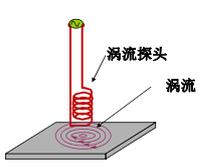
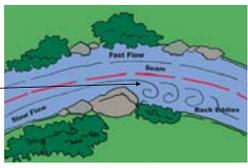
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**涡流检测原理**

涡流 (eddy currents): 将导体放置在变化着的磁场中, 导体将不断切割磁力线, 产生感应电动势, 形成一个自闭合回路的电流 (感生电流)。

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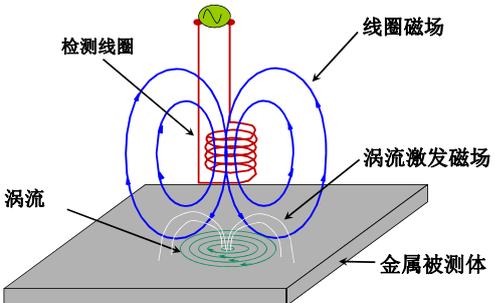
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**涡流检测原理**



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### 涡流检测原理

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### 趋肤效应 (Skin Effect)

> 趋肤效应: 感应出的涡流集中在靠近激励线圈的材料表面附近, 涡流密度随着距离表面的距离增加而减小, 从被检材料的表面到其内部按指数分布规律递减  
 > 趋肤深度 (skin depth, 渗透深度, standard depth of penetration): 涡流密度衰减为其表面密度的1/e时对应的深度

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

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### 不同材料的趋肤效应

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

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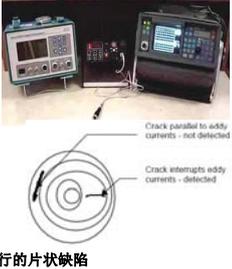
### 特点

**> 优点**

- 设备简单，使用方便
- 检测前对被检工件表面的清理工作简单
- 非接触式检测，易于自动化
- 通常为单面检测

**> 缺点**

- 探头须接近被检工件表面
- 检测信号不直观，检测人员需较多的培训
- 检测深度小
- 检测复杂形状工件的效率低
- 难以检测分层裂纹或其他与线圈缠绕方向平行的片状缺陷



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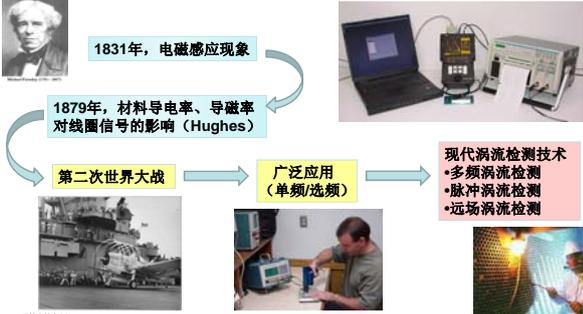
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### 发展



1831年，电磁感应现象

1879年，材料导电率、导磁率对线圈信号的影响 (Hughes)

第二次世界大战

广泛应用 (单频/选频)

现代涡流检测技术

- 多频涡流检测
- 脉冲涡流检测
- 远场涡流检测

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### 涡流检测系统

涡流检测系统具有多样性。对于某个特定的应用领域，检测系统的合理设计和搭建决定了系统检测性能的好坏。

总的来说，涡流检测系统包括：

- > 测试仪表 (Instrumentation)
- > 线圈 (coils)
- > 线圈骨架 (fixtures)
- > 试件 (testing specimens)
- > 数据记录仪 (recorders)
- > 标准试件 (reference standards)

信号发生器  
功率放大器  
信号检出电路  
相敏检波器  
滤波器  
幅度鉴别器

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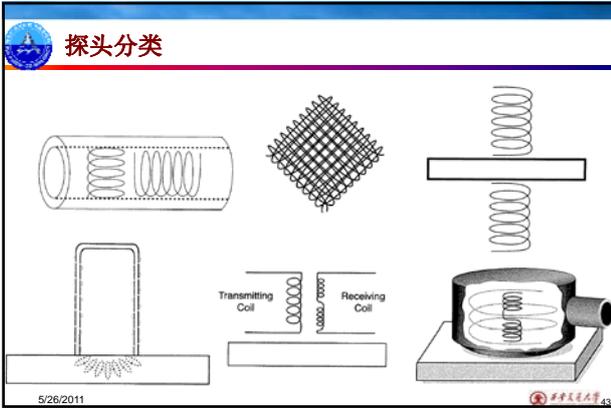
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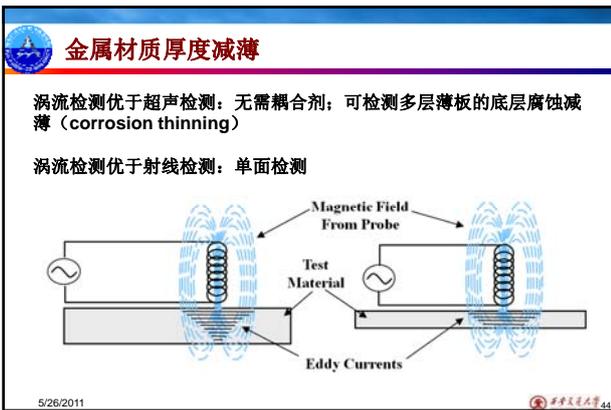
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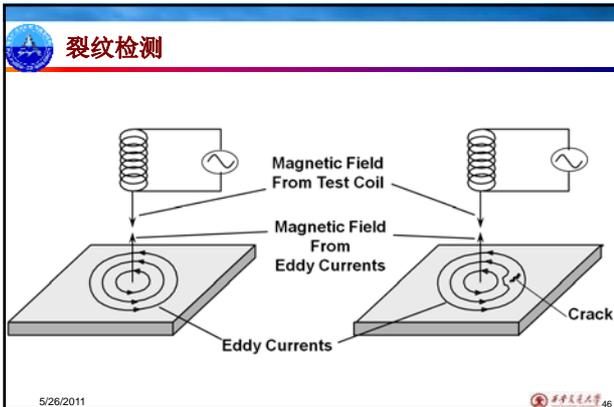
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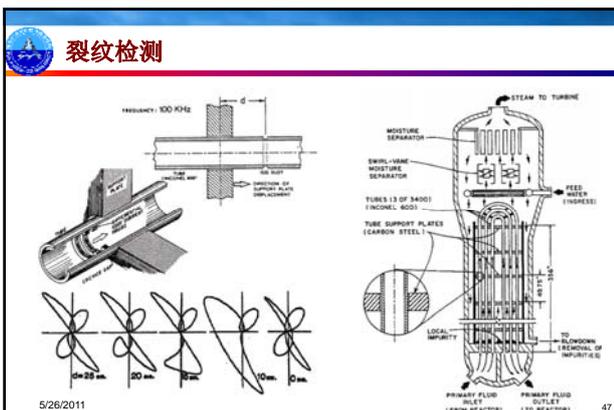
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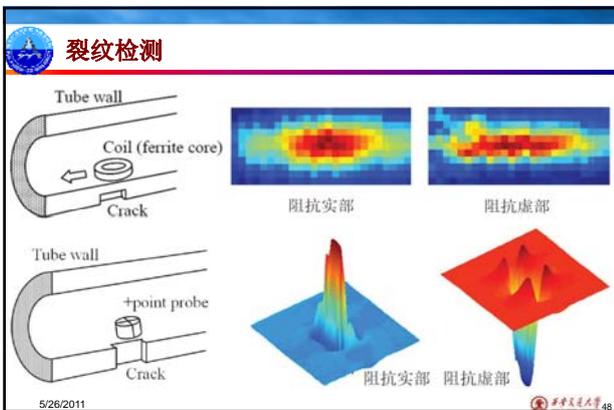
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### 裂纹检测

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### 材料电导率测定

—金属的电导率取决于其化学成分和应力状态，因此电导率测量结果可用于材料的分检和技术状态的判断  
—通常要求工件的厚度大于趋肤深度的三倍，使工件底部的涡流足够小  
—通常用于非铁磁金属材料

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### 材料电导率测定

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### 导电材料绝缘涂层厚度测量

绝缘涂层的存在事实上增大了线圈的提离

Nonconductive Coating  
Conductive Base Metal  
Eddy Currents

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### 导电材料绝缘涂层厚度测量

Increasing point thickness  
INCREASE

SWEEP OFF  
H-POS  
H-POS  
NO. BX  
SCREEN...  
BATTERY LOW  
DISPLAY

SWEEP H-POS H-POS | SCR... |

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### 多种材料参数测定 (汽轮机叶片涂层系统)

280-320 $\mu\text{m}$	陶瓷涂层(TBC)
80-120 $\mu\text{m}$	粘附层
0.565-1.265 S	
1.066 S	合金基体
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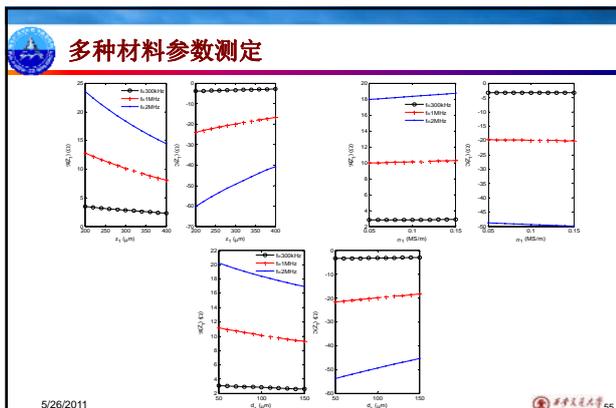
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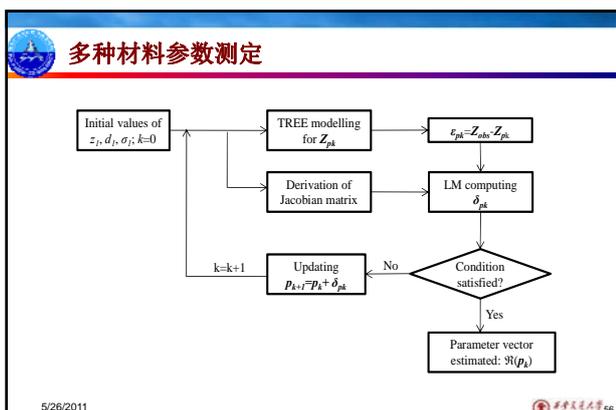
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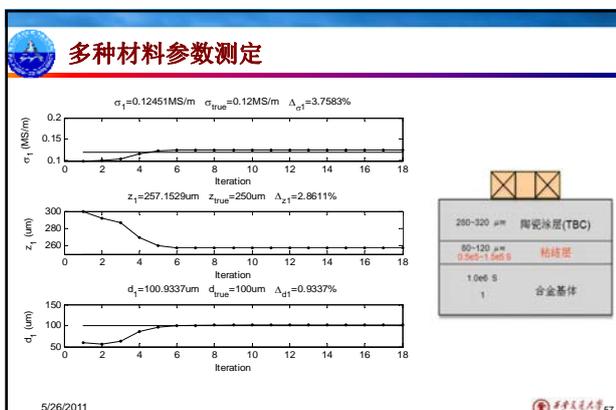
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**最近进展**

新式线圈

- 单向电流板
  - 可以在一定区域内产生均匀磁场
  - 被检金属板中的缺陷反映为垂直方向的磁场

The diagram shows a meander coil (a series of parallel lines connected at the ends) and a corresponding magnetic field distribution. The field is uniform in the center and shows a vertical component near the coil. A grid plot below shows the field intensity distribution.

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**最近进展**

- 回折线圈 (meander coil)
  - 被检金属板中的缺陷反映为平行于源电流方向的切向磁场

The diagram shows a meander coil and a grid plot of its magnetic field. The field is primarily tangential to the coil's current direction. Labels include 'Sensors', 'Meander Coil', and 'Component Detected by Sensors'.

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**最近进展**

- 巨磁阻传感器
  - 巨磁阻 (giant magneto-resistance, GMR) 效应: 非常弱小的磁场变化就能导致磁性材料发生非常显著的电阻变化
  - GMR传感器的基本结构: 两薄层的铁磁材料夹一薄层的非磁性导电材料
    - 当两层铁磁材料的磁矩方向相反时, 电阻最大
    - 当两层铁磁材料的磁矩方向相同时, 电阻最小
  - 费尔 (法国) 和格林贝格尔 (德国) 于1988年独立发现巨磁阻效应, 于2007年同获诺贝尔物理学奖
  - 根据巨磁阻效应开发的小型大容量硬盘已得到了广泛的应用

The diagram shows the GMR sensor structure: a magnetic layer, a non-magnetic conductor, and another magnetic layer. It illustrates the '电阻大' (high resistance) state when magnetic moments are antiparallel and the '电阻小' (low resistance) state when they are parallel. A small image of a hard disk is labeled '图2.5.57 硬盘'.

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### 最近进展

GMR sensor (biased) Eddy current coil  
Scanning direction & sensing axis  
Test Conductive Sample

GMR sensor (biased) Sensing axis Split-D coil  
Scanning direction  
Test Conductive Sample

5/26/2011

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### 最近进展

- 涡流阵列检测
  - 基本原理：探头由多个独立工作的线圈构成，这些线圈按照特殊的方式排列，且激励与检测线圈之间形成两种方向相互垂直的电磁场传递方式，以利于发现走向不同的线性缺陷

检测线圈 扫描方向 缺陷 激励线圈

图2.5.61 涡流阵列检测探头

5/26/2011

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### 最近进展

Array of Hall elements  
Excitation Coil  
Magnetic Camera

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