EHL Analyses of Cam-Roller Pairs of Internal Combustion Engines

内燃机凸轮–滚子接触的润滑分析

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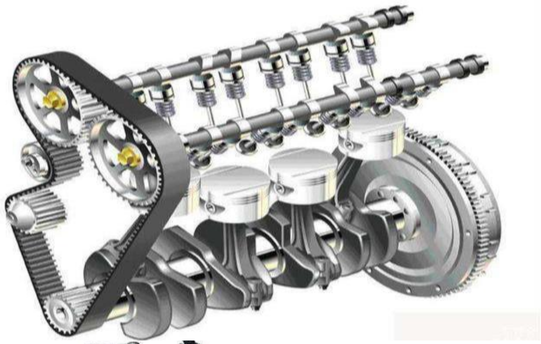

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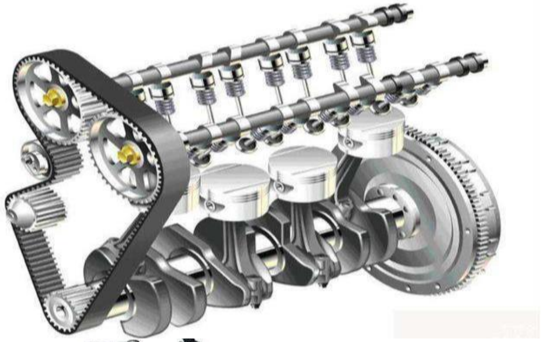

1. 研究背景 (Background)

➢ 机械装备的心脏-内燃机

Heart of equipment -- ICE

➢ 内燃机核心部件凸轮副磨损问题

Wear of the cams of ICE

✓ 载荷、速度、曲率等剧烈变化；

Changes of loads, speeds and radii

✓ 供油不稳定；

Unstable oil supply

✓ 内燃机向大功率、高速方向的发展。

Tendency of heavy loads and high speeds

➢ 凸轮-从动件接触副润滑分析 (Numerical lubricaiton analyses of cam-follower)

- 1978年，Holland首次分析了凸轮-从动件润滑问题；

  The first lubrication analyses of cam-followers by Holland in 1978;

- 之后，对凸轮-从动件润滑展开不同角度分析，如热效应(Wang et al. 2003)、时变效应(Jang 2008)、卷吸振动(Zhang et al. 2015)等；

  Work on lubrication of cam-followers: thermal effect (Wang et al. 2003)、transient effect (Jang 2008)、entrainment vibration (Zhang et al. 2015);

- 近期，研究了凸轮-从动件接触副的苛刻工况润滑 (Raisin et al. 2016)或弹塑性磨损问题(Torabi 2018);

  Recent Numerical analyses under sever conditions (Raisin et al. 2016, race car) , elasto-plastic wear (Torabi 2018)

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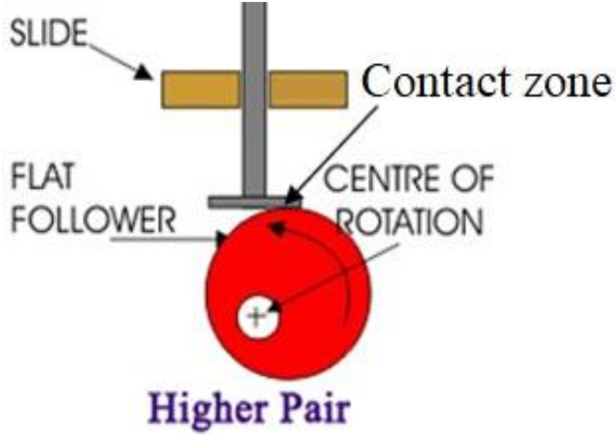
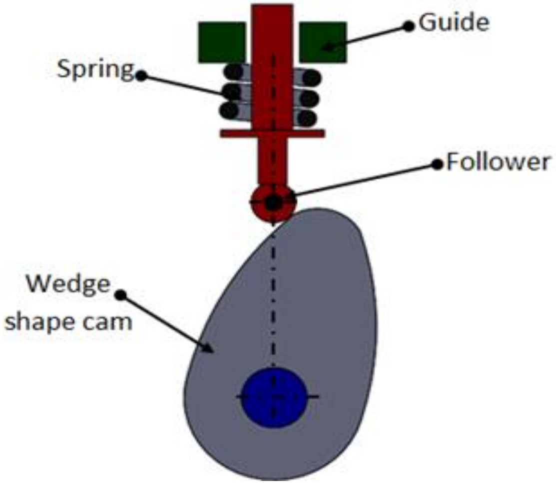
➢ 凸轮-从动件接触副润滑分析 (Numerical lubricaiton analyses of cam-follower)

凸轮-从动件接触 Cam-follower
- 凸轮-挺柱副(cam-tappet/Flat)
- 凸轮-滚轮副(cam-roller)

凸轮-滚轮副特点：





➢ 理论上处于纯滚状态，摩擦力小(low friction);

➢ 传递作用力大(large force)。

➢ 优化的凸轮外形设计(more flexible profile)。

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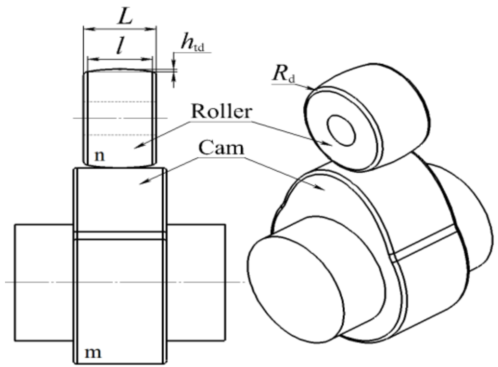
➢ 凸轮-滚轮副润滑分析 (Lubrication of cam-roller contact)

- ☐ 修形/偏斜问题(roller convexity modification/tilting)：多出现于在重载、接触区狭长工况
- ✓ 多见于滚子轴承相关研究，Wang et al. 2010, Liu et al. 2013、Zhang et al. 2016；
- ✓ 针对凸轮-滚轮副也有少量分析，Korte 2000, Koo 2002, Shirzadegan 2016;
- ● 但均在等温、无滑动条件下完成。



- ☐ 打滑问题(roller sliding)：理论上属于纯滚，但实际却存在滑动
- ✓ 实验测量，证实凸轮于滚轮间滑动的存在，Duffy 1993、Khurram et al. 2015；
- ✓ 理论分析，预测接触区滑动发生可能性并分析其影响，Chiu 1992、Ji et al. 1998、Alakhramsing et al. 2018;
- ● 但理论分析中缺少热效应、时变效应，或在无限长接触中进行，与实际工况差距大。

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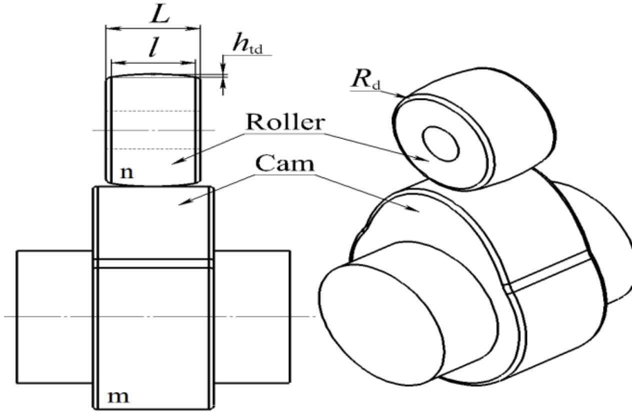
➢ 凸轮-滚轮副润滑分析

综上所述，虽然针对凸轮-滚轮副润滑已有一些相关研究，但仍有些问题需要进一步探讨，尤其企业关注的实际工况条件下最佳润滑设计问题。因此，有必要建立一个耦合时变效应、热效应的凸轮-滚轮副弹流润滑模型，从理论上分析实际工况中凸轮-滚轮副的润滑状态，从而为机构润滑设计提供基础的数据支持。



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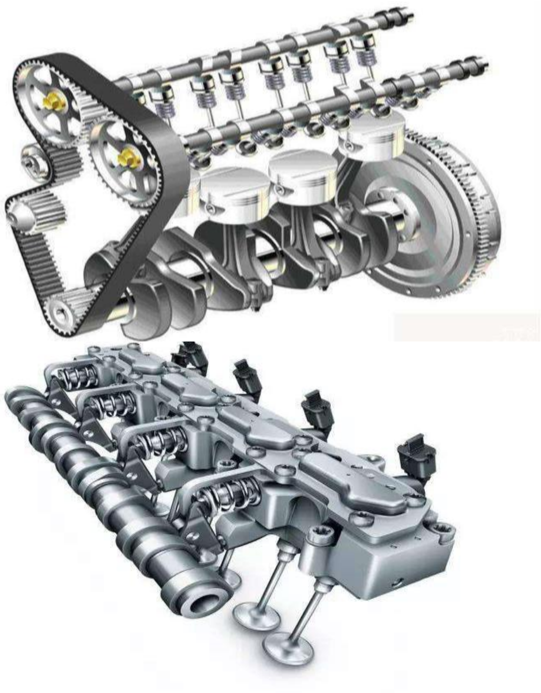

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Reynolds方程：

$$\frac{\partial}{\partial x}\left[\left[\left(\frac{\rho}{\eta}\right)_{e} h^{3}\frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\frac{\rho}{\eta}\right)_{e} h^{3}\frac{\partial p}{\partial y}\right]=6u_{m}\frac{\partial\left(\rho_{m}^{*}h\right)}{\partial x}+6u_{n}\frac{\partial\left(\rho_{n}^{*}h\right)}{\partial x}+12\frac{\partial\left(\rho_{e}h\right)}{\partial t}$$

膜厚方程：

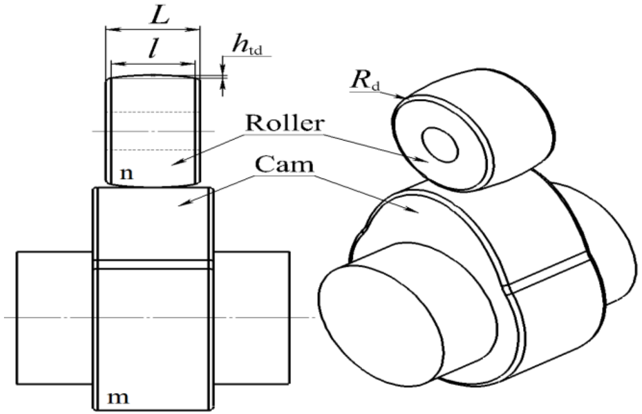
$$h(x,y,t)=h_{0}(t)+\frac{x^{2}}{2R}+\frac{(y\pm l/2)^{2}}{2R_{d}}f_{\Delta}+h_{td}\left[1-\left(\frac{y}{l/2}\right)^{2}\right](1-f_{\Delta})$$
$$+\frac{2}{\pi E'}\iint_{\Omega}\frac{p(x',y',t)}{\sqrt{(x-x')^{2}+(y-y')^{2}}}\mathrm{d}x'\mathrm{d}y'+y\tan\varphi$$

(若$y\le 0$，则为“+”；若$y>0$，则为“-”)

粘压方程： $\eta=\eta_{0}\exp\left\{(A_{1})\times\left[-1+(1+A_{2}p)^{z_{0}}(A_{3}/A_{4})^{-S_{0}}\right]\right\}$

密压方程： $\rho=\rho_{0}[1+C_{1}p/(1+C_{2}p)-C_{3}(T-T_{0})]$

载荷方程： $\iint p\mathrm{d}x\mathrm{d}y=w$



凸轮-滚轮接触模型

2. 数值计算模型 (Model)

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能量方程：

$$c\left(\rho u\frac{\partial T}{\partial x}+\rho v\frac{\partial T}{\partial y}-q\frac{\partial T}{\partial z}\right)=k\frac{\partial^2 T}{\partial z^2}-\frac{T}{\rho}\frac{\partial p}{\partial T}\left(u\frac{\partial p}{\partial x}+v\frac{\partial p}{\partial y}\right)+\eta\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]$$

入口处非逆流区边界条件： $T(x_{in},y,z)=T_0$

固体m、n热传导方程：

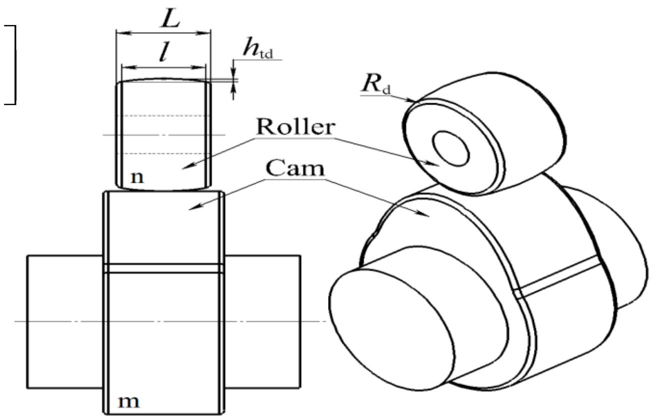
$$\begin{cases} c_m\rho_m u_m\dfrac{\partial T}{\partial x}=k_m\dfrac{\partial^2 T}{\partial z_m^2} \\ c_n\rho_n u_n\dfrac{\partial T}{\partial x}=k_n\dfrac{\partial^2 T}{\partial z_n^2} \end{cases}$$

固体m、n热传导方程边界条件：

$$\begin{cases} T(x_{in},y,z_m)=T_0,\ T(x,y,-d)=T_0 \\ T(x_{in},y,z_n)=T_0,\ T(x,y,d)=T_0 \end{cases}$$

油膜与固体界面连续条件：

$$\begin{cases} k_m(\partial T/\partial z_m)|_{z_m=0}=k(\partial T/\partial z)|_{z=0} \\ k_n(\partial T/\partial z_n)|_{z_n=0}=k(\partial T/\partial z)|_{z=h} \end{cases}$$



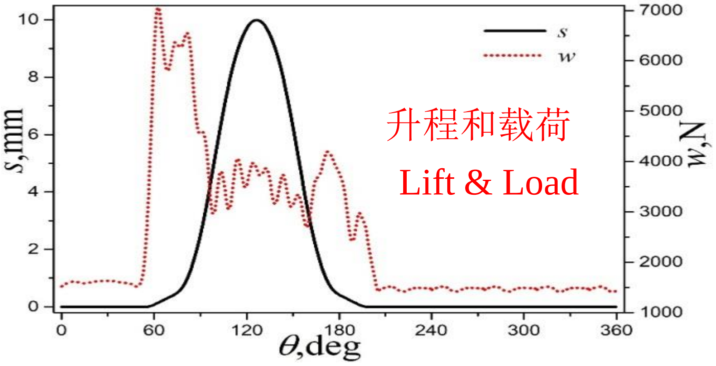
凸轮-滚轮接触模型

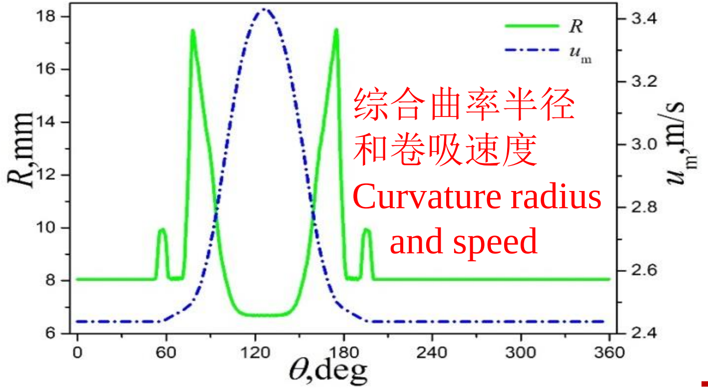
摩擦系数计算： $\mu=-\dfrac{1}{w}\iint\eta\dfrac{\partial u}{\partial z}\mathrm{d}x\mathrm{d}y$

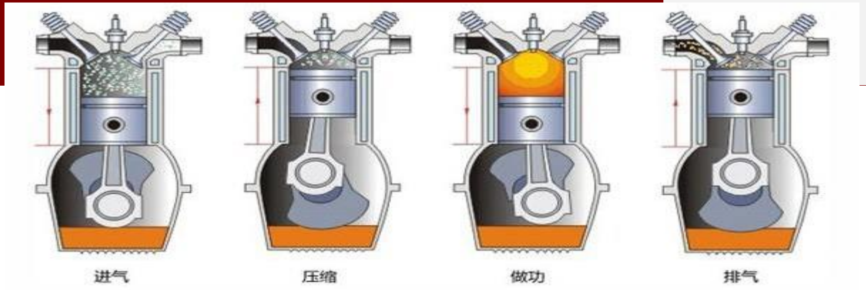
2. 数值计算模型 (Model)

输入参数（排气凸轮-滚轮副）

Input parameter (exhaust cam-roller)







相关工况参数

参 数	数 值
接触固体的综合弹性模量 E' / Pa	2.1×10^{11}
润滑油的环境密度 ρ_0 / (kg/m^3)	870
固体a、b的密度 $\rho_{a,b}$ / (kg/m^3)	7850
润滑油的比热 c_f / (J/kg·K)	1700
固体a、b的比热 $c_{a,b}$ / (J/kg·K)	470
润滑油的热传导系数 k_f / (W/m·K)	0.14
固体a、b的热传导系数 $k_{a,b}$ / (W/m·K)	46
粘压系数 α / Pa^{-1}	2.2×10^{-8}
粘温系数 β_0 / K^{-1}	0.042
环境温度 t_0 / K	313
旋转速度ω / rpm	950
滚轮总长 L / mm	18.7
滚轮中部长度 l / mm	16.7
滚轮端部修形圆弧半径 R_d / mm	12.5

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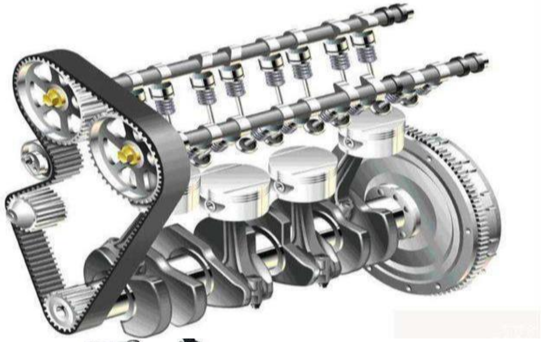


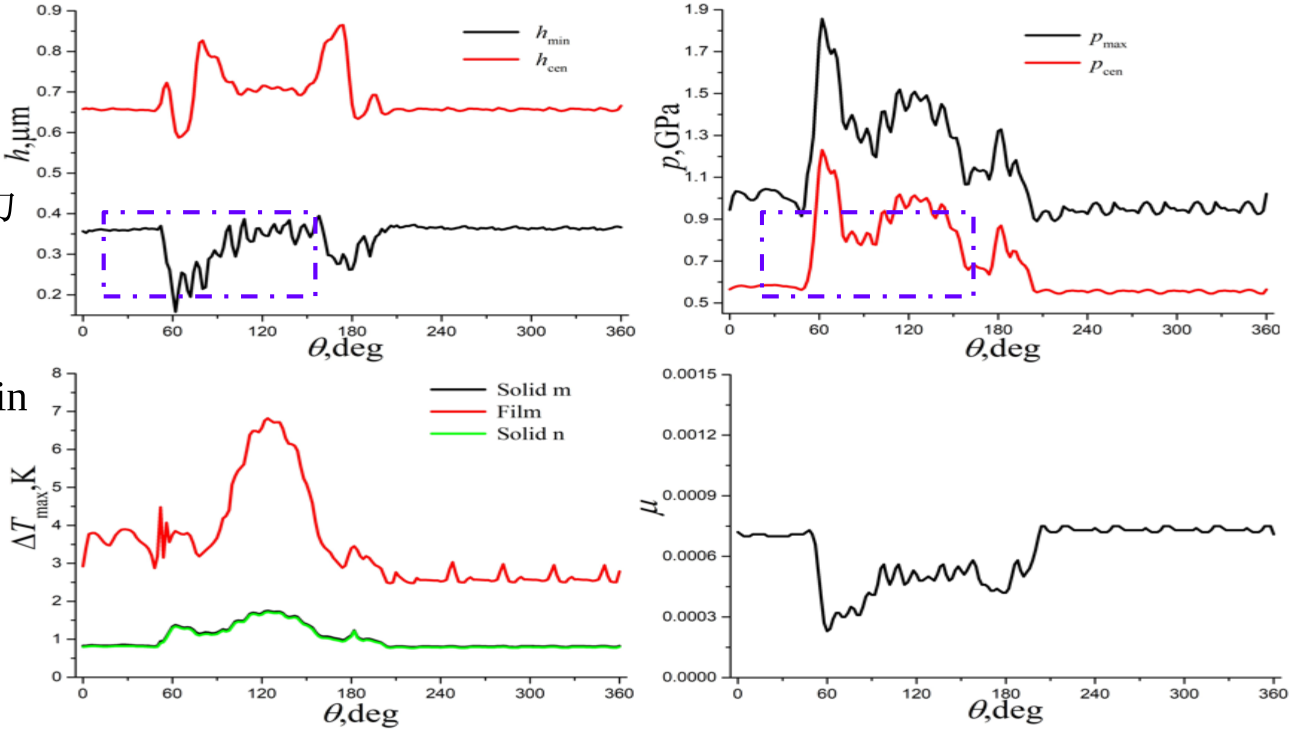
◻ 排气凸轮-滚轮副

Exhaust cam-roller

一个凸轮旋转周期内膜厚、压力、温度和摩擦系数的变化规律.

Film thickness, pressure, temperature rise and friction within a cam rotation cycle.

(h_{td} = 4 μm, φ = 0 deg, k_{SRR} = 0)



①54~200 deg，膜厚和压力变化剧烈，最大变化幅度：0.277 μm和0.892 GPa；温升和摩擦系数变化微弱。

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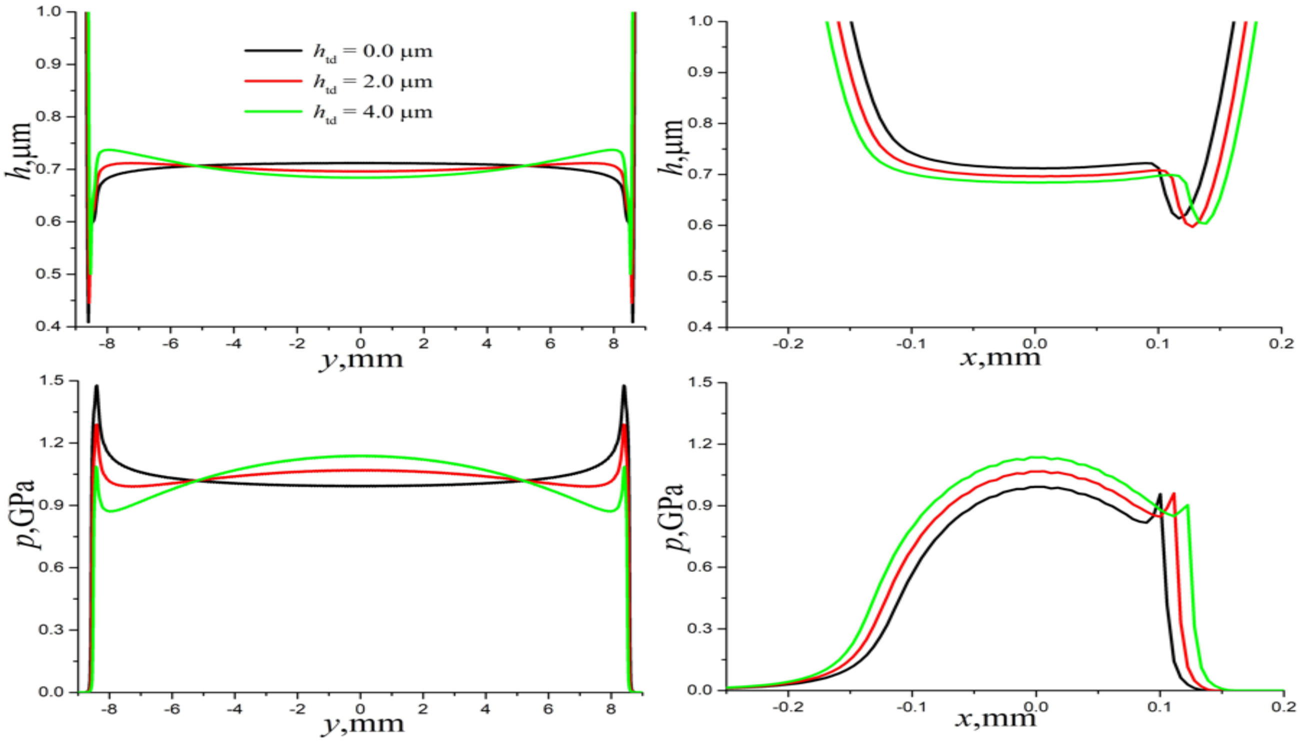
□ 滚轮凸度影响

influence of convexity

不同滚轮凸度下在x = 0和 y = 0截面上膜厚和压力分布.

Film profiles and pressure distributions at x = 0 and y = 0 for different roller convexity.

(θ = 127 deg, φ = 0 deg, k_{SRR} = 0)



x = 0 截面

y = 0 截面

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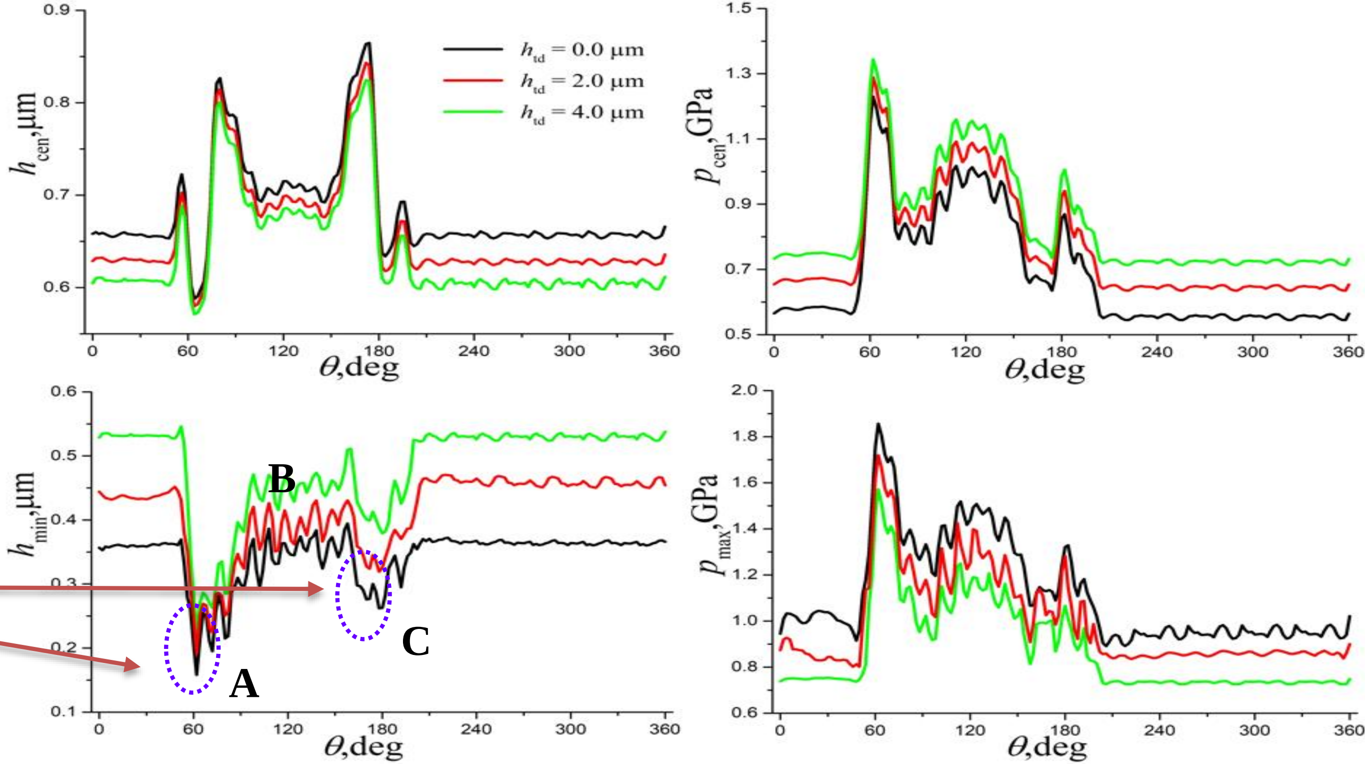
□ 滚轮凸度影响

Influence of convexity

一个周期内不同滚轮凸度对膜厚和压力的影响

Film thickness and pressure for different convexity.

(φ = 0 deg, k_{SRR} = 0)



磨损最易发生部位：润滑油膜易破裂区域

☐ 滚轮凸度影响

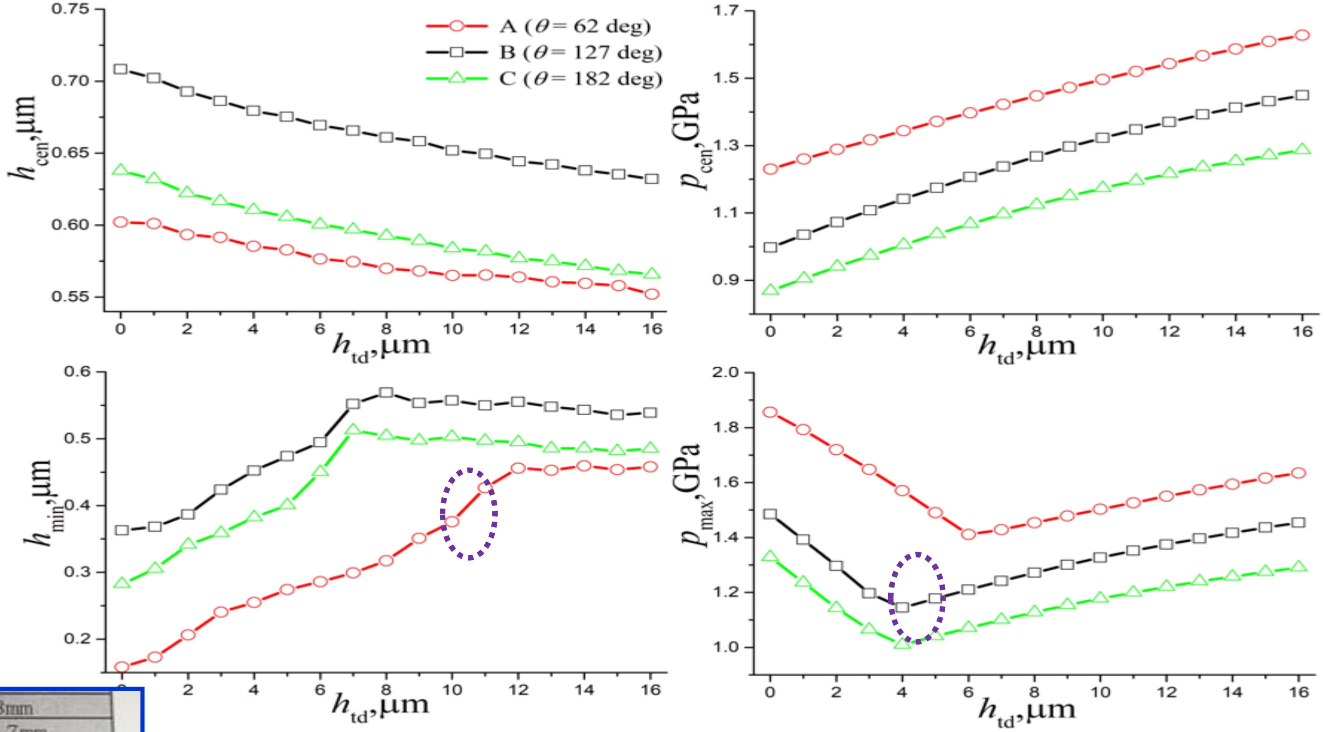
influence of convexity

滚轮凸度对接触区中心膜厚、最小膜厚、中心压力和最大压力的变化.

The central film thickness, the minimum film thickness, the central pressure and maximum pressure for different convexity values

(φ = 0 deg, k_{SRR} = 0)

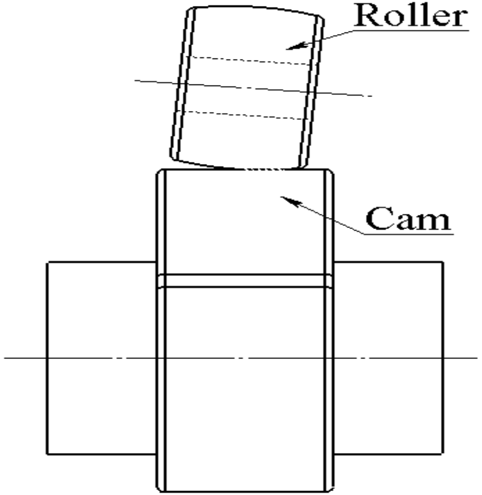
$h_{td} \approx 12\ \mu m$

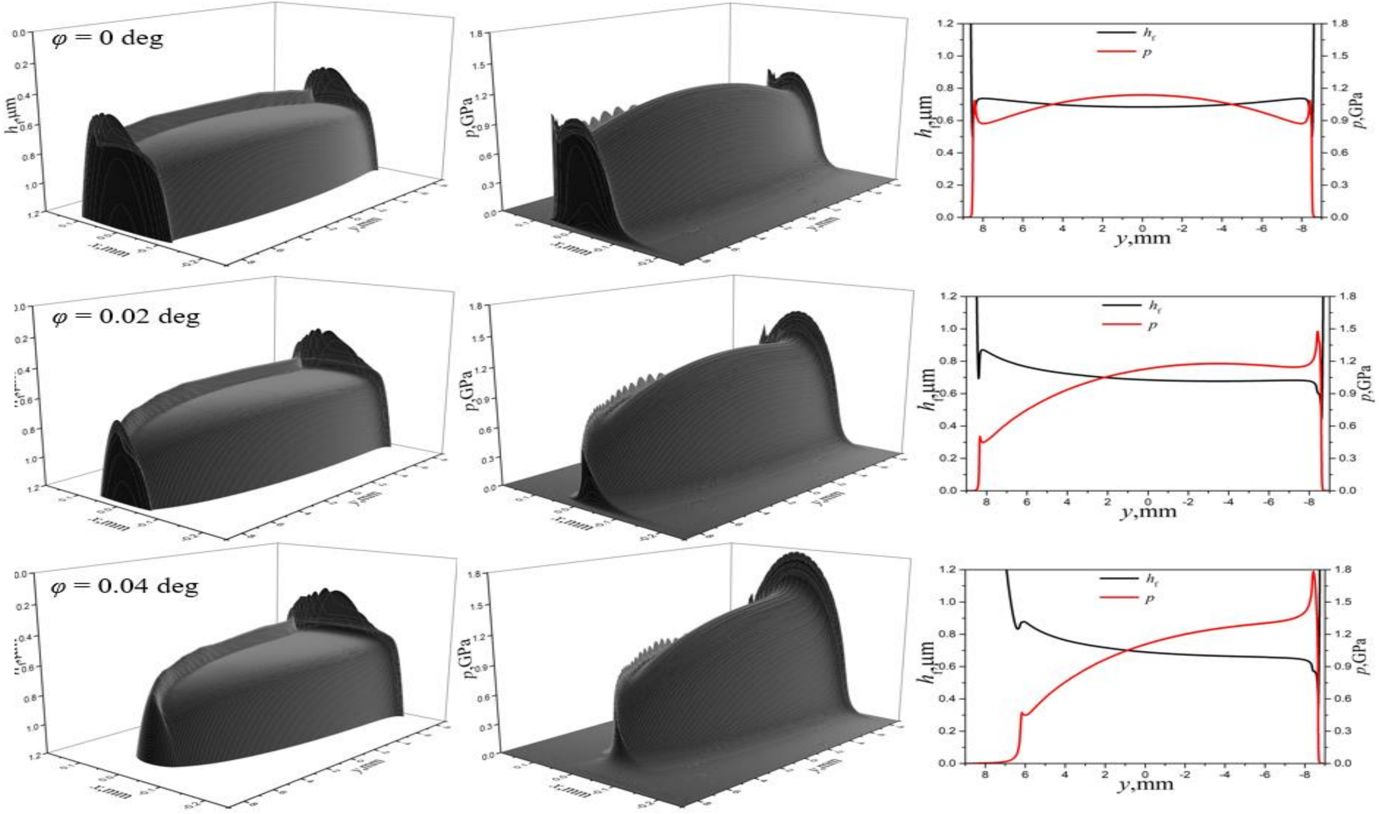


排气滚轮	直径	28mm
	宽度	18.7mm
	凸度	0.011~0.016mm

偏斜问题

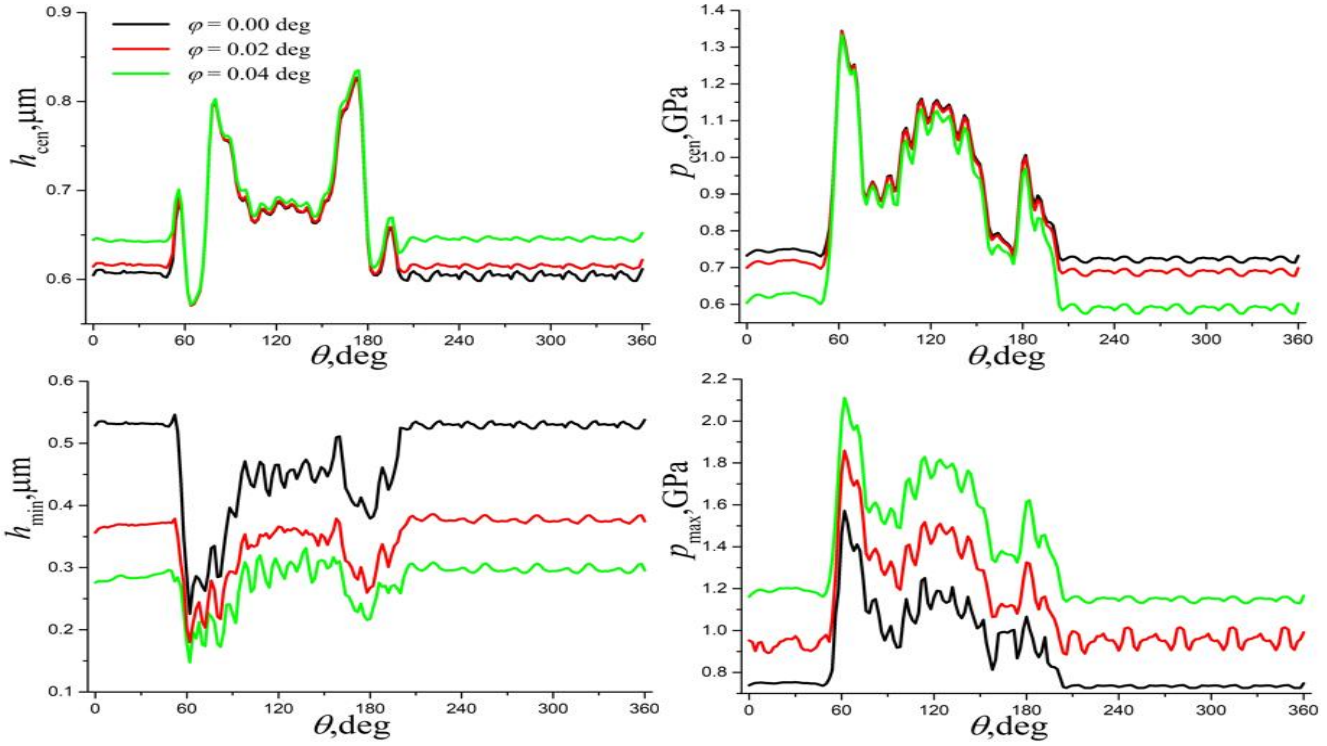
Tilting





不同偏斜角度下凸轮顶尖位置膜厚、压力三维图及截面曲线(θ = 127 deg, h_{td} = 4 μm, k_{SRR} = 0)

□ 偏斜问题
Tilting



一个周期内不同偏斜角对膜厚和压力的影响 (h_{td} = 4 μm, k_{SRR} = 0)

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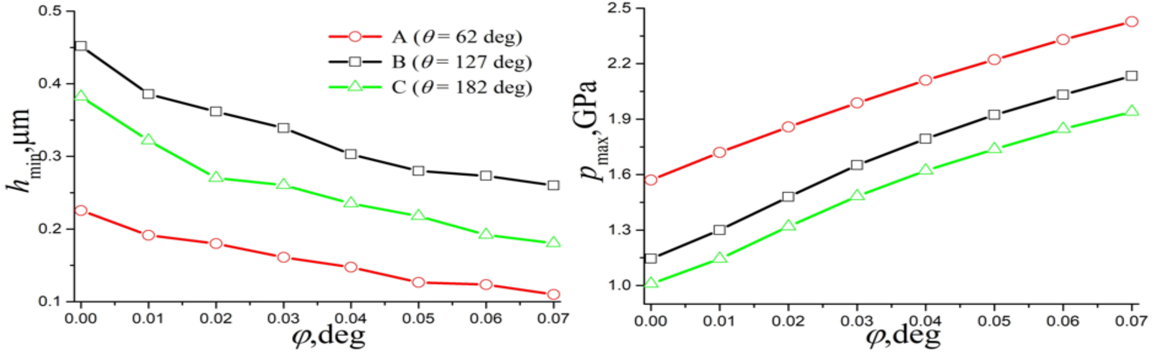
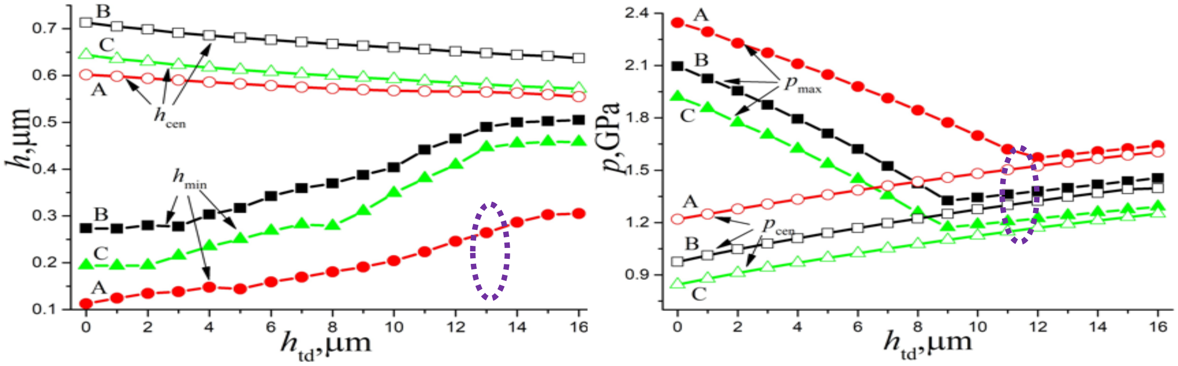
◻ 偏斜问题

Tilting



最小膜厚和最大压力随偏斜角度的变化曲线 (h_{td} = 4 μm, k_{SRR} = 0)

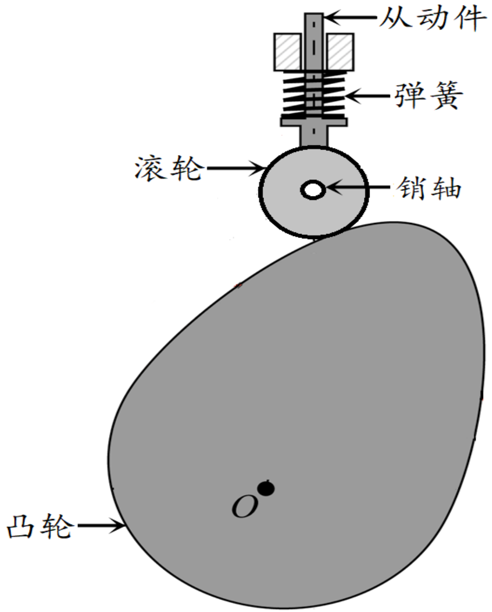
$h_{td} \approx 15$ μm

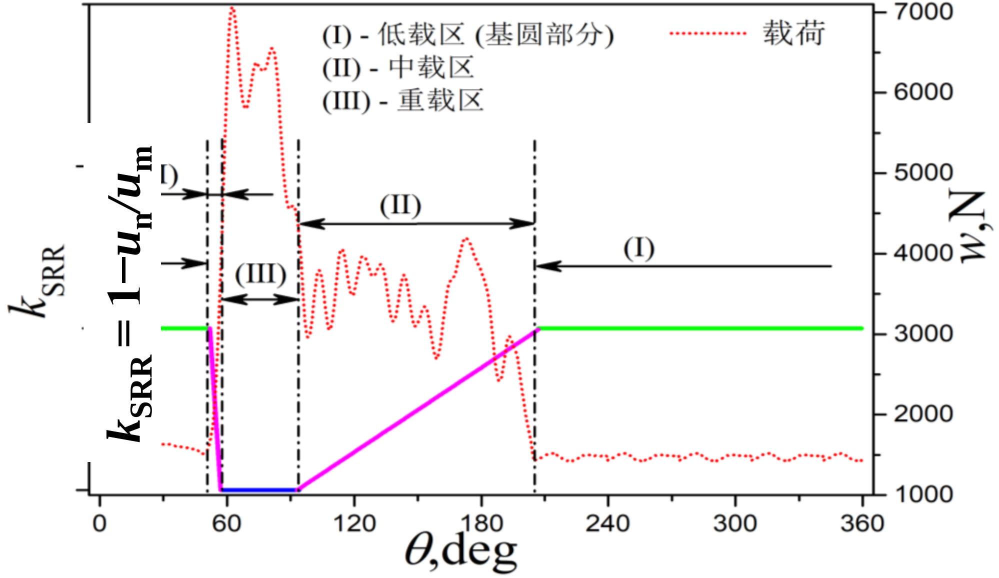


偏斜条件下滚轮凸度对膜厚和压力的影响 (φ = 0.04 deg, k_{SRR} = 0)

■ 打滑问题

Sliding





凸轮与滚轮间打滑定义模型

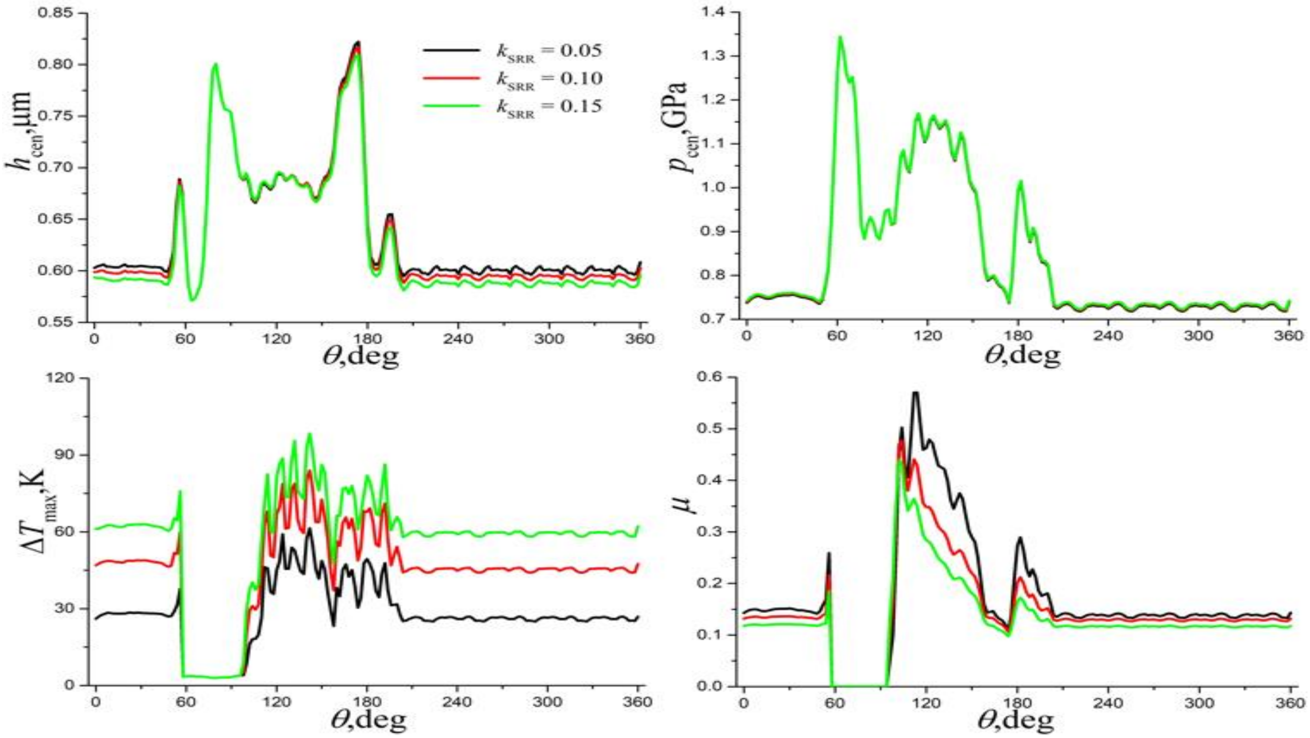
Sliding model of cam-roller

□ 打滑问题
Sliding

一个周期内不同打滑系数对中心膜厚、中心压力、最大温升和摩擦系数的影响.

Calculated central film thickness, central pressure, maximum temperature rise and friction in a cam cycle.

(h_{td} = 4 μm, φ = 0 deg)



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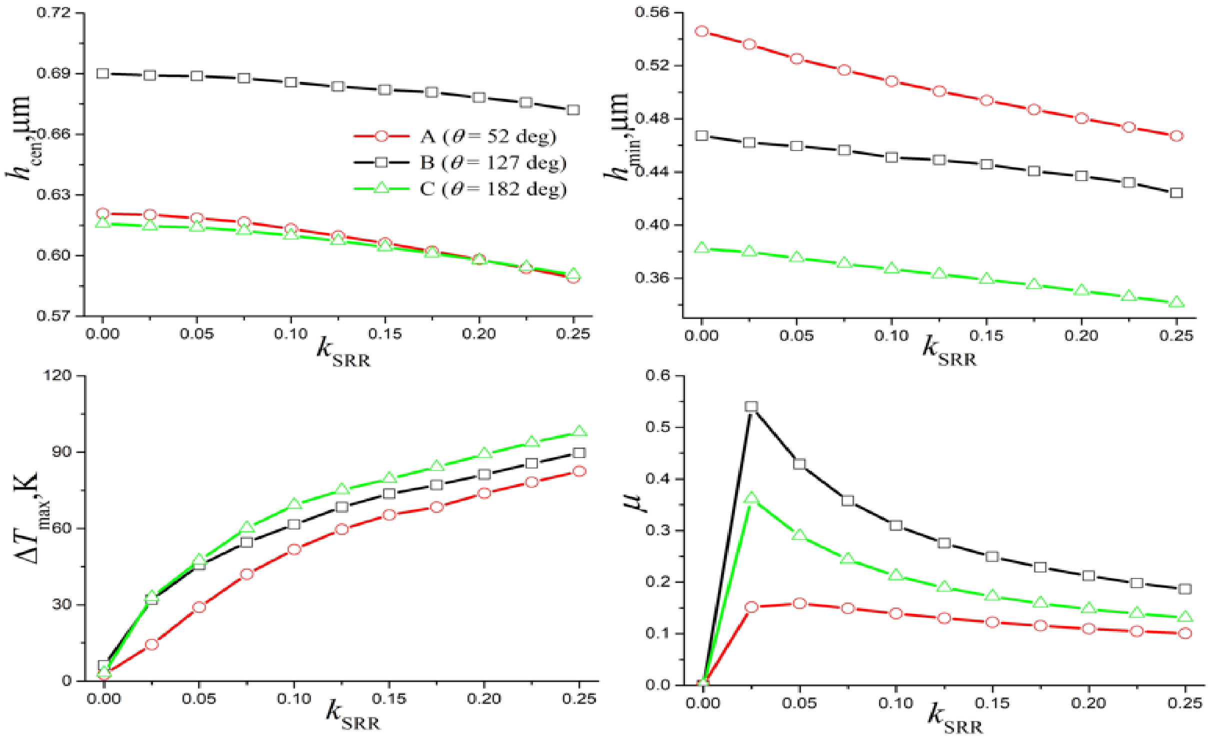
◻ 打滑问题

Sliding

三个凸轮角度下中心膜厚、最小膜厚、最大温升和摩擦系数随打滑系数的变化.

Calculated central film thickness, central pressure, maximum temperature rise and friction under different sliding coefficient for different cam angles.

(h_{td} = 4 μm, φ = 0 deg)



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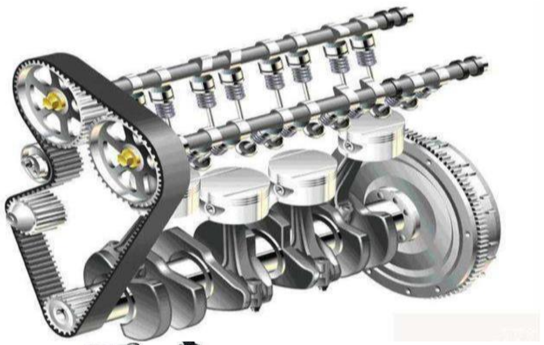

4. 结论(concluions)

通过数值计算模拟了实际载荷下排气凸轮-滚轮副完整周期内润滑状态，分析了滚轮凸度、偏斜及打滑问题，得到如下结论：

(1) 整个凸轮旋转周期内润滑状态可分为平稳期和波动期，与排气工况参数变化相对应；

(2) 滚轮凸度在一定范围内可以改善润滑状态，合适的滚轮凸度可以有效降低油膜破裂的可能性，并提高压力分布的均匀性；

(3) 凸轮与滚轮间的偏斜现象会使接触区润滑恶化，增加润滑失效的可能，而滚轮凸度设计可以在一定程度上有效缓解其不利影响；

(4) 凸轮与滚轮间打滑现象最显著的影响是接触区温升和摩擦系数。

4. 结论(conclluions)

The lubrication of a cam-roller pair under realistic exhaust load spectrum is simulated by numerical calculation. The influence of the roller convexity, the roller tilting and sliding on the lubrication performance is studied.

(1) The lubrication of a cam-roller pair in a complete cam cycle can be divided into pseudo-steady period and non-steady period, corresponding to the change of exhaust working conditions.

(2) The lubrication of the cam-roller contact can be improved by the roller convexity. The proper choice of roller convexity can effectively reduce the oil film rupture, and also improve the uniformity of pressure distribution in the contact zone.

(3) The roller tilting can deteriorate the lubrication of the cam-roller contact. And the roller convexity can effectively help to alleviate its adverse effects to a certain extent.

(4) The sliding between cam and roller can induce marked temperature rise and friction, and its effect will be further enhanced by the increased load.

致谢

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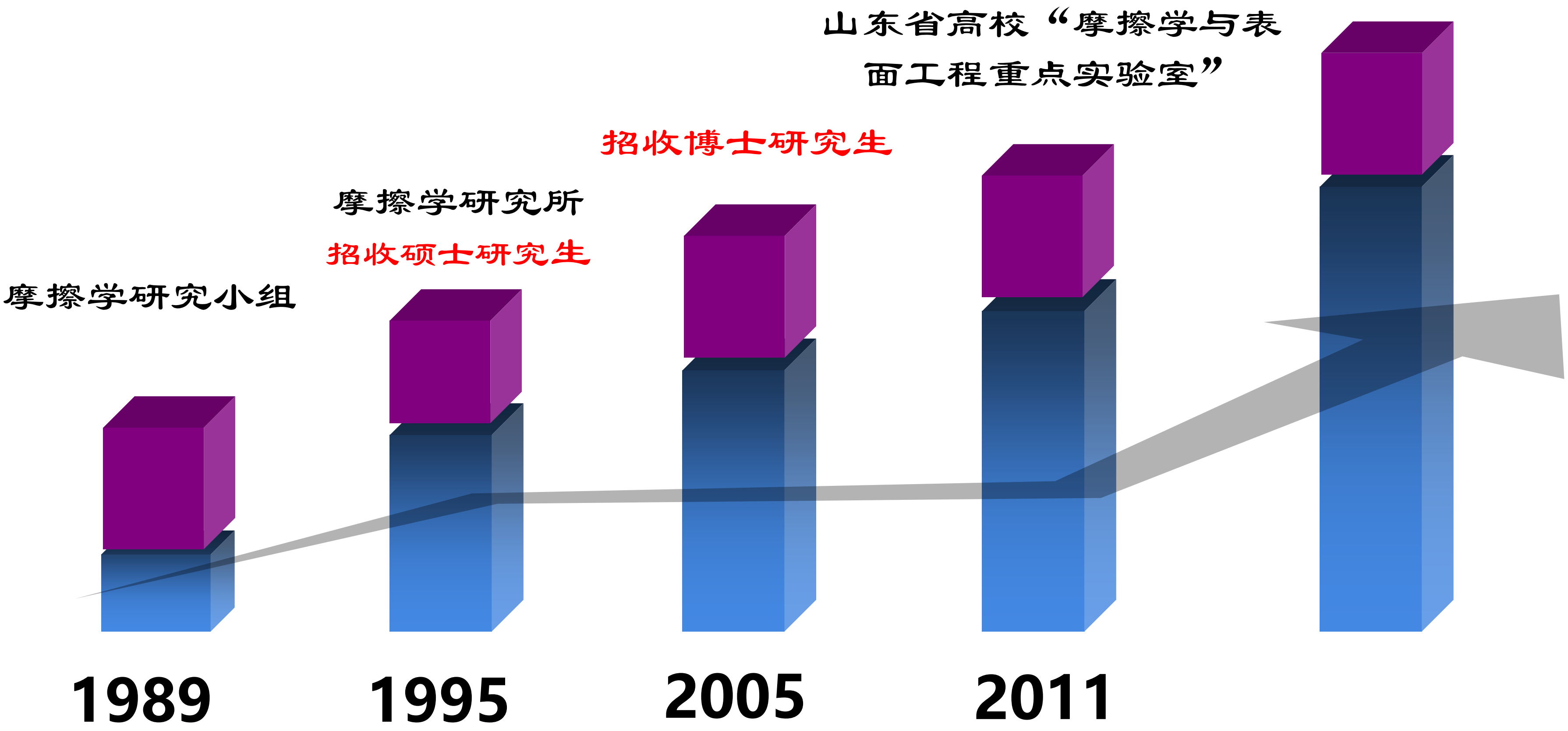
Thanks for your attention!

青岛理工大学

摩擦学与表面工程实验室

发展历程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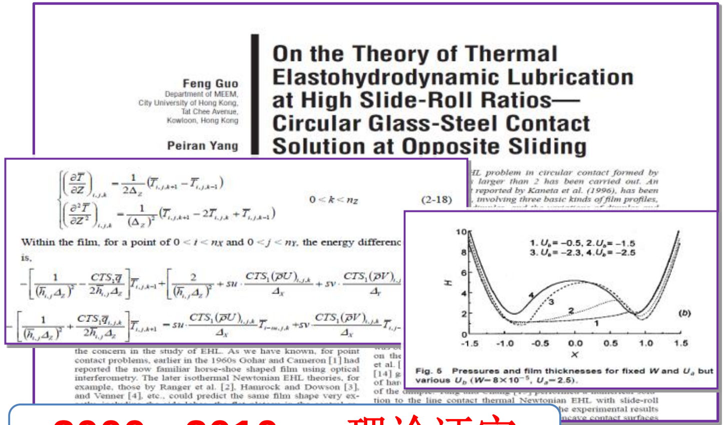
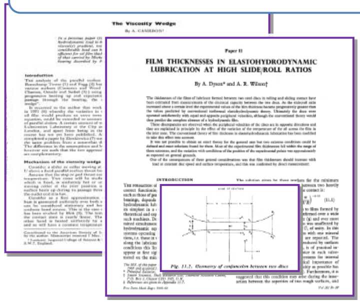
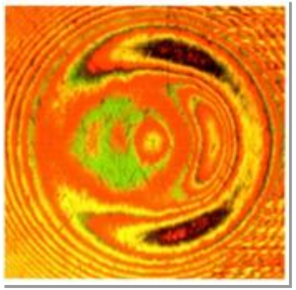


2000s-2010s：理论证实



1950s-1960s: 理论猜想

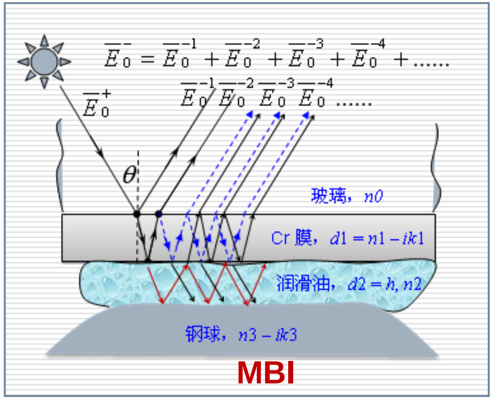


试验结果 **理论结果**

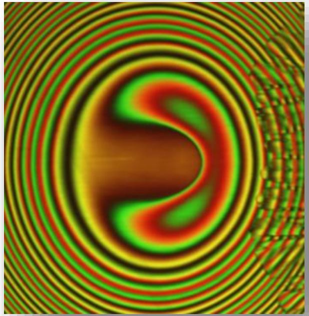
Kaneta弹流凹陷

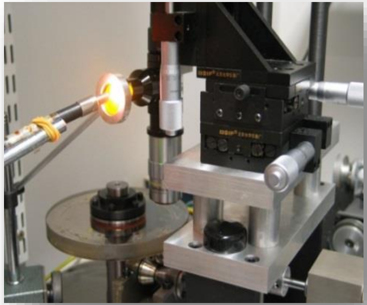
- 突破了超大滑滚比热弹流数值计算关键技术。
- 定量证明了油膜建立的猜想–热粘度楔理论。
- 确定了粘度楔机制是Kaneta弹流凹陷的唯一正确解释。

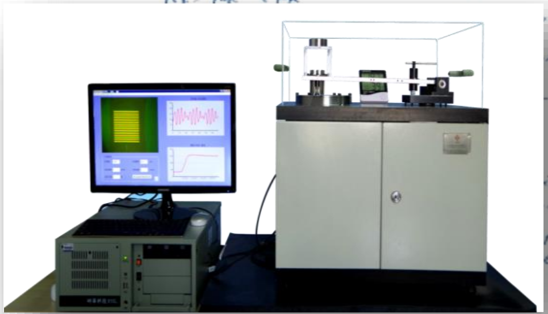
Kaneta教授，2004

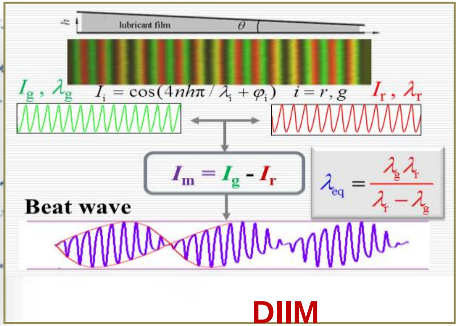


- 建立了完整的多光束干涉润滑油膜测量理论，解决了纳米油膜传统测量方法的误差问题。
- 提出了微纳米油膜的MBI和DIIM测量技术。
- 研发了国际首台面接触润滑油膜测量仪。



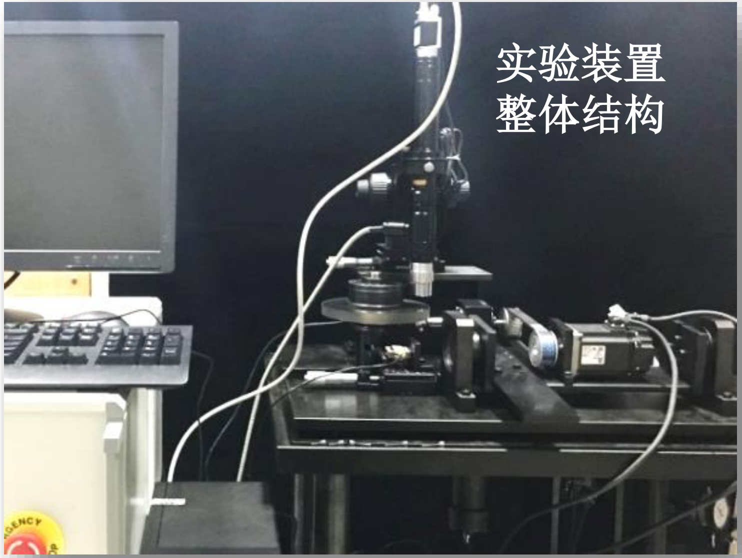


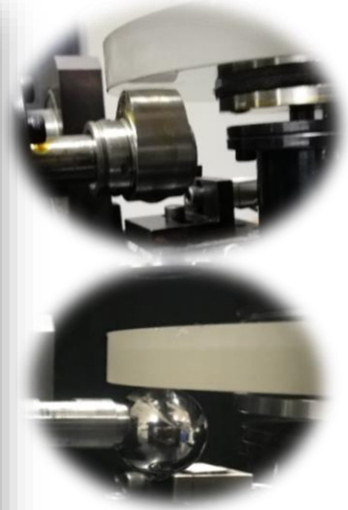




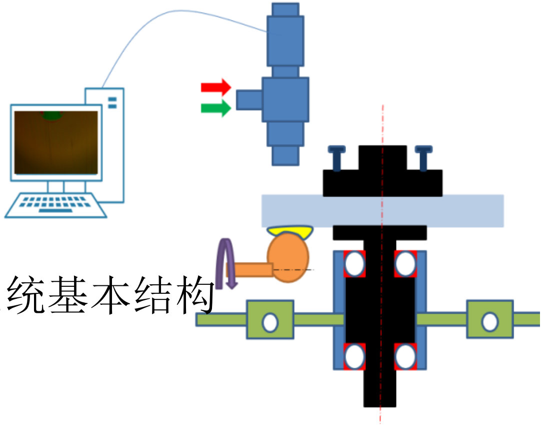
凸轮-挺柱副润滑测量装置

- 该系统同时测量油膜厚度和摩擦力。
- 试样采用两种方案：偏心轮（球）接触与凸轮接触。





两种试样接触



实验系统基本结构