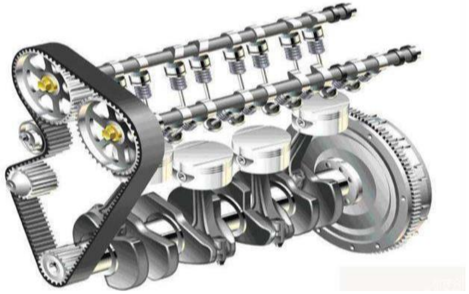
内燃机凸轮-滚轮-销轴接触的润滑分析

Lubrication analysis of cam-roller-pin in an internal combustion engine



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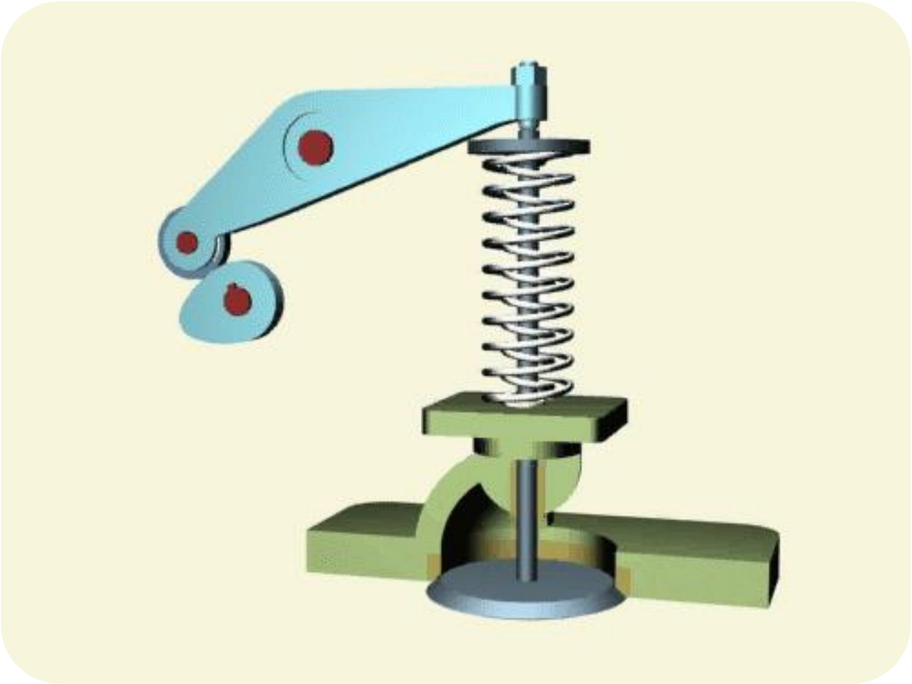
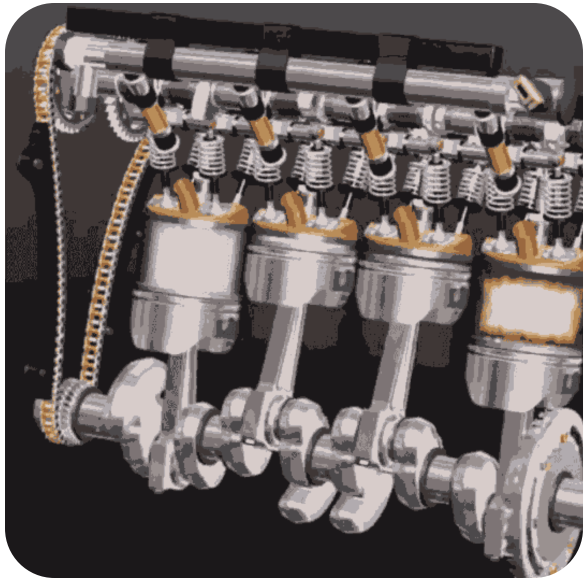


1. Background

- A cam-roller unit is the core component of valvetrain systems of an internal combustion engine.

- The surface of the tribo-pair is easy to wear, which affects the working accuracy of valve mechanism and reduces the reliability and service life of an internal combustion engine.

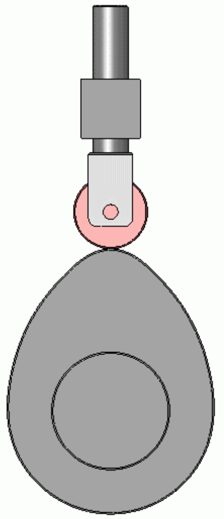


1. Background

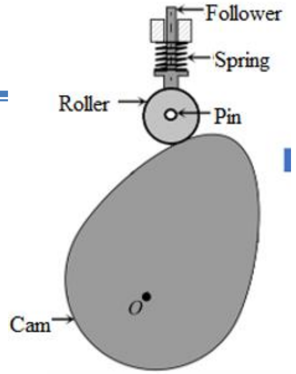
The tribological design of a cam-roller unit is a complicated and difficult task.

Friction and wear of a cam-roller unit

- **Lubrication**
  - Rotate speed
  - Surface characteristic
  - Type of lubricating
  - Supply of lubricating
  - **Skidding of cam and roller**
- Materials
- Machining precision
- Surface engineering
- ……



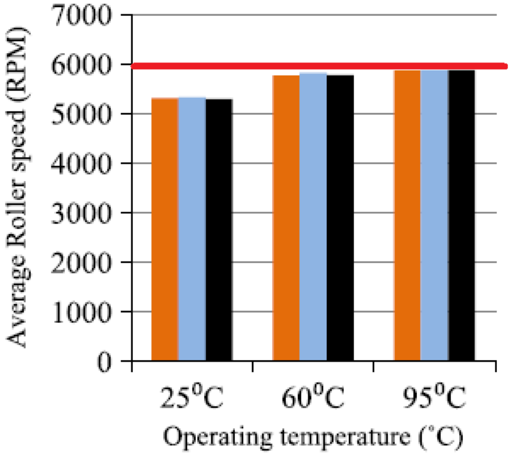
1. Background

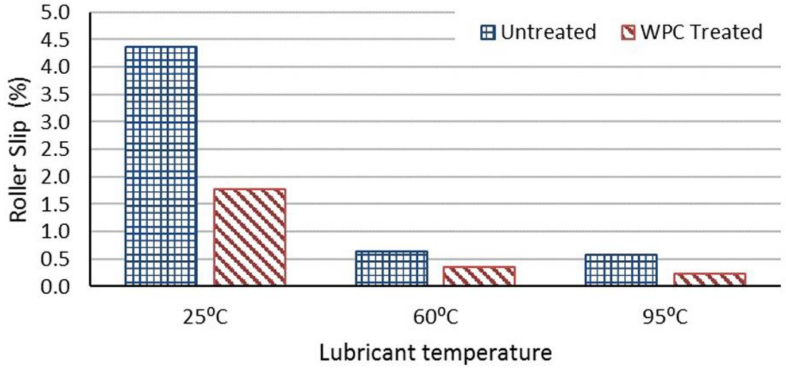


Skidding of cam and roller:

Cam and roller are in pure rolling state theoretically, but it is not so in practice

- Duffy et al. confirmed the existence of skidding between cam and roller through experiment(1993)
- Lee et al. pointed out that once the contact pair had skidding it would cause wear problem(1995)
- Khurram et al. experimentally studied the influence of oil viscosity on skidding(2016)
- Abdullah et al. pointed out that WPC treatment had a significant inhibition effect on skidding(2019)





1. Background

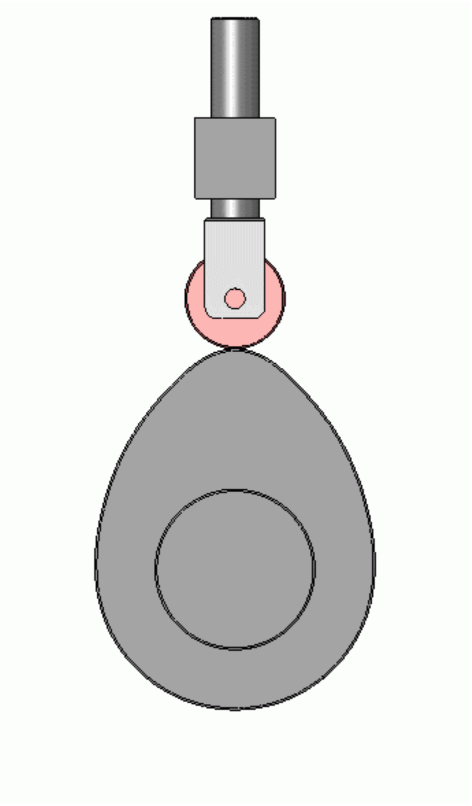
Research objective:

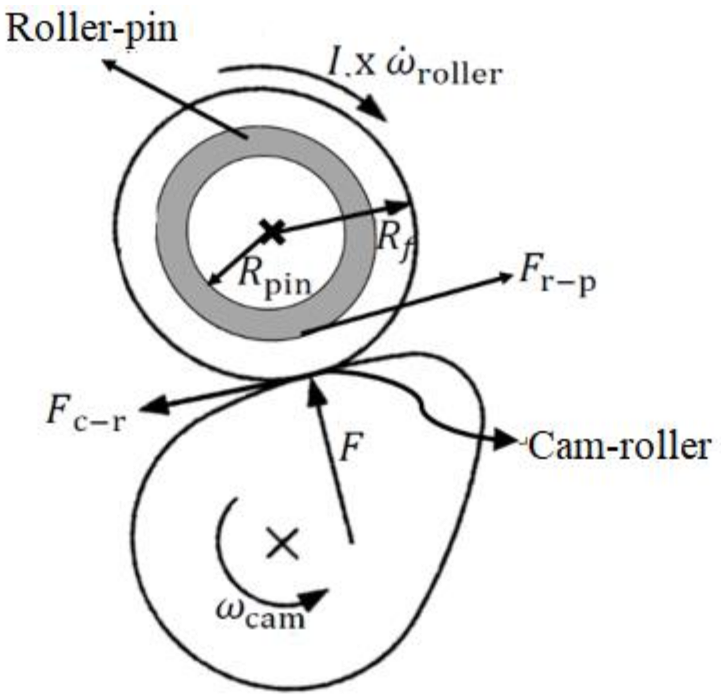
- **To establish the lubrication model of an cam-roller unit**
- **To study the factors dominating roller skidding**

2. Theoretical Analysis

2.1. Mathematical model

Cam-roller unit
- **Cam and roller contact**
- **Roller and pin contact**

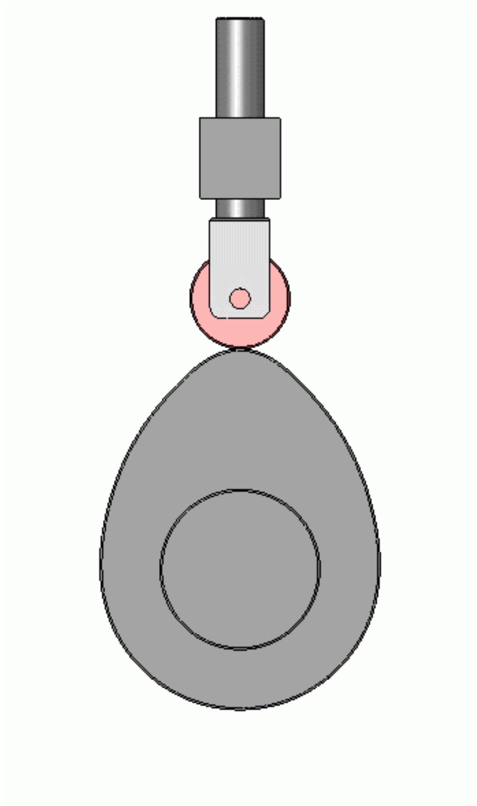




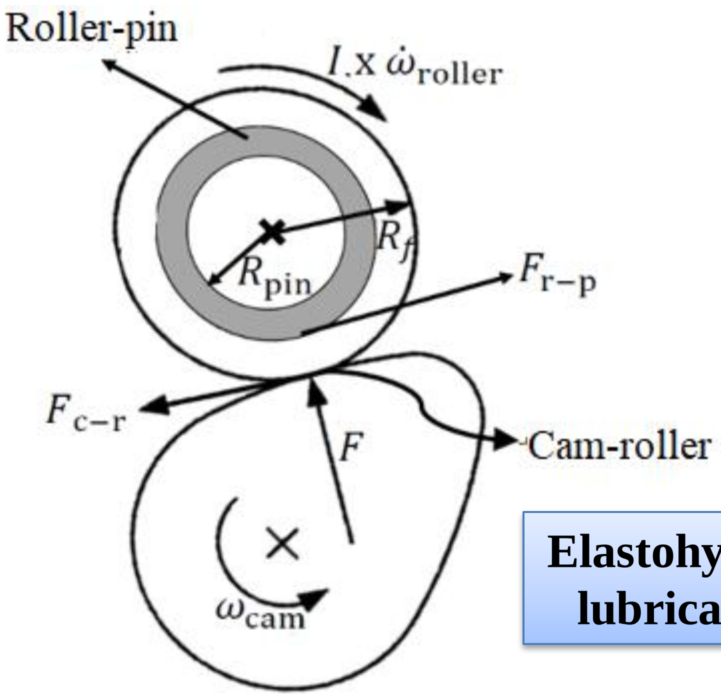
2. Theoretical Analysis

2.1. Mathematical model

Cam-roller unit
- Cam and roller contact
- Roller and pin contact



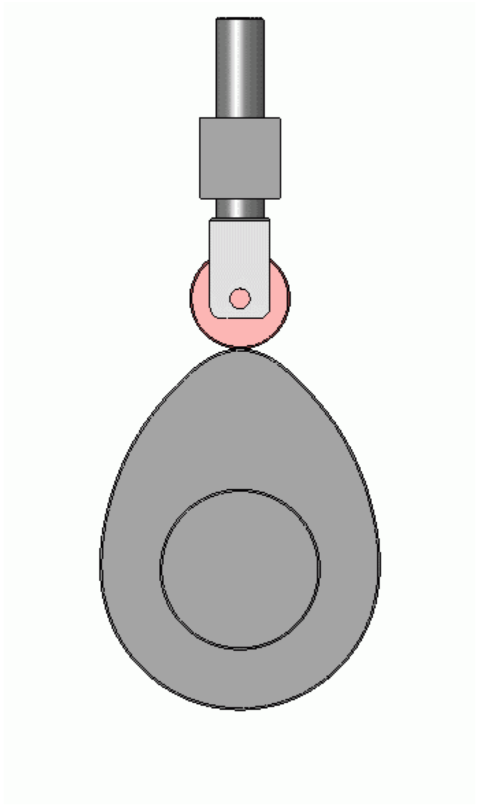
Hydrodynamic lubrication model



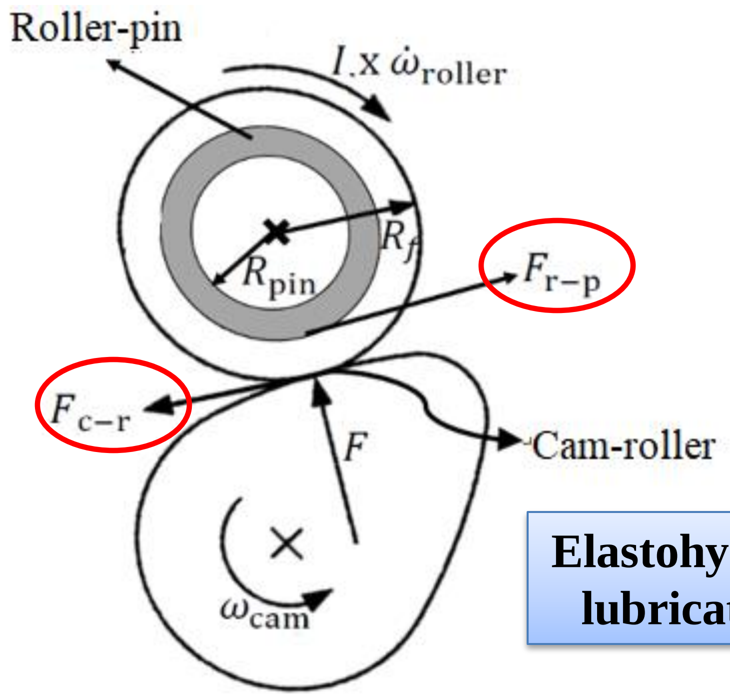
Elastohydrodynamic lubrication model

2. Theoretical Analysis

2.1. Mathematical model



Hydrodynamic lubrication model



Elastohydrodynamic lubrication model

Cam-roller unit
- Cam and roller contact
- Roller and pin contact

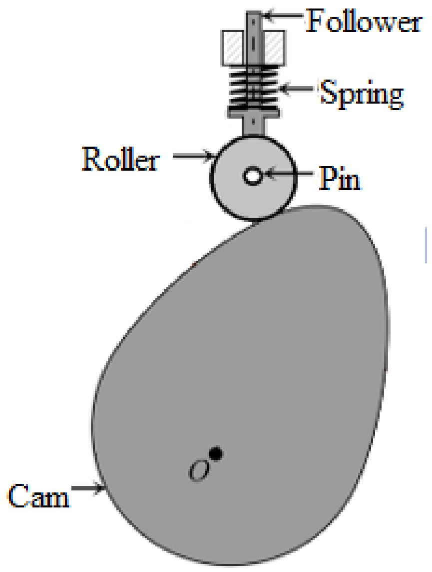
Coupled equation:

$$F_{c\text{-}r} R_f = F_{r\text{-}p} R_{pin} + I\dot{\omega}_{roller}$$

2. Theoretical Analysis

2.1. Mathematical model

- **Cam-roller contact:**

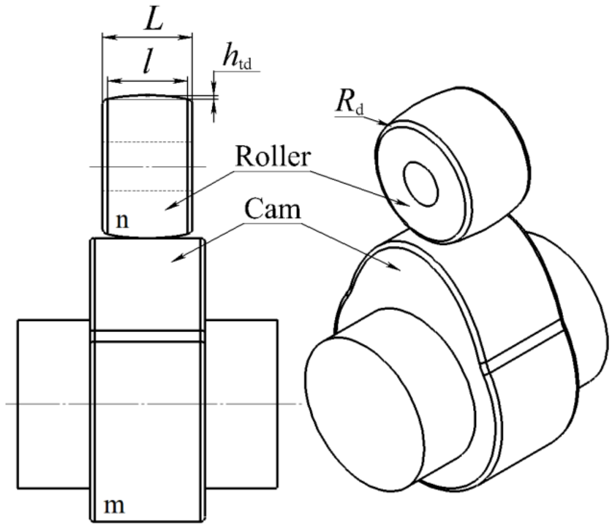


$$\frac{\partial}{\partial x}\left[\left[\left(\frac{\rho}{\eta}\right)_{\mathrm{e}} h^3 \frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\frac{\rho}{\eta}\right)_{\mathrm{e}} h^3 \frac{\partial p}{\partial y}\right]=6u_{\mathrm{a}}\frac{\partial\left(\rho_{\mathrm{a}}^{*}h\right)}{\partial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

$$p(x_{in}, y) = p(x_{out}, y) = p(x, y_{in}) = p(x, y_{out})$$

$$p(x, y) \geq 0 \ (x_{in} \leq x \leq x_{out},\ y_{in} \leq y \leq y_{out})$$

$$h(x,y,t)=h_0(t)+\frac{x^2}{2R}+\frac{(y\pm l/2)^2}{2R_{\mathrm{d}}}f_{\Delta}+h_{\mathrm{td}}\left[1-\left(\frac{y}{l/2}\right)^2\right](1-f_{\Delta})+\frac{2}{\pi E'}\iint_{\Omega}\frac{p(x',y',t)}{\sqrt{(x-x')^2+(y-y')^2}}\mathrm{d}x'\mathrm{d}y'$$



$$\eta^{*}=\eta_0\exp\left\{(A_1)\times\left[-1+(1+A_2 p)^{z_0}(A_3/A_4)^{-s_0}\right]\right\}$$

$$\eta=\eta^{*}\frac{\tau_{\mathrm{e}}/\tau_0}{\sinh(\tau_{\mathrm{e}}/\tau_0)}$$

$$\rho=\rho_0\left[1+C_1 p/(1+C_2 p)-C_3(T-T_0)\right]$$

$$\iint p\mathrm{d}x\mathrm{d}y=w+w_1$$

2. Theoretical Analysis

2.1. Mathematical model

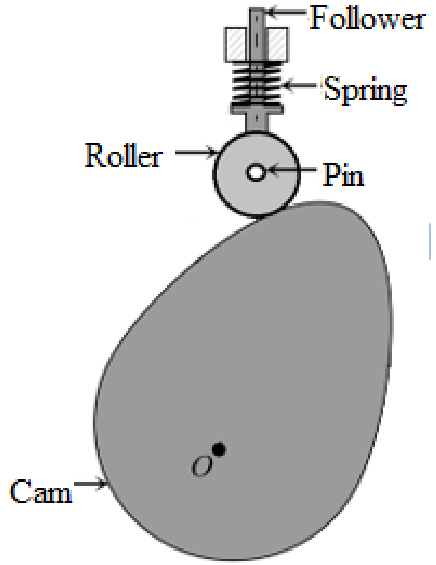
➢ **Roller-pin contact:**

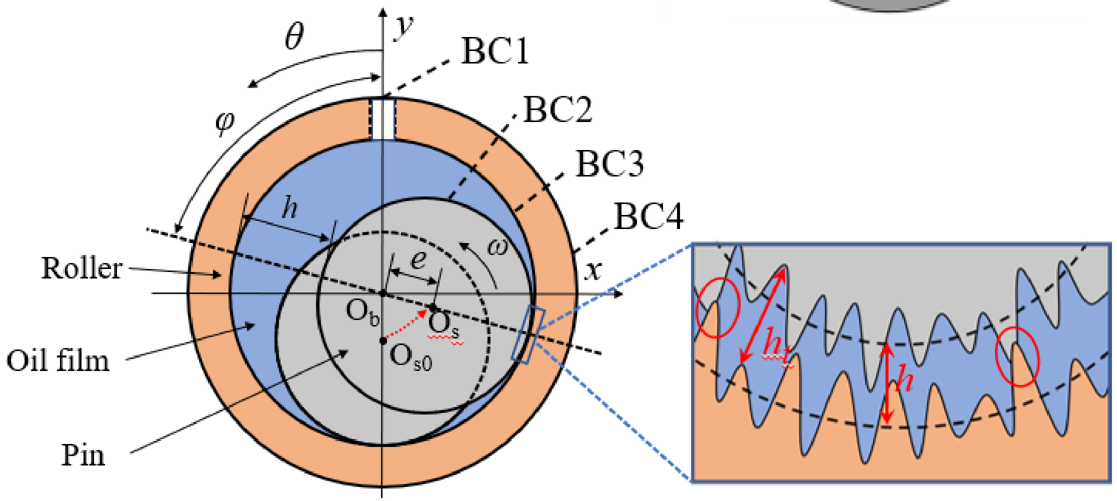
$$\frac{\partial}{R_b\partial\theta}\left(\phi_\theta\frac{h^3}{\eta}\frac{\partial p}{R_b\partial\theta}\right)+\frac{\partial}{\partial\lambda}\left(\phi_\lambda\frac{h^3}{\eta}\frac{\partial p}{\partial\lambda}\right)=6u_s\phi_c\frac{\partial h}{R_b\partial\theta}+6u_s\sigma\frac{\partial\phi_s}{R_b\partial\theta}+12\phi_c\frac{\partial h}{\partial t}$$

$$\begin{cases} p(\theta,0)=p(\theta,L)=0 \\ p(\theta_0,\lambda)=0,\dfrac{\partial p(\theta_0,\lambda)}{\partial\theta}=0 \end{cases}$$

$$h=c+e\cos(\theta-\varphi)+\delta=c\left(1+\varepsilon\cos(\theta-\varphi)\right)+\delta$$

$$\begin{cases} p_{asp}=\dfrac{12\sqrt{2}\pi}{15}(\sigma\beta D)^2\sqrt{\dfrac{\sigma}{\beta}}E^*F_{2.5}\left(\dfrac{h}{\sigma}\right) \\ A_c=\pi^2(\sigma\beta D)^2A_0F_{2.0}\left(\dfrac{h}{\sigma}\right) \end{cases}$$

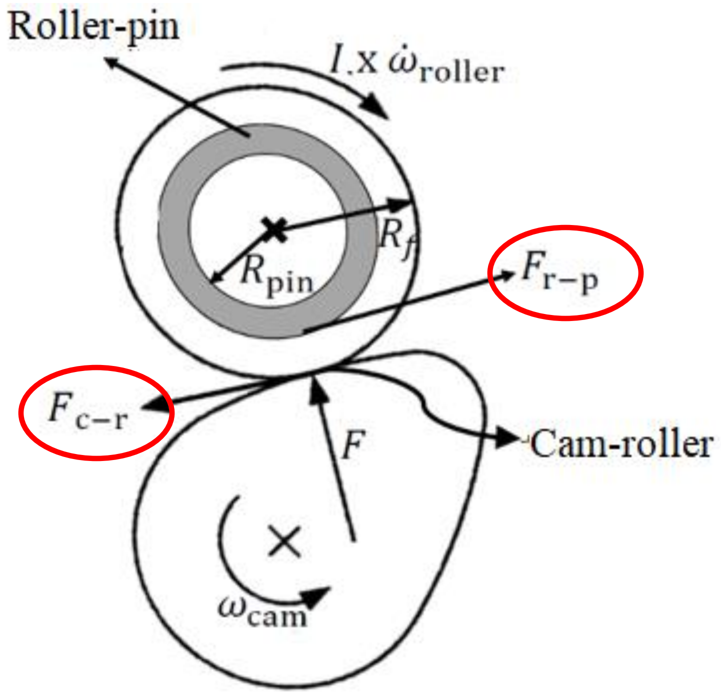




2. Theoretical Analysis

2.1. Mathematical model

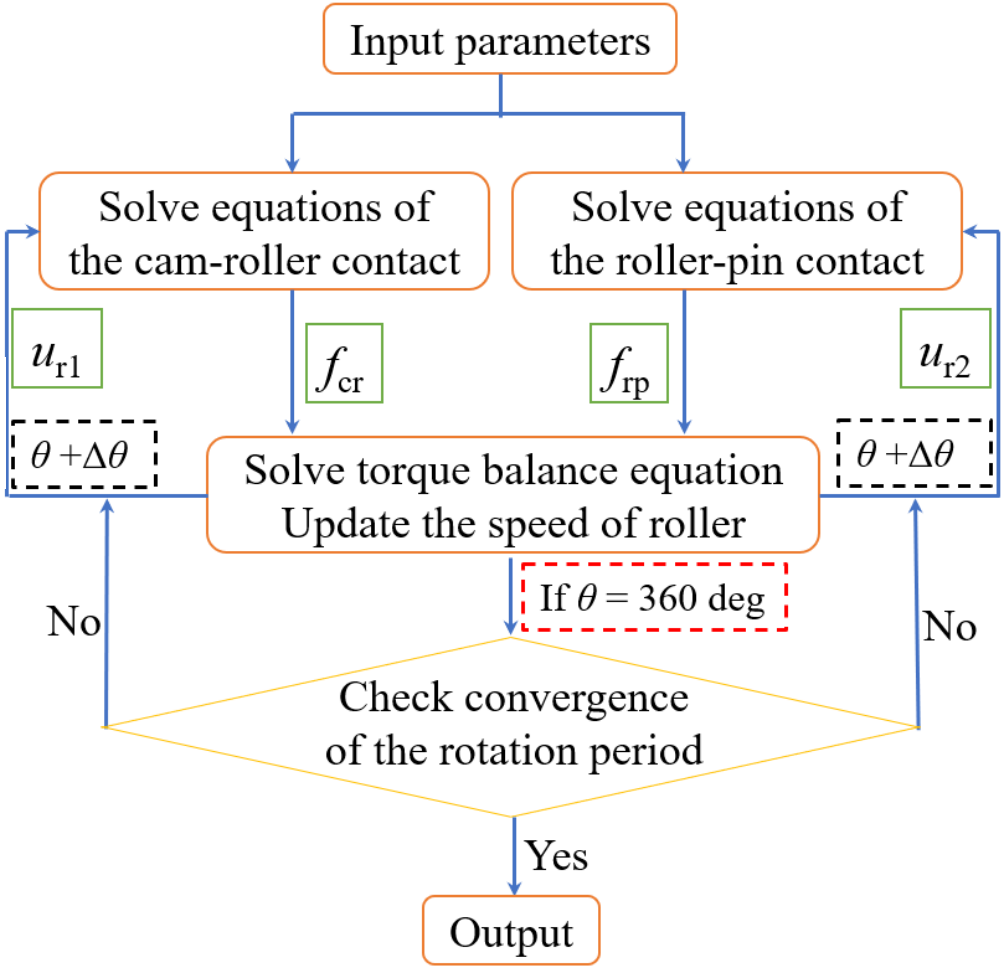
☐ Numerical calculation



Coupled equation:

$$F_{c\text{-}r} R_f = F_{r\text{-}p} R_{pin} + I\dot{\omega}_{roller}$$

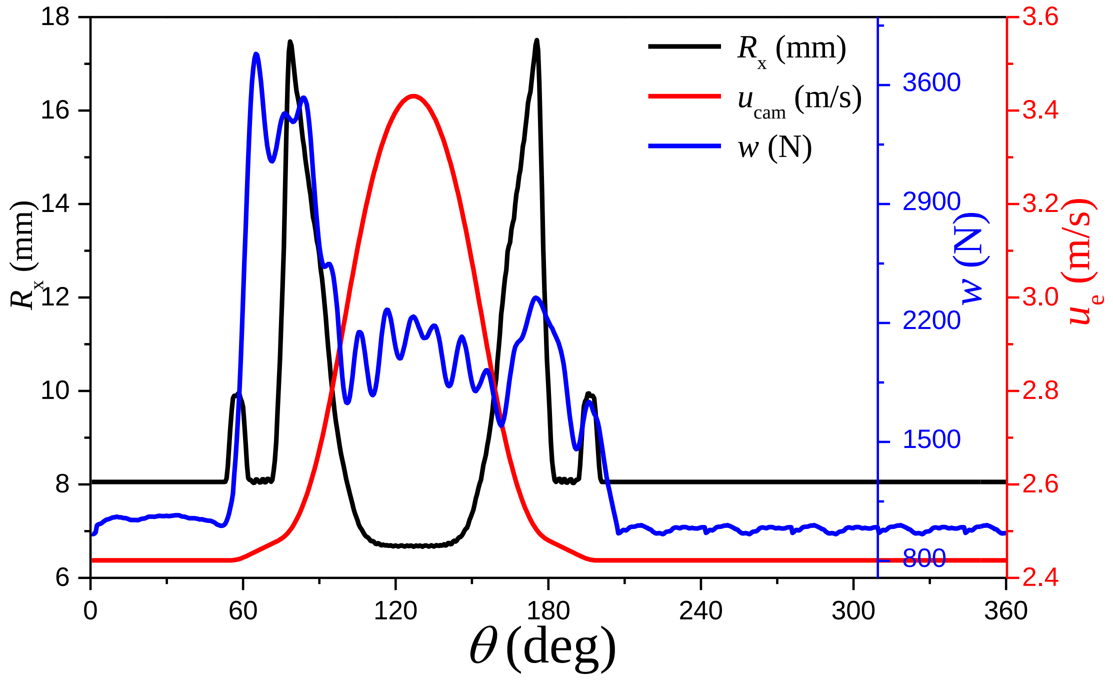
$$\omega_{roller}^{t} = \omega_{roller}^{t\text{-}1} + \dot{\omega}_{roller} \Delta t$$



2. Theoretical Analysis

2.2. Numerical Results

Parameters	Value
Length of roller (mm)	14
Middle length of roller (mm)	12
Inner radius of roller (mm)	16
Outer radius of roller (mm)	25.5
Radius gap (μm)	5
Elasticity modulus (GPa)	2.1
Pressure-viscosity coefficient (Pa^{-1})	2.2×10^{-8}
Solid density (kg/m^3)	7850
Viscosity (Pa·s)	0.08
Oil density (kg/m^3)	870
Surface roughness (μm)	0.5



Comprehensive radius, Speed and Load

2. Theoretical Analysis

2.2. Numerical Results

Parameters	Value
Length of roller (mm)	14
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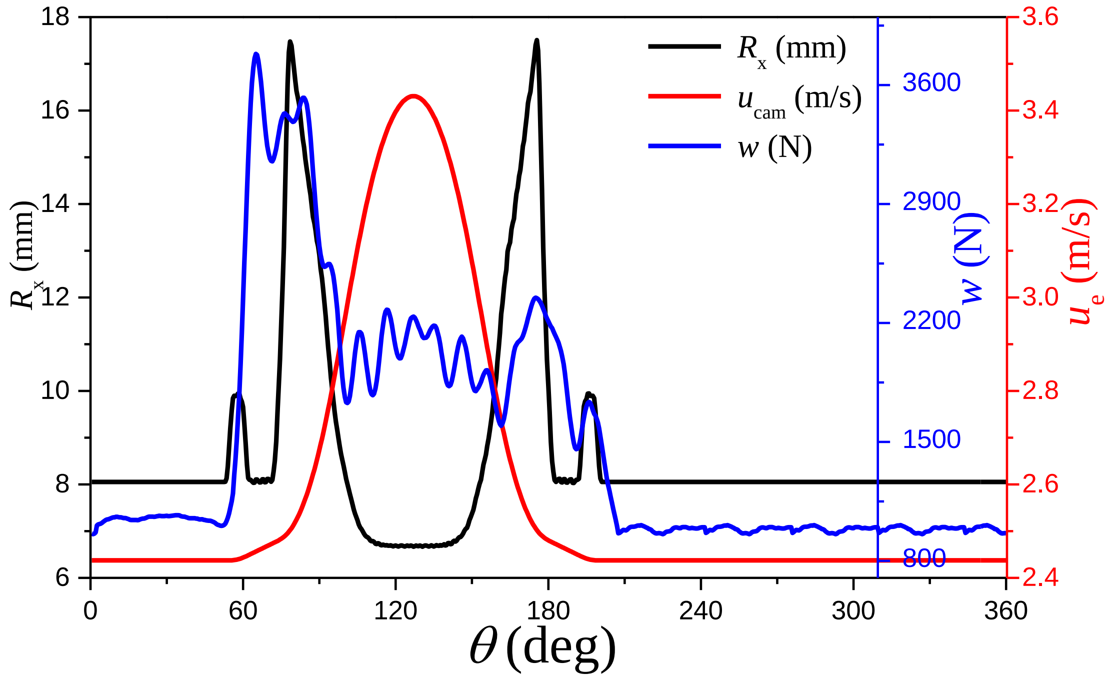


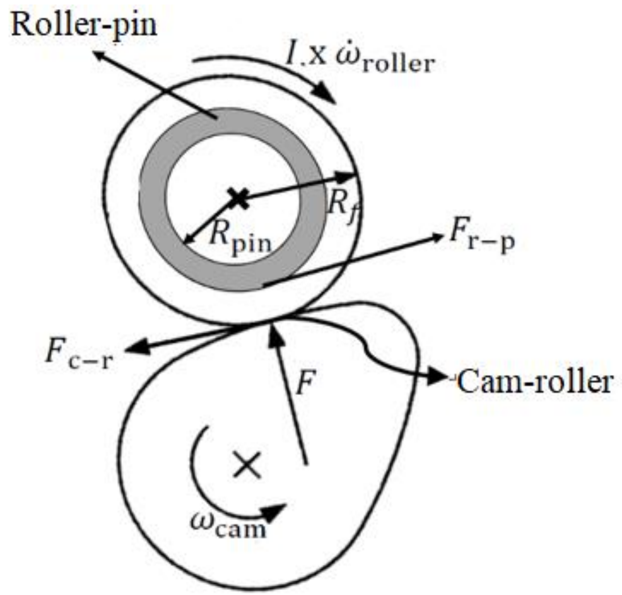
Comprehensive radius, Speed and Load

Skidding

- **Steady running**
- **Startup**

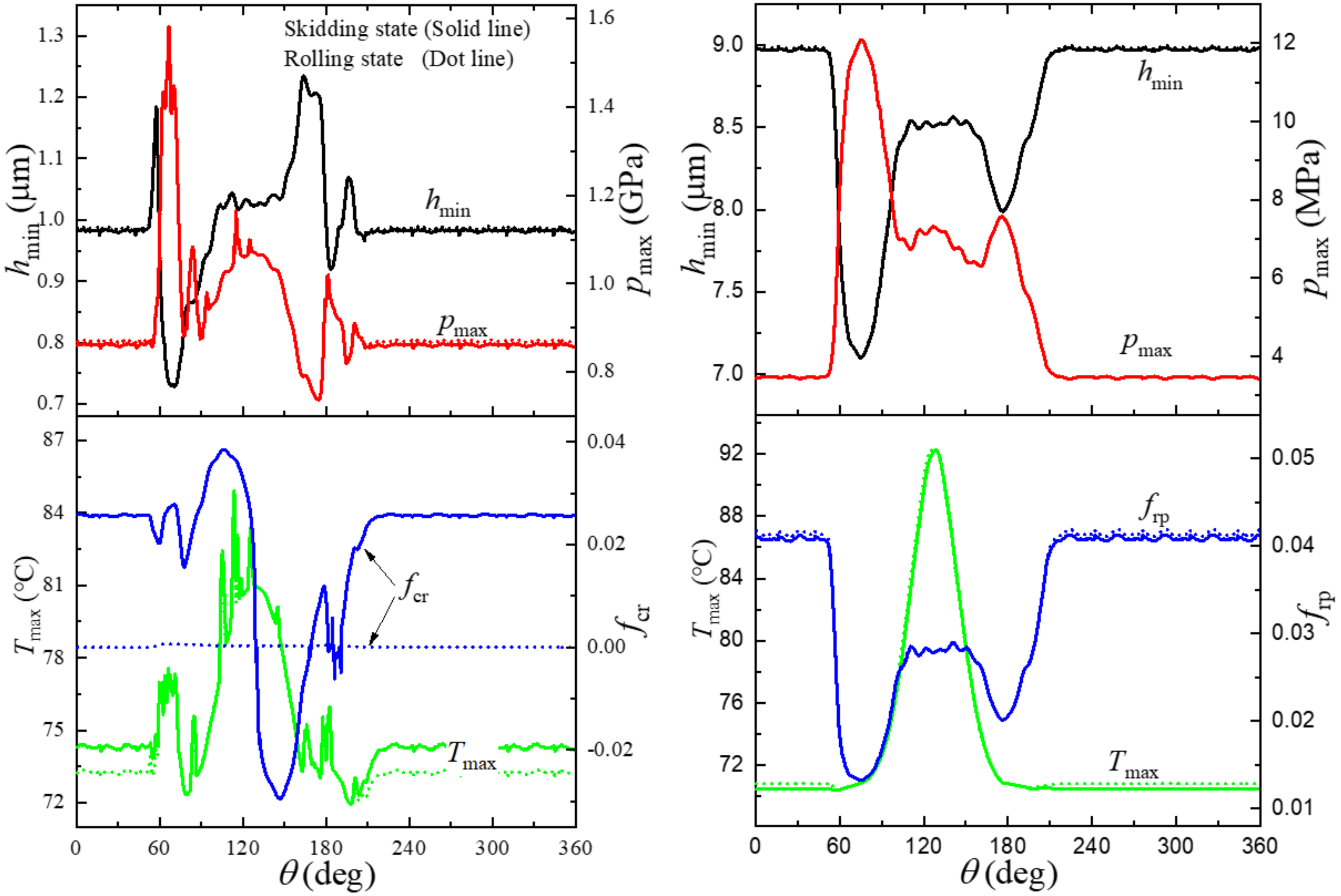
2. Theoretical Analysis

2.2.1. Steady running



Obvious difference at cam-roller pair:

- ☐ Friction coefficient
- ☐ Maximum temperature rise



(a) Cam-roller contact

(b) Roller-pin contact

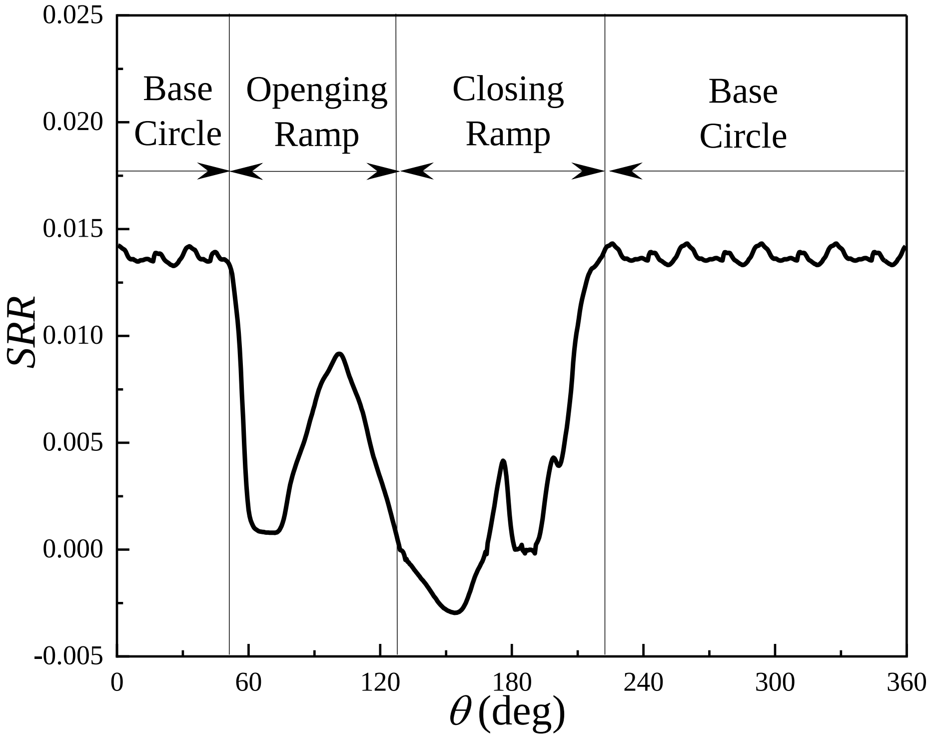
Under conditions of the skidding/rolling between cam and roller

2. heoretical Analysis

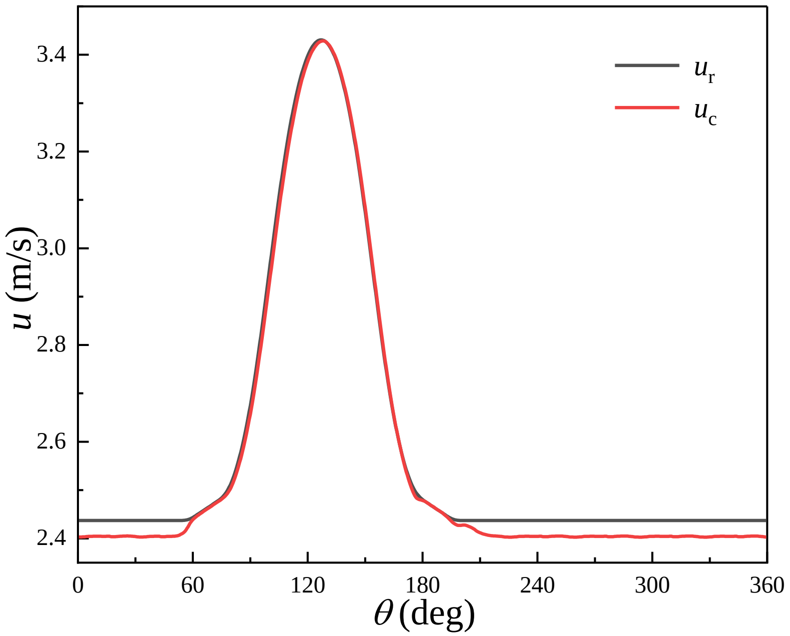
2.2.1. Steady running

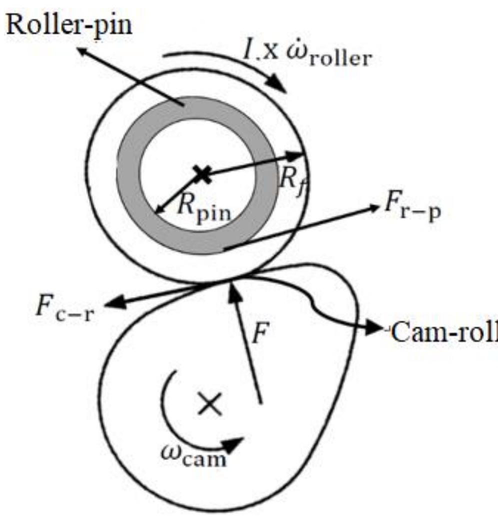
Skidding coefficient:

$$SRR = \frac{2(u_{cam} - u_{roller})}{u_{cam} + u_{roller}}$$



Contact point speed of cam and roller





Skidding coefficient:

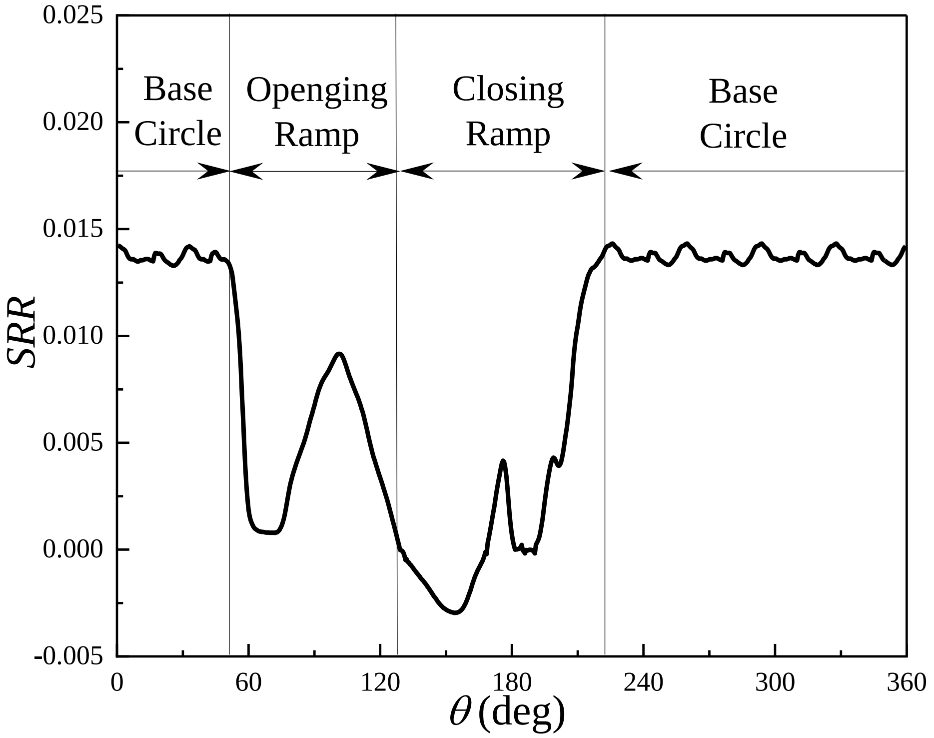
- The max value occurs in the base circle.
- The negative value appears at closing ramp part.

2. heoretical Analysis

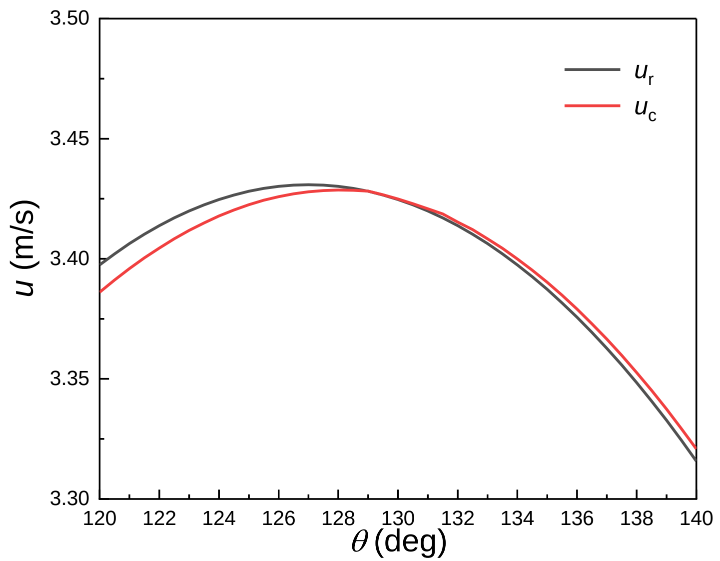
2.2.1. Steady running

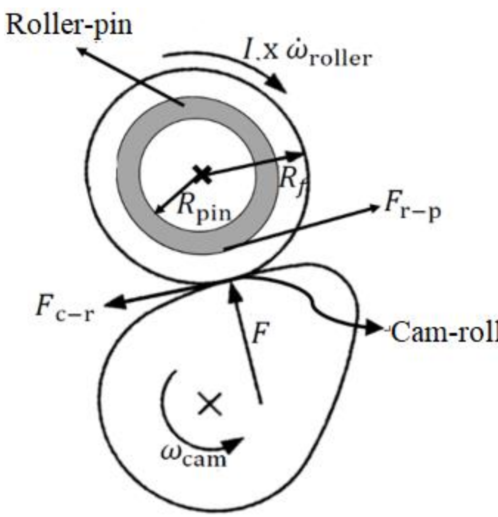
Skidding coefficient:

$$SRR = \frac{2(u_{cam} - u_{roller})}{u_{cam} + u_{roller}}$$



Contact point speed of cam and roller





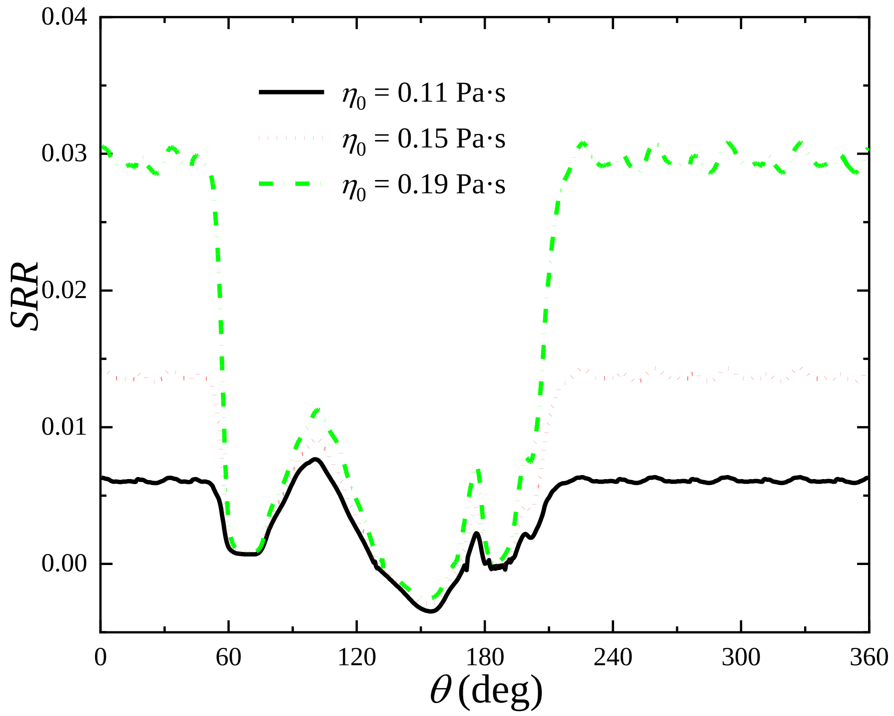
Skidding coefficient:

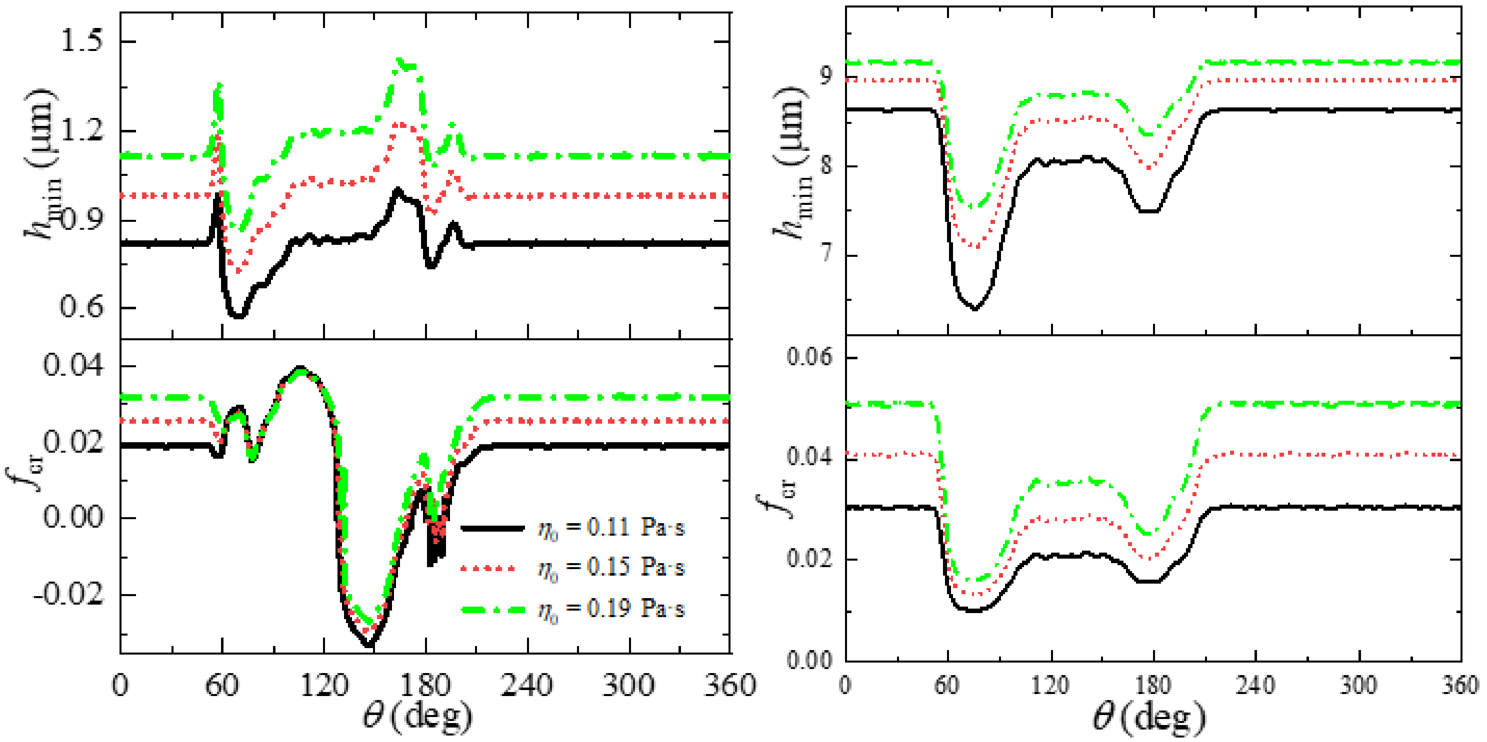
- The max value occurs in the base circle.
- The negative value appears at closing ramp part.

2. Theoretical Analysis

2.2.1. Steady running

- Effect of oil viscosity





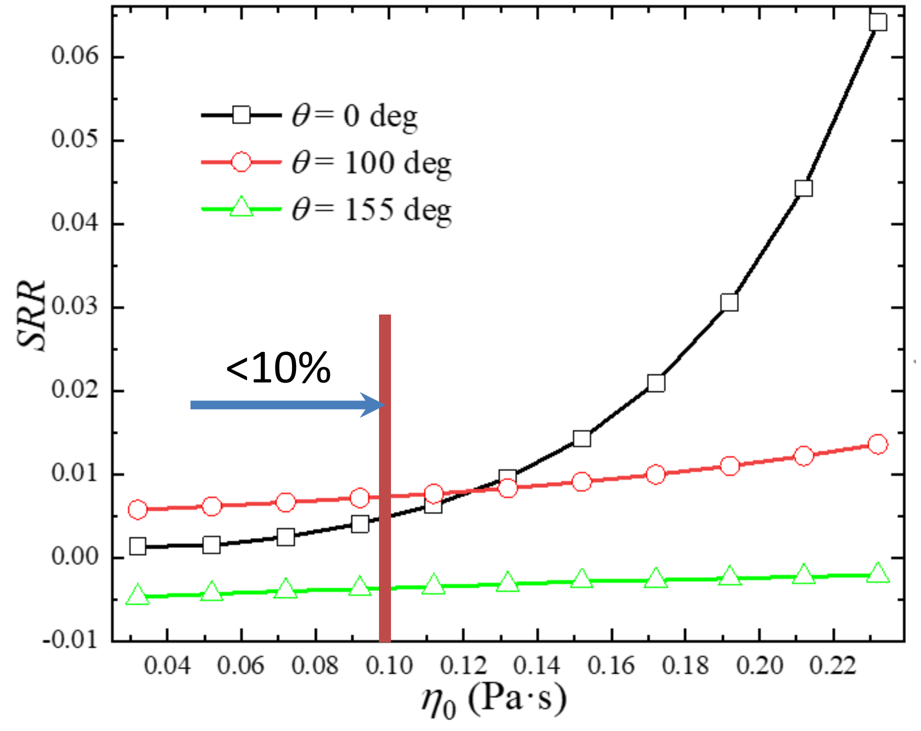
(a) Cam-roller (b) Roller-pin

For various viscosities

- More difference of skidding in the base circle.

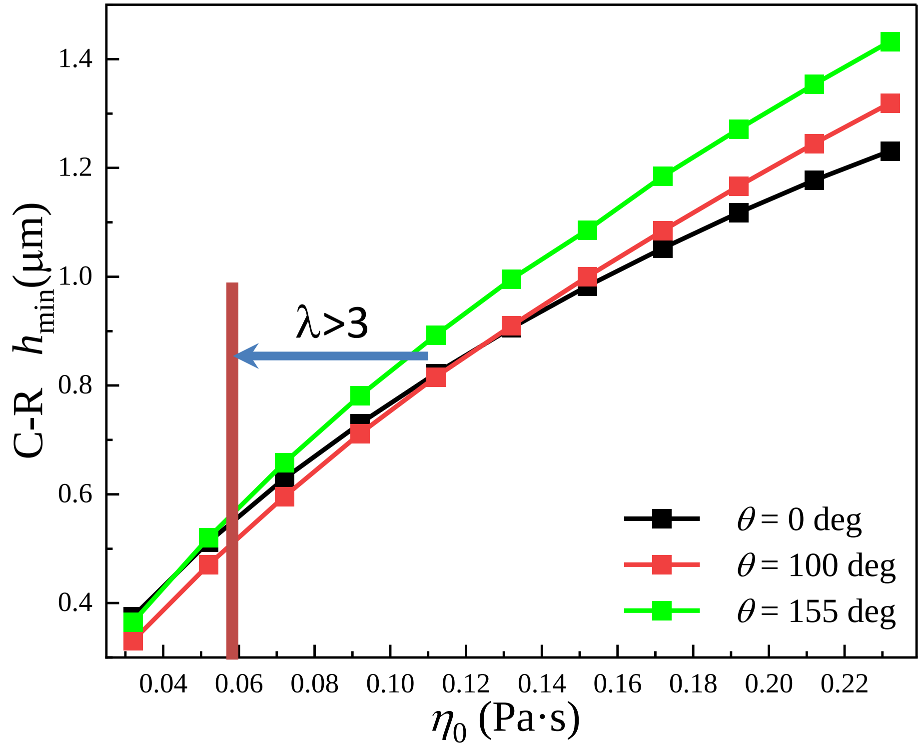
2.2.1. Steady running

- Effect of oil viscosity



SRR vs. viscosity on the three key point

The minimum film vs. viscosity in the cam-roller contact zone



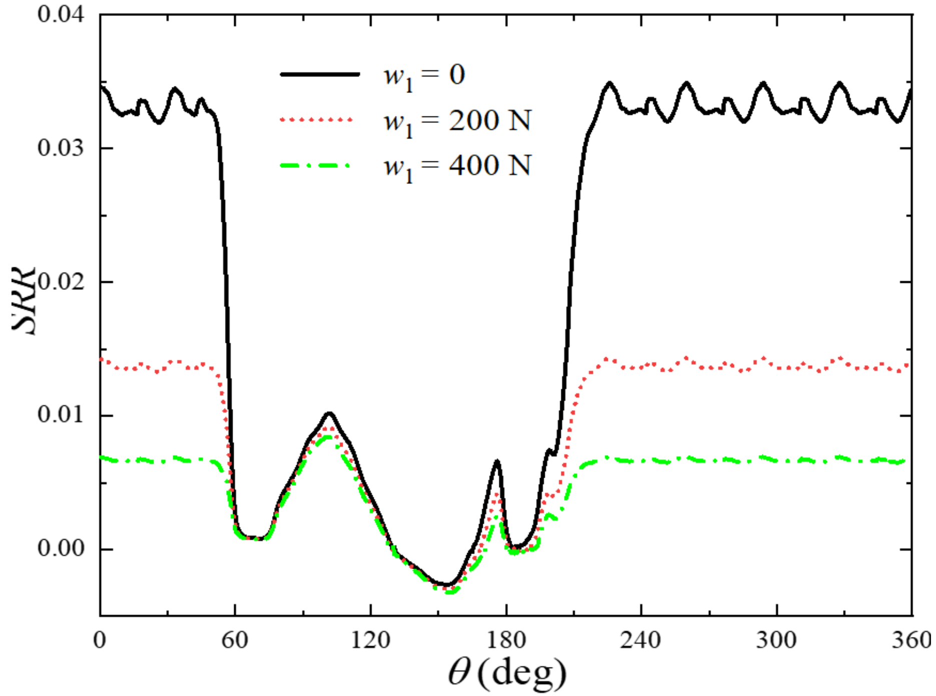
The optimum viscosity range ⟵ **The slide-roll ratio *(SRR)*** / **The minimum film thickness**

2. Theoretical Analysis

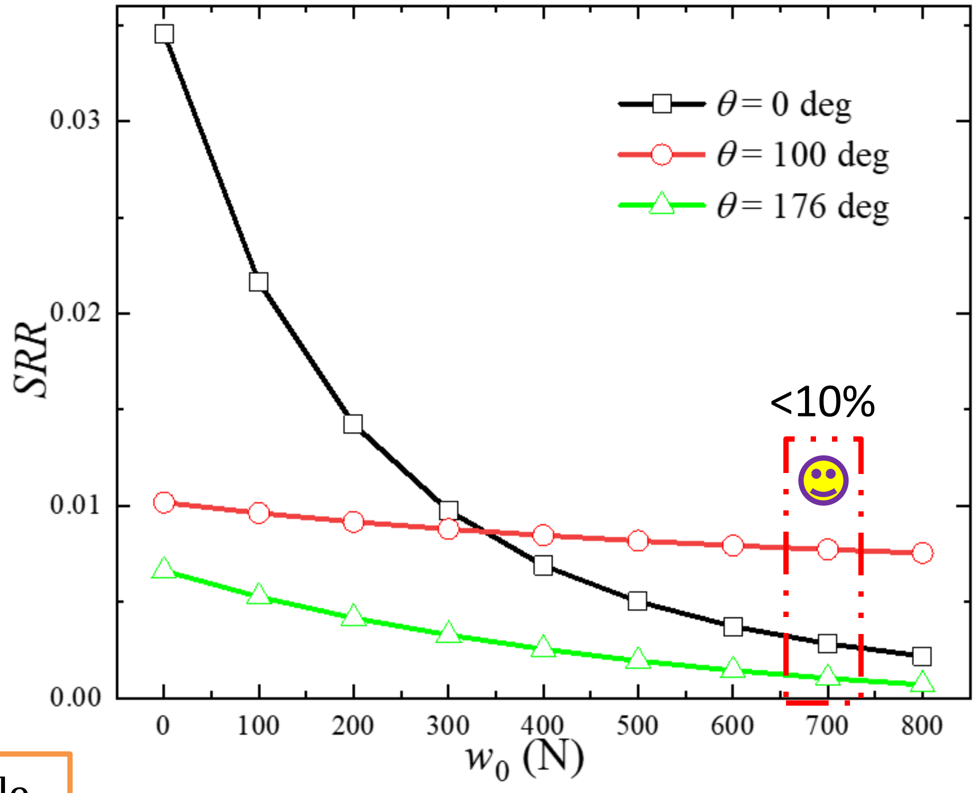
2.2.1. Steady running

- Effect of modified load

$$\iint p\,dxdy = w + w_1$$



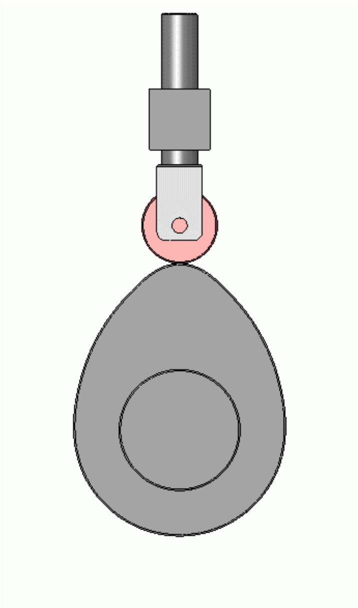
SRR vs. modified load on the three key point

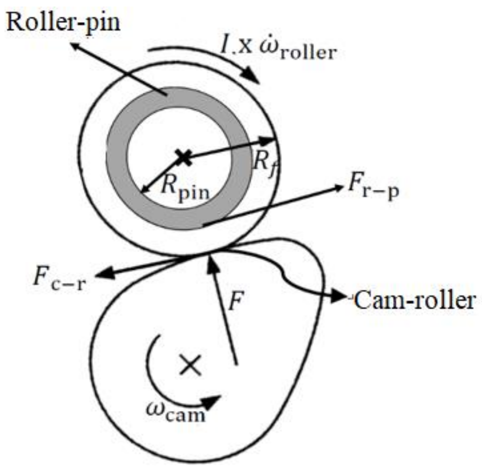


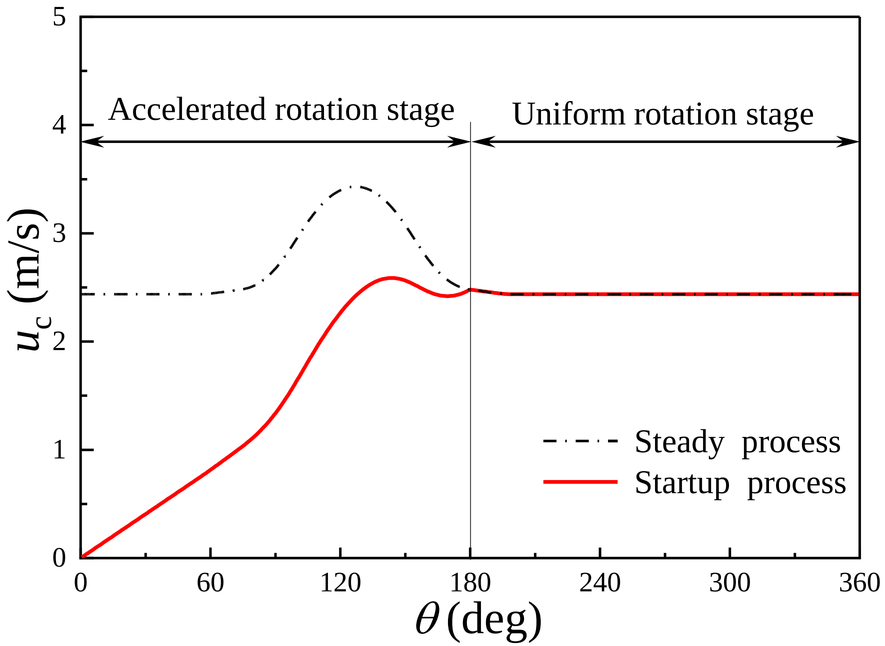
- ☐ Effect the skidding situation, especially in the base circle.
- ☐ the skidding situation will be reduced.

2. Theoretical Analysis

2.2.2. Startup



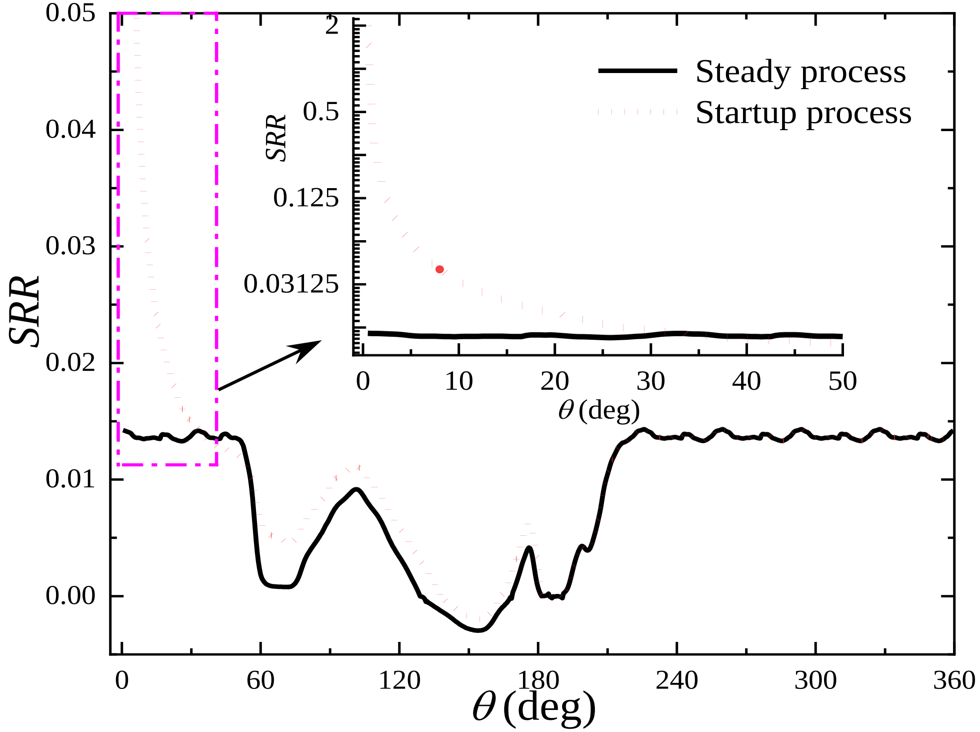




Schematic diagram of cam surface velocities in the startup running process

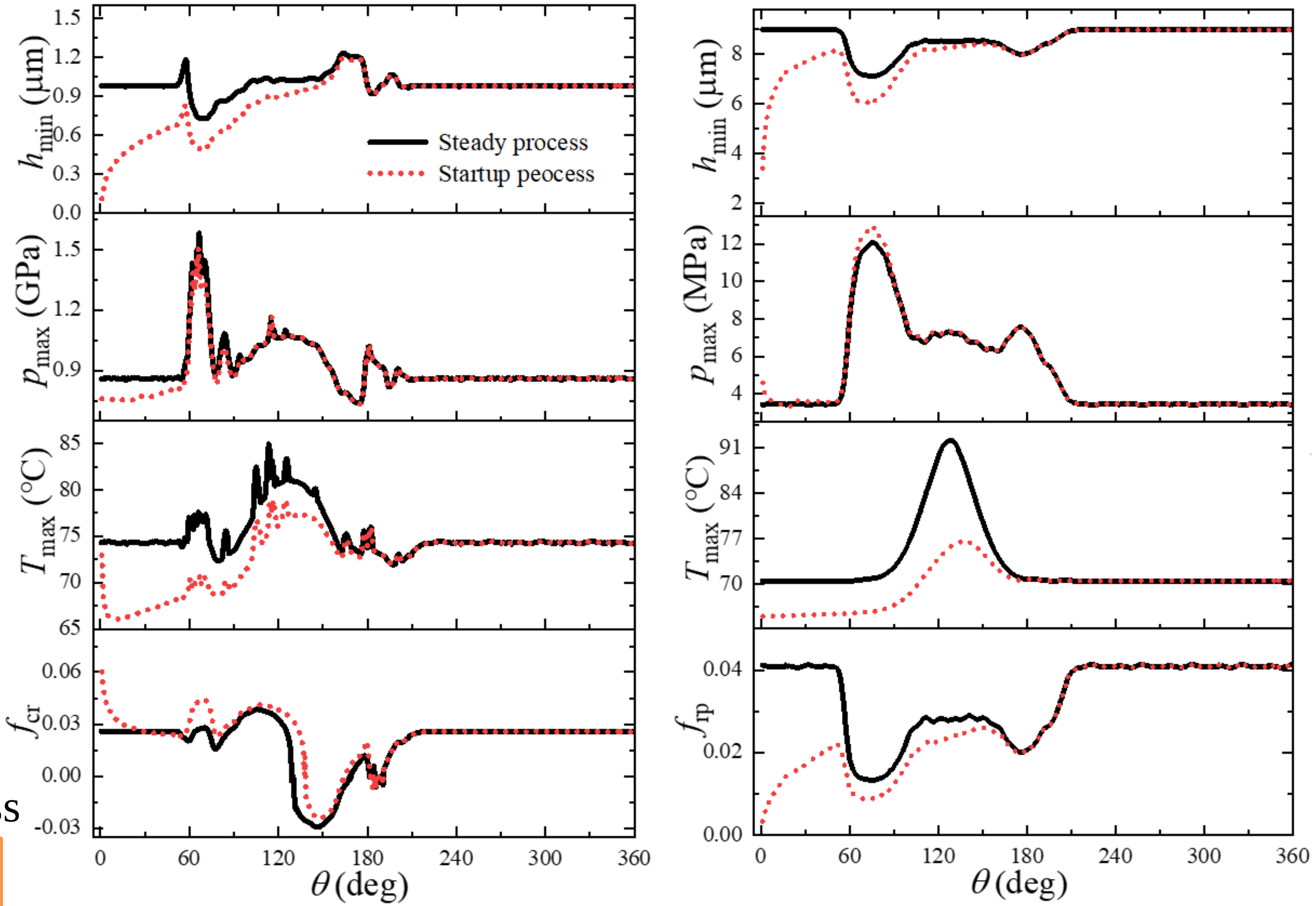
2. Theoretical Analysis

2.2.2. Startup



Comparison of *SRR* in the steady/startup running process

- The skidding situation is more serious in the startup running process.
- The difference of slide-roll ratio is greater than 50% in the beginning stage (0~18deg).



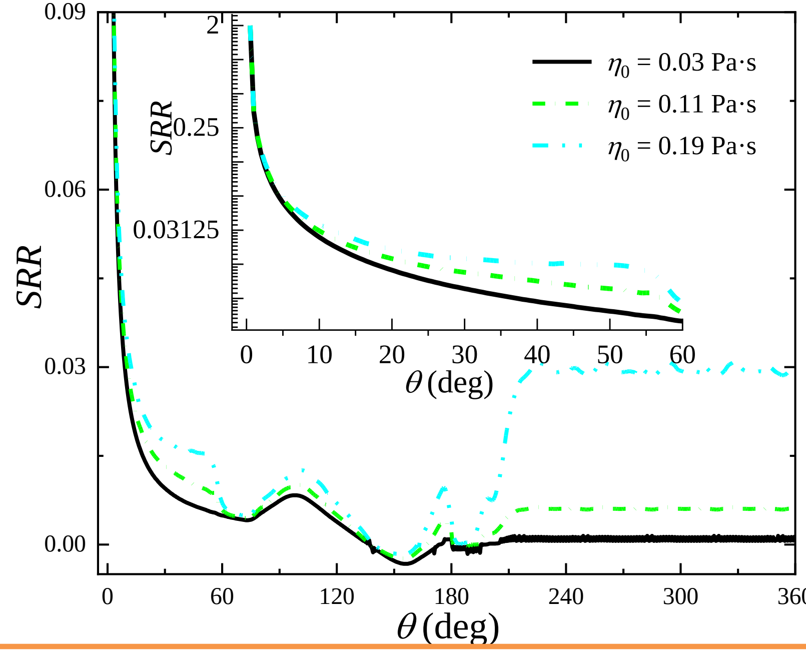
(a) Cam-roller contact (b) Roller-pin contact

Lubrication states of cam-roller unit in the steady/startup running process

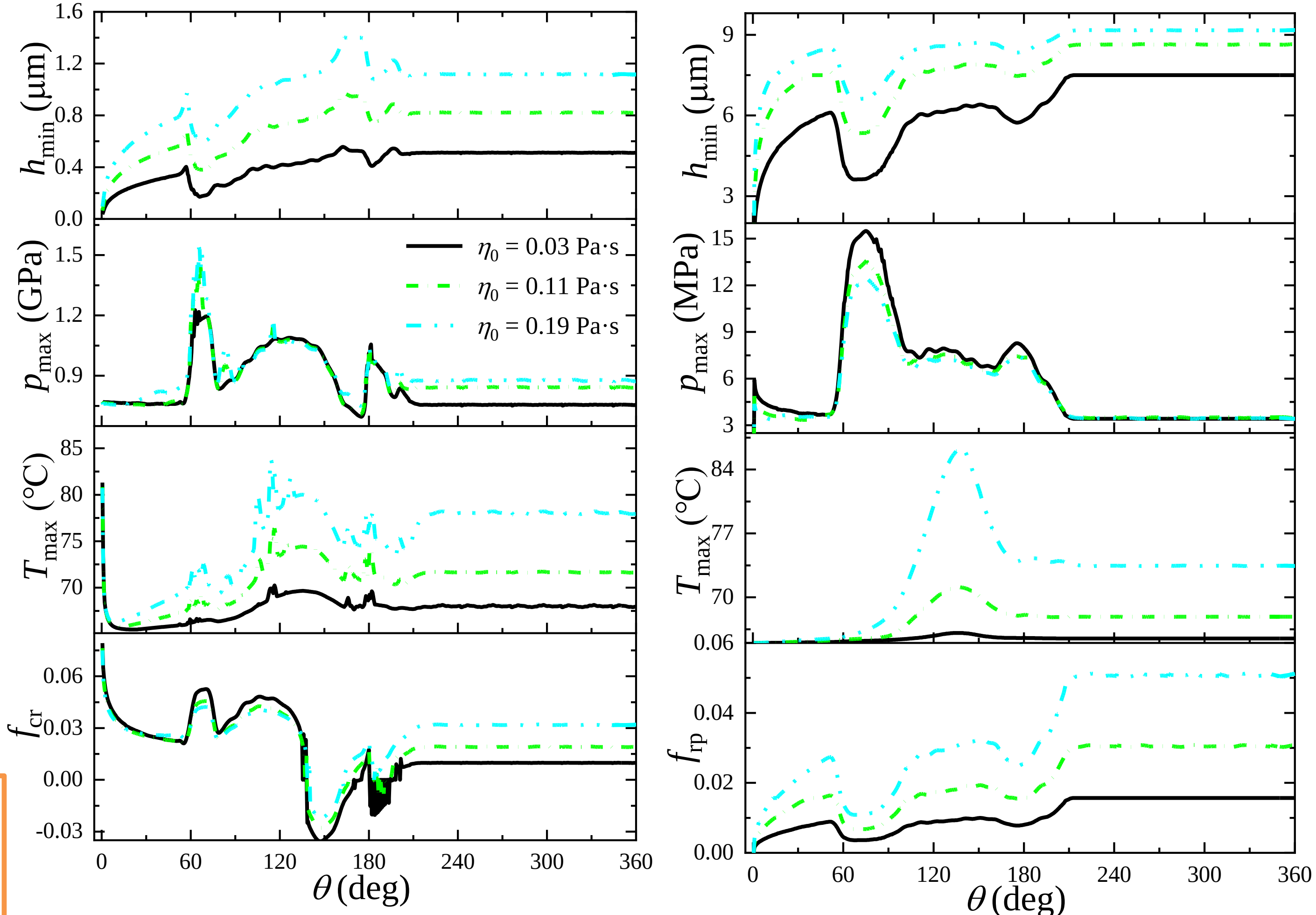
2. Theoretical Analysis

2.2.2. Startup

- Effect of viscosity



- Hardly affect the slide-roll ratio at the beginning of acceleration rotation stage(0~7deg).
- Relatively obvious affect the slide-roll ratio in the range of 7~58deg.

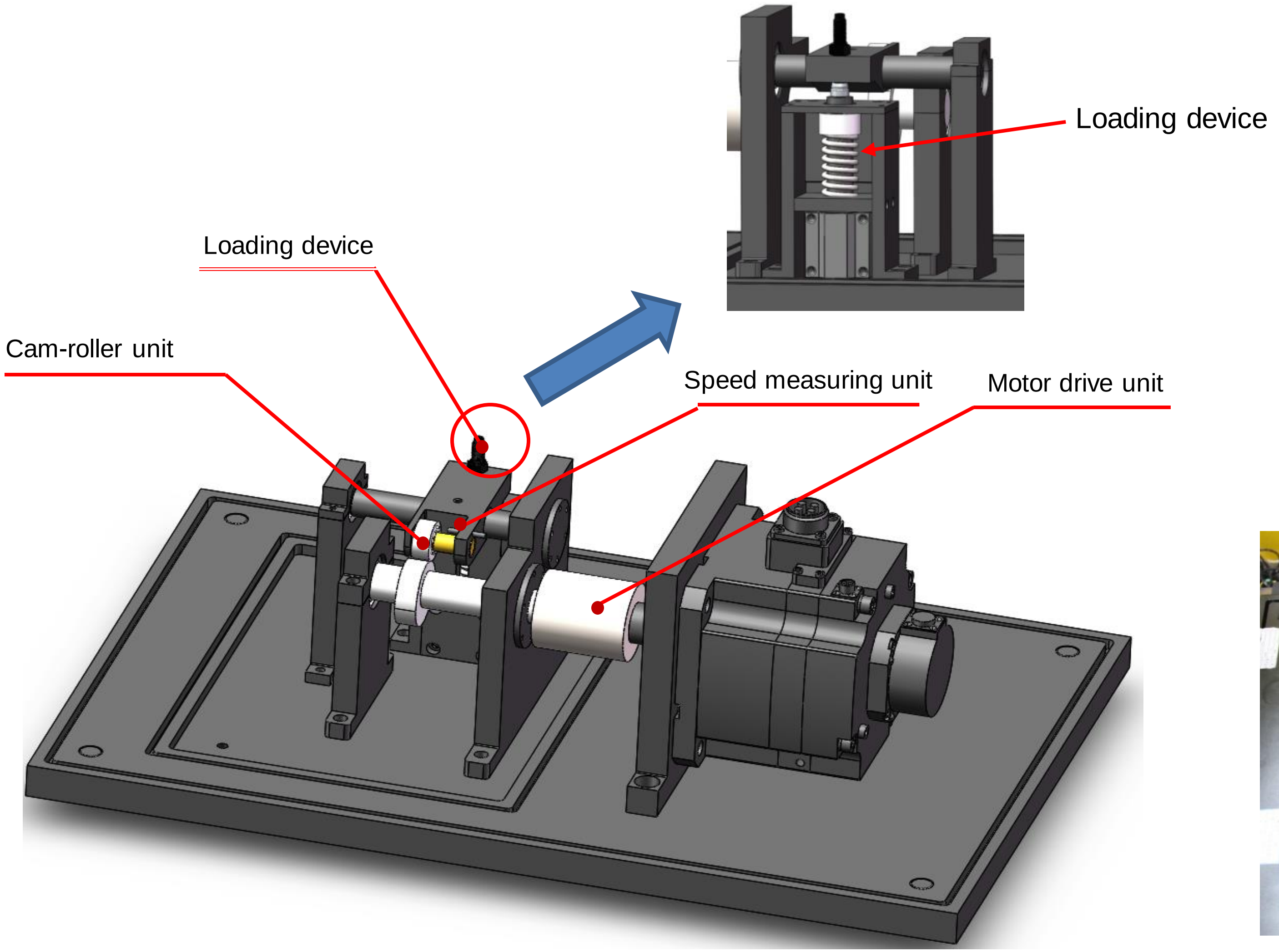


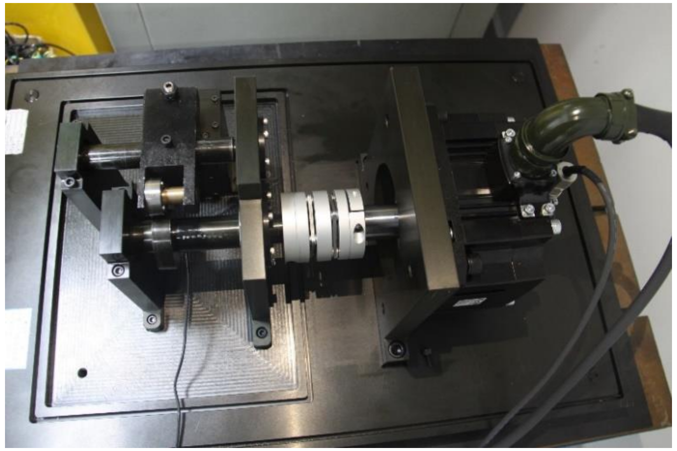
(a) Cam-roller (b) Roller-pin

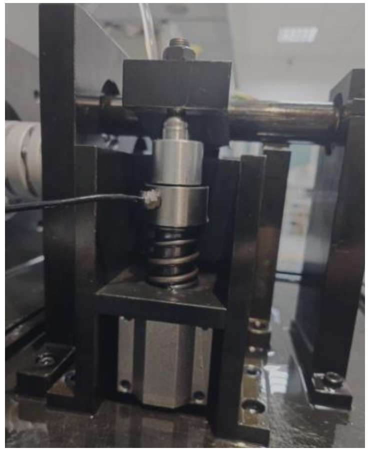
Effect of the viscosity in the startup running process

2. Theoretical Analysis

2.3. Experimental Device

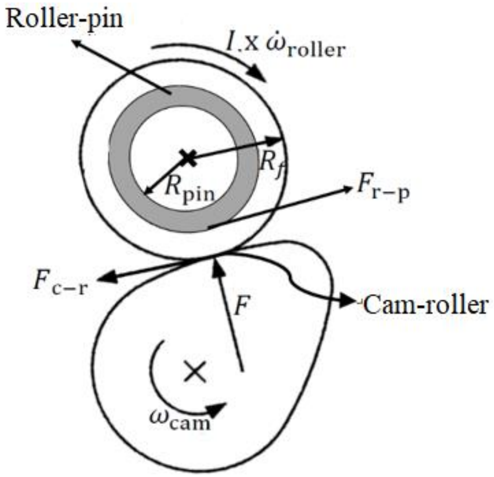


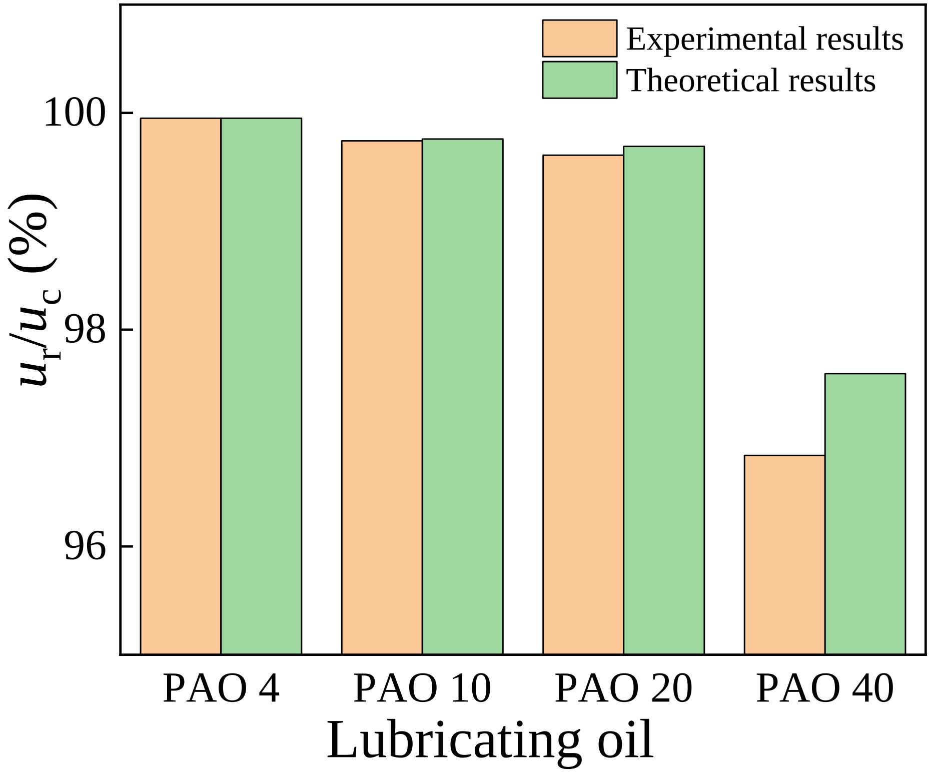




2. Theoretical Analysis

2.3. Experimental Device





Comparison of theoretical and experimental results

3、Conclusion

- Lubrication analyses of a cam-roller unit (cam-roller pair and roller-pin pair)has been successfully carried out. The lubrication state of two contact pairs in a cycle is obtained.

- The skidding is not constant, and the negative slide-roll ratio appears. In general, the skidding is more serious in the base part, and less skidding in other regions.

- Compared with the steady running, the skidding is more serious in the startup process, especially in the beginning of acceleration stage.

- The optimized viscosity in the calculation is well correlated to that used in the engines.

THANKS