Load carrying capacity and friction of a parabolic-flat piston ring of fixed width

C. Pettavino[1], N. Biboulet[1], A. A. Lubrecht[1]

[1]Université de Lyon, INSA-Lyon, LaMCoS, CNRS UMR 5259 Villeurbanne F69621, France

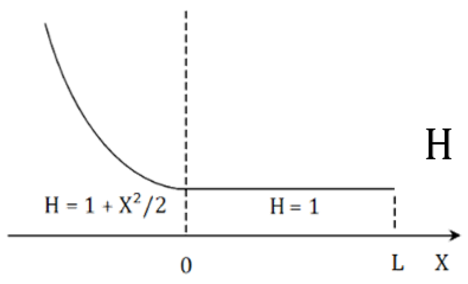
LaMCoS UMR 5259

Introduction

- Currently, friction reduction in internal combustion engines is paramount, as such friction prediction and reduction and oil consumption reduction are very important.
- An important component is the piston ring-cylinder liner contact; theoretical models have been studied for more than 40 years.
- Recent work by Biboulet et al.[1] has focused specifically on the origins of hydrodynamic load carrying capacity and friction generation under starved conditions. Starvation can either be caused by a limited lubricant availability, or by a limited geometry.
- Recent theoretical work by Noutary et al.[2] and Biboulet et al.[1] applied simplified boundary conditions to find analytical solutions of the starved lubrication problem. The current work extends the work by Biboulet et al.[1] by studying a more complex ring geometry of fixed width.

Theory

Dimensionless ring geometry



$$H = \begin{cases} 1 + \frac{X^2}{2}, & \text{if } X \le 0 \\ 1, & \text{if } 0 < X < L \end{cases}$$

- Dimensionless, incompressible, 1-D Reynolds integrated $\frac{\partial P}{\partial X} = \frac{H - H^*}{H^3}$ where $H^* = H|_{\partial P/\partial X = 0}$ with $\begin{cases} X = \frac{x}{\sqrt{h_0 R_x}} \\ H = \frac{h}{h_0} \end{cases}$
- Knowing the geometry, the pressure distribution can be obtained by integration

$$P(X) = \begin{cases} -\frac{H^* X}{(2+X^2)^2} + \left(1 - \frac{3H^*}{4}\right)\left(\frac{X}{2+X^2} + \frac{\sqrt{2}}{2}\arctan\left(\frac{X}{\sqrt{2}}\right)\right) + L(H^* - 1), & \text{if } X \le 0 \\ (H^* - 1)(L - X), & \text{if } 0 < X \le L \end{cases}$$

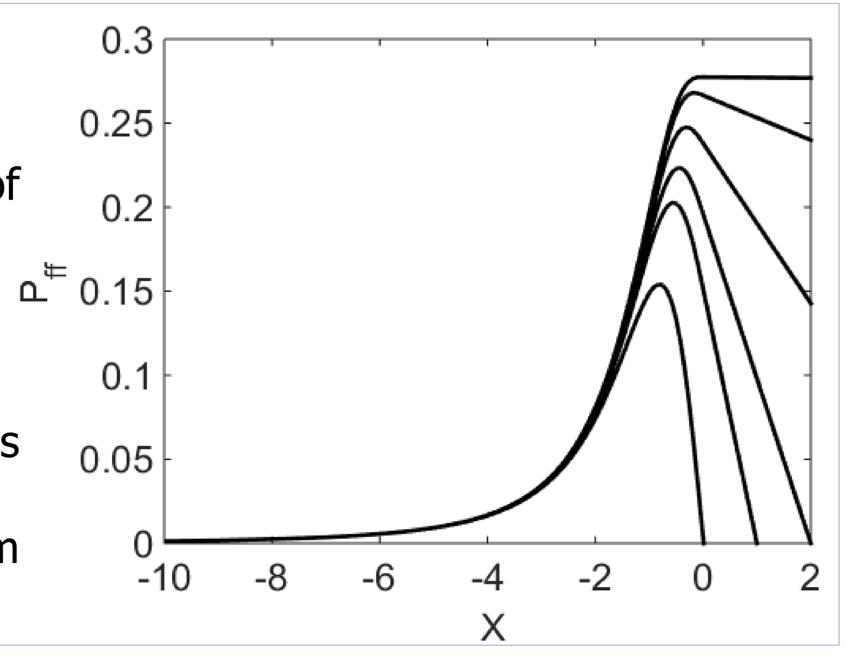
Results: fully-flooded regime

Pressure distribution

H^* determines the starvation level.
For the fully-flooded case, H^* is a function of the length of the flat part L:

$$H^*_{ff} = \frac{4\pi\sqrt{2} + 16L}{3\pi\sqrt{2} + 16L}$$

The figure shows the pressure distributions for L = 0, 1, 2, 5, 10, ∞ (bottom to top).
The maximum pressure roughly doubles from L = 0 to L = ∞.

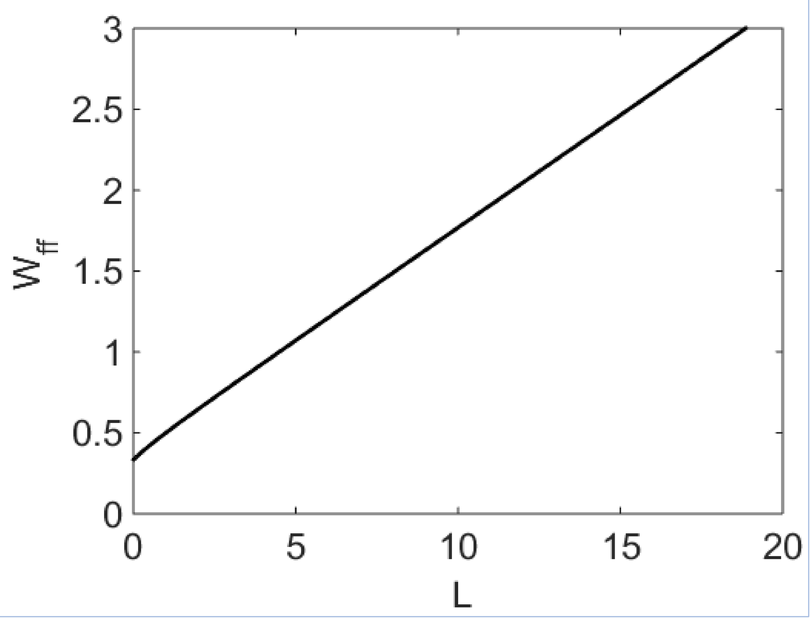


Load carrying capacity

Integrating the pressure distribution yields the load carrying capacity W as a function of L:

$$W_{ff} = \frac{1}{3\pi\sqrt{2} + 16L}\left(\pi\sqrt{2} + L\left(8 + \frac{\pi L}{\sqrt{2}}\right)\right)$$

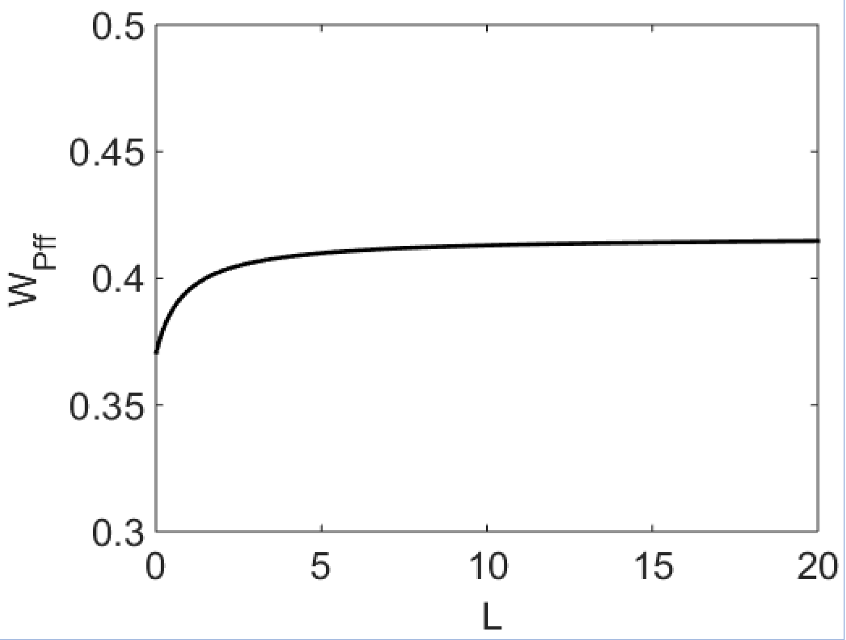
The figure shows how the load carrying capacity increases linearly with the length of the flat zone L, as the integral is dominated by the $LP_0/2$ term , ($P_0 = (H^*-1)L$).



Poiseuille tangential component

$$W_{Pff} = \frac{1}{\sqrt{2}(3\pi\sqrt{2} + 16L)}\left(3\pi L + \frac{\pi^2}{\sqrt{2}}\right)$$

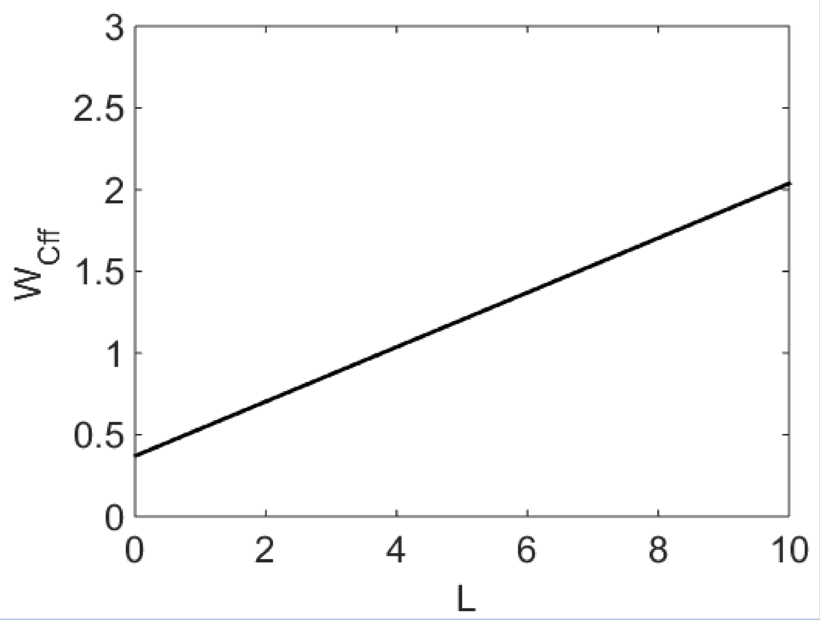
The figure shows that the Poiseuille tangential force W_P rapidly reaches an asymptotic value as the inlet contribution tends to a constant as well as the flat area that tends to $-P_0/2$.



Couette tangential component

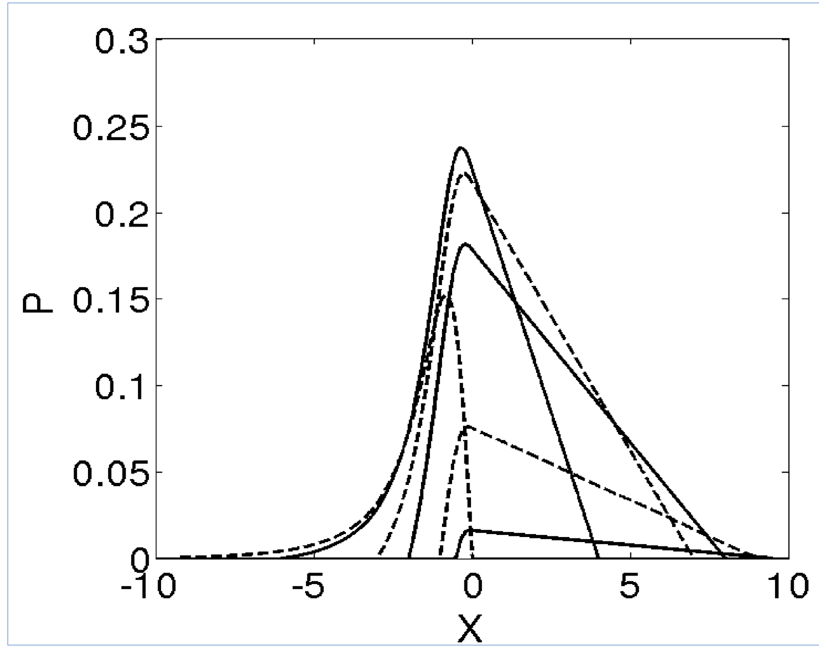
$$W_{Cff} = \frac{SRR}{12}\left(L + \frac{\pi}{\sqrt{2}}\right)$$ *(SRR = slide-to-roll ratio)*

The figure shows that the Couette force W_C increases linearly with the flat length L, as the friction depends on the geometry only. Hence the inlet zone contribution is constant and the flat zone contribution increases linearly with L.



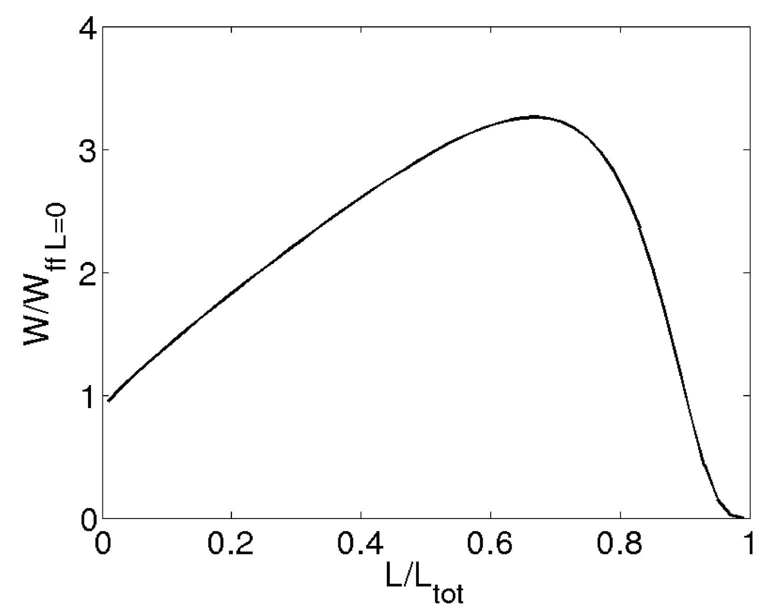
Results: starved regime

Pressure distribution



H^* varies from 1 to $H^*_{ff} \in [1; 4/3]$.
In that case one can study the behaviour as a function of the flat profile width divided by the total profile width $L_{tot} = 10$.
The figure shows the pressure distributions for various parabolic section starts (X = -10, -6, -3, -2, -1, -0.5). The flat section always begins at X = 0. The maximum pressure reaches its largest value for $L/L_{tot} \approx 0.45$.

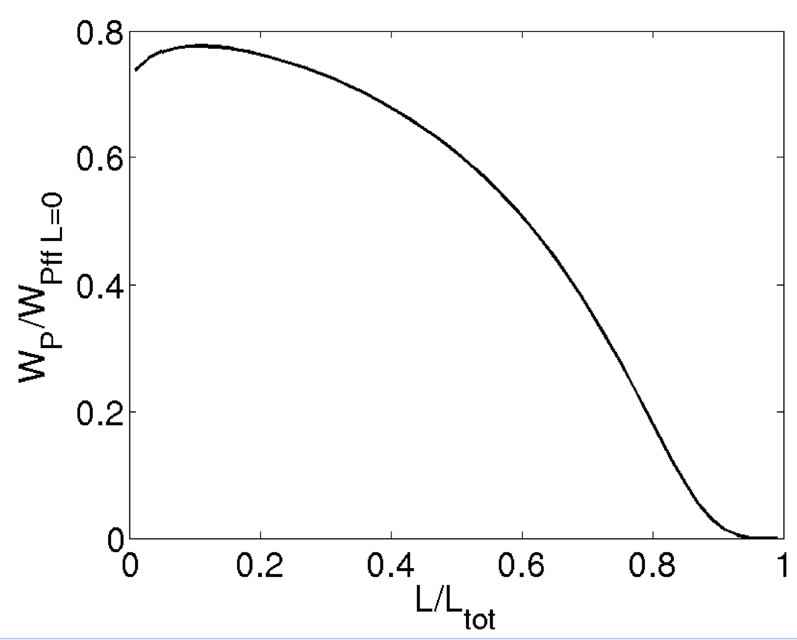
Load carrying capacity



$$W = \int_{X_a}^{L} P(X)dX = \int_{X_a}^{0} P(X)dX + \frac{LP_0}{2}$$

The LCC reaches a maximum for $L/L_{tot} \approx 0.67$.
The LCC is divided by the fully flooded parabolic value, as such the curve starts slightly below 1.
When the parabolic inlet length tends to 0, severe starvation occurs and as a consequence, the (relative) LCC tends to 0.

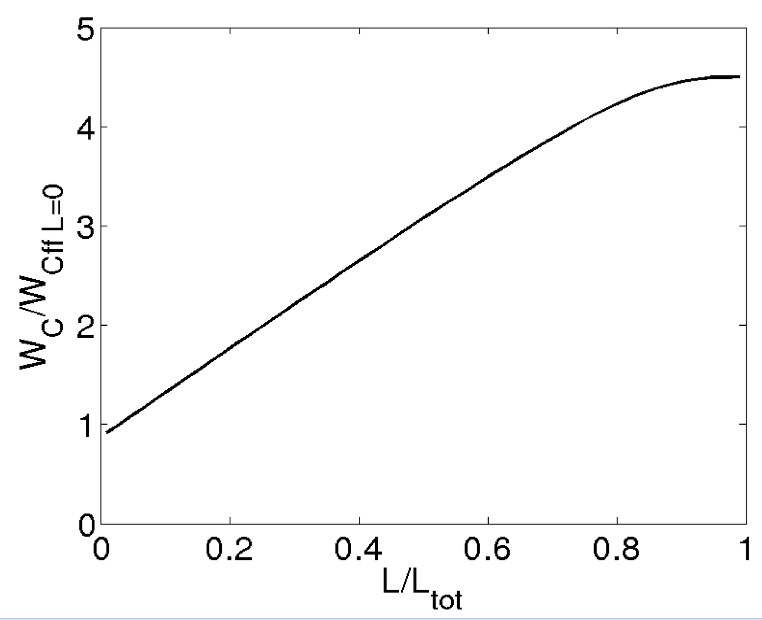
Poiseuille tangential component



$$W_P = \int_{X_a}^{L} \frac{H(X)}{2}\frac{\partial P}{\partial X}dX = \int_{X_a}^{0} \frac{H(X)}{2}\frac{\partial P}{\partial X}dX - \frac{P_0}{2}$$

The Poiseuille friction increases for small L values, as the maximum pressure increases.
For L/L_{tot} approaching 1, the friction tends to zero, as the entire pressure distribution tends to zero and pressure driven flow vanishes.

Couette tangential component



$$W_C = \frac{SRR}{12}\left(L - \sqrt{2}\arctan\left(\frac{X_a}{\sqrt{2}}\right)\right)$$

For low L values, the tangential Couette friction increases linearly with L, whereas for L values between 8 and 10, the friction reaches an asymptotic value, as the film thicknesses in inlet and flat part are close.

Conclusion

- Due to the simple geometry, it is possible to find analytical solutions for the pressure distribution, the load carrying capacity and the Couette and Poiseuille friction.
- Using the fully flooded results as reference, the fixed width ring behaviour is studied and the evolution of the friction and LCC outlined for a total ring width of $L_{tot} = 10$.
- The results are analysed and the trends explained in terms of geometrical starvation.

[1] Biboulet N., Colin F. and Lubrecht A.A., 2013, "Friction in Starved Hydrodynamically Lubricated Line Contacts", *Tribology International*, 58, pp. 1-6

[2] Noutary M.P. and Lubrecht A.A., 2002, "Starved Lubrication of Isoviscous Rigid Circular Contacts," *Proceedings of the 29th Leeds-Lyon Symposium on Tribology*, pp. 713-718

Leeds-Lyon, September 6-9, 2015

camille.pettavino@insa-lyon.fr
LaMCoS, Université de Lyon, CNRS, INSA-Lyon UMR5259, 18-20 rue des Sciences - F69621 Villeurbanne Cedex

LaMCoS Unité Mixte de Recherche 5259

Laboratoire de Mécanique des Contacts et des Structures