# Three-Dimensional Model of Lubrication and Dynamics for The Piston Ring-Pack in Internal Combustion Engines

(Ph.D. Proposal)

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## 1. Motivations

Development of engine power cylinder system, namely, piston, piston rings, and liner are driven by three factors. First, power cylinder system directly contributes to engine oil consumption, friction, and gas leakage called blow-by, all of which need to be minimized to meet engine performance requirements. Second, new engine development with a trend of higher specific power and downsizing engines constantly presents challenges to the power cylinder system design for fitting into new environment. Finally, reducing engine development lead time and minimizing amount engine tests are critical to engine and component manufacturers and thus better understanding of the power cylinder system with physically based models becomes necessary.

Lubrication and dynamics of piston ring pack are of great importance to the engine performance, as they play determining roles for engine oil consumption and ring friction that is a significant portion of the total engine friction. Most existing models [1-5] are mainly two-dimensional (2D) or quasi three-dimensional (3D) ones with negligence of the structure response of piston rings and they have been proved to be effective in assisting engineers to analyze piston ring overall behavior and to predict the performance of the power cylinder system [6,7]. However, there exist a number of important characteristics in the power cylinder system that are critical to the performance of the piston ring pack and understanding their effects require full resolution of the ring structure response to dynamic loadings and its effects on sealing and lubrication. By far, the modeling work that couples ring structure analysis with lubrication, dynamics, and gas flow has been limited in terms of physical considerations and practical usage.

First, a piston ring is not a perfect circle and has a gap. For compression rings, a proper free shape has to be designed to achieve designated ring tension and contact pressure distribution when a ring is fitted into the cylinder bore. Furthermore, the cross section of the ring may be designed to be asymmetrical so that a twist can be created when the ring is fitted into the bore to control oil and gas leakage. Currently piston ring designers rely on crude formula and experience to design ring free shape and twist chamfers with little consideration of the consequences of the ring reaction in a distorted bore under dynamic loadings during engine operation. A complete ring design tool with finite element structure analysis and physically based reaction force models can help ring designers to define rings more effectively.

Second, the cylinder bore is not perfectly rounded due to mechanical and thermal distortion. Higher bore distortion generally needs higher ring tension to control oil consumption and consequently brings in greater ring friction. Indeed, bore distortion perhaps can be regarded as the most critical factor for optimization of the ring pack to balance friction and oil consumption. Ability to answer the following questions is critical to developing most efficient engine effectively:

1. Given bore distortion, what is the best ring design that gives minimum friction and satisfies the oil consumption requirement?
2. What is the requirement of the bore distortion if one needs to reach certain friction and oil consumption requirements?

A theoretical model that can be of practical use needs coupling of ring/liner lubrication, ring conformability to the distorted bore and also the ring/groove interaction, and flow continuity among different rings in a piston ring pack.

Third, the interaction of ring and groove is not uniform along the circumference due to groove waviness, existence of ring gap, non-uniformity of ring twist, and piston dynamic tilt. As a result, the leakage of gas and oil through the groove may be much more complicated than what 2D model can describe. Additionally, there exists gas and oil flow on the piston lands in the circumferential direction due to non-uniform gas pressure distribution from one ring gap to the other. In fact, it was found experimentally, the oil flow driven by the gas flow on the piston lands may be the main mechanism to drive the oil down and thus is of great importance to oil consumption studies [8,9]. Furthermore, resolving ring twist along the circumference is a key step to model the ring/liner lubrication in a distorted bore.

In summary, it is recognized that further advancement in understanding the piston ring pack behavior in the power cylinder system needs modeling of a number of critical 3D features listed above, which is the main focus of this proposed thesis work.

## 2. Objectives and Methodology

This study will be focused on three subjects: ring conformability and ring free-shape calculation, ring dynamics (including blow-by gas flow), and ring lubrication. The ring conformability and ring free-shape calculation will be targeted for an independent ring design tool that can be used in the early stage of ring design. On the other hand, the calculated ring tension distribution for rings will be taken as input in the ring dynamics and lubrication calculations. For ring dynamics and ring lubrication, although they are associated to each other, author plans to treat them independently in some sense since it would be too difficult to couple them together. Finite element method will be used to resolve the displacement of the ring structure and the forces.

### 2.1 Ring Conformability and Ring Free-Shape Calculation

When a ring at its free state is inserted into the cylinder bore, the tension distribution along the ring circumference is determined by its free-shape. Calculating the tension distribution will be accomplished by employing step-by-step FEM, as the large deformation calculation is involved. As depicted in Fig.1, nodes on the ring are moved by external force to conform to the bore one after another. The force pattern applied on the ring at the moment when all the nodes coincide with the bore is the final tension distribution. For ring with asymmetric cross-section, the ring static twist will be calculated in this process, depending on the axial constrain applied.

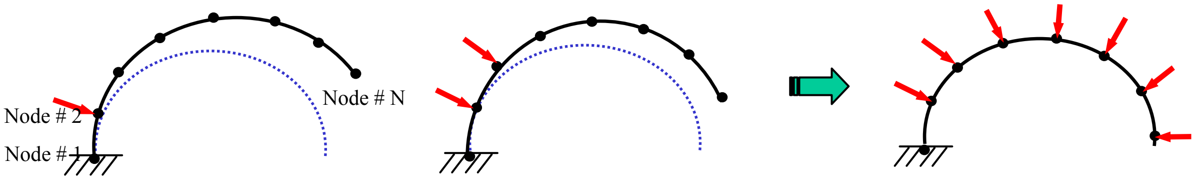

Figure 1

It’s of practical interest to calculate the free-shape of a ring to have a desired ring tension distribution. By going through the opposite process as stated above, we can archive this task. As shown in Fig.2, starting from a ring with desired tension pattern applied, release those loads one by one, until when there are no external force acting on the ring and the shape is the free-shape being after.

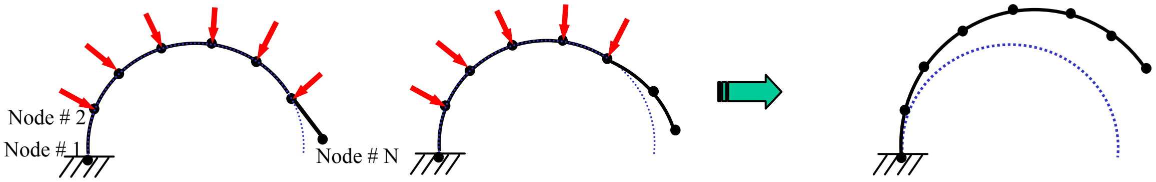

Figure 2

## 2.2 Ring dynamics Modeling

The ring dynamics calculation will address all the 3D effects brought by the ring structure and bore distortion as well as piston tilt for both compression rings and twin-land oil control ring. Blow-by gas flows inside and between all the regions will also be solved simultaneously with the ring dynamics.

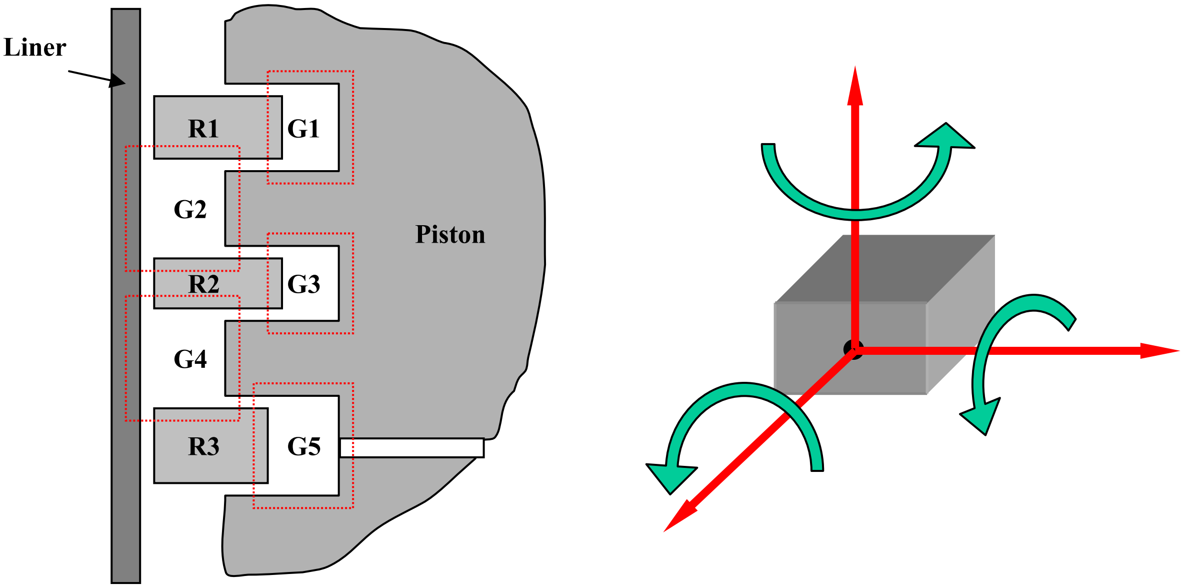

Figure 3

The whole system includes three piston rings and five gas zones that are formed by rings, piston and liner as sketched in Fig.3. System variables include the displacements of ring nodes and gas pressure in all the gas zone nodes. For each ring node, six degrees of freedom are identified (Fig.3), namely three linear displacements and three angular displacements. For each gas zone node, only pressure is considered as unknown. Thus there are twenty-three variables for every cross-section of this system. Appling Newton's 2nd Law to each ring gives:

$$M_m \ddot{U}_m + K_m U_m = R_m \quad (m = 1, 2, 3)$$

where $U_m$ is the vector of the displacement of the ring, $\ddot{U}_m$ is the vector of second order derivatives of the displacements, $M_m$ is the mass matrix of ring structure, $K_m$ is the stiffness matrix of the ring, and the $R_m$ is the load vector. In this formula, the velocity-dependent damping term is omitted and can be thought as included in the load vector $R_m$ if necessary. Ideal gas law for each gas zone node can be written as:

$$\frac{d}{dt}\left(\frac{P_{k,i} V_{k,i}}{RT}\right) = \dot{m}_{k,i} \quad (k = 1, 2, 3, 4, 5; i = 1 \cdots N)$$

Implicit integration scheme is employed to solve above nonlinear governing equations and calculate all the variables that are changing with time.

Forces applied to ring node coming from liner, groove and gas pressure. The ring-groove force is asperity contact force only, while the ring-liner force has two components: asperity contact and hydrodynamic lubrication. The hydrodynamic lubrication force, including radial force and axial friction, play important roles in ring dynamics. Coupling ring dynamics with precise ring lubrication is complicated, time consuming and thus will not be adopted in this study. In order to have a reasonable consideration of ring lubrication, simple lubrication model will be incorporated.

Gas flow in the channel between ring and groove, circumferential gas flow within piston lands and within groove can be modeled by fully developed viscous channel flow. While orifice flow is more suitable for gas flow through ring gaps.

### 2.3 Ring Lubrication Modeling

As stated in previous section, simplified hydrodynamics lubrication model will be incorporated with the 3D dynamics model. The details on the simplified hydrodynamic model are yet to be determined based on the tradeoff between the complexity and the accuracy. Once the 3D ring dynamics is successfully resolved, the ring-liner forces and ring-liner relative angles at all cross-sections along the ring circumference can be obtained. Those results will be used as input to existing 2D lubrication model, which has comprehensive consideration of ring-liner lubrication, to model ring lubrication. It's still a pseudo-3D approach but with more reasonable 3D ring tension and twist input. Communications between 2D and 3D model will be made to pursue the system convergence.

### 2.4 Experimental Verification

There are several experimental sources that can be utilized to verify the 3D ring dynamics and lubrication model.

- Blow-by gas flow rate and gas pressure in different zones are available.
- Ring axial lift data are available.
- The 2D LIF video can provide intuitive oil transportation information in lands, which can be used to estimate the circumferential gas flow in the lands.
- Ring and groove wear patterns after certain amount of testing hours is available to check the ring-groove interaction.
- As the bore distortion data is not easy to get, ring with free-shape that can provide equivalent ring-liner conformability as bore distortion will be designed and used in the engine test. The effects of ring-liner conformability on ring lubrication will be studied in both numerical and experimental approach and the results will be compared.

## Timetable

Ring design tool for ring conformability and free-shape calculation have been finished and extensive testing and application in industry is ongoing. High-quality results have been obtained. (current state)

3D ring dynamics model without ring lubrication has been developed. (current state)

Coupling 3D ring dynamics with simplified hydrodynamics lubrication. Making pesudo-3D ring lubrication analysis by using 2D model and comparing with the simplified lubrication model. Finalizing the model. (3 months)

Experimental data collection and model verification. (4 months)

Analysis, discussion and thesis writing. (5 months)

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