

# Novel design concept for Rayleigh step bearing with high robustness against step height change due to frictional wear

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**ABSTRACT** – In this study, a novel design concept for Rayleigh step bearings was developed focusing on the contact pressure distribution within the contact interface. In general cases, wear rate is proportional to the contact pressure. It indicates that shape changes due to friction wear can be controlled by the optimization of the pressure distribution. This paper presents a simplified model and an experiment for this concept.

## 1. INTRODUCTION

Rayleigh step bearings have been used in several mechanical systems with a fluid lubrication [1]. In these systems, shape changes due to wear commonly reduces their performance. Thus, the prevention of wear is the first choice to keep their designed performance.

In this study, for an alternation method, we developed a novel design concept for Rayleigh step bearings. In this concept, the normal contact pressure distribution was provided for controlling the wear rate distribution within the contact interface. In the region, in which a higher contact pressure was applied, a relatively large shape changes occur. In contrast, in lower pressure regions, shape changes will be small. It indicates that the optimization of the pressure distribution is one of the important design factors to determine the robustness against step height changes due to frictional wear. Based on the above idea, this paper demonstrated a simplified modeling and experimentation.

## 2. MODELING

Figure 1 illustrates a simplified model for wear processes in the proposed Rayleigh step bearing. The contact surface is comprised of separated two blocks (A and B), which are supported by two springs with spring constants  $k_A$  and  $k_B$ , respectively. A counter face moves in the  $X$  direction with a constant speed  $V$ . In the contact interface, the total normal load  $W$  was applied.

Figure 1(a) shows an initial condition, at which no normal load was applied; thus, there is a step height of  $H_0$ . The depicted symbols  $y_A$  and  $y_B$  mean natural lengths of springs A and B, respectively. And then, the normal load  $W$  was instantaneously applied, as illustrated in Figure 1(b). In both cases, the counter face has yet to be moved ( $t = 0$ ); these blocks have initial thickness  $l_{A0}$  and  $l_{B0}$ .

After a certain time  $t_1$ , some frictional wear occurs under an identical total load  $W$  (dead loading condition), as shown in Figure 2(c). The thickness of these blocks

changes to  $l_{A1}$  and  $l_{B1}$  because of wear. The lengths of springs are also changed to  $y_{A1}$  and  $y_{B1}$ . Therefore, the normal loads  $P_{A1}$  and  $P_{B1}$  applied on the blocks A and B were given,

$$\begin{cases} P_{A1} = k_A(y_A - y_{A1}) \\ P_{B1} = k_B(y_B - y_{B1}) \\ W = P_{A1} + P_{B1} \end{cases} \quad (1)$$

After a small time  $\Delta t$ , as shown in Figure 1(c), the wear processes slightly progress; thus, the thickness of these blocks were changed to  $l_{A2}$  and  $l_{B2}$ . The lengths of springs are also changed to  $y_{A2}$  and  $y_{B2}$ . As is the case in Figure 1(b), the normal loads  $P_{A2}$  and  $P_{B2}$  were given,

$$\begin{cases} P_{A2} = k_A(y_A - y_{A2}) \\ P_{B2} = k_B(y_B - y_{B2}) \\ W = P_{A2} + P_{B2} \end{cases} \quad (2)$$

Assuming that Archard's wear law can be used to describe the wear process [2], wear heights of these blocks  $\Delta l_A$  and  $\Delta l_B$  during small period  $\Delta t$  were given,

$$\begin{cases} \Delta l_A = KV P_{A1} \Delta t / S = \alpha P_{A1} \Delta t \\ \Delta l_B = KV P_{B1} \Delta t / S = \alpha P_{B1} \Delta t \end{cases} \quad (3)$$

Where  $K$  and  $S$  mean the comparative abrasion quantity and the area of contacting face, respectively. It should be noted that in this model, identical values of  $K$  and  $S$  were used between blocks A and B for the simplified discussion.

From equations (1) to (3), the changes of normal loads during period  $\Delta t$  were summarized as follows,

$$\begin{cases} P_{A2} - P_{A1} = \frac{\alpha k_A k_B}{k_A + k_B} (P_{B1} - P_{A1}) \Delta t \\ P_{B2} - P_{B1} = \frac{\alpha k_A k_B}{k_A + k_B} (P_{A1} - P_{B1}) \Delta t \end{cases} \quad (4)$$

Furthermore, above equations can be summarized as a single form using  $\Delta(P_A - P_B) = (P_{A2} - P_{B2}) - (P_{A1} - P_{B1})$ ,

$$\Delta(P_A - P_B) = -2 \frac{\alpha k_A k_B}{k_A + k_B} (P_{A1} - P_{B1}) \Delta t \quad (5)$$

Considering that the value of  $\Delta X$  was described as  $X_{i+1} - X_i = \alpha (P_{Ai} - P_{Bi}) \Delta t$ , the equation for describing the changes of the step height  $H$  was finally obtained,

$$X = \alpha C C' - \frac{k_A + k_B}{2 k_A k_B} C e^{-2 \frac{\alpha k_A k_B}{k_A + k_B} t} \quad (6)$$

Where integral constants  $C$  and  $C'$  were given

$$C = \left| \frac{k_A W - 2 k_A k_B H_0 - k_B W}{k_A + k_B} \right|, C' = \frac{H_0}{\alpha C} + \frac{k_A + k_B}{2 \alpha k_A k_B} \quad (7)$$

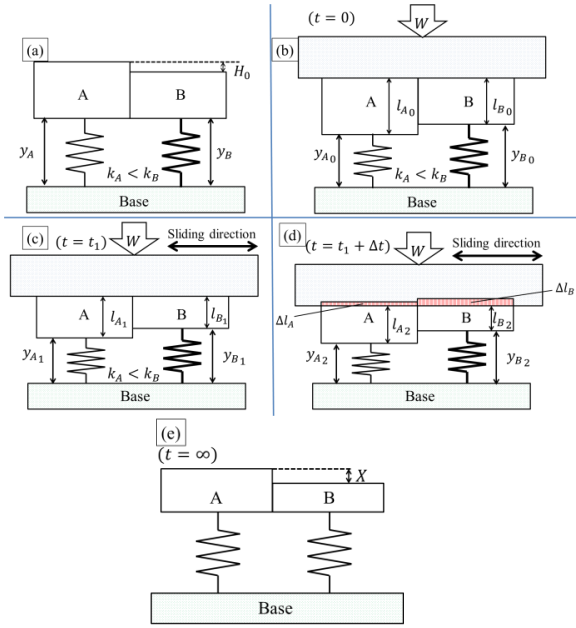


Figure 1 Wear process model.

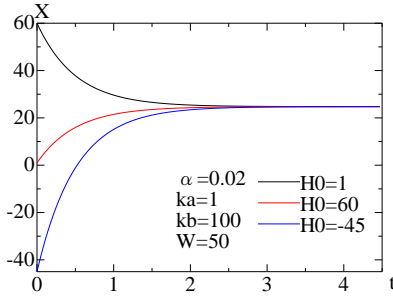


Figure 2 calculation results of Equation (6).

Figure 2 shows examples of the calculation results of Equation (6). All curves have a same asymmetric value. It means that the step height was spontaneously approaches to the designed value resulting from the progress of frictional wear, even if the initial height has a different value, as shown in Figure 1(e). Thus, it will be expected that, even if an unexpected height changes due to severe wear occur, the step height can be reshaped to the designed value by the positive use of frictional wear, i.e., high robustness.

### 3. EXPERIMENTAL DETAILS

To demonstrate the validity of this developed, a simple experiment shown in Figure 3 was performed. The difference of supporting stiffness in the models was given as the difference of supporting materials. The spring A and B correspond to a soft elastomer block made of polydimethyl siloxane (PDMS) (the Young's Modulus: 2.8MPa), and Aluminum block, i.e.,  $k_B \gg k_A$ . Cross-section area of blocks A and B are  $20 \times 20$  mm. The contact surface was frictioned against a polishing paper (#1500) at a constant normal load 5 N. Noted that as a lubricant, a common mineral oil was used. The step height between A and B was measured every 5 minutes by a profile-meter.

Figure 4 shows the experimental results. In the initial condition, the step height is relatively small. The step height gradually increases with time until 10 min. In contrast, after 10 min, no changes of step height were observed. Thus, as expected in the modeling, the value of step height approaches to an asymptotic value. The value was 100  $\mu$ m.

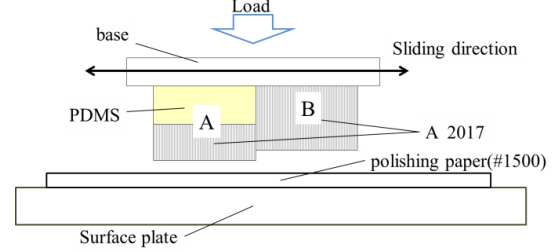


Figure 3 Schematic of experimental setup.

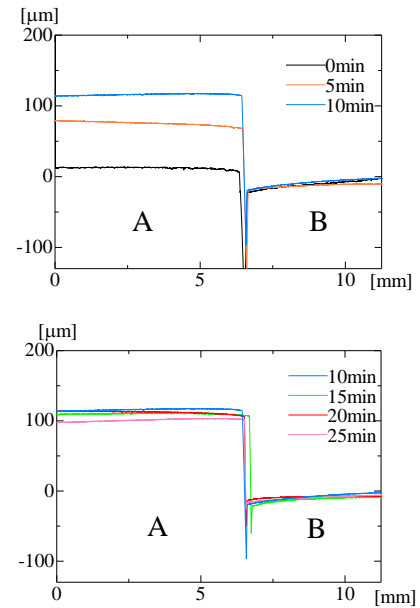


Figure 4 Height between A and B; upper (0 – 10 minutes), lower (10 - 25minutes).

### 4. CONCLUSION

We suggested a novel design concept for Rayleigh-Step bearings focusing on the positive use of frictional wear. The proposed concept was demonstrated by the simplified modeling and experimentation. The design of normal contact pressure distribution considering the progress of frictional wear will be a key to optimize the sliding performance of the Rayleigh step bearings.

### 5. REFERENCES

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