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Technical Note

Estimation of Probability Density Functions of Damage Parameter for Valve Leakage Detection in Reciprocating Pump Used in Nuclear Power Plants

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ABSTRACT

This paper presents an advanced estimation method for obtaining the probability density functions of a damage parameter for valve leakage detection in a reciprocating pump. The estimation method is based on a comparison of model data which are simulated by using a mathematical model, and experimental data which are measured on the inside and outside of the reciprocating pump in operation. The mathematical model, which is simplified and extended on the basis of previous models, describes not only the normal state of the pump, but also its abnormal state caused by valve leakage. The pressure in the cylinder is expressed as a function of the crankshaft angle, and an additional volume flow rate due to the valve leakage is quantified by a damage parameter in the mathematical model. The change in the cylinder pressure profiles due to the suction valve leakage is noticeable in the compression and expansion modes of the pump. The damage parameter value over 300 cycles is calculated in two ways, considering advance or delay in the opening and closing angles of the discharge valves. The probability density functions of the damage parameter are compared for diagnosis and prognosis on the basis of the probabilistic features of valve leakage.

1. Introduction

Because reciprocating pumps are widely used as fluid power pumps in fluid machines that require a high degree of safety, such as those in nuclear power plants, the number of studies on the monitoring and prognostics of the reciprocating pump during operation has been steadily increasing. Each cylinder of a reciprocating pump system consists of suction and

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discharge valves and a piston connected to a crankshaft driven by an electric motor. During one cycle, a low-pressure fluid enters through the suction valve and flows out through the discharge valve after it is compressed to a high pressure. The suction and discharge valves are opened or closed by the pressure difference between the two sides of each valve. Especially when each valve is closed, it impacts each valve stopper. Repeated impacts can damage the rim of the valve. In this study, a mathematical model is developed to quantize the damage of the suction valve, and an estimation method to obtain the probability density functions of a damage parameter is presented.

Mechanical behaviors of pumps have been investigated numerically and experimentally with mathematical models to accurately predict the mechanical behavior of each component in the pump design stage and to diagnose damage during operation [1–3]. Lee et al. [4] developed a unified mathematical model to explain not only the normal state of the reciprocating pump, but also its abnormal state. They successfully calculated the value of a damage parameter by comparing cylinder pressure profiles, which were simulated and measured in a compression mode, during each cycle. In that study, two cylinder pressure profiles in compression and expansion modes were compared for damage parameter calculation. The effective cross-sectional area related to the valve leakage was defined, and its probability density functions were obtained. In our study, the mathematical model is extended and simplified to compare measured and simulated pressure profiles, not only in a compression mode, but also in an expansion mode. Using the mathematical model, the probability density function of the effective cross-sectional area will be obtained.

Many studies have been carried out on the precise prediction of mechanical behavior in reciprocating pumps. Shu et al. [5] developed a model for pressure pulsation in a reciprocating pump piping system. Johnston [6] proposed a numerical model of a reciprocating pump with self-acting valves. Singh and Madavan [7] included the piping system in the reciprocating pump model for complete simulation. Able [8] considered the acceleration head in a reciprocating pump model. Rudolf et al. [9] optimally designed reciprocating pumps used in natural gas wells. Henshaw [10] studied the valve dynamics of the power pump. In addition, Jarell et al. [11] reviewed prognostics-based and condition-based maintenance of a scientific crystal ball.

This paper is organized as follows. A unified mathematical model developed in our previous work [4] is improved to explain the mechanical behavior of a single-cylinder reciprocating pump not only in a normal state, but also in an abnormal state brought on by suction valve damage. The simulated cylinder pressure profiles will be compared with measured cylinder pressure profiles not only in a compression mode, but also in an expansion mode. In a normal state, the specific values of the tuning parameters are determined and then an effective cross-sectional area related to the amount of damage of the suction valve is calculated. On the basis of the effective cross-sectional area calculated over 300 cycles, the probability density function of the damage parameter is obtained depending on the amount of damage in the suction valve.

2. Mathematical expression of single-cylinder reciprocating pump

To develop a mathematical model for the mechanical behavior of the single-cylinder reciprocating pump (see Fig. 1A), the previous approach [4] is recalled and simplified for the model under consideration. The water flows into the cylinder through the suction valve (see Fig. 1B) and flows out of the cylinder through the discharge valve (see Fig. 1C). The valves are opened and closed automatically depending on the force difference between the two sides of the valves. It is assumed that the crankshaft is rotating at a constant speed and the material properties of the working fluid (water) do not change during operation, except for its bulk modulus. In this study, a unified mathematical model developed in a previous study is improved to describe the normal and abnormal states of the reciprocating pump.

2.1. Volume flow rate

The volume flow rate (Q_c) of the cylinder is expressed in Eq. (1) by using the Reynolds transport theorem [12]:

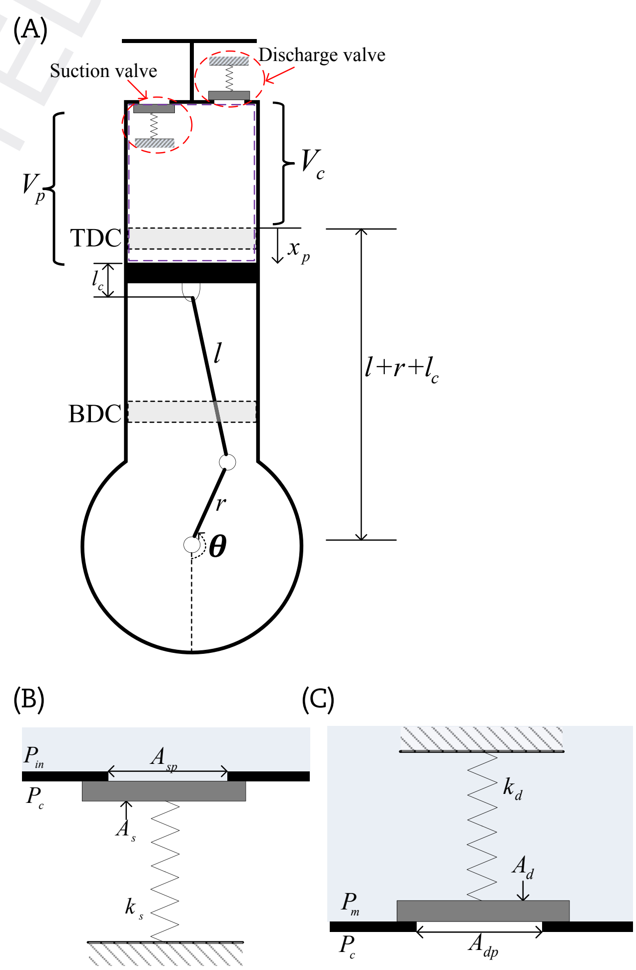

Fig. 1 – Single-cylinder reciprocating pump. (A) Schematic diagram, (B) suction valve, and (C) discharge valve. BDC, bottom dead center; TCD, top dead center.

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