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Determination of Effective Force Area and Valve Behavior on the Rolling Piston Type Compressor

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ABSTRACT

The design of valve plays the most critical part in determining the efficiency of compressors. Therefore, it is useful to have an analytical model and an empirical data of the effective flow and force area which govern the mass flow rates and the forces on the valves.

On the basis of these motivation, we set up test equipment, and carried on experiment of effective flow and force area. The natural frequency of valve is not constant due to boundary condition change during its motion from valve seat to retainer, considering the results of the modal test. Therefore, it is necessary to decide the contact (wrap) point between the valve and the retainer (stopper). For this, we develop the finite element modeling which can consider the effect of the retainer preventing valve from over - lift by assuming reaction (contact) force.

As a conclusion, we find out that it is possible to predict the valve dynamic behavior considering the retainer position according to the pressure variation.

INTRODUCTION

For the good design of compressors, there are a lot of research topics and study experiences around the world. In this study, we limit ourselves to valve design of the discharge system of compressors. The reason why we have interests in the valve system is that the valve behavior is closely related to over - compression loss and reliability problems[1]. When predict the dynamic behavior of valve, it is necessary to obtain the effective force area by including the effect of the retainer restricting over - lift. It might be not correct to assume a specific contact point between retainer and valve. For the evaluation of the wrapping of the valve around the retainer at some undertermined rate, the tangency point of the retainer to the valve was assumed to be clamping point[2]. However, the nonliner function of the natural frequency and the effective length of the valve against valve lifts are necessary in this method. Therefore, we introduce an assumed contact force induced from the retainer when the valve hits it, and decide the contact point by comparing height between the valve and the retainer.
1. **Valve dynamics**

The dynamics of valve is represented by the vibration of the valve plate. Assuming the valve as a beam with varying width and neglecting the shear, the valve dynamic equation can be described as follows:

\[
\frac{\partial^2}{\partial x^2} \{EI(x) \frac{\partial y(x,t)}{\partial x} \} + \rho A(x) \frac{\partial^2 y(x,t)}{\partial t^2} = F(x,t) \\
\]

(1)

where $E$: Young's module, $I(x)$: moment of inertia, $y(x)$: valve deflection, $\rho$: plate density, $A(x)$: valve section area, $F(x,t)$: force

2. **Finite element modeling**

For the calculation of valve deflection, and eigenvalues and eigenvectors, the shape function of beam is introduced. After application of finite element procedure, equation (1) be rearranged as follows:

\[
[M]_e \{\ddot{x}\} + [K]_e \{\dot{x}\} = \{f\}_e \\
\]

(2)

3. **Solution technique for eigenvalue problem**

For the efficient calculation of eigenvalues and eigenvectors, Irons-Guyan reduction method from IMSL (subroutine EIGZF) package is adopted:

\[
[M]_e \{\ddot{x}\} + [K]_e \{\dot{x}\} = \{f\}_e \\
\]

(3)

where $\{x_1\}^T = \{y_1, y_2, \ldots, y_n\}$, $\{x_2\}^T = \{\theta_1, \theta_2, \ldots, \theta_n\}$

In this case, Rayleigh-Ritz vector $R$ can be defined as [3]

\[
R = \begin{bmatrix} I \\ -k_{22}^{-1}k_{21} \end{bmatrix} \\
\]

(4)

Hence, the reduced eigenvalue problem can be arranged as follows:

\[
m^*\ddot{x}_1 + k^*x_1 = f^* \\
\]

(5)

where $k^* = R^T k R = k_{11} - k_{12}k_{22}^{-1}k_{21}$, $f^* = R^T f$

\[
m^* = R^T m R = m_{11} - m_{12}k_{22}^{-1}k_{21} - k_{12}k_{22}^{-1}(m_{21} - m_{22}k_{22}^{-1}k_{21}) \\
\]

Finally, the generalized coordinate form is obtained, thereby, it can be solved with well-known 4th-
orther Runge-Kutta algorithm:

\[ \ddot{q} + \Omega \dot{q} = Q \]  \hspace{1cm} (6)

where \( \Phi^T \Phi = I \), \( \Phi^T \Phi = \Lambda = \begin{bmatrix} \Omega_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \Omega_n \end{bmatrix}, \ Q = \Phi^T f^* \)

4. Determination of forces on the valve

4.1. Pressure force

Neglecting the force due to the gas momentum, the pressure force on the valve can be easily calculated by multiplying the pressure difference across the valve with an effective force area which is a function of valve deflection \([4]\). Therefore the generalized force form can be described as the equation below:

\[ F_{ip} = \sum_i A_{eff} (y(x_{fix}, t)) \Delta P(t) [N(\xi_i)] \]  \hspace{1cm} (7)

where, \( A_{eff} \) is the effective force area and \( x_{fix} \) is a distance between the valve clamped point and the center of discharge port.

4.2. Assumed reaction force due to the retainer

The maximum deflection of valve is maintained due to the retainer mounted above the valve. In case of rolling piston type compressor, the retainer has a curvature similar to the first mode shape of valve. Therefore, it is very difficult to decide the contact point between the valve and the retainer. For the modeling of the effect of retainer, the concept of an assumed reaction force is used.

\[ F_{ir} = K_i \delta_i(t) [N(\xi_i)] \]  \hspace{1cm} (8)

where, \( K_i \) is a contact stiffness and \( \delta_i(t) \) is a contact penetration

\( \delta_i(t) \) can be divided into two cases as following eq. (9) by comparing the valve deflection and the retainer height, and be described in Fig. 1.

\[ \text{if } y(x_i) \geq R(x_i), \quad F_{ir} = K_i (y(x_i) + V(x_i) \Delta t - R(x_i)) [N(\xi_i)] \]  \hspace{1cm} (9a)

where \( V(x_i) = \frac{dy(x_i)}{dt} \)

\[ \text{if } y(x_i)(R(x_i), \quad F_{ir} = 0 \]  \hspace{1cm} (9b)

where, \( y(x_i) \) is a valve deflection, \( R(x_i) \) is a retainer height

EXPERIMENT

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5. **Experiment of the effective force area**

5.1. The basic equation

The effective force area can be calculated from the equation below [5]:

\[ F = A_{\text{eff}} (P_u - P_d) \]  \hspace{1cm} (10)

where, \( A_{\text{eff}} \) is an effective force area, \( P_u \) is an upstream pressure and \( P_d \) is a downstream pressure.

5.2. Experimental apparatus

For the simple experiment, ambient air instead of freon gas is used as a working fluid. Experimental apparatus is described in Fig. 2. By controlling the function generator and audio amplifier, the solenoid valve can generate the arbitrary pressure profile. The air inhaled is accumulated in the wind house. And the compressor bearing is installed on the upper part of wind house for maintaining the exact valve seat condition. The pressure difference is measured by pressure transducer, and the valve deflection by the strain gage. Finally, measured data and electrical signals are converted by FFT system.

**RESULTS**

6. Results of experiment and numerical analysis

6.1. The case of non-contact of retainer

The effective force area, \( A_{\text{eff}} \) is obtained by eq.(10) and the result is shown in Fig. 3. The pressure difference is measured as in Fig. 4. The experimental and the simulation result are compared in Fig. 5. Even though there is a little difference of the maximum height between them, the trend of valve behavior is well matched each other.

6.2. The case of contact of retainer

In this case, the valve motion is restricted by retainer. The pressure difference is shown in Fig. 6. Also, the results of simulation using the assumed reaction force have good agreements with the ones by experiment on the maximum flat level in Fig. 7.

**CONCLUSION**

From this study, we can simulate the valve behavior using the effective force area obtained from the experiment, and also can consider the effects of the retainer which has a curvature shape using the assumed reaction force modeling.

Therefore, it is possible to predict the valve motion with the effective force area and the pressure
difference without calculation of the nonliner function of the natural frequency against the valve lifts.

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Fig. 2 Schematic diagram of test apparatus of displacement / effective force area
Fig. 1. Contact penetration

Fig. 2. Valve lift - effective force area without retainer

Fig. 3. Valve lift - effective force area without retainer

Fig. 4. Time - pressure difference without retainer

Fig. 5. Time - valve lift without retainer

Fig. 6. Time - pressure difference with retainer

Fig. 7. Time - valve lift with retainer