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STUDIES ON THE PRESSURE PULSATION OF PLENUM CHAMBER IN RECIPROCATING COMPRESSOR USING RECOGNITION TECHNIQUE

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ABSTRACT

In this paper, the plenum chamber is assumed to be a grey box . The gas flow is especially paid attention to in the observable parts outside the chamber, such as the valve plate at the suction or discharge pipe ends. Pressure excitation is used as the excitative source of gas pulsation in piping system. A mathematical model on the pressure pulsation at the end of the inlet is established by means of the reflective theory and the transmissive theory of plane wave with a revised factor introduced. Having recognizing the model by experiments, it is indicated that the theoretical calculation is in agreement with the experimental results. Thus, the boundary condition may be more accurately provided to solve the equation of gas pulsation in piping system.

INTRODUCTION

Having made a survey of the research on the gas pulsation in reciprocating compressors, most of the workers pay particular attention to the piping system. In these studies, the pulsation parameters of gas flow are considered to be even in the plenum chamber, or the pulsation pressure is identical at the inlet and outlet of plenum chamber. In addition, the excitative function of gas pulsation in piping system is the velocity excitation which is proportional to the piston speed[1] . In this study , the authors consider the effect of both the movement of the valve plate and the unevenness of the parameters of gas flow in plenum chamber on the gas pulsation in piping system should not be neglected. Moreover, a method has been proposed to study the pressure pulsation of plenum chamber is reciprocating compressor by using recognition technique.

In this study, the plenum chamber is assumed to be a grey box without analyzing the gas flow inside the chamber in detail. The gas flow is especially paid attention to in the observable parts outside the chamber, such as the valve plate and the pige ends. In solving for the pulsation pressure at various parts such as cylinder, valve plate, inlet or outlet of plenum chamber, and piping system, compressor and piping system are considered as a whole. At the same time, the pressure ahead of valve is used as the excitative function to solve for the pulsation pressure of the whole system. The function of pressure excitation is obtained from simultaneously solving movement equation and energy equation of valve.

In the function, the effect of valve movement on gas pulsation is considered. A revised factor is introduced in consideration of non one dimentional flow of the gas generated by the complex shape of the plenum chamber.

In this paper, the suction chamber is exemplified to establish a mathematical model for calculating the pulsation pressure at the outlet of suction chamber. A relevant experiment is designed for recognition. It is indicated that the theoretical calculation is in agreement with the experimental results. Making a comparison with the other models, this mathematical model more exactly expresses the pressure pulsation ahead of the suction valve plate, and objectively reflects the boundary condition of the piping system.

MODEL ESTABLISHMENT

Due to the irregular geometry of the plenum chamber in compressor, the gas flow in the chamber is more complex, thereby it is impossible that the gas flow is even. The fundamental equations can not be used to describe the gas change in the chamber, thus the effect of gas pulsation in the plenum chamber on the piping system can not be taken into account also.

In the present study, the plenum chamber is treated as an intermediate to link pipe and compressor. The plenum chamber is assumed to be a grey box. The movement mechanism is not studied inside the grey box, but the observable information on the connection of the plenum chamber to pipe and compressor. Now, the grey box problem used to treat the problem with unclear mechamism inside is often solved by using recognition technique. Thus, in this study, the pressure pulsation of plenum chamber is also solved by the recognition technique, and the main steps are given by a flowchart as shown in Fig.1. Then, the mathematical model is established on the basis of the reflective theory and the transmissive theory of plane wave.

The model is established taking the suction chamber for example, as shown in Fig.2. Due to the intermittent open and close of the valve plate, the pressure pulsation is caused ahead of the valve. Under the action of the pressure excitation, the pressure wave is transmitted to the plenum chamber. Some of the pressure wave is reflected back, and some of one is transmitted through. Therefore, the values of the pulsation pressure is different between the point 1 and point 2 in Fig.2. If the pressure value at point 1 is assumed as an input information, and the pressure value at point 2 is assumed as an output information, the relation between the input and output can be established on the basis of the plane wave theory.

Fig.3 gives a physical model of figure 2, and the plenum chamber is assumed as a volume element with the length of D and cross–section of S S_1 is the flow area of the valve, and S_2 is the flow area of suction pipe. To simplify, the end of suction pipe is assumed to be non–reflective. P_i^1 and P_r^1 express the incident wave and the reflective wave respectively in the pipe S_1 . P_{tt} and P_r express the transmissive wave in the plenum chamber, and the reflectieve wave generated in interface 2, respectively. P_t^2 is the transmissive wave in the pipe S_2 . Based on the solution of wave equation, there exist the

following expressions:
for the incident wave

$$P_i = A\, e^{j\omega(t - x/a)}$$

for the reflective wave

$$P_r = B\, e^{j\omega(t + x/a)}$$

Because the pressure is identical and the velocity is continuous at the interface, it is given that at the interface 1

$$P_i^1 + P_r^1 = P_{ti} + P_{ri},$$

$$S_1\, (u_i^1 + u_r^1) = S\, (u_{ti} + u_{ri})$$

at the interface 2

$$P_{ti} + P_{ri} = P_i^2$$

$$S\, (u_{ti} + u_{ri}) = S_2 u_i^2$$

Thus, the change of the amplitude of pressure wave before the plenum chamber and behind the chamber may be given as

$$\| P_{iA}^2 \| = \frac{2}{\left[\left(1 + \frac{S_2}{S_1} \right)^2 \cos^2 KD + \left(\frac{S}{S_1} + \frac{S_2}{S} \right)^2 \sin^2 KD \right]^{1/2}} \; \| P_{iA}^1 \| \qquad (1)$$

where K = ω / a, and a is the speed of sound.

In consideration of the irregularity of the chamber shape, non–one dimensional gas flow, reflection at the suction pipe end, effect of damping, and the refraction of the pressure wave, et al., a factor ζ is introduced to revise Eq.(1).

As the pressure wave is composed by multi–order simple harmonic wave, the incident wave at the interface 1 can be expressed as:

$$P^1 = \sum_{n=1}^{\infty} P_n^1 \sin(n\omega t + \varphi_n)$$

Thus, the transmissive wave revised at the interface 2 is

$$P^2 = \sum_{n=1}^{\infty} \zeta_n X_n \qquad (2)$$

or

$$P^2 = \zeta_1 X_1 + \zeta_2 X_2 + \cdots + \zeta_n X_n$$

where

$$X_n = \frac{2 P_n^1 \sin(n\omega t + \varphi_n)}{\left[\left(1 + \frac{S_2}{S_1} \right)^2 \cos^2 K_n D + \left(\frac{S}{S_1} + \frac{S_2}{S} \right) \sin^2 K_n D \right]^{1/2}} \qquad (3)$$

and ζ_n is the revised factor at the n th order, and independent on time. Eq.(2) expresses the relation between the input information (P_n^1) and the output information (P^2).

RECOGNITION

Based on the pulsation pressure measured at the interfaces 1 and 2, the revised factor ζ_i can be determined at various order by using the recognition technique. The values of pulsation pressure were measured in the interfaces 1 and 2 at different rotative speed of seven. 90 values were gotten for each period. The pulsation pressure p^1 at point 1 was analyzed by Fourier's series (for the first 10 orders). The X_i values at the vaious order were calculated by Eq.(3), and the model to be recognized is

$$P^2 = \zeta_1 X_1 + \zeta_2 X_2 + \cdots + \zeta_{10} X_{10}$$

where P^2 is the measured value from the experiment. The present task is to make the solved $\zeta_1 \cdots \zeta_{10}$ meet the following equation

$$\begin{bmatrix} P^2(1) \\ P^2(2) \\ \cdot \\ \cdot \\ P^2(630) \end{bmatrix} = \begin{bmatrix} X_1(1) & \cdots & X_{10}(1) \\ X_1(2) & \cdots & X_{10}(2) \\ \cdot & & \cdot \\ \cdot & & \cdot \\ X_1(630) & & X_{10}(630) \end{bmatrix} \begin{bmatrix} \zeta_1 \\ \zeta_2 \\ \\ \\ \zeta_{10} \end{bmatrix} \tag{4}$$

To simplify,

$$\overline{P} = \overline{X}\ \overline{\zeta}.$$

Due to the approximation of the model and the inaccuracy of the measurement, the determined $\overline{\zeta}$ value may not accurately meet the Eq.(2). The error vector is defined as

$$\overline{\varepsilon} = (\varepsilon_1, \varepsilon_2, \cdots, \varepsilon_{630})^T$$

Let

$$\overline{\varepsilon} = \overline{P} - \overline{X\zeta} \tag{5}$$

and

$$J = \sum_{i=1}^{630} \varepsilon_i^2 = \overline{\varepsilon}^T \varepsilon \tag{6}$$

where J is the criterion number. The determined $\overline{\zeta}$ value should make J value tend to minimum. That is,

$$\left.\frac{\partial J}{\partial \overline{\zeta}}\right|_{\overline{\zeta} = \overline{\zeta}'} = -2\overline{X}^T \overline{P} + 2\overline{X}^T \overline{X\zeta}' = 0 \tag{7}$$

where $\overline{\zeta}'$ is the estimated value of $\overline{\zeta}$. From the Eq.(7), we get

$$\overline{\zeta}' = (\overline{X}^T\ \overline{X})^{-1} \overline{X}^T \overline{P} \tag{8}$$

The 10 values of ζ' can be obtained by computer, as shown in the following table.

Table The ζ' values

Order(n)	1	2	3	4	5	6	7	8	9	10
ζ'_n	0.258	.539	0.034	0.665	0.239	1.343	0.688	1.013	0.528	0.440

The pulsation pressure at the end of suction pipe, that is the pulsation pressure at the interface 2 in Fig.3, can be describe by the following mathematical expression,

$$P^2 = \sum_{n=1}^{10} \zeta'_n \frac{2P^1_n \sin(n\omega t + \varphi_n)}{\left[\left(1 + \frac{S_2}{S_1}\right)^2 \cos^2 K_n D + \left(\frac{S}{S_1} + \frac{S_2}{S}\right)^2 \sin^2 K_n D\right]^{1/2}} \tag{9}$$

EXCITATIVE FUNCTION

Fig.4 shows the various gas parameters before and behind the valve plate. The gas pressure P_s before the value is considered as the pressure excitation function instead of P^1_n in Eq. (9). The pulsation pressure at the suction pipe end 2, and at the any other position of the suction pipe can be obtained.

As the gas pressure P_s before the valve is affected by the movement state of the valve plate, and the change of mass and energy during the gas going through the valve, the P_s value can be obtained by simultaneously solving the gas state equation, mass continuity equation, energy equation, mass–flow rate equation in valve, and movement equation of valve plate inside the control body as shown in Fig.5. The equations for the numerical calculation are shown as follows:

$$\begin{cases} \dfrac{dh}{d\theta} = y \\ \dfrac{dy}{d\theta} = \dfrac{1}{\omega^2 M_v} [\beta(P_s - P_c)S_1 - 2K(H_o + h)] \\ \dfrac{dP_c}{d\theta} = \dfrac{\sqrt{2(P_s - P_c)/(P_s/c)^{1/k}}\,(\alpha_v a_v)}{\omega V_c} \times \\ \qquad \dfrac{\left[kP_s + (k-1)(P_s - P_c)\left(\dfrac{P_s}{P_c}\right)^{1/k} \left(\dfrac{\alpha_v a_v}{S_1}\right)^2 - kP_c v_c A_c \right]}{\omega V_c} \\ \dfrac{P_s}{k-1} - c_o + (P_S - P_c)\left(\dfrac{P_s}{p_c}\right)^{1/k} \left(\dfrac{\alpha_v a_v}{S_1}\right)^2 = 0 \end{cases} \tag{10}$$

In the above equations Ps, Pc, y, h are the unknown, others are constants, among them Mv, β, Z, K, H_o , α_v and a_v represent the valve parameters: valve plate mass, push force coefficient of valve, number of the spring, spring stiffness, pre–compression valve, flow coefficient in valve gap, and area of valve gap, respectively, ω is the rotatory angle speed, k is the adiabatic exponent, A_c is the piston area, and C_0 is the constant.

The initial value and the boundary condition in Eq, (10) are: at the moment of valve open, that is, when $\theta = \theta_s$,

$$h = 0, y = 0, p_c = p_0 - \frac{2KH_0}{S_1}$$

when h = 0, $P_s = P_0$
when h = H, $y_{reb} = -c_R y_{imp}$
where sub reb is the rebound elasticity, Sub imp is the impact, C_R is the coefficient of the rebound elasticity. The Eq.(10) can be solved from the Runge –Kutta method. By the Fourier's analysis, the $P_1^1, P_2^1 \cdots P_{10}^1$ can be obtained from the computed P_s value.

EXPERIMENTAL VERIFICATION

In this experiment the pulsation pressure at different position of plenum chamber was measured. It was proved that there existed the unevenness of pressure distribution in the chamber, as shown in Fig.5. Based on the requirement of establishing model and recognition, the pulsation pressure was measured at 7 different rotatory speeds in points 1 and 2. Then, the established simultaneous equation group (10) was verified. Due to the limit of the paper length, only the results at 500 rpm are given. The curves from our theoretical calculation, the measurement, and the theoretical calculation based on the reference

[1] are given respectively for comparison. Fig.6 shows the pulsation pressure ahead of the valve plate. It is clear that the calculation value based on the present pulsation pressure waveshape is in agreement with the measured value. The calculation indicates the effect of high frequency wave very well due to the movement of the valve plate. However, the calculation result based on the theory proposed in reference[1], in which velocity excitation is used, and the pressure in chamber is evenly distributed, that is, the pulsation pressure is identical at points 1 and 2, is more deviated from the experimental result, and the low frequency wave is reflected well, but the high frequency wave can not be reflected.

The pulsation pressure at pointz calculated by using Eq.(9) is in comparison with the measured value, as shown in Fig.7. The general trend of the pressure wave, and the pulsation amplitude is similar with the measured results. That is because only 10 order excitation is considered in Eq.(9).

CONCLUSION

By means of the pressure pulsation model in plenum chamber established on the basis of the recognition technique and the numerical solution of the pressure excitation, the pressure ahead of the valve, and the pressure pulsation at the end of the suction pipe can be discribed very well.

REFERENCE

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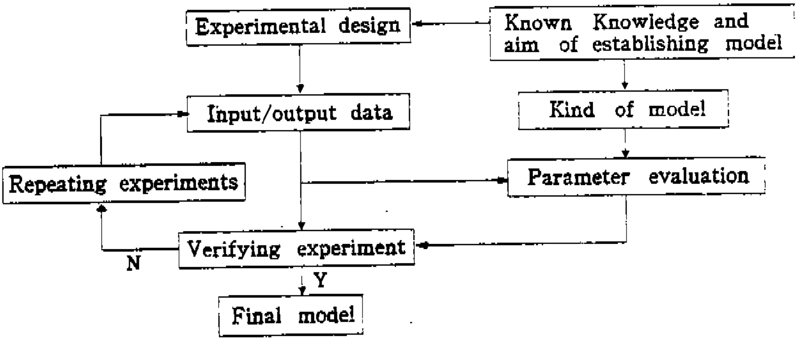
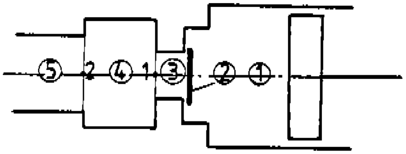


Fig.1 Flowchart



① Cylinder ② Valve plate ③ Passage of the valve
④ Suction chamber ⑤ Suction pipe

Fig.2 Schematic of the suction chamber

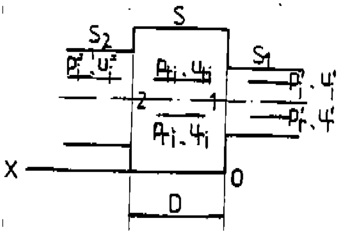
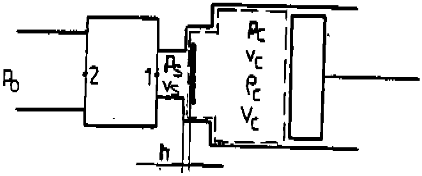


Fig.3 Physical model



p_c, v_c, ρ_c, V_c — Pressure, velocity, density and volume of the gas in cylinder;
p_s, v_s — Pressure and velocity of the gas ahead of the valve;
p_c — Atmosphere.

Fig.4 Schematic of controlling body

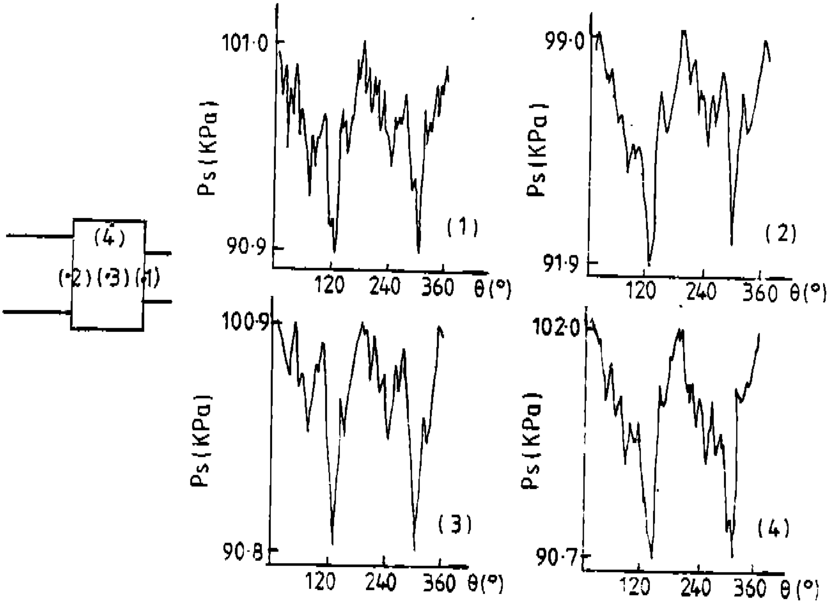


Fig.5 Pulsation pressure wave at various point measured in the plenum chamber

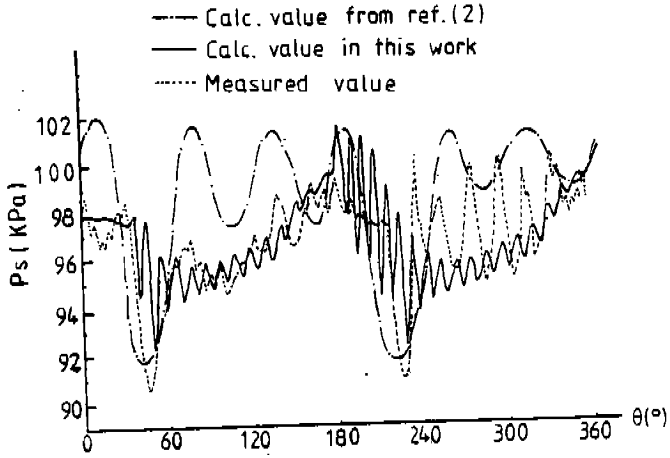


Fig.6 Comparison of the pulsation pressure wave ahead of the valve

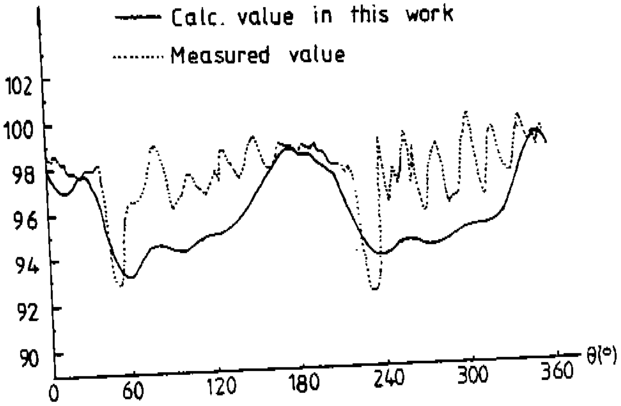


Fig.7 Comparision of the pulsation pressure wave at the end of the suction pipe