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ESTIMATION TECHNIQUE OF AIR CONTENT IN AUTOMATIC TRANSMISSION FLUID BY MEASURING EFFECTIVE BULK MODULUS

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ABSTRACT–It is well known that the entrained air in oil causes appreciable reduction in the stiffness of hydraulic systems. It makes the response delay of the systems and sometimes destroys the stability. Because the hydraulic systems of automatic transmissions are operated in relatively low pressure and high temperature, it is very important to analyze the effects of the air included in automatic transmission fluid. However, it is difficult to derive the generalized model to describe the effective bulk modulus theoretically or measure it in actual operating conditions of automatic transmissions. This paper reviews previous studies of the air effects in hydraulic systems and the measurement techniques of the effective bulk modulus in operating conditions. Based on this work, the theoretical model with moderate complexity and the measurement technique of the effective bulk modulus considering entrained air effect at real operating conditions are suggested. Our paper also shows that the quantity of the entrained air in the automatic transmission fluid can be estimated from the experimental results.

KEY WORDS : Hydraulic system, Bulk modulus, Automatic transmission fluid

NOMENCLATURES

β : Bulk modulus of oil
β_a : Bulk modulus of air
β_e : Effective bulk modulus
γ : Ratio of specific heats for air
ρ : Density of oil
ρ_0 : Density of oil at atmospheric pressure
c : Constant coefficient
c_1 : Correction coefficient for solubility
L : Propagation distance of pressure ripple
m : Mass of air/oil mixture
P : Gauge pressure
P_0 : Atmospheric pressure
R : Air/oil volume ratio at atmospheric pressure
t : Propagation time of pressure ripple
V : Volume
V_0 : Initial volume
V_a : Volume of air
V_{a0} : Volume of air at atmospheric pressure
V_f : Volume of oil
V_{f0} : Volume of oil at atmospheric pressure
v : Velocity of sound

1. INTRODUCTION

Bulk modulus, the reciprocal term of compressibility, is the index of stiffness among the physical properties of fluid. Generally, the bulk modulus of the pure oil used in hydraulic systems is very high, but the entered air during the operations of the systems causes the appreciable reduction of the system stiffness. A part of the mixed air dissolves in molecular form and has little effect on the bulk modulus. On the other hand, the rest of it, entrained air, exists in the form of small bubbles, and significantly reduces the effective bulk modulus of the fluid. It makes the system slow, and sometimes unstable. As the hydraulic systems of automatic transmissions are operated in relatively low pressure and high temperature, the entrained air in automatic transmission fluid has large volume and low solubility. Therefore, it is important to analyze the effect of the entrained air on the compressibility or the bulk modulus. However, it is difficult to derive the generalized theoretical model of the effective bulk modulus for air-oil mixture with moderate complexity. Additionally, it is not easy to measure the effective bulk modulus during the operation of the system in various real situations.

This paper carefully reviews previous studies about the

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effects of the air in hydraulic systems and the measurement techniques of the effective bulk modulus in operating conditions. Based on this work, we derive the theoretical model for the effective bulk modulus considering the effect of entrained air at relatively low pressure and high temperature commonly occurred in automatic transmissions. Finally, we suggest the estimation technique of air content from the measurement of the effective bulk modulus.

2. REVIEWS OF THE PREVIOUS STUDIES

2.1. Definitions of Bulk Modulus

There are some kinds of the definitions of the bulk modulus, and they are only applicable to their own specific conditions. Followings are widely used ones in many textbooks.

2.1.1 Secant bulk modulus

$$\beta=-\frac{\Delta P}{\Delta V/V_0} \tag{1}$$

Secant bulk modulus in Equation (1) is expressed as pressure change to volume change per unit volume from initial state. It is sometimes called average bulk modulus, and can be applied to the static process.

2.1.2. Tangent bulk modulus

$$\beta=-V\frac{\partial P}{\partial V} \tag{2}$$

Tangent bulk modulus shown in Equation (2) is the dynamic bulk modulus defined by the differential form of the pressure to the volume. It is generally used in the process that pressure and volume change rapidly near the given pressure. When applied to isentropic process, it is called adiabatic bulk modulus.

2.1.3. Sonic bulk modulus

$$\beta=\rho v^2 \tag{3}$$

Equation (3) expresses the sonic bulk modulus derived only from the sonic velocity in the fluid and its density. Assuming the constant density of the fluid, it is easily obtained from the propagation velocity of pressure wave, so that widely used to measure the dynamic bulk modulus. The sonic bulk modulus has the same value of the adiabatic bulk modulus (Smith, 1960).

2.2. Theoretical Models of Effective Bulk Modulus

In most textbooks, effective bulk modulus is derived from the definition of secant bulk modulus like Equation (4), neglecting the flexibility of the container or the boundary wall (Merritt, 1967; McCloy, 1980).

$$\frac{1}{\beta_e}=\frac{R}{\beta_a}+\frac{1}{\beta} \tag{4}$$

Even though it is simple and clear theoretically, it is difficult to measure the secant bulk modulus in real operating conditions. Therefore, it is impossible to obtain the effective bulk modulus using Equation (4) from experimental data.

Hayward (1960) suggested the Equation (5) for tangent bulk modulus in adiabatic process from the studies of many pioneers.

$$\beta_e=\frac{\frac{1}{R}+\frac{P_0}{P}}{\frac{1}{R}+\frac{P_0\beta}{P}} \tag{5}$$

However, he confused to use the absolute and gauge pressure in Equation (5) without notice, and it is not applicable to measurements for operating condition owing to the assumption of the isothermal process.

Watton (1980) expanded the result of Hayward (1960) for the adiabatic process like Equation (6).

$$\frac{\beta_e}{\beta}=\frac{\left(\frac{P}{P_0}\right)+R}{\frac{R\beta}{\gamma P}\left(\frac{P}{P_0}\right)^{\gamma}} \tag{6}$$

But it is impossible to derive it from Equation (5), and it isn't acceptable that the effective bulk modulus is linearly dependent to the pressure when the process is isothermal.

Yu (1994) suggested the Equation (7) considering solubility of the air in his study on the measurement of bulk modulus in real operating conditions. Furthermore, he suggested and compared some results from its simplified form.

$$\beta_e=\frac{\beta\left(1+\frac{P}{P_0}\right)^{1+\frac{1}{\gamma}}}{\left(1+\frac{P}{P_0}\right)^{1+\frac{1}{\gamma}}+R(1-c_1P)\left(\frac{\beta P_0}{\gamma}-1-\frac{P}{P_0}\right)} \tag{7}$$

In spite of his pioneering study, it is difficult to use the experimental data in operating conditions based on the definition of sonic bulk modulus, because Equation (7) was basically derived from the definition of secant bulk modulus. Additionally, it has some demerits that it is very complex with many unknown parameters including the solubility of the air depending on pressure and temperature.

2.3. Experiments of Effective Bulk Modulus

Measuring bulk modulus of fluid is well standardized for each definitions. But, it is hard to obtain the effective bulk modulus experimentally in hydraulic system under real operating conditions.

Yu (1994) suggested the measurement technique of effective bulk modulus in real operating condition using sonic bulk modulus and method to optimize the unknown parameters. However, he assumed the constant density of fluid in dynamic process that conflicts with the definition of bulk modulus, the gradient of density to pressure.

Manring (1997) pointed out this conflict and attempted to overcome it by volumetric flow measurement. In this case, it is not comfortable to insert the flow rate transducer in real system without any disturbance. Furthermore, as flow rate transducers are generally less accurate than pressure transducers, it has some limitations to use practically.

3. THEORETICAL MODEL

3.1. Assumptions

The maximum system pressure used in most of the automatic transmissions is less than about 10bar. It is relatively low pressure comparable to those of industrial hydraulic applications. On the contrary, the working temperatures of the automatic transmissions are very high, up to about 130°C. Therefore, following assumptions are reasonable (Kemp, 1990).

- Because all passages of the hydraulic system of the automatic transmission are closed and the mechanical contact between air and oil only occurs in the sump, total air content is constant.
- The solubility of the air is constant, because it is very low and hardly changes at low pressure and high temperature.
- The bulk modulus of pure oil is almost constant, because the working pressure of automatic transmissions is significantly lower than the bulk modulus of pure oil.
- The mass of mixed air is negligible compared to that of oil.

3.2. Effective Bulk Modulus

The theoretical model of the effective bulk modulus can be derived from the Equation (5) which is expanded to the adiabatic process. The volume of the air can be represented as the function of the pressure like Equation (8).

$$V_a = \left(\frac{P_0}{P+P_0}\right)^{\frac{1}{\gamma}} V_{a0} \tag{8}$$

For pure oil, Equation (9) can be obtained from Equation (2)

$$\frac{dP}{dV} = -\frac{\beta}{V} \tag{9}$$

Integrating Equation (9), the pressurized volume of the oil can be written as Equation (10) assuming constant bulk modulus.

$$V_f = V_{f0} e^{-\frac{P}{\beta}} \tag{10}$$

For the air-oil mixture, the total volume under same pressure is Equation (11), sum of Equation (8) and Equation (10).

$$\begin{aligned} V &= V_a + V_f \\ &= V_{f0}\left[\left(\frac{P_0}{P+P_0}\right)^{\frac{1}{\gamma}} R + e^{-\frac{P}{\beta}}\right] \end{aligned} \tag{11}$$

where, $R \equiv V_{a0}/V_{f0}$

Equation (12) is the derivative for pressure of Equation (11).

$$\frac{dV}{dP} = -\frac{V_{f0}}{\beta}\left[\frac{R}{\gamma}\left(\frac{P_0}{P+P_0}\right)^{\frac{1}{\gamma}} \frac{\beta}{P+P_0} + e^{-\frac{P}{\beta}}\right] \tag{12}$$

Applying Equation (11) and Equation (12) to Equation (2), it is easy to obtain the effective bulk modulus as Equation (13).

$$\beta_e = \beta\left[\frac{R + \left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}} e^{-\frac{P}{\beta}}}{\frac{R}{\gamma}\frac{\beta}{P+P_0} + \left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}} e^{-\frac{P}{\beta}}}\right] \tag{13}$$

If the pressure is significantly lower than the bulk modulus of oil, the exponential terms in the Equation (13) can be replaced by unity. Therefore, the approximated form of Equation (13) can be expressed like Equation (14).

$$\beta_e = \beta\left[\frac{R + \left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}}{\frac{R}{\gamma}\frac{\beta}{P+P_0} + \left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}}\right] \tag{14}$$

3.3. Estimation of Air Content

To measure the effective bulk modulus of the automatic transmission fluid in real operating conditions, sonic bulk modulus should be used. Yu (1994) assumed that the density of mixed fluid is constant and derived the effective bulk modulus from the sonic velocity directly. However, the density of the fluid is the function of temperature and pressure. Moreover, the pressure variation makes the change of density in spite of constant temperature. Neglecting the mass of air, Equation (3) can be expressed as Equation (15).

$$\beta_e=\frac{m}{V}\left(\frac{L}{t}\right)^2=\frac{\rho_0 V_{f0}}{V}\left(\frac{L}{t}\right)^2 \tag{15}$$

Applying Equation (11) to Equation (15) and replace the exponential terms to unity, the sonic bulk modulus can be obtained as the function of pressure like Equation (16).

$$\beta_e=\rho_0\left(\frac{L}{t}\right)^2\frac{\left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}}{R+\left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}} \tag{16}$$

For adiabatic process, tangent bulk modulus, Equation (15), and the sonic bulk modulus, Equation (16), have the same value. Therefore, the delay time of the pressure propagation between given distance can be expressed as the function of air content and pressure like as Equation (17).

$$t=f(R,P)$$

$$=\frac{\sqrt{\frac{L^2\rho_0}{\beta}\left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}\left[\frac{R}{\gamma}\frac{\beta}{P+P_0}+\left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}\right]}}{R+\left(\frac{P}{P_0}+1\right)^{\frac{1}{\gamma}}} \tag{17}$$

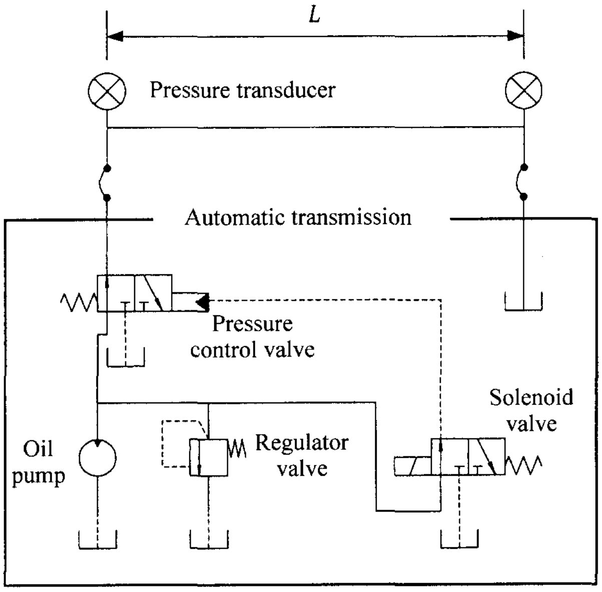

Figure 1. Hydraulic circuit diagram.

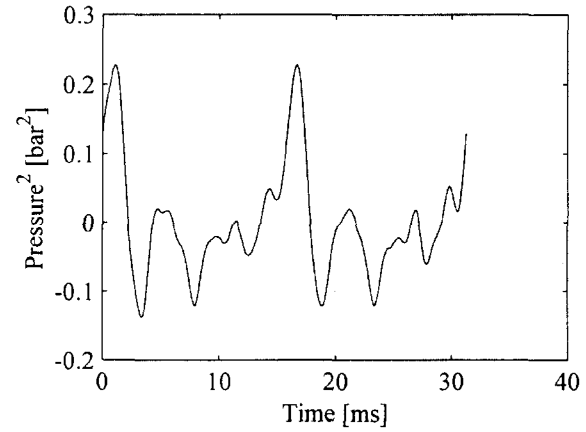

Figure 2. Cross correlation function.

4. EXPERIMENT

4.1. Experimental Apparatus

To measure the sonic velocity in fluid, it is commonly used to measure the propagation time of the wave and calculate the cross correlation function (Childers, 1997). Most of the modern automatic transmissions use the solenoid valve to control the pressure. Using it, the pressure wave can be made, and the waveforms can be captured to calculate the propagation delay time.

Figure 1 depicts the hydraulic circuit diagram of the experimental apparatus. The solenoid valve is the pulse width modulation type and its carrier frequency is 60 Hz. It is used combined with the second stage spool valve, pressure control valve, to amplify flow rate. The external rigid circuit with known length and two pressure transducers are added to the transmission to measure the sonic velocity in the automatic transmission fluid in real operating conditions.

A dual channel dynamic signal analyzer captures the waveforms and calculates the cross correlation function. To reject the noise, it calculates the cross power density spectrum from the multiple data set, averages them in frequency domain, and then performs inverse Fourier transform to get a clean cross correlation function (Peebles, Jr. 1993). This procedure is carried out repeatedly under various pressures.

4.2. Results and Discussions

Figure 2 shows one of the results. The time when the first peak of the waveform occurs means the propagation delay time, and the time between the first and the second peak, about 16ms, is the period of the solenoid valve carrier signal.

From the results and using Equation (17), we can estimate the air content numerically to minimize the

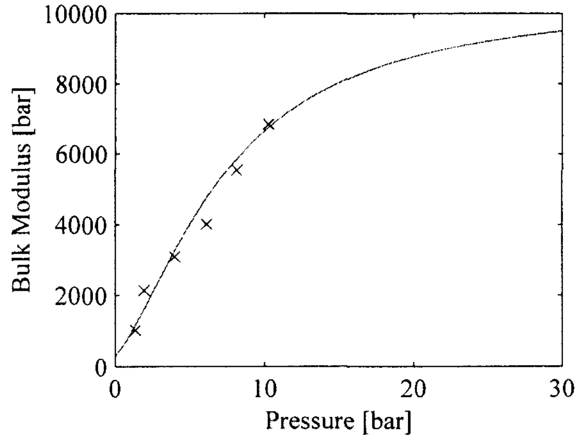

Figure 3. Effective bulk modulus of automatic transmission fluid.

objective function, Equation (18) (Coleman, 1999).

$$\lim_{R}\frac{1}{2}\|f(R,P)-t\|_2^2 \tag{18}$$

Using the estimated air content, the effective bulk modulus regard to the pressure is shown in Figure 3. Under 10bar, the effective bulk modulus drops down rapidly. On the other hand, at higher pressure, the effective bulk modulus asymptotically approaches to the bulk modulus of pure oil.

5. CONCLUSION

Followings are some conclusions of this study:

- The previous studies for the theoretical models and measuring techniques of the effective bulk modulus were reviewed, compared and analyzed. As a result, it pointed out the necessity of the new model and the measurement technique for the hydraulic system operated in relatively low pressure and high temperature.
- The expanded model of the effective bulk modulus for adiabatic process and the theoretical model of sonic bulk modulus considering the variable density for pressure change were established with some assumptions. From these results, it was shown that the air content of the fluid could be estimated from the experimental data.
- From the experiments, the effective bulk modulus of the automatic transmission fluid in certain condition was obtained. We can find that the effective bulk modulus drops down rapidly in low pressure, and at higher pressure, it asymptotically approaches to the bulk modulus of pure oil.

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