Estimating the Air Volume Fraction in Hydraulic Oil by Measuring the Effective Bulk Modulus

Sayako Sakama*, Yuki Kitazawa*, Yoshiki Sugawara* and Yutaka Tanaka**

Aoyama Gakuin University, Department of Mechanical Engineering,
5-10-1 Fuchinobe, Chuo, Sagamihara, Kanagawa, 252-5258, Japan *

Hosei University, Faculty of Engineering and Design, 2-17-1 Fujimi, Chiyodaku, Tokyo 102-8160, Japan **

E-Mail: sakama@me.aoyama.ac.jp

This study demonstrates the utility of estimating the volume fraction of air in hydraulic oil by measuring the effective bulk modulus of the oil. In this paper, we propose a method for measuring and calculating the effective bulk modulus and volume fraction of air in oil and report experiments that show the validity of the method by comparing with the results measured by another method. Our results clarify that the volume fraction of air in oil can be determined by measuring the effective bulk modulus of the oil.

Keywords: Air volume fraction, Effective bulk modulus, Fluid density, Hydraulic system

Target audience: Industrial Hydraulics

1 Introduction

Air bubbles entrained in oil cause many problems in hydraulic systems, such as accelerating oil degradation, reducing thermal conductivity, causing erosion by cavitation and deteriorating the system's overall dynamic characteristics [1/2/]. To prevent these problems, air bubbles must be removed from oil, and the amount of air mixed in the hydraulic system must also be monitored regularly.

To measure the amount of air bubbles in oil, mechanical, optical or electrical methods are available. K. Schrank et al. compared several methods to determine the amount of mixed air in oil in terms of difficulty of application, accuracy and influence of the measuring systems on the flow in the circuit [3/]. In that study, they investigated four methods: measuring fluid compressibility to test mechanical methods, measuring fluid density to test mechanical methods, taking photographs to test an optical method and measuring the electrical permittivity of the fluid. They found that measuring fluid compressibility was the most accurate, although this method suffers the disadvantages of being difficult and influencing the flow in the hydraulic circuit. Since even a tiny amount of air mixed in oil may influence system performance with respect to positioning, power loss, response time and stability, accuracy is vital when measuring the amount of air in a hydraulic system. High-accuracy sensors are expensive and difficult to install in most hydraulic systems, however. To reduce the cost of an air-monitoring system, changes in fluid compressibility can be measured with relatively inexpensive sensors. Moreover, at least in theory, compressibility measurements can indicate the air volume fraction even if a great amount of air bubbles is mixed in.

This study investigates the accuracy of estimating the amount of entrained air by monitoring changes in the compressibility of a hydraulic fluid. We find that this method is nearly as accurate as methods that use expensive sensors. Compressibility can be evaluated by measuring the fluid's bulk modulus. The effective bulk modulus of a fluid decreases when the air volume fraction increases [4/]. In this paper, we propose a method for calculating the air volume fraction from measurements of the fluid's effective bulk modulus. In experimental tests, we measured the effective bulk moduli of hydraulic oil with air bubbles and determined the air volume fraction using the present calculation method.

2 Air Volume Fraction and Effective Bulk Modulus of Oil

The bulk modulus, which indicates the compressibility of a hydraulic fluid, has two definitions: secant bulk modulus $\bar{K}$ and tangent bulk modulus $K/5$. They are expressed as

$$\bar{K} = -V_{p0} \frac{\Delta p}{\Delta V} \quad (1)$$

$$K = -V_p \frac{dp}{dV}, \quad (2)$$

where Δp is the pressure change from initial pressure p_0 to the operating pressure p , V_{p0} and V_p are the fluid volume at p_0 and p , respectively, and ΔV is the fluid volume change from V_{p0} to V_p . A key difference between them is the reference pressure: the reference pressures of $\bar{K}$ and K are p_0 and p , respectively. In this paper, we use the secant bulk modulus $\bar{K}$ to estimate the volume fraction of air at p_0 .

The effective secant bulk modulus of hydraulic fluids depends on the specific fluid, the air volume fraction of the fluid and the operating pressure of the fluid. It can be derived from Equation (3) as

$$\frac{1}{\bar{K}_e} = - \left(\frac{1-x_{p0}}{V_{Hp0}} \frac{\Delta V_H}{\Delta p} + \frac{x_{p0}}{V_{Bp0}} \frac{\Delta V_B}{\Delta p} \right), \quad (3)$$

where V_{Hp0} and V_{Bp0} are the volumes of pure oil and air at p_0 , respectively, and ΔV_H and ΔV_B are the changes in the volume of pure oil and air when the pressure changes from p_0 to p , respectively. In addition, x_{p0} is the volume fraction of air at p_0 and is represented by $x_{p0} = V_{Bp0}/(V_{Hp0} + V_{Bp0})$. Substituting for the secant bulk modulus of pure oil, $\bar{K}_H$, the pure air secant bulk modulus $\bar{K}_B$ and x_{p0} , Equation (3) can be represented according to Equation (4).

$$\bar{K}_e = \frac{\bar{K}_H \bar{K}_B}{\bar{K}_B + x_{p0} (\bar{K}_H - \bar{K}_B)} 1, \quad (4)$$

where $\bar{K}_H$ and $\bar{K}_B$ are functions of the operating pressure:

$$\bar{K}_H = K_{Hatm} + m(p - p_{atm}) \quad (5)$$

$$\bar{K}_B = - \frac{\Delta p}{1 - \left(\frac{p}{p_0} \right)^n} \quad (6)$$

p_{atm} is the atmospheric pressure, K_{Hatm} is the bulk modulus of the pure oil at p_{atm} , m is the slope of the curve relating the oil bulk modulus versus pressure and n is the polytropic constant of air. In this study, we experimentally estimated m and K_{H0} to be 6.6 and 1510 MPa, respectively, as described in the previous study [4/]. We assumed that the fluid is compressed adiabatically, and set n to 1.4. Moreover, each of the experiments in this paper was conducted for a several seconds, so we ignored the volume fraction change caused by air dissolving because dissolution of air into oil takes several tens of seconds [5/].

Using Equations (4)–(6), the volume fraction of air in oil can be calculated using Equation (7).

$$x_{p0} = \frac{\bar{K}_B (\bar{K}_H - \bar{K}_e)}{\bar{K}_e (\bar{K}_H - \bar{K}_B)}. \quad (7)$$

Figure 1 plots the relationship between the effective secant bulk modulus $\bar{K}_e$ and air volume fraction x_{p0} as calculated numerically. The horizontal axis value is the dimensionless bulk modulus calculated by dividing the effective secant bulk modulus by the pure oil secant bulk modulus. The air volume fraction decreases as the

Figure 1: Relationship between the air volume fraction and the ratio of the effective bulk modulus to the oil bulk modulus.

effective bulk modulus increases, which confirms that x_{p0} can be obtained by measuring the effective bulk modulus of the fluid $\bar{K}_e$ when the bulk moduli of pure oil and air are both known. We obtained the effective secant bulk modulus of oil containing air bubbles $\bar{K}_e$ experimentally by measuring the pressure and volume change of the oil and calculating using Equation (1). Then, the volume fraction of air in the fluid was calculated using Equation (7), assuming that $\bar{K}_e = \bar{K}$.

3 Experiment for Measuring the Effective Bulk Modulus

3.1 Experimental setup and condition

The experimental setup for measuring the bulk modulus is diagrammed in Figure 2. The experimental setup consists of a hydraulic-fluid filling circuit, pressure vessel and hydraulic servo cylinder. The open end of the pressure vessel is connected to the tip of the hydraulic servo cylinder. The hydraulic fluid in the pressure vessel is pressurised by the cylinder. The pressure vessel is covered in heat-insulating materials.

ISO VG32 hydraulic oil was used as the test liquid. An air compressor infuses air bubbles into the hydraulic fluid. A precise amount of air bubbles cannot be mixed into the oil without great difficulty, so we could not conduct these experiments with a known amount of air bubbles in the fluid. Therefore, we confirmed the validity of the proposed method for determining x_{p0} from the effective bulk modulus by comparing the results with measurements taken using a Coriolis mass flow metre. This flow metre is placed in-line in the hydraulic-fluid filling circuit and can measure the effective density of the fluid through the circuit. Although the sensor is expensive, it can measure the effective fluid density with high accuracy. When the effective fluid density ρ_{e0} is measured, the volume fraction of air can be estimated using Equation (8) as

$$x_{p0} = \frac{\rho_{Hp0} - \rho_{e0}}{\rho_{Hp0} - \rho_{Bp0}}, \quad (8)$$

where ρ_{Hp0} and ρ_{Bp0} are the oil and air densities, respectively.

Before measuring the bulk modulus, the hydraulic oil with or without air bubbles was circulated through the pressure vessel for a sufficient time to allow measurements of x_{p0} by the Coriolis mass flow metre as the oil

Figure 2: Experimental setup for the measurement of bulk modulus.

Table 1: Experimental conditions.

No.	Air blower	Oil temperature [°C]	Volume fraction of air measured by the Coriolis mass flow meter $x_{p0} \times 100$ [%]
1	OFF	30	0.0
2	ON	35	1.5
3	ON	32	2.9

circulated. We conducted three trials with different air contents in the hydraulic fluid. Table 1 lists the experimental conditions and the measurements of x_{p0} taken by the Coriolis mass flow metre. After the hydraulic fluid in the reservoir circulated adequately in the oil-filling circuit, shutoff valves A and B were closed, and the hydraulic fluid was sampled, confined and stored in the pressure vessel. The sampled hydraulic fluid was then rapidly pressurised by the hydraulic servo cylinder at 10 mm/s. The displacement of the cylinder was then measured using a position sensor and relayed to a personal computer (PC) through a digital controller. The pressure in the pressure vessel was measured using a pressure transducer and logged in the PC. The sampling frequency for displacement and pressure was 1 kHz.

3.2 Experimental results

Pressure–volume curves with the experimental data from all three trials are plotted in Figure 3. In the low-pressure regime, the slope of the curve decreased as the air content increased. This decrease occurred because the air bubble compressibility had more of an effect when the volume fraction of air increased. The broken line through the origin of the coordinate axes is the pressure–volume curve as calculated from the secant bulk modulus of pure oil. Although the experimental result for trial 1, in which the Coriolis mass flow metre measured x_{p0} at 0.0 %, was close to the broken line, a slight difference is noticeable between the two lines. This indicates that the oil in trial 1 could have included a small volume of air bubbles that could not be measured by the Coriolis mass flow metre. The other two broken lines plot the asymptotes of the curves for trials 2 and 3, the slopes of which are equal to $\bar{K}_H / 1$. In many studies [3/ 6/ 7/ 8/], the air volume fraction x_{p0} was estimated by plotting these asymptote and considering $-\Delta V/V_{p0}$ at p_0 to be equal to x_{p0} . The air volume fractions x_{p0} estimated by the present method for trials 2 and 3 were about 1.3 % and 2.7 %, respectively. These values were close to x_{p0} measured by the Coriolis mass

flow metre. Using this method, we could determine the air volume fraction with relatively good accuracy, but the pressure–volume curve must be plotted first.

The effective bulk modulus $\bar{K}_e$ can be calculated from Equation (1) if we assume that it is equal to $\bar{K}$. The changes to the effective bulk moduli are shown in Figure 4, in which the horizontal axis is pressure change Δp . These results clarify that the effective bulk modulus decreased when many air bubbles were mixed in the oil.

When the effective bulk modulus $\bar{K}_e$ of oil containing air bubbles is obtained, the air volume fraction x_{p0} of the oil can be also calculated using Equation (7) without plotting the pressure–volume curve. The effective bulk modulus $\bar{K}_e$ and the air volume fraction x_{p0} when $\Delta p = 20$ MPa are shown in Table 2. These results show that the

Figure 3: Pressure and volume changes of oil with air bubbles and without air bubbles.

Figure 4: Measurement results for the bulk moduli of oil with air bubbles and without air bubbles.

Table 2: Experimental results of the effective bulk moduli and air volume fraction at $\Delta p = 20$ MPa.

No.	Effective secant bulk modulus $\bar{K}_e$ [MPa]	Volume fraction of air calculated by bulk modulus $x_{p0} \times 100$ [%]
1	1640.6	0.0
2	804.9	1.4
3	513.1	2.9

values of x_{p0} calculated from $\bar{K}_e$ shown in Table 2 are in good agreement with those calculated from ρ_{e0} shown in Table 1. We conclude that measuring the effective bulk modulus of the fluid allows us to estimate the air volume fraction in oil. Moreover, we can estimate the air volume fraction using Equation (7) without needing to plot the pressure–volume curves. Although the measuring system of the proposed method is somewhat complicated and cannot estimate volume fraction of air continuously, the system can be constructed with relatively inexpensive parts and can accurately estimate the volume fraction of air in hydraulic oil.

4 Conclusion

In this study, we proposed the method of estimating the air volume fraction of hydraulic oil by measuring the effective bulk modulus of oil with air bubbles. To evaluate the validity of the method, the effective bulk moduli of hydraulic oil with various amounts of entrained air were measured experimentally, and then, the air volume fraction was estimated. Comparison of these estimates with the results obtained by other estimation methods shows that the proposed method can determine the air volume fraction accurately. This method is successful because entrained air has a significant effect on the effective bulk modulus of the fluid.

5 Acknowledgements

This research was supported by the JSPS KAKENHI Grant Number 26420086, 17K18076, the Precise Measurement Technology Promotion Foundation the MIKIYA Science and Technology Foundation, and a grant-in-aid from the Ministry of Economy, Trade and Industry, Japan.

Nomenclature

Variable	Description	Unit
$\bar{K}$	Secant bulk modulus	[MPa]
K	Tangent bulk modulus	[MPa]
$\bar{K}_e$	Effective bulk modulus of oil containing air bubbles	[MPa]
$\bar{K}_B$	Secant bulk modulus of entrained air	[MPa]
$\bar{K}_H$	Secant bulk modulus of oil	[MPa]
K_{H0}	Bulk modulus of air-free oil at atmospheric pressure	[MPa]
m	Slope of the oil bulk modulus versus pressure curve	[–]
n	Polytropic constant of air	[–]
p	Fluid pressure after compression	[MPa]
p_0	Fluid pressure before compression	[MPa]

V_p	Volume of oil containing air bubbles at pressure p	[m ³]
V_{p0}	Volume of oil containing air bubbles at initial pressure p_0	[m ³]
V_{Bp0}	Volume of air at initial pressure p_0	[m ³]
ΔV_B	Volume change of air	[m ³]
V_{Hp0}	Volume of air-free oil at initial pressure p_0	[m ³]
ΔV_H	Volume change of air-free oil	[m ³]
x_{p0}	Air volume fraction of oil at initial pressure p_0	[–]
ρ_{e0}	Density of oil containing air bubbles at initial pressure p_0	[kg/m ³]
ρ_{Bp0}	Density of air at initial pressure p_0	[kg/m ³]
ρ_{Hp0}	Density of air-free oil at initial pressure p_0	[kg/m ³]

References

- /1/ Backe, W., and Lipphardt, P., *Influence of Dispersed Air on the Pressure Medium*, In: Proc. Proceeding of IMechE., C97/76, pp.77-84, 1976.
- /2/ Sakama, S., Goto, H., Higashi, H., Suzuki, R., and Tanaka, Y., *Air Bubble Separation and Elimination from Working Fluids for Performance Improvement of Hydraulic Systems*, In: Proceedings of IFPE 2014, Paper No. 27.1, 2014.
- /3/ Schrank, K., Murrenhoff, H., and, Stammen, C., *Investigation of Different Methods to Measure the Entrained Air Content in Hydraulic Oils*, In: ASME/BATH 2014 Symposium on Fluid Power and Motion Control, Bath, United Kingdom, 2014.
- /4/ Sakama, S., Tanaka, Y., and, Goto, H., *Mathematical model for bulk modulus of hydraulic oil containing air bubbles*, In: Mechanical Engineering Journal, Vol. 2, No. 6, Paper No. 15-00347, 2015.
- /5/ Kazama, T., and Totten, G., E., *Physical Properties and Their Determination*, Handbook of Hydraulic Fluid Technology, 2nd ed., CRC Press, pp. 103-179, 2012.
- /6/ Kim, S., and, Murrenhoff, H., *Measurement of Effective Bulk Modulus for Hydraulic Oil at Low Pressure*, In: Journal of Fluids Engineering, Vol. 134, No. 2, Paper No. 021201, 2012.
- /7/ Gholizadeh, H., Bitner, D., Burton, R., and Schoenau, G., *Modeling and Experimental Validation of the Effective Bulk Modulus of a Mixture of Hydraulic Oil and Air*, In: Journal of Dynamic Systems, Measurement, and Control, Vol. 136, No. 5, Paper No. 051013, 2014.
- /8/ Zhou, J., Vacca, A., and Manhartgruber, B., *A Novel Approach for the Prediction of Dynamic Features of Air Release and Absorption in Hydraulic Oils*, In: Journal of Fluids Engineering, Vol. 135, No. 9, Paper No. 091305, 2013.