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PRESSURE RESPONSE OF HYDRAULIC VESSEL WITH REMOVING ENTRAINED AIR

Iori MASUHARA*, Sayako SAKAMA** and Yutaka TANAKA***

* Graduate School of Engineering and Design, Hosei University
2-17-1 Fujimi, Chiyoda-ku, Tokyo, 102-8160 Japan
(E-mail: iori.masuhara.6y@stu.hosei.ac.jp)
** College of Science and Engineering, Aoyama Gakuin University
5-10-1 Fuchinobe, Chuo-ku, Sagamihara-shi, Kanagawa, 252-5258 Japan
(E-mail: sakama@me.aoyama.ac.jp)
*** Faculty of Engineering and Design, Hosei University
2-17-1 Fujimi, Chiyoda-ku, Tokyo, 102-8160 Japan
(E-mail: y_tanaka@hosei.ac.jp)

Abstract. Hydraulic actuators have high-power density because its oil transmitting power has high rigidity. However, when air bubbles are mixed into working oil, they reduce oil stiffness and decrease actuator efficiency. We have developed a bubble eliminator to separate and eliminate air bubbles from the working oil efficiently. We focus on the relationship between the change in an effective bulk modulus and elimination of air bubbles from the hydraulic oil by the bubble eliminator. Pressure responses and effective bulk moduli of the hydraulic oil with and without air bubbles are experimentally investigated. We conclude that the small volume of air contained in the oil significantly influence the pressure response of the hydraulic system because of changing the bulk modulus of the hydraulic oil.

Keywords: Air bubble, Bulk modulus, Hydraulic actuator, Working oil

INTRODUCTION

Hydraulic actuators have high-power density because its oil transmitting power has high rigidity. However, when air bubbles are mixed into working oil, they reduce oil stiffness and decrease actuator efficiency. Air bubbles are typically mixed into the oil during system operation because of breathing from pump suction ports, excitation and mixing in oil reservoirs, and the occurrence of cavitation. These air bubbles reduce the effective bulk modulus of oil. Bulk modulus is a property that indicates the compressibility of a hydraulic fluid. Oil compressibility strongly influences the performance of hydraulic servo systems [1] and the dynamic behavior of a hydraulic positive displacement actuator [2].

Air bubbles entrained in oil cause many problems to hydraulic systems, such as the acceleration of oil degradation, a decrease in lubricity, a reduction in thermal conductivity, cavitation erosion, and higher noise emissions [3]. To prevent these problems, we have developed a bubble eliminator to separate and eliminate air bubbles from the working oil efficiently [4].

In this paper, we focus on the relationship between the change in an effective bulk modulus and elimination of air bubbles from the hydraulic oil by the bubble eliminator. Pressure responses and effective bulk moduli of the hydraulic oil with and without air bubbles are experimentally investigated.

EFFECTIVE BULK MODULUS

Many researchers [5] have studied and proposed models for the effective bulk modulus that depend on entrained air. The effective bulk modulus of hydraulic oil in low-pressure conditions has been reported by Kim and Murrenhoff [6]. The effective bulk modulus of hydraulic fluid has been measured and expressed as a function of the working pressure when the air content is known [7]. The mathematical model representing the differences of not only the amount of air bubbles but also the process of the pressure change has proposed by Zhou et. al [8]. In the proposed model, some coefficients are determined empirically and depend on the experimental environment. The authors have also proposed the versatile mathematical model by considering the air content and the difference between the pressurized and depressurized processes [9].

A secant bulk modulus of a fluid K is determined by Eq. (1).

$$\frac{1}{K} = -\frac{\Delta V / V_0}{\Delta p} \quad , \tag{1}$$

where V_0 is the initial fluid volume, ΔV (= V-V_0) is the fluid volume change, and Δp (= p-p_0) is the pressure change.
Figure 1 shows a simple model of the compressibility of oil and entrained air with a series of oil and air springs. Therefore, the secant effective bulk modulus of oil and entrained air, K_e, is derived as

$$\frac{1}{K_e} = -\left((1-x_0)\frac{\Delta V_H / V_{H0}}{\Delta p} + x_0 \frac{\Delta V_B / V_{B0}}{\Delta p} \right) , \tag{2}$$

where V_H, V_B, and x_0 are the oil volume, the air volume, and the volume fraction of air in the oil at initial pressure p_0, respectively.
Arranging Eq. (2) using the secant bulk moduli of oil and air, the secant effective bulk modulus K_e can be expressed as follows:

$$K_e = \frac{K_H K_B}{K_B + x_0 (K_H - K_B)} , \tag{3}$$

where K_H and K_B are the secant bulk modulus of oil and air as function of the pressure p, respectively. These values, K_H, K_B are derived from the following representations [10].

$$K_H = K_{H0} + m(p - p_0) \tag{4}$$

$$K_B = np \quad , \tag{5}$$

where K_{H0} (= 1510 MPa) is the bulk modulus of oil at initial pressure p_0, m (= 6.6) is the slope of the oil bulk modulus versus the pressure curve and n (= 1.4) is the polytropic constant of air.
Figure 2 shows the effective bulk modulus change as a function of the operating pressure p calculated by Eq. (3). A small amount of air much influences the effective bulk modulus.

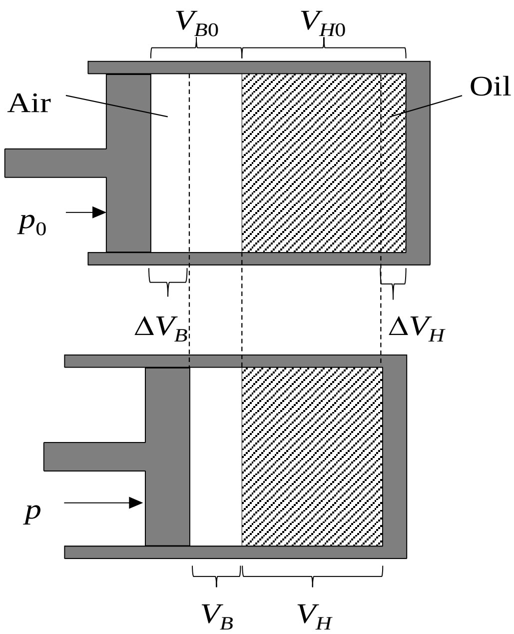

FIGURE 1. Model of the compressibility of entrained air and oil with a series of oil and air springs

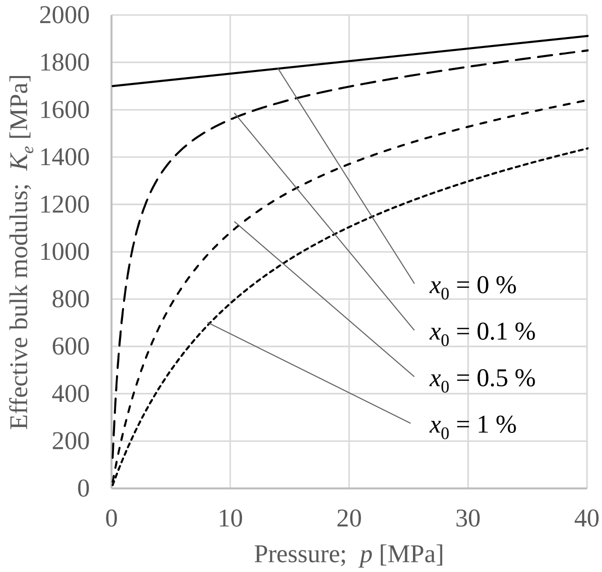

FIGURE 2. Effective bulk moduli as a function of pressure

PRESSURE RESPONSE OF HYDRAULIC VESSEL

Experimental setup and procedure

The experimental setup for the measurement of pressure response is shown in Figure 3. The setup consists of a pressure vessel, oil-filling-circuit, hydraulic servo cylinder, and bubble elimination circuit. The open end of the pressure vessel is connected to the hydraulic servo cylinder. The oil entrained air is pressurized by the servo cylinder. Air bubbles are intentionally infused into the oil at the suction line of the pump of the oil-filling circuit. The amount of air infused into the hydraulic fluid is adjusted via a restrictor and measured using a volumetric flow sensor. The bubble elimination circuit is separately placed at the reservoir. When the air blower is turned off and the bubble eliminator is run for approximately 10 minutes, the air bubbles in the oil are sufficiently separated and eliminated from the oil in the reservoir by the bubble eliminator.

In the experimental procedure, after the oil in the reservoir adequately circulated in the oil-filling circuit, shutoff

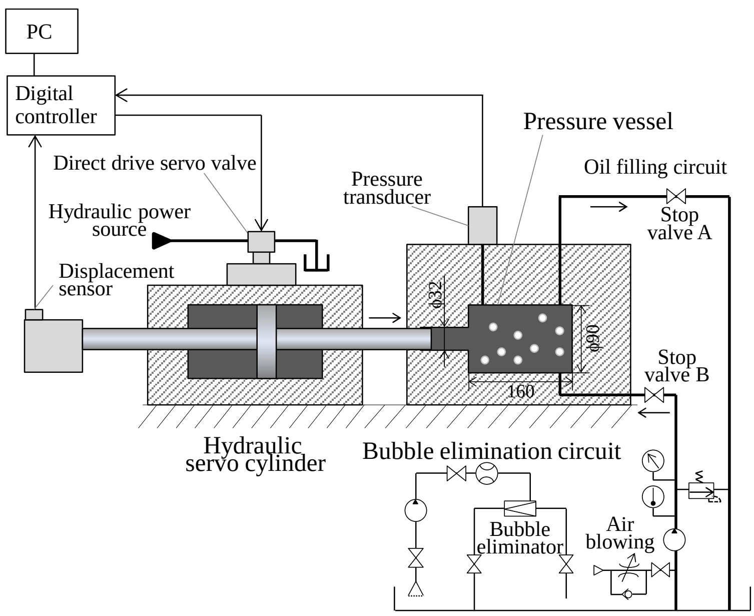

FIGURE 3. Experimental setup for measurement of pressure responses

valves A and B were closed, and the oil was sampled, confined, and stored in the pressure vessel. The sampled oil was immediately pressurized by the hydraulic servo cylinder.
The displacement of the cylinder is measured using a position sensor and fed back to a personal computer (PC) through a digital controller. The pressure in the pressure vessel is measured using a pressure transducer and the results are stored in the PC.

Volume and Pressure Changes

The changes in volume and pressure of the sampled oil for three conditions with air bubbles (Bubbled oil (1) and bubbled oil (2)) and without air bubbles (bubble eliminated oil) are shown in Figure 4, when a step command of the displacement is applied to the servo cylinder. The relative volume change is as small as 0.7%, and the same with and without the air bubbles. The pressure with the bubble eliminator turned on increases up to 10 MPa according to the volume change. On the other hand, the pressure with the eliminator turned off and the bubbled oil (1) and (2) increases up to less than 9 MPa because of the entrained air. The entrained air much influences the pressure response of the vessel.
The pressure–volume curves are plotted in Figure 5. The slope of the tangent to the curve represents the tangent effective bulk modulus. In the low-pressure range, the slope of the curve obtained with the bubble eliminator turned on is larger than that obtained with the bubble eliminator turned off. Clearly, the curves with the bubble eliminator turned on and off are not congruent.
The secant effective bulk moduli calculated by the pressure-volume curves according to each reference pressure in Figure 5 are plotted in Figure 6. The secant bulk modulus of the bubble eliminated oil at the pressure change Δp from atmospheric pressure p_0 (= 0.101 MPa) to the reference pressure p (= 5.00 MPa) is calculated to be 1.41 GPa. The effective secant bulk moduli with air bubbles at the same condition are calculated to be 1.21 GPa (bubbled oil (1)) and 0.82 GPa (bubbled oil (2)), respectively. The volume fraction of air in the oil at initial pressure p_0 can be calculated and estimated by Eq. (3). The estimated values are tabulated in Table 1. These values have good agreement with other estimated values calculated from the oil densities measured by Coriolis flow meter.

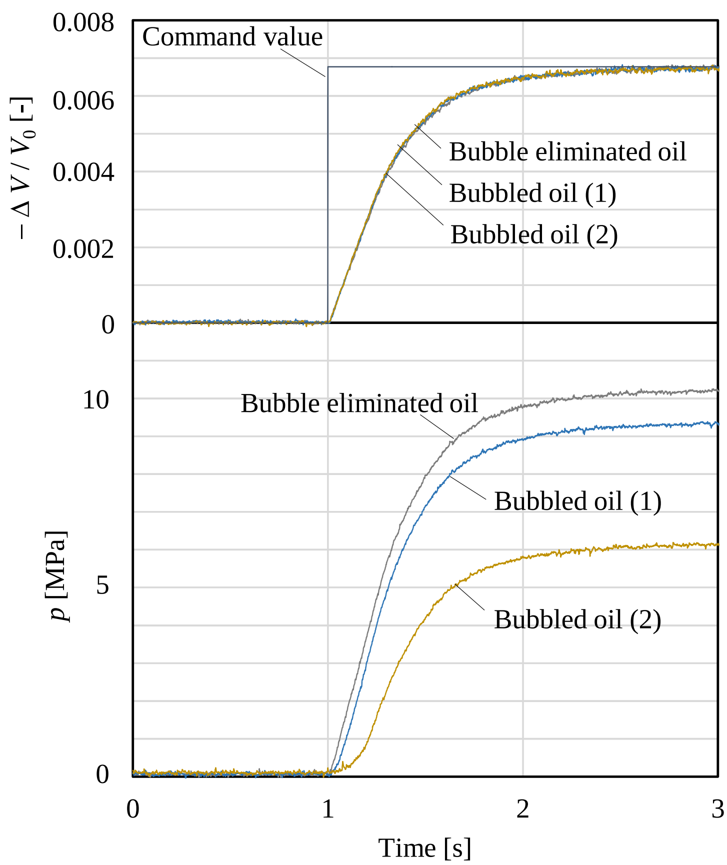

FIGURE 4. Volume and pressure change, with and without bubbles, with step response

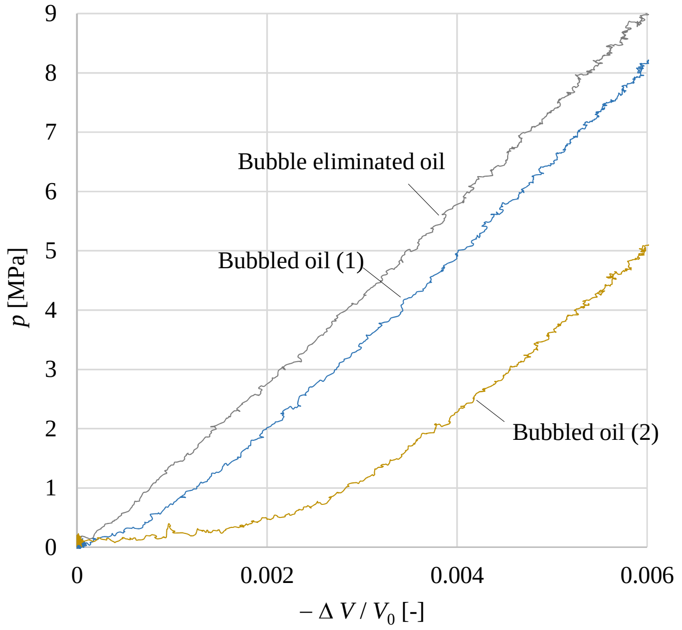

FIGURE 5. Pressure–volume characteristics depending on air contents

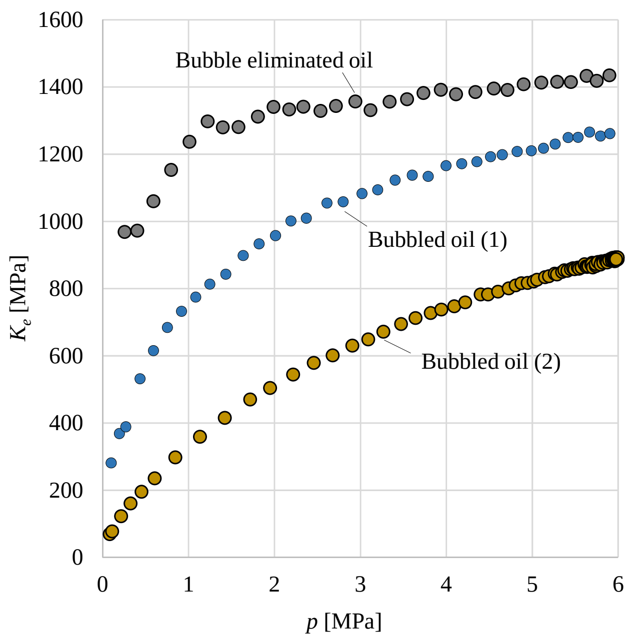

FIGURE 6. Calculated effective bulk moduli by pressure-volume changes

TABLE 1. Estimated volume fraction of air

	Effective bulk modulus [MPa]	Volume fraction of air [%]
Bubble eliminated oil	1407	0.04
Bubbled oil (1)	1209	0.13
Bubbled oil (2)	821	0.41

CONCLUSIONS

In this paper, we focus on the relationship between the change in an effective bulk modulus and elimination of air bubbles from the hydraulic oil by the bubble eliminator. Pressure responses and effective bulk moduli of the hydraulic oil with and without air bubbles are experimentally investigated. We conclude that the small volume of air contained in the oil significantly influences the pressure response of hydraulic systems because of changing the bulk modulus of the hydraulic oil. The volume fraction of air in the oil can be estimated by the mathematical model of the effective bulk modulus.

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