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Measuring Pressure Wave Velocity in a Hydraulic System

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***Abstract*—**Pressure wave velocity in a hydraulic system was determined using piezo pressure sensors without removing fluid from the system. The measurements were carried out in a low pressure range (0.2 – 6 bar) and the results were compared with the results of other studies. This method is not as accurate as measurement with separate measurement equipment, but the fluid is in the actual machine the whole time and the effect of air is taken into consideration if air is present in the system. The amount of air is estimated by calculations and comparisons between other studies. This measurement equipment can also be installed in an existing machine and it can be programmed so that it measures in real time. Thus, it could be used e.g. to control dampers.

***Keywords*—**Bulk modulus, pressure wave, sound velocity.

I. Introduction

PRESSURE wave velocity (sound velocity) is an important factor when hydraulic systems are analyzed and devised. It is a parameter in many equations that model the dynamics of hydraulic systems and it is also an important parameter when dampers of hydraulic systems are dimensioned. With the help of pressure wave velocity the bulk modulus of a hydraulic system can be defined, or vice versa.

Different means for measuring pressure wave velocity are presented in many studies. Normally these measurements are carried out in separate measurement equipment, so that the measured fluid is removed from the original machine. This affects certain characteristics of the fluid, such as the amount of air or moisture concentration, and the results of pressure wave velocity measurements may differ from the original situation. Separate wave velocity measurement instrumentation is very often designed in such a way that at least entrained air can be removed from the measured fluid. Thus, the results of measurement do not take the effect of air into consideration, or only dissolved air is noticed. This does not correspond to real systems, because air is present in fluids, especially at low pressures. Separate pressure wave measurement equipment usually cannot be connected to the machine, so real-time measurement of wave velocity is impossible.

In many earlier studies pressure wave velocity has been measured with ultrasonic transducers. The ultrasound technique may be based on, e.g. time-of-flight or pulse-echo principles. This method is very accurate; an accuracy of even ±0.005 $^{m}/_{s}$ can be achieved, [1] although larger errors have also been presented in the literature [2]-[4]. Benefits of the ultrasound technique are, e.g. long-term stability, precision, sensitivity, capability of applying to optically opaque, concentrated and electrically non-conducting systems and the possibility to automate the measurement. However, instrumentation design and the sample studied may affect the accuracy of the method. [5.]

Another method for defining pressure wave velocity is to measure the bulk modulus of a fluid using a method based on determination of the volume change of the sample under compression or expansion. [6]-[9.] Use of this technique prevents unwanted pressure gradients between the sample and the surrounding system. The useful pressure range of the method is wide (0.1-350 MPa). The amount of entrained air can also be taken into consideration. Drawbacks of the method are the need to first determine the specific volume of the sample under atmospheric pressure and the obvious requirement of measuring the density of the sample under all the pressures used. Thus, this method cannot be used for continuous real-time measurements. Calculation of the bulk modulus and furthermore the pressure wave velocity (sound velocity) is shown in (1) and (2) in chapter II.

Some researchers have used pressure transducers to detect pressure wave velocities in oils. Harms and Prinke [10] presented a method based on phase difference. In this method excitation should be constant, e.g. pump rippling, because the signal is compared at two points and the value of the wave velocity is calculated from the time difference of these signals [10]. Cho *et al*. [11] and Yu *et al*. [12] measured the wave propagation time and calculated a cross-correlation function of the pressure signals. Methods based on pressure measurements make real-time measurements possible and the influence of air can be taken into consideration.

Yet another method for determining pressure wave velocity was presented by Apfel [13]. This method is a technique that measures the adiabatic compressibility and density of a fluid when the sample amounts are extremely small, 4 nl - 4μl. Pressure wave velocities can be calculated from these data. This method is applicable, e.g. for supercooled or superheated samples, biological or hazardous samples or in every case when the bulk properties of fluids have to be determined from small sample amounts. The fluid studied is acoustically levitated on an immiscible host liquid at a certain spot of the test equipment. A reference measurement of a fluid whose properties are well-known is made at the exact same spot. The results are relatively accurate (within a 2 % margin compared with the same values determined by traditional methods). In order to calculate pressure wave velocities, the density of the sample has to be measured using different equipment. Obviously, this method is suitable for laboratory experiments only. [13]-[14.]

Pressure wave velocity (sound velocity) can be used to evaluate various important characteristic properties of fluids. For instance, it has been used to determine the concentration of solvents in oils [4], to calculate the physical properties of hydraulic and other lubricating fluids, as well as fuel oils [7], [15]-[17], to estimate the structural and mechanical properties of fats [18] and the physical properties of petroleum fractions and petroleum reservoir fluids [3], [5] and to determine the composition of oil-water mixtures and emulsions [2] or to measure the properties of magnetorheological (MR) fluids [19].

The most important aim of this study was to develop a method for measuring pressure wave velocity that enables real-time measurements, which are necessary if, e.g. real-time control systems for hydraulics are constructed. Another aim was to collect data for future research with a Helmholtz resonator attached to this system.

II. Theoretical Aspects of Pressure Wave Velocity Determinations

The bulk modulus of elastic material *B* is defined as the quotient of pressure variation and relative volume variation affected by pressure variation

$$B = -\frac{dP}{dV/V} \qquad (1)$$

where *P* is pressure and *V* is volume [20].

Pressure waves considered in this paper are similar to waves that produce audible sound. Thus, pressure waves are handled as longitudinal vibration – molecules moving back and forth in the direction of propagation of the wave, producing successive condensations and expansions in the medium. These alterations of densities are similar to those produced by longitudinal waves in a bar. As seen in many studies, mentioned also in this paper, the difficulty of the mathematics is sidestepped by restricting the waves under consideration to one dimension. [21.] It is worth noting that a travelling wave does not carry material, just the wave and its energy move.

Cho *et al*. [11] have presented three definitions for bulk modulus, which are widely used in many textbooks. These definitions are only applicable to their own specific conditions, and in this paper the sonic bulk modulus (2) is used, which has the same value as the adiabatic bulk modulus. The sonic bulk modulus *B* is derived from the sonic velocity in the fluid and fluid density [11], [20]

$$B = \rho a^2 \qquad (2)$$

where ρ is density and *a* is wave velocity (sound velocity). Equation (2) can be solved for the bulk modulus or wave velocity, depending on which one is the known factor. In this paper density is known and wave velocity is measured, so the bulk modulus can be calculated. But as (2) presents, the same parameters that affect the value of wave velocity also affect the bulk modulus and this is taken into consideration in the theory review.

The main factors that affect the value of the effective bulk modulus of a hydraulic system are fluid pressure and temperature. Their effects are presented in Fig. 1. Other factors that affect the value of the effective bulk modulus are, e.g. the air content of the fluid, pipe rigidity and interface conditions between the fluid and the air [12].

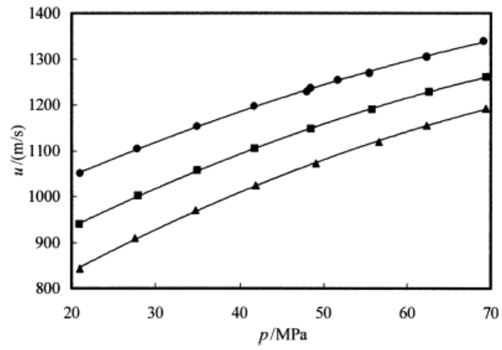

Fig. 1 Effect of temperature and pressure on wave velocity in an oil sample: ● 335.1 K, ■ 370.7 K, ▲ 402.1 K [5]

Part of the air content dissolves in a molecular form and the rest of it, entrained air, exists in the form of small bubbles. Dissolved air has only a little effect on the bulk modulus [11], but the volumetric percent of entrained air within a fluid is one of the most influential variables when the bulk modulus is evaluated. It has been proved that one percent entrained air can reduce the effective bulk modulus of a fluid by as much as 1085 MPa, which corresponds to a 75 percent decrease in the fluid manufacturer's value [22]. It should be noted that also other gases, not only air, affect the bulk modulus and sonic wave velocity, and the type of gas has a greater effect than does the quantity of the gas [23]. The lower the molecular weight of the gas, the greater the effect on the sonic wave velocity [23].

Fluid pressure has an effect on the value of the bulk modulus, particularly in the lower range of pressure. One reason for the effect of pressure on the bulk modulus is the relationship between entrained air content and dissolved air content in a fluid. Some entrained air becomes dissolved air when pressure increases. [12.] The influence of pressure can be discussed at the molecular level, also. If the pressure of the fluid under study is low, the fluid molecules fit among each other easily and a significant amount of free space is still available. When the fluid is compressed, the free space decreases quickly at lower pressures. When the pressure of the system is high, the free space is almost negligible. At this point a further decrease in volume is connected with interactions between fluid molecules and their neighbouring molecules. [24.] If a hydraulic system's pressure is more than

50 bar, the effect of free air is only minor [9].

Fluid temperature affects the density of the air content, the size of air bubbles in the fluid and therefore the equivalent compressibility of the fluid. An increment of temperature also causes changes in the molecular level of the fluid. More vigorous collisions between molecules are observed, which may eventually cause changes in molecular structures, and a decrease in their effective volume is probable. [24.] Thereby temperature has an important influence on the bulk modulus and sonic wave velocity, especially in dynamic situations. The influence of temperature has been studied, e.g. by [23]. Their studies included a temperature range between -30 °C and 130 °C, and the effect of temperature on sonic wave velocity seemed to be significant [23]. However, the effect of fluid temperature can be ignored if the fluid temperature is approximately constant [12], and in many studies this has been done. In addition, the bulk modulus of lubricating oils at low pressures can be almost independent of the temperature [25].

The density and bulk modulus of solid parts (e.g. pipes) will not vary as much as the density of a fluid when temperature and pressure vary [10]. Thus, the effect of pipe rigidity on the bulk modulus can be ignored if rigid pipes are assumed in a hydraulic system [12]. The moisture content of the fluid may also play a role if pressure wave velocities are determined; it slightly reduces the value of the pressure wave velocity [23]. The viscosity of the fluid also affects the pressure wave velocity [26], but of course the viscosity of a fluid depends on its molecular structure in the first place, hence the effect of viscosity on the pressure wave velocity varies with different fluids.

III. Test Equipment

The test equipment and the principle of measurement are depicted in Figs. 2 and 3, respectively. The measurements were carried out by identifying a pressure pulse at two points, P_1 and P_2, using piezo sensors. The distance between points P_1 and P_2 (variable L in Fig. 3) is known and two different distances were used in the tests. The shorter distance was 2.75 m and the longer was 4.26 m. Distances L_1 and L_2 were always 1.03 m and 0.11 m, respectively. A pressure wave was excited by means of a piston inside a pipe. This excitation system enables excitation of a pure pressure wave, because unnecessary elbows and interfaces are avoided, so that reflections and transmissions of the wave are minimized. The piston was moved lightly but rapidly with a hammer. A spherical plug valve and an adjustable valve were installed in the test equipment so that flow and pressure could be controlled during the measurements. This property was used in the measurements so that two measurement series were carried out. The first one was done under constant pressure without flow with the both valves closed. The second one was done with flow, so that flow (and pressure) was controlled with the adjustable valve. The effect of flow on wave velocity is insignificant, as seen later in the text.

The measurements were carried out over two days so that temperature could be assumed to be constant. The test equipment did not include a temperature sensor, but the test equipment was inside a laboratory so that the fluid temperature could be assumed to be the same as the surrounding temperature.

The lowest pressure used was 0.2 bar and the highest was 6.1 bar, and 545 measurements were executed between these limits. Examples of the measurement results are depicted in Figs. 4 and 5.

The measurement system included one Kyowa PG-20KU pressure sensor (for reference pressure), two Kulite HKM-375M-7barVG pressure sensors (for recognizing a pressure wave at two points), a Kyowa Strain Amplifier DPM-6H (for the Kyowa pressure sensor), a Thandar 30V-2A precision power supply (for the Kulite pressure sensors), a National Instruments USB-6211 16-input (16 bit 250 $^{kS}/_{s}$) DAQ card, a HP Compaq nx9010 laptop computer with Microsoft Windows XP, DasyLab v.8.00.004 measurement software and Measurement&Automation Explorer v.4.1.0.3001. The measurement frequency was 25 kHz (0.04 ms) and the block size was 1024 bit.

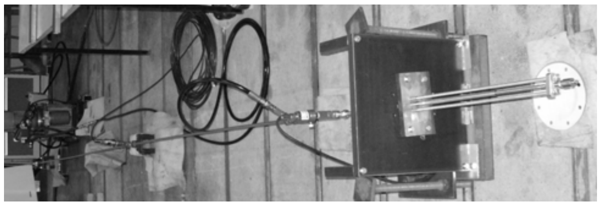

Fig. 2 Test equipment

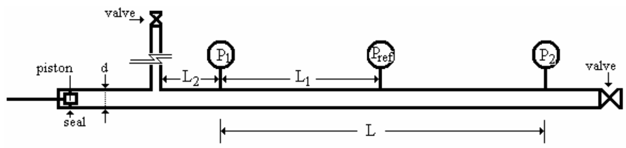

Fig. 3 Principle of the measurements

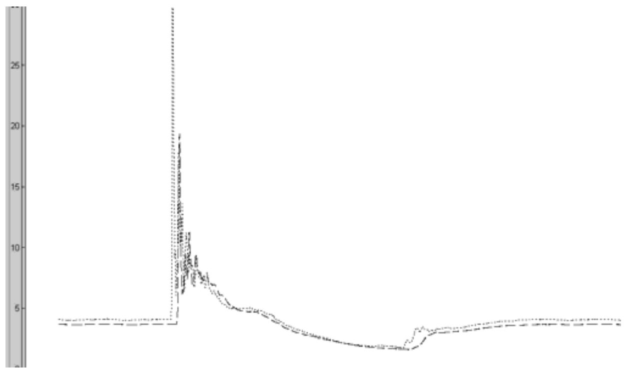

Fig. 4 Response of the pressure wave at detection point one (upper, dotted line) and two (lower, dashed line). Note the pressure difference between the detection points because of flow

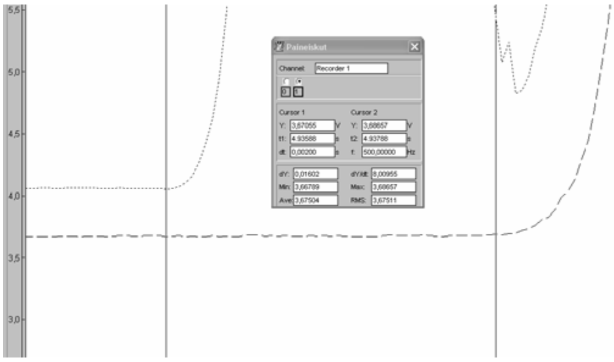

Fig. 5 Same case as above. The time difference between the detection points can be read from the survey box. Note that the lines are modified for publishing by decreasing their resolutions notably from the original

The volume flow of the test equipment Q can be estimated with the Hagen-Poiseulle equation (3) [27]

$$Q = \frac{\pi d^4}{128\eta l}(p_1 - p_2) \quad (3)$$

where d is pipe diameter, η is dynamic viscosity, l is pipe length, p_1 is pressure at point 1 and p_2 is pressure at point 2.

During the measurements pressure will vary from zero to 0.5 bar (pipe length 2.75 m) or to almost one bar (pipe length 4.26 m). This means that the absolute maximum flow, which is even overestimated here on purpose, is constantly less than 1.2 $^{l}/_{min}$ (0.4 $^{m}/_{s}$) at a temperature of 18 ˚C and its effect on the results is impossible to notice in this arrangement.

Fluid viscosity was measured with a Brookfield DV-II+ rotation viscometer and density by using the specific weight method (weighing an accurate volume of the fluid at the desired temperature). Fluid density was 874 $^{kg}/_{m^3}$ at a temperature of 18 ˚C and 864 $^{kg}/_{m^3}$ at a temperature of 40 ˚C. The dynamic fluid viscosities at the corresponding temperatures were 121 cP and 42 cP. The fluid was a commercial mineral oil-based hydraulic oil.

IV. Results of Measurements

Altogether 545 measurements were analyzed. The average pressure of the measurements was 2.9 bar and the measured average pressure wave velocity (sound velocity), 1377 $^{m}/_{s}$. The results of all the measurements are presented in Fig. 6, which indicates the magnitude of the wave velocity in the pressure range between 0.2 bar and 6 bar. In Fig. 6 the measured results of the flow situation and non-flow situation are separated, but as calculated earlier, this measurement arrangement is not accurate enough to recognize the effect of flow. Thus, all the results are handled together from here on.

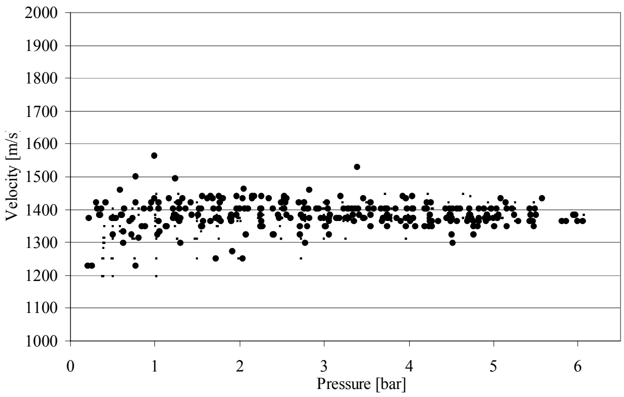

Fig. 6 All the measured results, 545 measurements. ● were measured without flow and ■ were measured with flow

All the results are presented together in Table I so that the measured pressure is rounded to an accuracy of 0.1 bar and the average wave velocity of all the measurements in the rounded pressure area is calculated. Note that the declared value of pressure is always measured by a reference pressure sensor (see P_{ref} in Fig. 3). Thus, in Table I pressure is in the first column (p), the number of measurements in the pressure range $-0.05 \leq p_i \leq +0.14$ bar is in column 2 (n) and the average wave velocity of measurements at the declared pressure are in column 3 (a). The results of Table I are illustrated in Fig. 7.

TABLE I
PRESSURE WAVE VELOCITIES AT DIFFERENT PRESSURES. P = PRESSURE OF THE SYSTEM [BAR], N = NUMBER OF MEASUREMENTS AND A = THE DETERMINED PRESSURE WAVE VELOCITY [M/S]

p	*n*	*a*	*p*	*n*	*a*	*p*	*n*	*a*
0.2	2	1313	**2.3**	9	1383	**4.4**	2	1375
0.3	4	1366	**2.4**	3	1331	**4.5**	23	1377
0.4	15	1295	**2.5**	20	1383	**4.6**	6	1387
0.5	14	1326	**2.6**	4	1411	**4.7**	17	1388
0.6	9	1368	**2.7**	13	1359	**4.8**	7	1365
0.7	9	1360	**2.8**	14	1390	**4.9**	7	1388
0.8	12	1348	**2.9**	3	1405	**5.0**	17	1383
0.9	3	1390	**3.0**	17	1384	**5.1**	5	1389
1.0	20	1357	**3.1**	6	1371	**5.2**	5	1393
1.1	3	1360	**3.2**	10	1393	**5.3**	4	1397
1.2	9	1400	**3.3**	13	1373	**5.4**	3	1389
1.3	19	1379	**3.4**	5	1423	**5.5**	10	1393
1.4	3	1390	**3.5**	19	1393	**5.6**	1	1447
1.5	17	1360	**3.6**	3	1390	**5.7**	0	-
1.6	5	1407	**3.7**	16	1396	**5.8**	1	1365
1.7	15	1371	**3.8**	10	1384	**5.9**	2	1374
1.8	9	1391	**3.9**	3	1390	**6.0**	2	1374
1.9	5	1350	**4.0**	20	1391	**6.1**	4	1374
2.0	20	1377	**4.1**	5	1384			
2.1	5	1403	**4.2**	17	1387	average	sum	average
2.2	13	1382	**4.3**	8	1397	**2.9**	545	1377

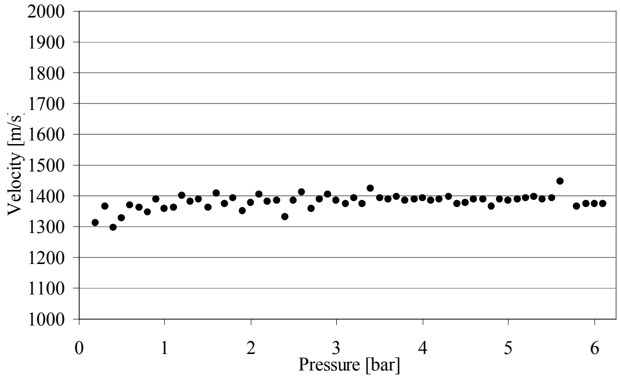

Fig. 7 Calculated average pressure wave velocities in the pressure range between 0.2 and 6.1 bar

The measurements were started by removing air from the system through the pressure sensors' bleeder screws. After air was removed measurements were started from the lowest rational pressure (0.2 bar) and the pressure was raised after approximately every three impacts up to 5 bar. Above 5 bar only some measurements were carried out because the pressure sensors' maximum pressure was 7 bar. This explains why there are relatively more measurements in the area from 1 to 5 bar than in the area from 5 to 6 bar. When the maximum level was reached, air was removed again and measurements were carried out so that after every third impact the pressure was decreased until the output level was reached. This "measurement ramp" was repeated four times, using two different measurement distances and both flow and non-flow situations. It should be noted that the adjustable valve was not absolutely tight, and it allowed some pressure to leak through after impact. This means that in the non-flow situations the pressure decreased during the three impacts a little bit. This event did not exist in the flow situation, where the pressure was constant during the three impacts. This explains why some pressures include more measurements than others.

Albeit the measurement frequency was 25 kHz, the results are not discussed so accurately. In the results the pressure is discussed using an accuracy of 0.1 bar and time is discussed with an accuracy of 0.1 ms (10 kHz). This means that the measured results of the longer pipe should be more accurate than those of the shorter pipe, because the speed difference affected by 0.1 ms is about 45 $^{m}/_{s}$ in the longer pipe and 70 $^{m}/_{s}$ in the shorter pipe if the wave velocity is about 1377 $^{m}/_{s}$. It is true that the longer pipe decreases dispersion of the results, but it is worth noticing that the pipe cannot be too long, because the pulse is damped in fluid and the damped pulse does not arise as sharply as a fresh pulse. See Figs 4 and 5, where the starting points of both pulses are clear. Another explanation for the decreasing dispersion might be the amount of air. When the pressure rises, the percentage volume of air decreases and the system is more stabile and the results of pulse measurements do not differ from each other as much.

V. Comparison of Results

The measured average value of the pressure wave velocity was 1377 $^{m}/_{s}$. Thus, the calculated value of the bulk modulus of the fluid used at room temperature is 1.65 GPa. Unfortunately, we do not have exact values of the bulk modulus and wave velocity of the oil used. However, it is possible to compare the measured results with other researchers' results to estimate the accuracy of our measurements.

In their paper Tat *et al*. [15] have presented equations for calculating the density, bulk modulus and speed of sound of ethyl soyate as a function of pressure at room temperature (21±1 ˚C). The results are depicted in Table II, in which *Δ* means the difference between the calculated results at two different pressures. For example, the difference in wave velocity (sound velocity) between 1 bar and 5 bar is just 0.11 %. In the test arrangement used in this study the difference of 0.11 % means a ±12 $^{m}/_{s}$ difference in the measured wave velocity. It is impossible to notice with the arrangement we used, albeit it is possible to notice an ascending trend in the wave velocity in Fig. 7.

TABLE II
Properties of Ethyl Soyate [15]

	P_1 5 bar	P_2 1 bar	*Δ*
Density [$^{kg}/_{m^3}$]	874.5	874.3	0.2 (0.02 %)
Sound velocity [$^{m}/_{s}$]	1405.0	1403.5	1.5 (0.11 %)
Bulk modulus [GPa]	1.723	1.719	0.004 (0.23 %)

In their paper Dzida and Prusakiewicz [17] have presented the measured wave velocities and densities of biodiesel as a function of temperature and pressure as presented in Table III, in which *Δa* means the wave velocity difference between the calculated results at two different pressures (column) or at two different temperatures (row) and *Δρ* means the density difference between two different temperatures.

TABLE III
Properties of biodiesel [17]

T	P_1 152 bar	P_2 1 bar	*Δa*		*P* 1 atm
20˚C	1482.1 $^{m}/_{s}$	1415.0 $^{m}/_{s}$	67.1 $^{m}/_{s}$ (4.5 %)	$\rho_{20^\circ C}$	879.8 $^{kg}/_{m^3}$
25˚C	1463.9 $^{m}/_{s}$	1395.7 $^{m}/_{s}$	68.2 $^{m}/_{s}$ (4.7 %)	$\rho_{25^\circ C}$	876.2 $^{kg}/_{m^3}$
Δa	18.2 $^{m}/_{s}$ (1.2 %)	19.3 $^{m}/_{s}$ (1.4 %)		Δρ	3.6 $^{kg}/_{m^3}$ (0.4 %)

The bulk modulus of biodiesel is 1.76 GPa. The results of Table III are used to solve the wave velocity at a pressure of 5 bar and a temperature of 20 ˚C. The interpolated value of the wave velocity at 5 bar is 1417 m/s, which shows that the difference in wave velocity is only 2 m/s when the pressure is changed to 5 bar.

The densities presented in Tables II and III are close to the density of the oil used in this study, so they can be used at least in a rough comparison with the results of this paper. Both the presented example results show that the wave velocity should be around 1400 $^m/_s$ and the bulk modulus should be close to 1.72 GPa. The results of this study are a little bit smaller, and the reason for the difference can be inaccuracy of the measurements or dissolved and entrained air. Differences in the molecular level of the compared fluids may also play a certain role here. However, this could not be examined thoroughly because of a lack of time and required equipment.

Now it is expected that the measured values (1377 $^m/_s$ and 1.65 GPa) are correct and the difference with other researchers´ results is caused by air within the system. The amount of air can be estimated by using (4) [27]

$$\frac{1}{B}=\frac{1}{B_{fluid}}+\sum\frac{V_{cyl}}{V_{tot}}\frac{1}{B_{cyl}}+\sum\frac{V_p}{V_{tot}}\frac{1}{B_p}+\sum\frac{V_h}{V_{tot}}\frac{1}{B_h}+\frac{V_{air}}{V_{tot}}\frac{1}{B_{air}} \quad (4)$$

where B_{fluid} is the bulk modulus of the fluid, V_{cyl} is the volume of the cylinder, V_{tot} is the total volume of the system, B_{cyl} is the bulk modulus of the cylinder, V_p is the volume of the pipe, B_p is the bulk modulus of the pipe, V_h is volume of the hose, B_h is the bulk modulus of the hose, V_{air} is the amount of air and B_{air} is the bulk modulus of air.

The bulk modulus of the cylinder, pipe and hose are expected to be hundredfold times the bulk modulus of fluid, so they can be neglected now. The system was also expected to be adiabatic, so (5) can be used to estimate the bulk modulus of air [27].

$$B_{air} = 1.4\ P \quad (5)$$

where P is pressure. The reshaped (4) contains only four factors

$$\frac{1}{B}=\frac{1}{B_{fluid}}+\frac{V_{air}}{V_{tot}}\frac{1}{B_{air}}\,. \quad (6)$$

where B is 1650 MPa (measured result), B_{fluid} is 1720 MPa (measured result by Tat *et al.* [15]), V_{tot} is $1.78\cdot10^{-4}$ m^3 (the volume of the main pipe from the piston to the valve if the distance L is 2.75 m, see Fig. 3) and B_{air} is 0.406 MPa (pressure is assumed to be 2.9 bar). Now it is possible to solve the volume of air

$$V_{air} = 1.783\cdot10^{-9}\ m^3$$

which is 0.001 % of the main pipe's volume. Naturally, this calculation is only an estimation because the exact properties of the oil used in the study are unknown. The effect of air content is depicted in Fig. 8.

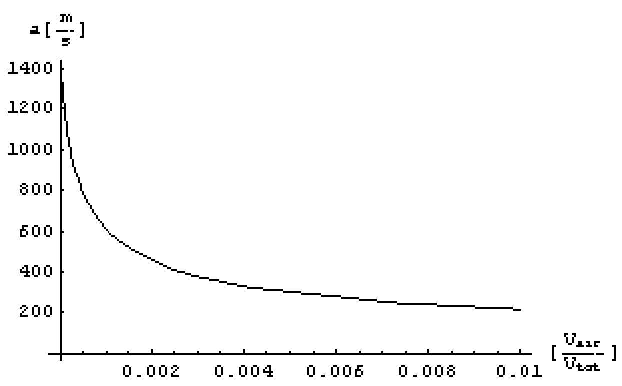

Fig. 8 Analytically calculated effect of air content on wave velocity

VI. Conclusions

The pressure wave velocity (sound velocity) in the test equipment was succeeded to measure by using the developed method and the results were well comparable with the results obtained by other researchers using different methods, e.g. an ultrasound technique. As seen from the presented comparison values (Table II), the variation in the pressure wave velocity between 0 and 5 bar is negligible and it cannot be detected using the measurement technique proposed in this study. However, even this accuracy is sufficient for continuing the process of developing a control system of a semi-active damper. The next stage of determining pressure waves requires an accurate sensor in order to separate measurement error and the influence of entrained air. In addition, accurate temperature control would be beneficial in future research.

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References

[1] E. Høgseth, G. Hedwig, and H. Høiland, "Rubidium clock sound velocity meter," Rev. Sci. Instrum., vol. 71, no. 12, pp. 4679-4680, 2000.
[2] G. Meng, A. J. Jaworski, and N. M. White, "Composition measurements of crude oil and process water emulsions using thick-film ultrasonic transducers," Chem. Eng. Process., vol. 45, pp. 383-391, 2006.
[3] B. Lagourette, and J. L. Daridon, "Speed of sound, density and compressibility of petroleum fractions from ultrasonic measurements under pressure," J. Chem. Thermodyn., vol. 31, pp. 987-1000, 1999.
[4] C. González, J. M. Resa, J. Lanz, and A. M. Fanega, "Speed of sound and isentropic compressibility of organic solvents + sunflower oil mixtures at 298.15 K," JAOCS, vol. 79, no. 6, pp. 543-548, 2002.
[5] S. J. Ball, A. R. H. Goodwin, and J. P. M. Trusler, "Phase behavior and physical properties of petroleum reservoir fluids from acoustic measurements," J. Petrol. Sci. Eng., vol. 34, pp. 1-11, 2002.
[6] H. S. Song, E. E. Klaus, and J. L. Duda, "Prediction of bulk moduli for mineral oil based lubricants, polymer solutions, and several classes of synthetic fluids," J. Tribol. –T. ASME, vol. 113, pp. 675-680, October 1991.
[7] C. Aparicio, B. Guignon, L. M. Rodríguez-Antón, and P. D. Sanz, "Determination of rapeseed methyl ester oil volumetric properties in

high pressure (0.1 to 350 MPa)," J. Therm. Anal. Calorim., vol. 89, pp. 13-19, 2007.
[8] J. Kajaste, H. Kauranne, A. Ellman, and M. Pietola, "Experimental validation of different models for bulk modulus of hydraulic fluid," in Proc. 9th Scandinavian Int. Conf. on Fluid Power, SICFP`05, Linköping, Sweden, 2005, 16 p.
[9] J. Kajaste, H. Kauranne, A. Ellman, and M. Pietola, "Computational models for effective bulk modulus of hydraulic fluid," in Proc. 2nd Int. Conf. Computational Methods in Fluid Power, FPNI`06, Aalborg, Denmark, 2006, 7 p.
[10] H. – H. Harms, and D. Prinke, "Messverfahren zur Bestimmung der Schallgeschwindigkeit in Mineralölen," o+p ölhydraulik und pneumatik, vol. 23, no. 3, pp. 191-194, 1979. In German.
[11] B. - H. Cho, H. - W. Lee, and J. - S. Oh, "Estimation technique of air content in automatic transmission fluid by measuring effective bulk modulus," Int. J. Automot. Techn., vol. 3, no. 2, pp. 57-61, 2002.
[12] J. Yu, Z. Chen, and Y. Lu, "The variation of oil effective bulk modulus with pressure in hydraulic systems," J. Dyn. Systems – T. ASME, vol. 116, pp. 146-150, March 1994.
[13] R. E. Apfel, "Technique for measuring the adiabatic compressibility, density, and sound speed of submicroliter liquid samples," J. Acoust. Soc. Am., vol. 59, no. 2, pp. 339-343, 1976.
[14] R. E. Apfel, R. E. Young, U. Varanasi, J. R. Maloney, and D. C. Malins, "Sound velocity in lipids, oils, waxes, and their mixtures using an acoustic levitation technique," J. Acoust. Soc. Am,. vol. 78, no. 3, pp. 868-870, 1985.
[15] M. E. Tat, J. H. Van Gerpen, S. Soylu, M. Canakci, A. Monyem, and S. Wormley, "The speed of sound and isentropic bulk modulus of biodiesel at 21 ˚C from atmospheric pressure to 35 MPa," JAOCS, vol. 77, no. 3, pp. 285-289, 2000.
[16] M. E. Tat, and J. H. Van Gerpen, "Speed of sound and isentropic bulk modulus of alkyl monoesters at elevated temperatures and pressures," JAOCS, vol. 80, no. 12, pp. 1249-1256, 2003.
[17] M. Dzida, and P. Prusakiewicz, "The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel," Fuel, 2007, doi:10.1016/j.fuel.2007.10.010.
[18] F. Maleky, R. Campos, and A. G. Marangoni, "Structural and mechanical properties of fats quantified by ultrasonics," J. Amer. Oil. Chem. Soc., vol. 84, pp. 331-338, 2007.
[19] J. Kim, and K. - M. Park, "Material characterization of MR fluid at high frequencies," J. Sound Vib., vol. 283, pp. 121-133, 2005.
[20] A. L. Boehman, D. Morris, J. Szybist, and E. Esen, "The impact of the bulk modulus of diesel fuels on fuel injection timing," Energ. Fuel., vol. 18, pp. 1877-1882, 2004.
[21] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, Fundamentals of acoustics. 3rd ed., USA: John Wiley & Sons, 1982.
[22] N. D. Manring, "The effective fluid bulk-modulus within a hydrostatic transmission," J. Dyn. Systems – T. ASME, vol. 119, pp. 462-466, September 1997.
[23] E. Howells, and E. T. Norton, "Parameters affecting the velocity of sound in transformer oil," IEEE T. Power Ap. Syst., vol. PAS-103, no. 5, pp. 1111-1115, 1984.
[24] K. S. Varde, "Bulk modulus of vegetable oil-diesel fuel blends," Fuel, vol. 63, pp. 713-715, 1984.
[25] B. O. Jacobson, and P. Vinet, "A model for the influence of pressure on the bulk modulus and the influence of temperature on the solidification pressure for liquid lubricants," J. Tribol. – T. ASME, vol. 109, pp. 709-714, October 1987.
[26] M. Fukuhara, and T. Tsubouchi, "Naphthenic hydrocarbon oils transmissible for transverse waves," Chem. Phys. Lett., vol. 371, pp. 184-188, 2003.
[27] H. Kauranne, J. Kajaste, and M. Vilenius, Hydraulitekniikan perusteet. 3.-5. painos, Vantaa, Finland: Werner Söderström Osakeyhtiö, 2004. In Finnish.