MEASURING AND MODELLING HYDRAULIC FLUID DYNAMICS AT HIGH PRESSURE – ACCURATE AND SIMPLE APPROACH

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Abstract

Dynamic properties of hydraulic fluids have to be taken into account in ever increasing fluid power applications. The main reasons are increasing accuracy demands in control and modelling, as well as increasing operating pressure and temperature ranges. Moreover, the already wide spectrum of different hydraulic fluids is also expanding all the time. However, information on dynamic hydraulic fluid behavior is still very difficult to be obtained. On the other hand, existing fluid models tend to be either too inaccurate, or at least highly non-generic for most practical applications.

This article introduces simple, yet accurate approaches for measuring and predicting the most important dynamic fluid parameters: bulk modulus, density and speed of sound in fluid. The methods are basically applicable to any standard hydraulic fluid, without any extra system-related constraints, at least at the presented conditions. The studied pressure range reaches 1500 bar, and the temperatures cover a normal operating range of industrial applications. Examples of both measured and predicted results for selected commercial hydraulic fluids are given. The results have also been found to be in excellent agreement with existing reference data.

Keywords: adiabatic, bulk modulus, density, dynamics, high-pressure, hydraulic fluid, isothermal, measuring, modelling, second order polynomial, speed of sound

1 Introduction

Most fluid power engineers agree on hydraulic fluid being one of the most important components in every fluid power system. In addition to e.g., lubrication, heat transfer and contamination control, fluid is first and foremost the power transmitting medium. Therefore, it might be even argued that fluid is the most important single component.

Possibly, fluid properties have not been as significant design parameters in former applications as they are today. Therefore, there is very limited or no reliable, measured information on fluid behavior available for system designers – especially at pressure levels over 300 bar, or for different types of hydraulic fluids. However, operating pressures have been increasing throughout the fluid power field. Moreover, the selection of different hydraulic fluids is increasing all the time – mineral oil based fluids are being replaced e.g., with vegetable oil or synthetic ester based fluids. Therefore, fluid parameter variation has become an important design aspect in many cases.

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On the other hand, it would be important to have useful tools for predicting different fluid parameters. There are a number of models also for fluid parameters, but unfortunately they usually fall into two different categories. Some models are too simplified and therefore inaccurate. Other models might possibly be accurate, but they are impossible to use in practice, due to the parameterization, which assumes information, which is very difficult or usually even impossible to find. Both of these kinds of models are, in effect, as useful from a system designer's point of view as no fluid model at all.

In this article, the effects of pressure, temperature and fluid type on dynamic fluid parameters are studied. An accurate, yet simple and cost effective approach for measuring the most important dynamic fluid parameters is presented, and a method for predicting the observed behavior in a very generalized manner is suggested – the fluid parameters being speed of sound in a fluid, fluid density and fluid bulk modulus. The presented pressure range reaches 1500 bar, and the temperature range of 40 - 70°C covers normal industrial solutions.

2 Measuring Method

2.1 Reference Methods

There are many reported methods for measuring different dynamic fluid parameters. A short overview of the most typical reference methods is given in the following. Reference methods have also been surveyed in Karjalainen (2011b).

2.1.1 Bulk Modulus

In Gholizadeh (2011), a relatively thorough literature survey was recently performed concentrating particularly on fluid bulk modulus measurement. Gholizadeh (2011) also creditably explains how there are four different definitions for fluid bulk modulus – it can be either secant or tangent, and isothermal or adiabatic. Which value of bulk modulus should be used in which cases is a somewhat controversial subject. This article will not focus on that part, some discussion may be found e.g., in Gholizadeh (2011) and its references, also in Karjalainen (2011b).

As it is also stated in Gholizadeh (2011), the most typical ways to measure fluid bulk modulus are based on using some kind of fluid compressing device, or on defining the speed of sound in a fluid. Using compression (e.g. ASTM-D6793-02) leads usually to isothermal secant bulk moduli, whereas speed of sound methods are expected to lead to adiabatic tangent values. Of course, there are certain relationships between different definitions of bulk moduli, which might allow defining another values based on another. However, for example, heat capacity factors are not commonly available for many hydraulic fluids.

Using compressing devices, the reached pressure ranges are usually reported higher, evidently even up to 690 MPa. However, compression methods may be quite sensitive to errors, e.g., due to unexpected structural compliances of the measuring device. Moreover, compression methods are more expensive and difficult to apply in many situations e.g., when studying new and unknown fluids.

2.1.2 Speed of Sound in Fluid

In Gholizadeh (2011), also the most typical ways to measure speed of sound in fluid were surveyed. For example, an ISO standard (ISO 15086-2:2000) presents two possible methods. However, these methods are known to be tested more specifically at pressure levels under 500 bar. Therefore, elevated pressure levels present many challenges to the equipment depicted e.g., in the standard. In particular, producing continuous pressure fluctuation at high pressures may be difficult and very expensive. It is also worth mentioning that the possible viscosity range of measured fluids will be narrowed, if e.g., a hydraulic pump is used for producing the demanded pressure fluctuation. Some other possible aspects needed to be considered with continuous pumping have been discussed e.g., in Karjalainen (2005, 2011b).

2.1.3 Density

Also in Gholizadeh (2011), an inclusive survey of density measuring methods was given. Most of the density measuring methods are based on some special laboratory equipment which is not that commonly usually available for an average fluid power engineer. Moreover, this kind of equipment may be quite expensive. One such accurate and commercially available device, vibrating tube densitometer, is e.g., based on measuring oscillation periods inside a fluid filled tube. On the other hand, density may be defined e.g., from mass of a fluid and using a similar type of compression device as used in defining isothermal bulk modulus.

2.2 The Studied Measuring Method

One possibility of defining all the three parameters with the same system is given in Karjalainen (2011b). The measuring system consists of typical fluid power components and is relatively easy and cost effective to build. It is also easy to maintain which is a benefit, particularly when dealing with previously unknown fluids or operating conditions. The method is based on measuring speed of sound in fluid directly, fluid density and bulk modulus may be determined iteratively. This article is based on the described method.

2.2.1 The Studied Measuring System for Speed of Sound

A schematic picture of the studied measuring system for speed of sound in a fluid line is shown in Fig. 1.

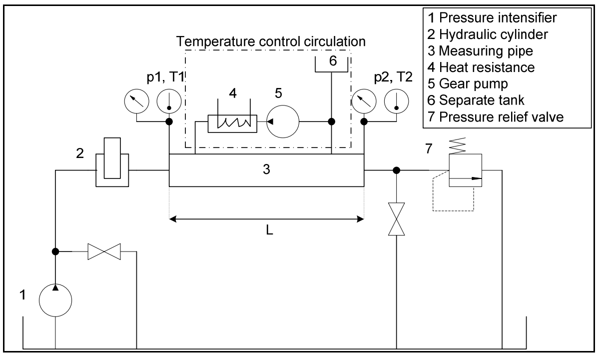

Fig. 1: *The schematic picture of the studied measuring system*

A closed, straight, fluid filled measuring pipe is pressurized with a pneumatically driven single-piston pump, which acts as a pressure intensifier. The high-pressure measuring pipe is enclosed in an outer, oil-filled low-pressure pipe for temperature control circulation. With a PID controller, the temperature of the actual measuring pipe can be maintained accurately independent of possible changes e.g., in room temperature. Oil temperature is measured at the both ends of the measuring pipe. The temperature circulation is driven with a simple gear pump. The pressure relief valve in the measuring line is a safety valve, which remains closed in normal operation.

Once a desired pressure level is reached, the pneumatic pump is shut and a single pressure transient is produced into the statically pressurized measuring pipe by knocking a hydraulic cylinder. Two fast piezo-electric pressure transducers record the pressure wave at two points, at known distance from each other. With cross-correlation algorithm, the delay of the pressure wave propagation can be found from the phase shift of the two pressure transients. And since pressure wave is traveling at a speed of sound in a fluid line, this will lead to the effective value of the speed of sound.

The removal of the effect of system compliances is explained in Section 2.2.3. After that, following an iterative procedure (explained in Section 2.2.2) it will lead to the desired values of speed of sound in fluid, adiabatic tangent fluid bulk modulus, and fluid density. The reliability of this non-standard measuring system has been justified in detail in Karjalainen (2011b).

The repeatability of measuring pressure wave propagation has been found to be excellent. Figure 2 shows an example scatter of three consecutive measurements (t1 - t3) with Shell Tellus VG 46 mineral hydraulic oil at 40°C temperature. The dashed line represents a second order p ial fitting of the reported delay. The maximum error in repeatability at the same operating pressure is one sample period – in this case only 20 µs with 50 kHz sampling rate. During the testing phase of the measuring system the repeatability in normal operation has been found to be within ± one sample period even with statistically larger investigation.

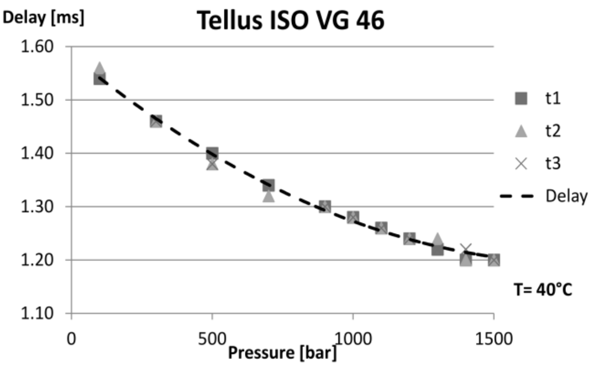

Fig. 2: *Example of the repeatability of measuring pressure wave delay in a mineral hydraulic oil.*

Unlike e.g., in (ISO 15086-2:2000), Johnston (1991), Kojima (2000) and Yu (1994), this method does not have a hydraulic pump for producing pressure fluctuation. Therefore, this approach has certain advantages. The viscosity range of a measured fluid is not so limited. With the presented system, fluids with kinematic viscosities of 1 - 1100 cSt have been measured successfully. Moreover, temperature can be controlled more easily when there is no volumetric flow through the measuring line.

Basically, the presented method does not make any restrictions for measuring temperatures. Of course, some method of cooling the system is needed for lower temperatures. Moreover, fluid should be in such a state in the measuring pipe that a detectable pressure transient can still be produced with the cylinder. The studied pressure range so far has reached 1500 bar. However, there are components available for raising the pressure level safely at least up to 2500 bar.

2.2.2 The Iterative Procedure for Bulk Modulus and Density

The originally used iteration procedure for fluid bulk modulus and density was published e.g., in Karjalainen (2005, 2006, 2007, 2009, 2011a) leading to a systematic 1 - 2 % referenced maximum error at pressure range of 1500 bar (Karjalainen, 2011b; Kuss, 1976). However, the procedure was slightly revised to its final form in Karjalainen (2011b) leading to e.g., referenced maximum error of density of less than 0.5 % (Karjalainen, 2011b; Kuss, 1976). The revision process has been explained in detail in Karjalainen (2011b). The revised final iteration procedure is presented in the following.

Once a speed of sound in the fluid line is measured according to Section 2.2.1, there are two equations, Eq. 1 (Merritt, 1967) and Eq. 2 (Karjalainen, 2011b; Garbacik, 2000) for iterative determination of effective adiabatic tangent bulk modulus and fluid density. As already mentioned in Section 2.1.1, the heat capacity factors in Eq. 2 might be difficult to find for every fluid. Therefore, also an estimated equation Eq. 3 (Karjalainen, 2011b) may be used instead of Eq. 2 with good accuracy in practice. The ratio of the fluid heat capacity factors has been replaced with an estimate that isothermal tangent bulk modulus is approximately 200 MPa smaller than the corresponding adiabatic tangent value. In practice, this is a fair assumption according to e.g., Hodges (1996) and Borghi (2003). The results of this study have been defined using the estimate equation, with the above reported accuracy.

$$c = \sqrt{\frac{B_{eff\,a}}{\rho_n}} \tag{1}$$

$$\rho_n = \rho_{atm,T}\, e^{\frac{p - p_{atm}}{\frac{1}{n}\left(\sum_{n=1} B_{eff\,a}\right)\frac{C_v}{C_p}}} \tag{2}$$

$$\hat{\rho}_n = \rho_{atm,T}\, e^{\frac{p - p_{atm}}{\frac{1}{n}\left(\sum_{n=1} B_{eff\,a}\right) - 0.2\cdot 10^9}} \tag{3}$$

The iteration procedure should be started at the atmospheric pressure, or close to it, and the first values for effective bulk modulus and density are received. After that, all the preceding effective bulk moduli, as well as the presently iterated effective bulk modulus, should be summed in either of the used equations Eq. 2 or Eq. 3. Presented mathematically the above would mean:

$$B_{eff_{mean}} = \text{mean}\,(B_{eff_{atm}}, B_{eff_{p1}}, B_{eff_{p2}}, \ldots, B_{eff_p})$$

where the value B_{eff_p} is the currently iterated adiabatic value of the effective bulk modulus at the pressure in question. All the other values are received from the preceding pressure steps.

The size of consecutive pressure steps can e.g., follow normal pressure steps of these kinds of measurements. In Karjalainen (2011b) it has been shown that this will lead to similarly good accuracy than by using very small pressure steps, which would only lead to more tedious calculation routines.

2.2.3 The Removal of System Compliances

As in this studied case, the measuring line should be designed to have no dead volumes. Moreover, the measuring line should be de-aerated with thorough flushing. In this study, the flushing of the system was performed at a pressure level of over 1000 bar. With the above conditions, system compliances can be estimated very well with equations Eq. 4 and Eq. 5 (Karjalainen, 2011b; Merritt, 1967) for a rigid thick-walled pipe.

$$B_p = \frac{1}{\frac{2}{E_k} \cdot \left[\frac{(1+\mu_p) \cdot D_p^2 + (1-\mu_p) \cdot d_p^2}{(D_p - d_p) \cdot (D_p + d_p)} \right]} \tag{4}$$

$$B_n = \frac{B_{eff} \cdot B_p}{B_p - B_{eff}} \tag{5}$$

3 Measurement Results

Eight different commercial hydraulic fluids were selected for this study. Speed of sound in fluid, adiabatic tangent fluid bulk modulus and fluid density were measured according to Chapter 2. The studied pressure range was 100 - 1500 bar which covers e.g., state-of-art common rail injection pressures. The studied temperature range of 40 - 70°C was selected to cover the normal range of industrial fluid power applications. The selected fluids and the received results are presented in the following.

3.1 The Selected Fluids

Different commercial fluids were selected to cover the most typical spectrum of the hydraulic fluids being used at the moment – water had to be abandoned at this stage e.g., due to possible rusting problems. Water viscosity would not have been a problem. Different base fluids were selected for finding out whether it would affect the fluid dynamics. The effect of viscosity grades and additives were researched by selecting different mineral oil based fluids.

Table 1: The fluid characteristics of the studied hydraulic fluids (Karjalainen 2011b)

ISO- standardized fluid characteristics data				
Fluid	Viscosity T= 40°C [cSt]	Viscosity T= 100°C [cSt]	Density p_atm, T= 15°C [kg/m³]	Density correction coefficient (α) [kg/(m³·°C)]
Shell Tellus VG 32	32	5.4	875	0.65
Shell Tellus S VG 46	46	6.9	875	0.65
Shell Tellus TX VG 46	46	8.4	880	0.65
Comet SAE 10W-30	73	11.3	880	0.65
Shell Rimula x30 VG 93	93	11	890	0.65
Shell Calibration fluid S-9365	2.6	---	827	0.68
Shell Naturelle HF-E VG 46	46	9.1	919	0.65
Comet ECO Pine Oil VG 46	46.3	9.86	928	0.63

The fluid characteristics of the selected fluids are listed in Table 1. The six first fluids are mineral oil based. Shell Tellus VG 32 and VG 46 can be regarded as standard industrial hydraulic fluids. Shell Tellus TX is basically the same fluid as the previous ones, but it has viscosity index enhancing additives. Comet SAE and Shell Rimula are diesel engine motor oils. Shell Calibration fluid is a standard calibration fluid used e.g., in injection motors. Shell Naturelle HF-E is a synthetic ester fluid, and Comet ECO Pine is pine oil based natural ester fluid.

3.2 Speed of Sound in Fluid

The measured speeds of sound are presented in Fig. 3 and 4. As it can be seen, only calibration fluid stands out, clearly having the lowest value for speed of sound. All the other fluids present somewhat similar absolute values regardless of different base fluids, viscosity grades or additives. In practice, the trend of speed of sound behavior will not change between the fluids or temperatures. In fact, the measurements are following uniform second order polynomials (Karjalainen, 2009; 2011b) – this discovery has been used in defining the prediction method of Section 4.3.

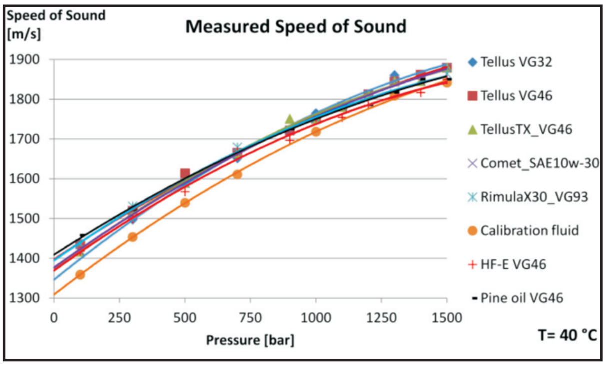

Fig. 3: *The measured speeds of sound in the studied hydraulic fluids at 40°C*

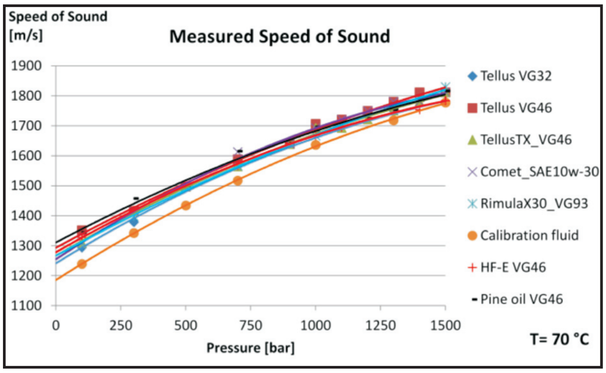

Fig. 4: *The measured speeds of sound in the studied hydraulic fluids at 70°C*

Speed of sound in fluid is known to set the upper limit for the fastest possible frequency response (Smith, 1960). However, it does not necessarily mean that the fastest possible response could be used in practice – it might even lead to unstable control response. Moreover, in sections 3.3 and 3.4 it is shown that there are significant differences in bulk moduli and densities between fluids with similar measured speeds of sound.

3.3 Adiabatic Tangent Bulk Modulus

The measured adiabatic tangent bulk moduli are presented in figures 5 and 6. It can be seen that the pine oil has the highest bulk modulus. Also the HF-E fluid has a bit higher bulk modulus than the studied mineral oils. The calibration fluid has the lowest bulk modulus, whereas the other five mineral oils are presenting highly similar behavior – despite different viscosity grades or additives. Therefore, base fluid would seem to have the biggest effect on fluid's bulk modulus.

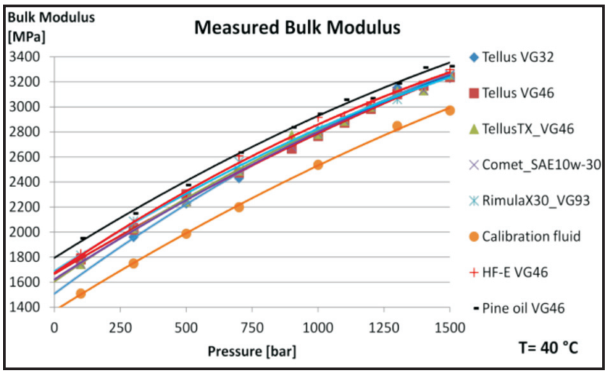

Fig. 5: *The measured adiabatic tangent bulk moduli in the studied hydraulic fluids at 40°C*

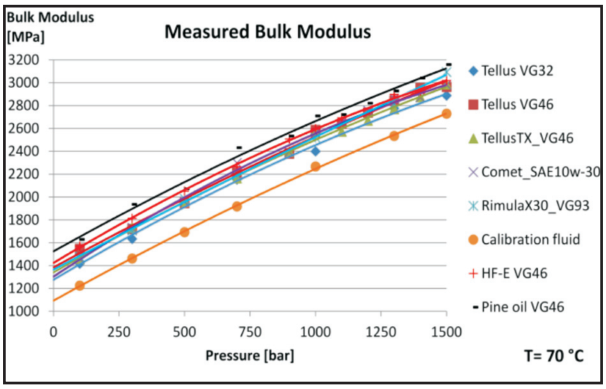

Fig. 6: *The measured adiabatic tangent bulk moduli in the studied hydraulic fluids at 70°C*

There are differences in absolute values between the fluids – definitely big enough to affect certain applications. However, the trend of the bulk modulus behavior will not change between the fluids or temperatures. Again, the measurements are following uniform second order polynomials (Karjalainen, 2009; 2011b) – this discovery has been used in defining the prediction method of Section 4.1.

3.4 Density

The measured densities of the studied fluids are presented in figures 7 and 8. The absolute values may vary significantly between the fluids. However, the five fluids (Tellus VG 32, Tellus VG 46, Tellus TX, Comet SAE, Rimula x30) having highly similar mineral oil base fluid are forming one group. Pine oil has the highest density, followed by the HF-E fluid. Calibration fluid clearly has the lowest density. Based on the results it seems quite clear that base fluid has the dominant effect on fluid density, rather than viscosity grade or additives.

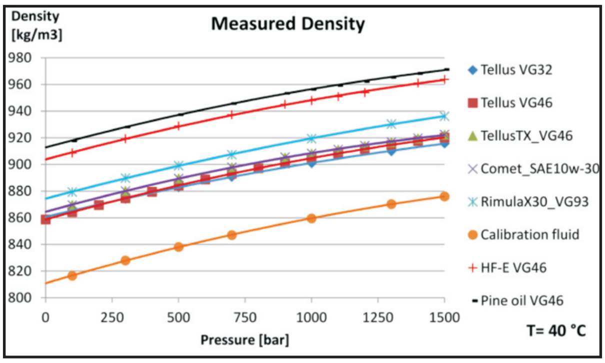

Fig. 7: *The measured densities of the studied hydraulic fluids at 40°C*

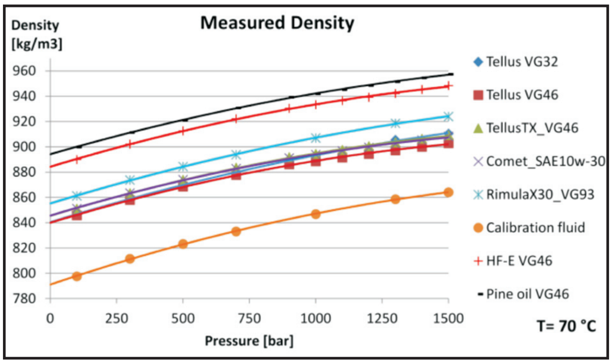

Fig. 8: *The measured densities of the studied hydraulic fluids at 70°C*

Similar to speed of sound and bulk modulus, the trend of the density behavior will not change between the fluids or temperatures. Also these measurements are following uniform second order polynomials (Karjalainen, 2009; 2011b) – this discovery has been used in defining the prediction method of Section 4.2.

4 Prediction Method

As mentioned in the introduction, there are different models also for dynamic fluid parameters. However, the existing models are usually too simplified and inaccurate, or the models require parameters, which cannot be realized in practice. On the other hand, the high-pressure behavior of hydraulic fluid dynamics is still quite an unknown research area. Even any measured data is very rare for pressure levels over 300 bar – especially when the fluid is not mineral oil based.

Quite simple prediction method has been developed at IHA for speed of sound in fluid, fluid bulk modulus and fluid density. As stated in Chapter 3, measurements seem to follow a uniform second order polynomial trend. Therefore, with simple second order polynomials it is possible to predict the dynamic fluid behavior. Furthermore, the most important aspect with this method is that the parameterization is possible for any standard hydraulic fluid – only ISO standardized fluid characteristics is needed. The actual development of the models has been explained more in detail in Karjalainen (2009, 2011b).

Despite the simple models, they have proven to be very accurate at the presented operating range of 40 -

70°C and up to 1500 bar, with many different types of fluids. In Chapter 5 of this article, the received prediction accuracy is demonstrated. More results have been reported in Karjalainen (2011b). When the operating conditions clearly differ from the presented ones some restrictions may occur with the presented equations. This is discussed in Section 4.4. Further research is in progress for narrowing down these restrictions.

4.1 Bulk Modulus Model

According to the second order polynomials fitted to measured data, the second and first order terms may be estimated quite well for the best fit. The constant term is a fluid and temperature dependent factor. The equation for fluid tangent bulk modulus is given in Eq. 6 (Karjalainen, 2011b). The pressure is expressed in [bar] and bulk modulus in [MPa].

$$B(p,T) = -0.0001 \cdot p^2 + 1.2 \cdot p + C_B(p_{atm},T) \tag{6}$$

The constant term of the second order model of adiabatic tangent bulk modulus can be estimated using Eq. 7 (Borghi, 2003; Karjalainen, 2011b). Eq. 8 (Borghi, 2003; Karjalainen, 2011b) may be used for isothermal tangent bulk modulus. All the parameters of the constant term equations can be found for any standard hydraulic fluid. The kinematic viscosity at atmospheric pressure and 20°C may e.g., be calculated with the well-known Walther equation (Hodges, 1996). In these equations, kinematic viscosity is expressed in [cSt] and temperature in [°C].

$$C_B(p_{atm},T) = 0.1 \cdot \left[1.57 + 0.15 \cdot \log(v_{atm,20^\circ C})\right] \cdot 10^{4+\frac{20-T}{417}} \tag{7}$$

$$C_B(p_{atm},T) = 0.1 \cdot \left[1.3 + 0.15 \cdot \log(v_{atm,20^\circ C})\right] \cdot 10^{4+\frac{20-T}{435}} \tag{8}$$

4.2 Density Model

The first version of the density model was already published in Karjalainen (2009, 2011a). However, the second and first order terms of the model were slightly revised in Karjalainen (2011b). The first version can be expected to lead to an additional systematic maximum full scale error of about 1 - 2 %, and the model presented in this article should be used instead for better accuracy.

Also for fluid density model, the second and first order polynomial terms may be estimated for the best fit, at the presented temperature range. The constant term is a fluid and temperature dependent factor. The equation for fluid density is given in Eq. 9 (Karjalainen, 2011b). Pressure is expressed in [bar] and density in [kg/m³].

$$\rho(p,T) = -1 \cdot 10^{-5} \cdot p^2 + 0.056 \cdot p + C_D(p_{atm},T) \tag{9}$$

For the constant term, there is a commonly used procedure for finding a density value at atmospheric pressure and at operating temperature. Eq. 10 (Hodges, 1996) is based on fluid heat expansion, and gives directly the needed constant term for the model. The density correction coefficients α are listed e.g., in (ASTM/IP) and Hodges (1996). For the studied fluids the coefficients are also listed in Table 1. In Eq. 10, temperature is expressed in [°C], α in [kg/(m³·°C)] and density in [kg/m³].

$$C_D(p_{atm},T) = \rho_{atm,15^\circ C} - \alpha \cdot (T - 15^\circ C) \tag{10}$$

4.3 Speed of Sound Model

As with bulk modulus and density, the second and first order terms of speed of sound model have been selected for the best fit. The constant term is a temperature and fluid dependent factor. The equation for speed of sound in fluid is given in Eq. 11 (Karjalainen, 2009; 2011a; 2011b). Pressure is expressed in [bar] and speed of sound is expressed in [m/s].

$$c(p,T) = -0.0001 \cdot p^2 + 0.48 \cdot p + C_C(p_{atm},T) \tag{11}$$

The constant term of speed of sound equation can be calculated from the previously presented constant terms of fluid tangent bulk modulus (Eq. 7 or Eq. 8) and density (Eq. 10), using also the previously presented Eq. 1. Combined, this will lead to Eq. 12 (Karjalainen, 2009; 2011a; 2011b).

$$C_C(p_{atm},T) = \sqrt{\frac{C_B(p_{atm},T)}{C_D(p_{atm},T)}} \tag{12}$$

4.4 Current Restrictions

The presented temperature range covers 40 - 70°C. Further research has been also performed for temperature range of 20 - 130°C. Based on first results with the expanded temperature range, the density equation (Eq. 9) may be modified for a better accuracy by giving some simple temperature relation for the first order term. It would seem clear that the first order term slightly increases with increasing temperature – the effect of which is insignificant with the presented range of 40 - 70°C. The speed of sound and bulk modulus models would not seem to be that affected by temperature.

However, some further research has also been made using mineral oil and petrol based fluids with densities as high as 1000 kg/m³. With these fluids the constant terms of speed of sound and bulk modulus models might need some kind of simple density related factor. It would seem that with high-density fluids there is a systematic uniform shift between the measured and predicted values – the predicted ones being somewhat lower than the actually measured ones. Same kind of behavior could also be discovered with the pine oil studied for this article – the results and received modelling accuracies of the pine oil are given more in detail in Karjalainen (2011b).

Fluid behavior at temperatures below 0°C will clearly need more research, but in theory the basic fluid behavior should remain unchanged with fluids designed for lower temperatures. Fluid behavior at pressures over 1500 bar will be researched in near future – it is possible that elevated pressure will slightly modify the presented equations. However, its effect is insignificant at the pressure range presented in this article.

5 Prediction Results

In the following, the measured results of Chapter 3 are compared to the prediction results, which were received with the equations of Chapter 4. Due to the length of the material to be considered, only the results of Shell Tellus VG 46 are shown graphically in this article. Shell Tellus VG 46 was selected due to its generally well-known behavior. More results can be found in Karjalainen (2011b). Nevertheless, the received modelling errors for all the eight studied fluids are given in Section 5.4.

5.1 Speed of Sound in Fluid

Figure 9 illustrates the comparison of measured speeds of sound in the selected Shell Tellus VG 46 mineral hydraulic oil (data points) with the predicted ones (continuous lines), at 40°C and 70°C. With visual examination, the prediction seems to perform well at the presented operating range. There are no significant uniform shift errors, and the predicted polynomials clearly follow the measurements. The values for modelling errors are given in Table 2, in Section 5.4. Possible restrictions of the presented model were discussed in Section 4.4.

5.2 Adiabatic Tangent Bulk Modulus

Figure 10 shows the comparison of measured adiabatic tangent bulk moduli of the selected Shell Tellus VG 46 mineral hydraulic oil (data points), with the predicted ones (continuous lines), at 40°C and 70°C. As it can be seen, the prediction method performs very well at the presented operating range. The modelling errors are given in Table 2, in Section 5.4. Possible restrictions of the presented model were discussed in Section 4.4.

5.3 Density

Figure 11 represents a comparison of measured densities of the selected Shell Tellus VG 46 mineral hydraulic oil (data points) with the predicted ones (continuous lines), at 40°C and 70°C. Again with visual inspection, the prediction performs well at the presented operating range. The modelling errors are also given in Table 2, in Section 5.4. Possible restrictions of the presented model were discussed in Section 4.4.

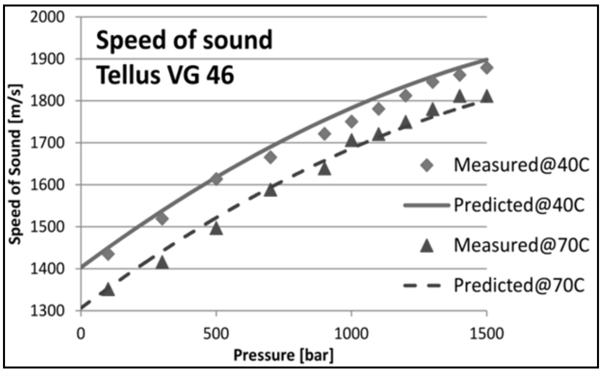

Fig. 9: *The comparison of measured and predicted speeds of sound in Shell Tellus VG 46, at 40°C and 70°C*

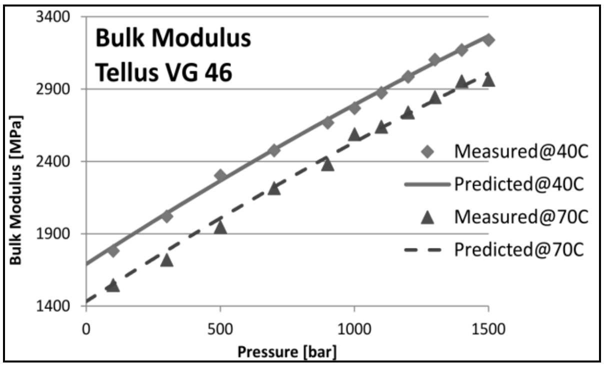

Fig. 10: *The comparison of measured and predicted adiabatic tangent bulk moduli of Shell Tellus VG 46, at 40°C and 70°C*

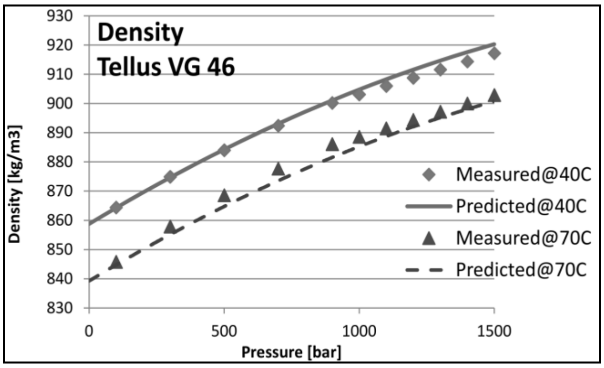

Fig. 11: *The comparison of measured and predicted densities of Shell Tellus VG 46, at 40°C and 70°C*

5.4 Modelling Error

The modelling errors between the prediction method of Chapter 4 and the measurement results of Chapter 3 are listed in Table 2, for all the eight studied fluids. The average modelling errors in Table 2 have been calculated as percentages from the maximum value of the fluid parameter at 1500 bar pressure (from full scale, 'FS').

Apart from few exceptions, all the studied full scale errors are within two percent. The results are excellent, especially keeping in mind the universally applicable nature of the models.

Table 2: The average prediction errors of the second order polynomial models

Fluid	Bulk modulus		Density		Speed of sound	
	40°C	70°C	40°C	70°C	40°C	70°C
	FS [%]	FS [%]	FS [%]	FS [%]	FS [%]	FS [%]
Tellus VG 32	1.2	2.8	0.2	0.7	1.0	1.5
Tellus S VG 46	0.6	1.1	0.2	0.3	1.1	0.9
Tellus TX VG 46	0.8	1.5	0.2	0.4	0.9	0.8
Comet SAE 10W-30	1.0	1.5	0.2	0.3	1.6	0.9
Rimula x30 VG 93	1.2	2.4	0.0	0.6	1.7	1.8
Calibrat. fluid S-9365	1.7	4.0	0.3	1.0	0.9	1.7
Naturelle HF-E VG 46	1.8	1.7	0.1	0.4	0.6	1.0
ECO Pine Oil VG 46	4.2	4.3	0.2	0.3	1.1	2.4

In Karjalainen (2011b) the average modelling errors have also been calculated as percentages from the absolute value variation of the fluid parameters between pressures 0 - 1500 bar. In most of the studied cases, even this much tighter condition of error evaluation gives an error under five percent.

When the operating conditions clearly change from the presented ones, some modifications to the presented models may be needed for achieving similar accuracy – this was discussed in Section 4.4.

6 Conclusions

In this article, simple yet accurate methods for measuring and predicting the most important dynamic hydraulic fluid parameters were introduced. The fluid parameters; speed of sound in fluid, adiabatic tangent bulk modulus and density; were studied at the normal operating temperatures of industrial fluid power systems. The studied pressure range was up to 1500 bar. These methods were applied to eight different commercial hydraulic fluids. It was shown that at the presented conditions both the measuring system and the prediction method performed very well.

Based on the results, the studied fluids were compared in terms of dynamic fluid behavior. It is quite evident that base fluid has the dominant effect on these fluid parameters. Viscosity grade or additives did not seem to have any significant impact. Practically, all the studied fluids were discovered to behave similarly in terms of changing temperatures. Moreover, all the fluids were presenting similar pressure trends. However, significant differences in absolute values were recorded between the fluids at the same operating conditions.

The experimental results of e.g., fluid bulk moduli might seem to be counterintuitive. For example, it may be surprising that the slope of bulk modulus has been discovered to reduce as pressure is increased, when it could be expected to even increase due to increasing molecular forces of a compressed fluid. The actual physics behind this phenomenon would clearly need more research which is beyond the scope of this article. However, similar reducing trend in speed of sound measurements at elevated pressures has also been discovered in e.g., Beyer (1998), where speed of sound in diesel fuels was discovered to follow decreasing fourth order polynomials. Moreover as stated in Section 2.2.2, the measured densities of this article have been found to be in excellent agreement with references even in numerical values. These will give additional confidence also to the experimental discoveries and observations of this article.

Future work is already in progress for expanding the operating range of the measuring system. Pressure level will be raised up to about 2500 bar. The temperature range has already been raised up to 130°C, results will be published later. In addition, research on expanding the presented prediction models to cover a wider operating range with similar accuracy has been started. At this stage, it would not seem to demand any major modifications – naturally these future modifications will not affect the results of this article at the presented operating conditions.

Fluid behavior at temperatures below 0°C needs to be researched. It will need some controlled cooling method which will be added to the presented measuring system. Also, results with water should be tested – there is quite good reference data available for water dynamics.

Nomenclature

B_{eff}	Effective bulk modulus	[Pa]
B_{eff_a}	Effective adiabatic bulk modulus	[Pa]
B_n	Fluid bulk modulus	[Pa]
B_p	Pipe bulk modulus	[Pa]
C	Speed of sound	[m/s]
$C_{B(Patm^T)}$	Constant term of tangent bulk modulus	[Pa]
$C_{C(Patm^T)}$	Constant term of speed of sound	[m/s]
$C_{D(Patm^T)}$	Constant term of fluid density	[kg/m³]
C_p	Fluid heat capacity factor at constant pressure	[-]
C_v	Fluid heat capacity factor at constant volume	[-]
d_p	Pipe inner diameter	[m]
D_p	Pipe outer diameter	[m]
E_k	Modulus of elasticity	[Pa]
L	Measuring pipe length	[m]
P	Pressure	[Pa]
P_{atm}	Atmospheric pressure	[Pa]
T	Temperature	[ºC]
A	Density correction coefficient	[kg/m³·°C]
μ_p	Poisson's ratio for hydraulic pipe material	[-]
ρ_n	Density at measured pressure and temperature	[kg/m³]
$\hat{\rho}_n$	Density estimate at measured pressure and temperature	[kg/m³]
$\rho_{atm,T}$	Density at atm. pressure and at temperature T	[kg/m³]
$\rho_{atm,15°C}$	Density at atm. pressure and at 15°C temperature	[kg/m³]
$\nu_{atm,20°C}$	Kinematic viscosity at atm. pressure and temperature of 20ºC	[m²/s]

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