99PC-380

MEASUREMENT OF FLUID BULK MODULUS USING IMPEDANCE OF HYDRAULIC CIRCUITS

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ABSTRACT

Certain properties of fluid change with pressure, temperature and other operating system conditions. In automotive hydraulic systems driven by pumps, air usually enters the system as dissolved matter or very small bubbles. Such air will change certain properties of the fluid like the density, bulk modulus and viscosity. Measuring these properties for evaluating system performance in real operating conditions is one of the big challenges that face engineers.

In this paper, the bulk modulus of certain power steering fluids is measured using standard impedance and flow ripple tests for pumps. The effects of pressure, temperature and speed on the bulk modulus are studied thoroughly.

INTRODUCTION

It is found as early as 1967 that obtaining reliable material properties for fluids like bulk modulus is a challenging and important task [1]. The prediction of the performance of such fluids in systems depends heavily on accurate and reliable properties for such fluids. For example, proper impedance and ripple characteristics of pumps, gears and fluid lines in general require accurate bulk modulus of fluids. The fact that air may be introduced in the system to varying degrees in various tests require the calculation of the bulk modulus while conducting the test itself for impedance and ripple measurements.

Only recently standards were published for the measurement of ripple and impedance data for pumps and fluid line components [2]. Such standards were the results of a considerable effort conducted at the University of Bath [3-5]. Several recent studies appeared on the subject [6,7].

The purpose of this paper is to use normal impedance and ripple apparatus published by the International Standards Organization (ISO 10767-1) to find the bulk modulus of fluids under normal operating conditions.

IMPEDANCE AND RIPPLE EXPERIMENT

An experiment was built that adheres to the ISO 10767-1 standards. Static pressure and temperature can be controlled up to 1%. A description of the test rig and the experimental procedure used follows.

THE TEST RIG

The test rig is built together with the following main components

1. Reservoir. A test rig with two reservoirs is used in order to conveniently switch between fluids if needed. A valve is used to choose which of the reservoirs is to be used in a particular experiment. The reservoir contains a heater, which kicks in if the temperature is less than the target testing temperature.

2. Variable speed primary motor. This is the motor that drives the pump. The speed of the motor is controlled within 1 rpm digitally. It is capable of driving the pump up to 5000 rpm.

3. Variable speed secondary motor and accessories. This motor is used to develop pressure pulses along the fluid line. It is only used for impedance testing.

4. Data acquisition system. Three pressure transducers are assembled at varying lengths from the outlet of the pump and before the secondary source. These are connected to a data acquisition system and to a PC for processing and viewing the data.

5. Pressure valve. This is used to apply load to the pump

6. Cooling unit. The fluid is processed into a cooling unit with a fan that kicks in when the temperature is to be reduced.

Other accessories like pressure valves and sensors were attached. Reference 2 describes the method in more details. A picture of the test rig is shown in Fig. 1.

Fig. 1 Experimental set-up for testing pumps

A circuit diagram of the test rig can be found in Reference 2.

EVLAUATION OF THE BULK MODULUS

BEHAVIOUR OF RIGID PIPES

The complex amplitudes of the pressure and flow ripple at a position *x* along the pipe can be determined using the following equations:

$$P_x = P_F e^{-\gamma x} + P_R e^{\gamma x}, \qquad Q_x = P_x / Z_o$$

Where P_F and P_R are the pressure waves at x=0 traveling in the forward and reverse directions respectively. The damping coefficient γ and the pipe impedance Z_0 are given by

$$\gamma = \frac{j\varpi}{c_0}\xi, \qquad Z_0 = \frac{\rho c_0}{A}\xi$$

$$\text{where} \qquad c_0 = \sqrt{\frac{B_E}{\rho}}$$

Where ρ is the fluid density, A is the cross sectional area of the pipe, B_E is the effective bulk modulus of the fluid and the pipe and ϖ is the frequency. It should be noted that the effective bulk modulus B_E should be used as this considers the bulk modulus of both the fluid and the tubing system [1]. ξ is defined by

$$\xi = \left[1 - \frac{2}{zj^{3/2}} \frac{J_1\left(zj^{3/2}\right)}{J_0\left(zj^{3/2}\right)}\right]^{-\frac{1}{2}}, \qquad where \qquad z = r_p\sqrt{\frac{\rho\varpi}{\mu}}$$

μ is the absolute viscosity, r_p is the radius of the pipe, and J_o and J_1 are Bessel functions. Alternatively, reference 2 defines ξ as

$$\xi = \left[K_1 + \frac{8jK_2}{N_s^2}\right]^{-\frac{1}{2}}$$

Where N_s is the wave shear number

$$N_s = 0.5d\sqrt{\varpi / \nu}$$

Where d is the internal diameter of the discharge pipe and ν is the kinematic viscosity, and

$$\left.\begin{aligned} K_1 &= 1 + \frac{\sqrt{2}}{N_s} \\ K_2 &= 0.425 + 0.175N \end{aligned}\right\} For \qquad N_s \geq 8$$

$$\left.\begin{aligned} K_1 &= 1.333 - 4.66\times10^{-3} N_s^2 + 2.73\times10^{-4} N_s^3 \\ K_2 &= 1.0 + 2.03\times10^{-2} N_s^2 - 7.81\times10^{-4} N_s^3 \end{aligned}\right\} For\ N_s < 8$$

CALCULATION OF BULK MODULUS

An iterative method is employed for the calculation of the speed of sound and bulk modulus. A starting value for the effective bulk modulus is required, call it $B_{eff,0}$. From this value an initial guess for the speed of sound (C_0) can be made using previous equations and assuming that fluid density remains constant. A correction to the speed of sound is made using [2]:

$$\Delta C = \frac{\sum_{i=1}^{n} \mathrm{Re}(\varepsilon_i \overline{\zeta}_i)}{\sum_{i=1}^{n} \zeta_i \overline{\zeta}_i}$$

where

$$\varepsilon_i = P_{1,i} \sin[k(x_3 - x_2)] + P_{2,i} \sin[k(x_1 - x_3)] + P_{1,i} \sin[k(x_2 - x_1)]$$

$$\zeta_i = \frac{k}{c_o} \left\{ P_{1,i}(x_3 - x_2)\cos[k(x_3 - x_2)] + P_{2,i}(x_1 - x_3)\cos[k(x_1 - x_3)] + P_{31,i}(x_2 - x_1)\cos[k(x_2 - x_1)] \right\}$$

and

$$k = \frac{\varpi_i \sqrt{K_1}}{c_o}$$

The revised speed of sound can then be found using

$c_l = c_o + \beta \, \Delta c$

Where β is a relaxation factor used to control speed and stability of the convergence. It is a positive number less than one, typically taken at 0.7.

RESULTS

Figure 2 shows readings of pressure transducers obtained at three various locations along the pipe from the pump discharge. The data is shown after being processed with a Fast Fourier Transform (FFT). This data is processed with the algorithm described earlier for the speed of sound and bulk modulus calculations.

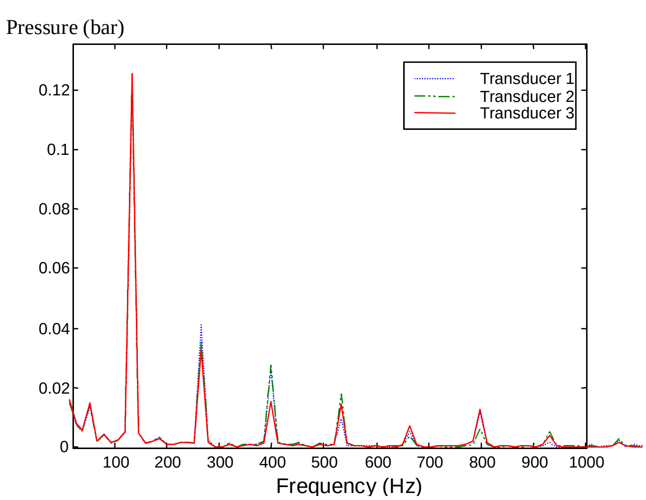

Fig. 2 Readings obtained from the three pressure transducers

Table 1 shows converged values for the bulk modulus. Ripple and impedance data was collected for pressure of 2, 10, 40 and 80 bar. For each pressure value, readings are made for pump speeds of 800, 1200, 1600 and 200 rpm. Each test is repeated twice. Table 1 shows the *average* values of the bulk modulus. A general roller-vane pump is used in the analysis with a general power steering fluid.

Table 1 Bulk modulus of power steering fluid for various pressures

Pressure (bars)	Bulk Modulus at 65 C (bars)	Bulk Modulus at 50 C (1000)
2	12977.21	
10	13810.53	14427.68
40	14700.64	14938.28
80	15129.20	

The pump speed is found to have limited effect on the bulk modulus of the fluid.

The above results show that the only possibility for power steering fluid to have such variations in bulk modulus due to pressure changes is aeration. Air bubbles in the system will be compressed under pressure thus increasing the bulk modulus of the fluid. Figure 3 below shows the bulk modulus variation as a function of pressure.

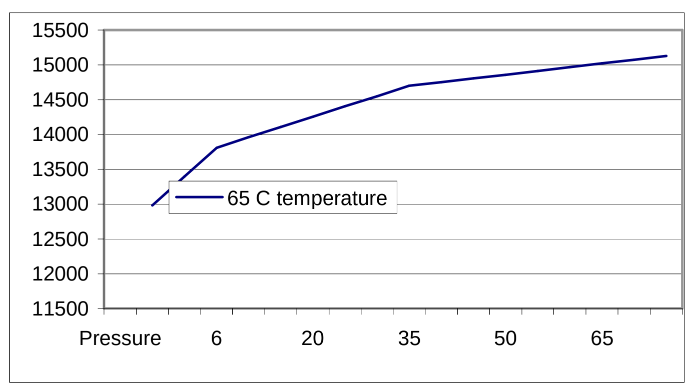

Fig. 3 Bulk modulus of power steering fluid as a function of pressure

CONCLUSION

The variation in aeration in automotive hydraulic circuits dictates the need for finding fluid properties during testing. A simple procedure for extracting bulk modulus from ripple data collected at various lengths from the pump is used here. Variations in bulk modulus measurements are observed. Averaged values, however, of series of tests showed trends that can explain the existence of air bubbles in the automotive hydraulic system in application. The effect of aeration on the characterestics of fluid lines, pumps and gears will be the subject of future studies.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Don Walker for running the experiment, Mr. Dave Llewellyn and Dr. Devendra Kumar for reviewing the manuscript.

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