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Compressibility and Density of Lubricants in Transient Loading

by

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PREFACE

I would like to thank my supervisors, professor Erik Höglund and doctor K G Sundin, who have provided valuable support and encouragement all through the work of this thesis.
I would also like to thank all my colleagues at the Department of Mechanical Engineering and especially those at the Division of Machine Elements.
Last but not least, I would like to express my gratitude to my wife Maria and my daughter Frida for their support during the work of this thesis.

This thesis comprises the following papers:

A. Lindqvist, S. , Höglund, E. , and Sundin, K. G., 1996, "A modified Split-Hopkinson Pressure Bar Method for Determination of Dilatation-Pressure Relation of Lubricants used in EHL", Submitted for publication

B Lindqvist, S. , 1996, "Dynamic Density Measurement and Dilatation-Pressure Relation for Lubricating Oils and Greses", Submitted for publication

INTRODUCTION

Tribology is the name of the science that deals with lubrication, wear and friction.
Everywhere were moving parts can be found, i.e., were two surfaces in contact are moving relative to each other, frictional losses are a fact. A common way to reduce friction is to lubricate with oil or grease or to use solid lubricants. Other purposes to use lubricants except for friction reduction, is to separate two surfaces so that no wear appears, to cool, to seal, to supply additives or to remove debris.

Very high costs are connected with both frictional losses and damage on moving machine elements due to insufficient lubrication. British and American investigations have shown that tribology related economical losses in an industrialised country such as Sweden can be as high as 7 % of GNP. It is possible to reduce these losses with up to 15% by using the knowledge of today, and by further research even more can be saved. Research in this area aims at giving lower friction, lower energy consumption, less use of raw materials, longer service life and a better environment.

There are two types of full film lubrication, hydrodynamic lubrication (HD) at low pressures and elastohydrodynamic lubrication (EHL), at high pressures. In the latter case the two surfaces separated by a thin film (1 μm) of lubricant are elastically deformed.

To develop both better lubricants and better machine elements it is important to understand more about what happens in a lubricated contact, that is, how the surfaces and the lubricant interact. To achieve this knowledge it is necessary to perform experiments under relevant conditions. Results from such experiments can be used for establishing mathematical models describing the mechanical/physical behaviour. To calculate film thickness, pressure distribution and friction in EHL it is necessary to know the viscosity, compressibility and density of the lubricant and how they are affected by pressure, temperature and loading rate.
Several investigations have been performed concerning the compressibility of lubricants. Most of these investigations have been made under static conditions, i.e., no influence of temperature gradients and loading-unloading time is included.
A difficulty in experiments is to isolate and measure the influence of a single specific parameter. In a real lubricated contact, the loading-unloading cycle is usually transient. In for example a

bearing or a gear pressures often reach several GPa and the loading-unloading time is a few hundred microseconds.
In this thesis, dilatation and the density's dependence on pressure at transient loading has been investigated.

Dilatation and density

Dilatation or relative change in volume, is defined as

$$\frac{\Delta V}{V_0} \tag{1}$$

For lubricating oils it has been measured statically up to 400 MPa, Dowson and Higginson (1966), and to 2.2 GPa, Hamrock et.al. (1987). In a real EHL contact however the loading cycle is usually very short which affects the dilatation's and density's dependence on pressure. At short loading times the temperature rise due to adiabatic compression may make the dilatation-pressure relation weaker and the density increase lower than in an isothermal case. Transient measurements have been performed, Ramesh (1991) and Feng and Ramesh (1993), but under conditions with shorter loading times, 1-10 μs, compared to a real conjunction. At static measurements there is a significant change in behaviour, a phase transition, at a certain pressure. This phase transition may occur also in dynamic measurements but it is not obvious at what pressure this phase transition will occur.

Density can be derived directly from the dilatation by assuming constant mass.
Dowson and Higginson (1966) measured statically up to 400 MPa and presented their well known density-pressure relationship

$$\frac{\rho}{\rho_0} = 1 + \frac{0.6p}{1+1.7p} \tag{2}$$

Transient measurements up to 5 GPa were made by Ramesh (1991) and Feng and Ramesh (1993) who suggested the relationship

$$p = \frac{K\{1 - V/V_0\}}{\left[1 + a\{V/V_0 - 1\}\right]^2} \tag{3}$$

between dilatation and pressure.

Their measurements gave one point per "shot" for the compressibility, so a lot of experiments had to be made before a tendency could be seen.
Some questions appear at once when transient measurements are discussed. Is the loading time relevant and if not may that affect the compressibility results in some way? Is there any leakage and how much? It is always difficult to contain oil and grease at high pressures and have control of the mass during fast compression. Equipment for containing and compressing the oil has been built considering the points above.

Paper A

In paper A a modified split-Hopkinson pressure bar (SHPB) set-up, Färm and Sundin (1994), is used to determine the dilatation-pressure relation of lubricants. It makes it possible to test oils and greases under conditions similar to those found in a real EHL contact; loading-unloading times of 100 and 300 μs respectively and pressures up to 1.9 GPa.
A schematic picture of the experimental set-up can be seen in figure 1.

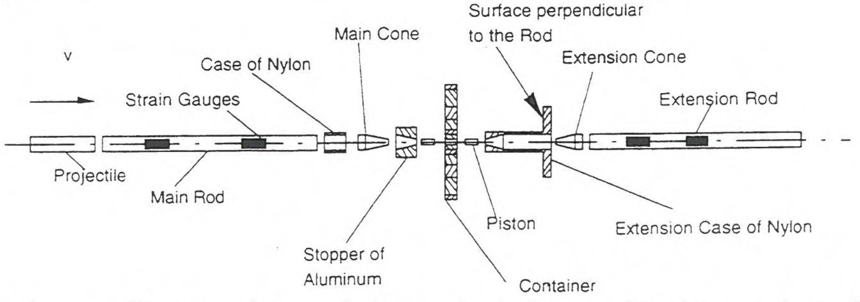

Fig. 1 Blow-up picture of the mechanical parts for the experimental set-up.

The container, diameter 200 mm and width 30 mm, is designed with an inset made of cemented carbide and is pre-stressed using a shrink-fit assembly of five rings. The two pistons, diameter 8 mm, are made of cemented carbide and the clearance between the piston and the cylindrical hole is between 1 and 2 μm.

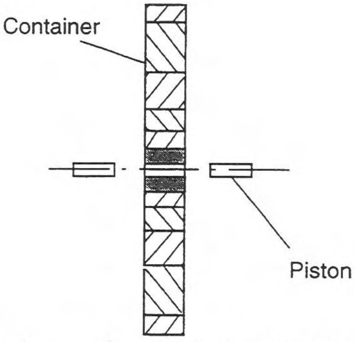

Fig. 2 The pre-stressed container and the pistons.

Strain gauges are used to measure the strains in the rods as a function of time at two positions on each rod. One dimensional wave propagation theory is used to calculate the pressure, the dilatation and the dilatation rate at the contact between the confined oil and the piston on both sides of the oil column.

Two oils were tested, one naphthenic base oil and one synthetic, 5P4E.

A two term polynomial curve fit was made to describe the oils empirically,

$$p = c_1 \frac{\Delta V}{V_0} + c_2 \left(\frac{\Delta V}{V_0} \right)^2 \tag{4}$$

A comparison between the results from the present investigation and the Dowson and Higginson (1966) and the Feng and Ramesh (1993) models can bee seen in figure 3 for the naphthenic mineral oil and in figure 4 for the synthetic 5P4E and one mineral oil (Dowson and Higginson).

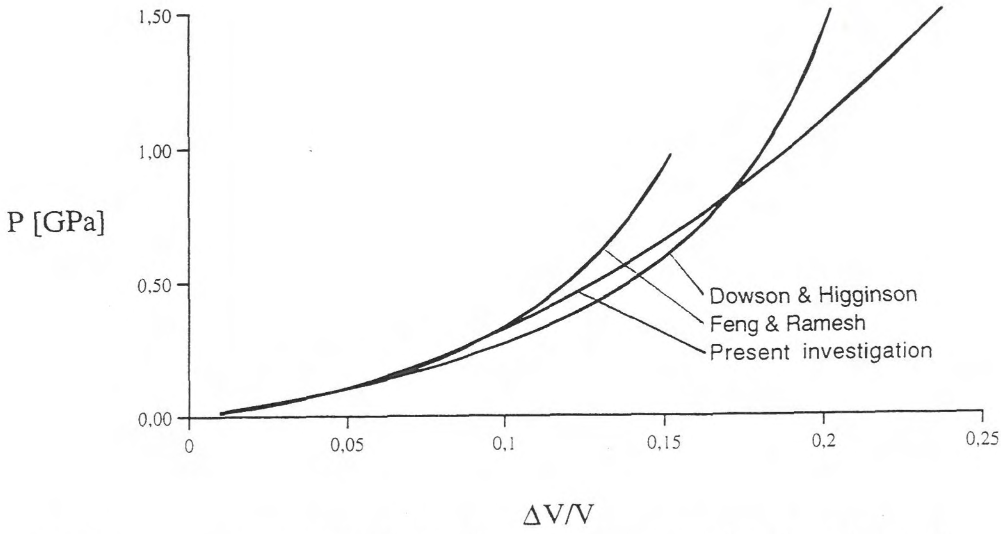

Fig. 3 A comparison of the dilatation-pressure relation for mineral oil.

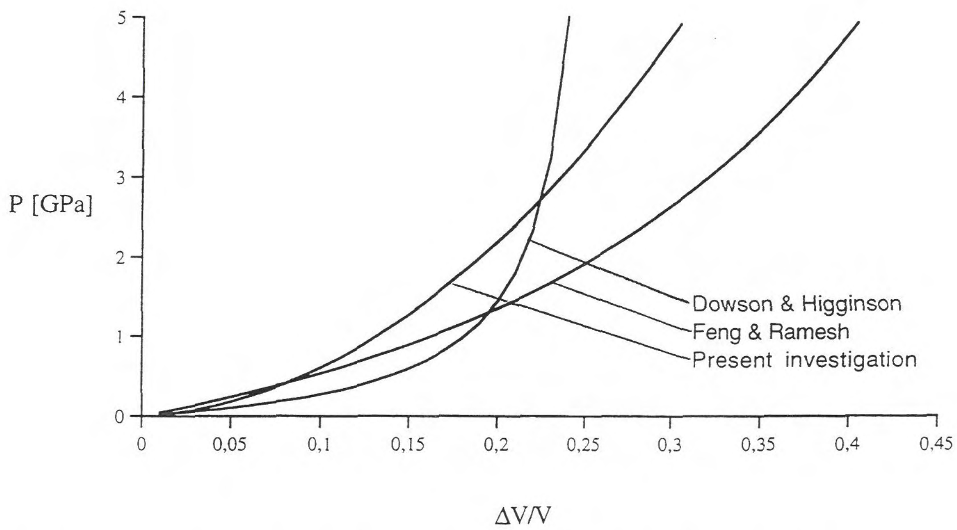

Fig. 4 A comparison of dilatation-pressure relations by Feng and Ramesh, Dowson and Higginson and the present investigation on the synthetic oil 5P4E.

In figure 4 the results for the present investigation and the Dowson and Higginson model have been extrapolated to make it possible to compare the three dilatation-pressure relations at common pressures of 2-5 GPa, which are typical in EHL contacts.

Paper B

In paper B the split-Hopkinson pressure bar (SHPB) set-up has been used for further investigations of 7 oils and 2 greases.
The relation for dilatation-pressure, equation 4, has been modified with a constant c_3 and recalculated to a density-pressure relation,

$$\frac{\rho}{\rho_0} = \frac{1}{1 + \frac{c_1}{2c_2}\left[1 - \sqrt{1 + \frac{4c_2(p - c_3)}{c_1^2}}\right]} \tag{5}$$

The Feng and Ramesh expression for dilatation-pressure relation, equation 3, has also been recalculated to a density-pressure relation.
In figure 5 the comparison between the seven oils can be seen. The dependence between the different molecular structure of the oils and the dilatation-pressure relation has also been investigated. Long straight molecules like PAO, esters and polyglycols have a relatively weak behaviour. The molecules in a well refined mineral oil like the naphthenic or the paraffinic oils have less possibilities to adopt different kind of configurations, and the oil is therefore expected to have a stiffer behaviour. The 5P4E has the stiffest behaviour of the tested oils.

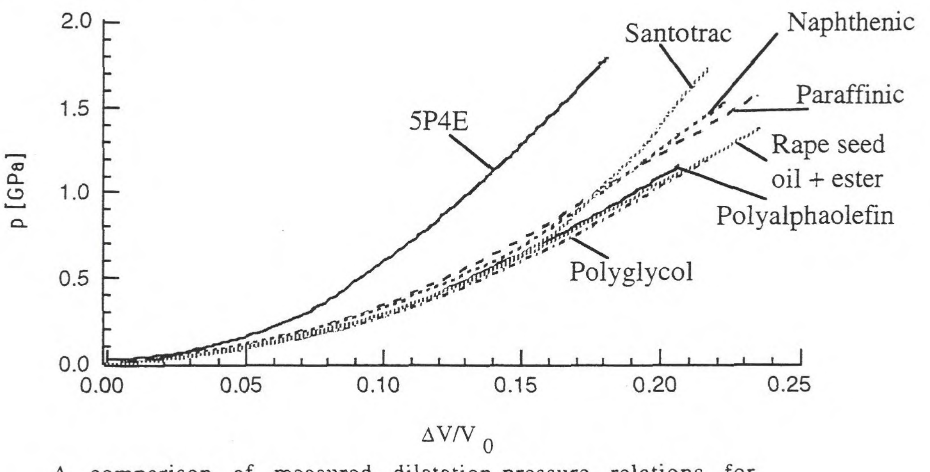

Fig 5. A comparison of measured dilatation-pressure relations for seven tested oils.

Two of the oils have also been tested at a temperature of 70°C. High temperature gives a weaker dilatation-pressure behaviour.
Equation (5) describes the density-pressure relation in a more detailed way than the Dowson and Higginson or the Feng and

Ramesh equations. It is more adopted to different kind of lubricants under more relevant conditions. The equation can be used as a new density-pressure model in EHL calculation programs. In fig 6 a comparison between the three models can be seen.

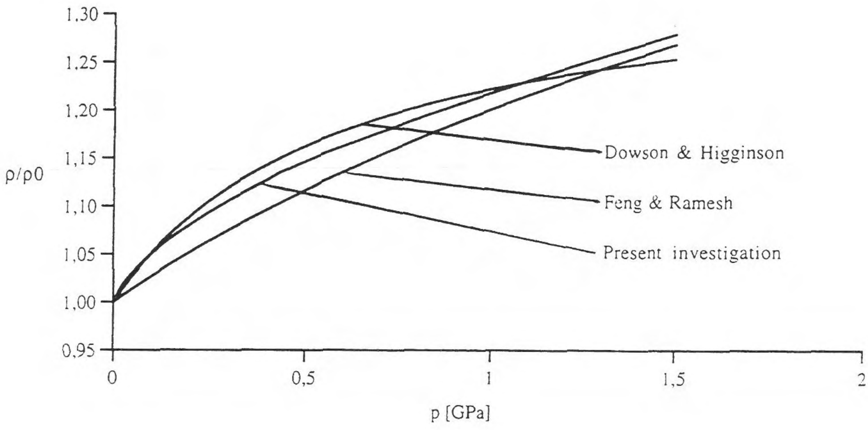

Fig. 6 Relative density as a function of pressure for mineral oil.

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NOMENCLATURE

a	dimensionless materials constant	
c_1	material constant	[GPa]
c_2	material constant	[GPa]
c_3	material constant	[GPa]
K	material constant	[GPa]
p	pressure above atmospheric	[GPa]
V	volume at p pressure	[m^3]
V_0	volume at atmospheric pressure	[m^3]
ΔV	change in volume, $V-V_0$	[m^3]
ρ	density of oil at p pressure	[kg/m^3]
ρ_0	density of oil at atmospheric pressure	[kg/m^3]

A Modified Split-Hopkinson Pressure Bar Method for Determination of Dilatation-Pressure Relation of Lubricants used in EHL

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ABSTRACT

In theoretical calculations of film thickness, pressure distribution and friction in an elastohydrodynamically lubricated (EHL) conjunction it is necessary to understand the physical/mechanical behaviour of the oil. It is important to know, for example, the compressibility defined as the derivative of dilatation with respect to pressure, and the density-pressure relationship. In this paper a modified split-Hopkinson pressure bar system for determination of the compressibility of oil is presented. It makes it possible to test oils under conditions similar to those found in real EHL contacts; loading-unloading times of about 100-300 μs and pressures of almost 2 GPa. An empirical model has been suggested to mathematically describe the dilatation-pressure relation of the specific oils. A naphthenic mineral oil and a synthetic oil, 5P4E, have been tested at pressures up to 1.5 and 1.9 GPa, respectively.

1. INTRODUCTION

In an EHL contact the lubricant is in many situations subjected to pressures of several GPa and short loading and unloading times, typically 100 to 500 μs. Such conditions can be found in many machine elements such as rolling element bearings or gears where two nonconformal surfaces are separated by a thin film of lubricant. To be able to theoretically model and numerically calculate the film thickness and pressure distribution in such an elastohydrodynamic conjunction, it is of great importance to know not only the viscosity-pressure relation but also the dilatation-pressure and density-pressure relationships of the lubricant. If these relations are not known, only solutions based on isoviscous and incompressible conditions can be obtained.

Several investigations have been made using static conditions. Dowson and Higginson (1966) used static pressures up to 400 MPa and suggested the density-pressure relationship

$$\frac{\rho}{\rho_0} = 1 + \frac{0.6p}{1 + 1.7p} \tag{1}$$

where the unit of pressure is GPa. It has been commonly used also in situations where the pressure by far exceeds 400 MPa. Using mass conservation equation (1) can be rewritten as a relation between pressure and dilatation

$$p = \frac{\frac{\Delta V}{V_0}}{0.6 - 2.3\frac{\Delta V}{V_0}} \tag{2}$$

Hamrock et al (1987) made static measurements between 0.4 and 2.2 GPa and fitted curves in two pressure regions. One curve in the region below the solidification pressure and another in the region above. The solidification pressure is defined as the pressure at which a lubricating oil undergoes a phase change from a liquid to an amorphous solid exhibiting a limited shear strength. In the solid state the compressibility decreases dramatically.

Static investigations, however, include neither the rapid loading and unloading encountered in EHL, which itself may have an effect on the compressibility nor the associated temperature rise due to the rapid compression in the EHD contact. The increase of temperature will presumably counteract the pressure induced density increase.

Investigations based on plate impact experiments up to 5 GPa, Ramesh (1991), led Feng and Ramesh (1993) to suggest the relationship

$$p = \frac{K\left\{1 - V/V_0\right\}}{\left[1 + a\left\{V/V_0 - 1\right\}\right]^2} \tag{3}$$

between pressure and volume ratio where the constants were based on measurements made with a Kolsky bar. The oil film layer in the plate impact experiment was 50 μm thick giving a loading time of 1 μs which is much shorter than in a real EHL contact. These measurements gave one point per "shot" for the dilatation-pressure relationship, thus a lot of experiments were needed to cover a wide pressure range.

The aim of the present paper is to present continuous measurements of the relation between dilatation and pressure up to pressures typical for a real EHL contact. A modified split-Hopkinson pressure bar set-up (SHPB), Färm and Sundin (1994), has been used.

2. EXPERIMENTS

2.1 Set-up

In a classical SHPB-set-up a specimen is placed between two elastic rods (main and extension rod) and loaded by an incoming compressive wave in the main rod. The conditions in the specimen during loading are evaluated from strain histories measured at the rods. The method has been modified, Färm and Sundin (1994), with conical adapters of high-strength material.

In the present investigation the modified version of the SHPB has been completed with a cylindrical container and two pistons for confining and loading the liquid specimen, see figures 1 and 2. The rods have a diameter of 25 mm and a length of 1.7 m, and are made from high alloy steel. Two cones made of powder steel connect the rods with the cemented carbide (Sandvik H10F) pistons. The cones are 70 mm long with a cylindrical part with length 20 mm and diameter 25 mm and a conical part with diameters 25 mm and 8 mm. A case of nylon mounted on the main rod aligns the rod and the cone. On the extension rod another case of nylon is mounted for alignment and also to facilitate monitoring of the initial length of the oil column. This length is measured with a position transducer on the surface of the nylon case which is perpendicular to the rod, see figure 1. The initial length of the oil column was chosen in the range 2 to 5 mm.

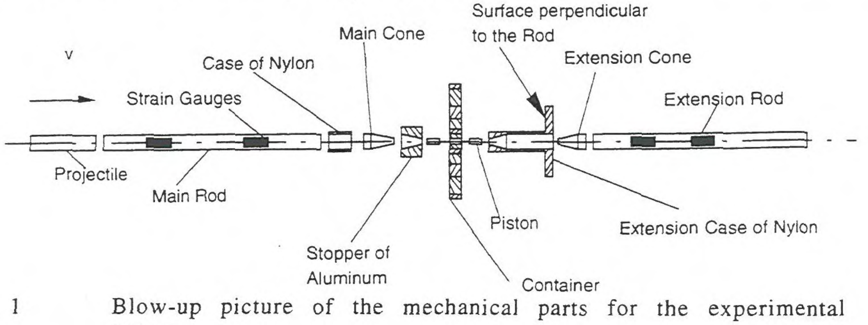

Fig. 1 Blow-up picture of the mechanical parts for the experimental set-up.

A stopper of aluminum is mounted on the main side of the container to prevent the main rod and cone from hitting it.

The container, figure 2, is designed with an inset made of cemented carbide (CG40/HIP), outer diameter 30 mm with a central hole of 8 mm, which is pre-stressed using a shrink-fit assembly of five rings of high alloy steel (SS2142, SS2550 and SS2172). It has an outer diameter of 200 mm and a width of 30 mm. The pistons have a diameter of 8 mm and a length of 30 mm.

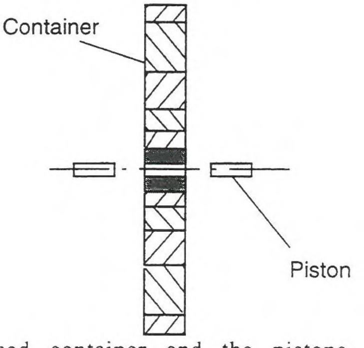

Fig. 2 The pre-stressed container and the pistons.

They are carefully ground and individually fitted to the cylindrical hole to minimise the leakage and yet avoid metal-metal friction. The diametral clearance between the hole and the pistons is between 1 and 2 μm.

To generate an elastic wave an air gun accelerates a projectile with diameter 25 or 30 mm and length 305 mm which impacts the end of the main rod. By controlling the pressure in the air tank and changing the acceleration distance for the projectile it is possible to control the speed of the projectile and thus the dynamic loading of the specimen. The speed of the projectile is in the order of 20 m/s. A pad of thick paper was placed on the impacted end of the main rod as a damper to reduce dispersive effects. A pre-applied static axial force of about 100 N on the extension bar ensures that all parts are in good contact with each other when the projectile impacts.

Strain gauges (Micro-Measurements CEA-06-250UN-350) were glued in diametrically opposite positions at cross sections on the main and extension rods. Every pair of strain gauges were coupled for summation in a Wheatstone bridge to avoid influence from bending. The strain signals from the bridges are amplified (Measurement Group 2210) and recorded (Lucas Datalab DL6034) with twelve bit resolution. The sampling interval was 0.8 μs and the recording time 1.6 ms. All the signals were transferred on line to a Macintosh Quadra computer and evaluated with a program written in LabWIEW II.

2.2 Evaluation

The pressure, the dilatation and the dilatation rate in the oil column were evaluated from the force, the displacement and the particle velocity at the piston-oil interfaces. They are related as follows,

$$p(t) = \frac{F_E(t)}{A} \tag{4}$$

$$\frac{\Delta V}{V_0}(t) = \frac{(u_M(t) - u_E(t))}{L} \tag{5}$$

$$\frac{\partial\left(\dfrac{\Delta V}{V_0}\right)}{\partial t} = \frac{(v_M(t) - v_E(t))}{L} \tag{6}$$

The force F_E and the particle velocity v at the main (index M) and extension (index E) side of the lubricant specimen were determined from the strain histories measured on the rods, Lundberg et al (1990). The displacements u_M and u_E are determined by integration of the velocities v_M and v_E respectively and pressure, dilatation and dilatation rate are evaluated according to equations (4) - (6). It was assumed that the radial expansion of the container can be neglected as the cemented carbide and shrink fitted steel rings are much stiffer than the oil.

2.3 Calibration procedure

In order to verify the accuracy of the measuring system a calibration was performed with cylindrical test specimens made of either aluminum or steel fitted into the cylindrical hole in the container. The specimen was free to expand in radial direction. The length of the specimen was manually measured before and after the experiment using a dial gauge, and the change in length was compared to the change in length measured by the SHPB-system. The difference was within 2%, indicating that the accuracy of the system is good.

2.4 Tested oils

Two oils where tested, one naphthenic mineral base and one synthetic, see table 1. These two oils were chosen because the naphthenic oil is a commonly used base oil and the synthetic 5P4E has been well investigated in EHL applications.

Type of oil	Name	Viscosity (20°C) [mPas]	Viscosity (40°C) [mPas]	Density (15°C) [kg/m^3]
Mineral	Naphthenic	66	25	894
Synthetic	Polyphenyl Ether 5P4E	4400	390	904

Table 1 Properties of the two tested oils.

2.5 Test Procedure

The parts in contact with the lubricant were carefully cleaned with alcohol solvent before every test. Also, before every test, a position measurement was made on the complete system without specimen. This was made to determine the reference position for the surface of the nylon case from which the length of the oil specimen was determined in the following experiment.

The extension piston, cone and rod were removed during the filling of oil in the container and then put back again. Great care was taken to avoid air in the oil volume. A static axial force was applied to the system and a small axial leakage of oil through the clearance between the pistons and the hole was obtained. When the length of the oil column had decreased to a predermined value between 2-5 mm the projectile was fired.

The oils were tested several times to make sure that the measurements were repeatable. Two different pairs of cones and pistons were used. Two projectiles with different diameter were used and finally the length of the oil column was changed several times between 2 and 5 mm. All this was done to ensure that the results were not depending on the experimental set-up. All measurements were performed at room temperature, 20°C.

3. RESULTS AND DISCUSSION

Time histories typical of the experiments for pressure p, dilatation $\frac{\Delta V}{V_0}$ and dilatation rate $\frac{\partial}{\partial t}\left(\frac{\Delta V}{V_0}\right)$ are shown in figures 3-5 respectively. Experiments have been made up to pressures of 1.9 GPa. The measurements of the pressure-dilatation relation is based only on the first loading phase. The second peak in, e.g., figure 3 is a second loading-unloading phase emanating from reflections. The duration of the loading phase is about 100 μs and that of the unloading phase about 300 μs for the 5P4E oil, see figure 3. These times are typical for both of the tested oils.

In figure 6 a complete loading-unloading, dilatation-pressure cycle can be seen. The loading part has been used to determine the dilatation-pressure relation.

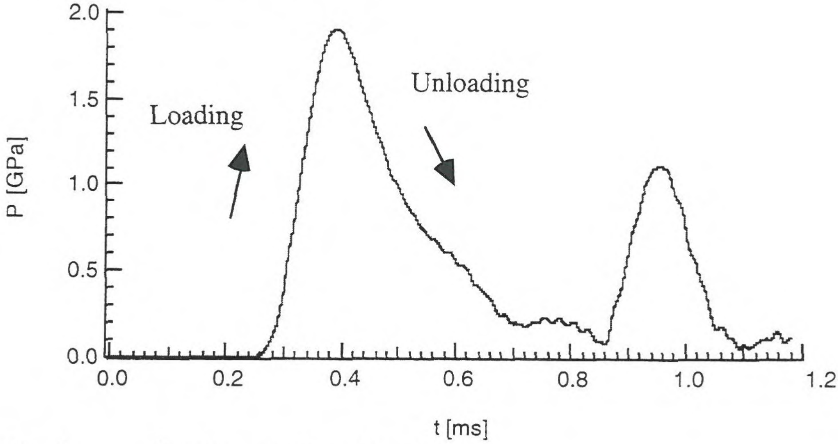

Fig. 3 Pressure vs time for 5P4E.

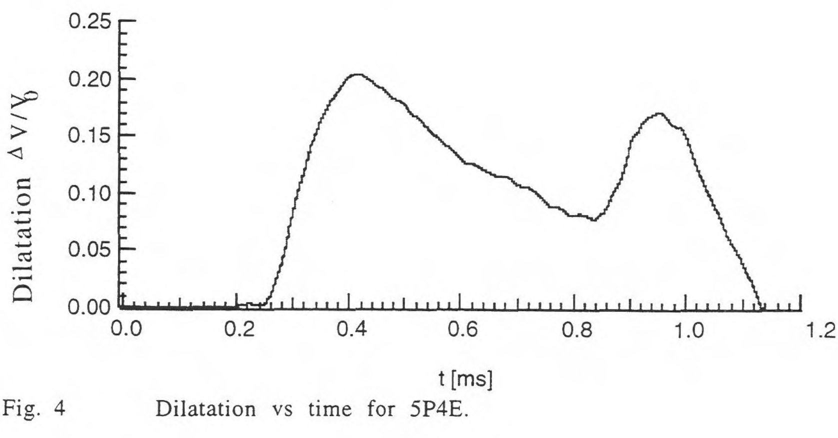

Fig. 4 Dilatation vs time for 5P4E.

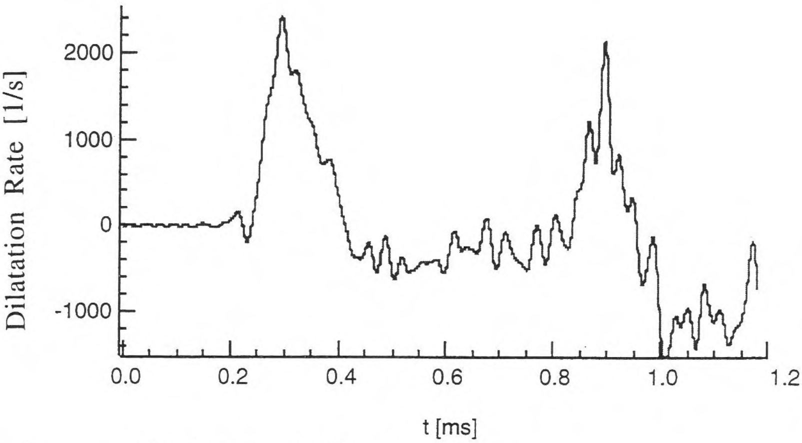

Fig. 5 Dilatation rate vs time for 5P4E.

The leakage can be observed from the loading and unloading curve, see figure 6, and can be estimated to be less than 3 to 5 per cent of the total enclosed oil volume. Since the loading time is about one third of the unloading time it is reasonable to assume that the major part of the leakage takes place during the unloading phase. If air is present in the oil specimen the curve will have an initial part which is almost horisontal, while the air is compressed. In such a case the curve was adjusted horisontally for compensation.

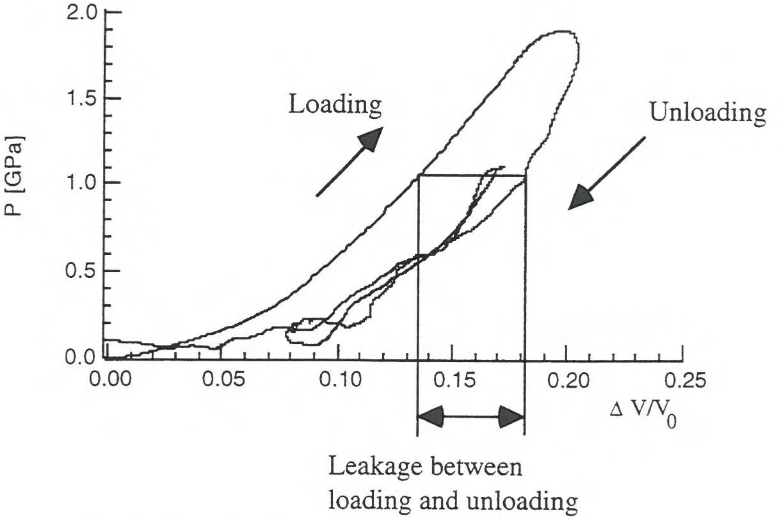

Fig. 6 Loading and unloading curve for the synthetic oil 5P4E. The difference between the loading and the unloading phase is the leakage.

Dilatation-pressure curves for 5P4E and the naphthenic oil can be seen in figure 7 and 8. The repeatability is very high although the experimental set-up is varied indicating that the results are independent of the experimental set-up. The results show that it is possible to determine the entire dilatation-pressure relation in one single experiment with high accuracy.

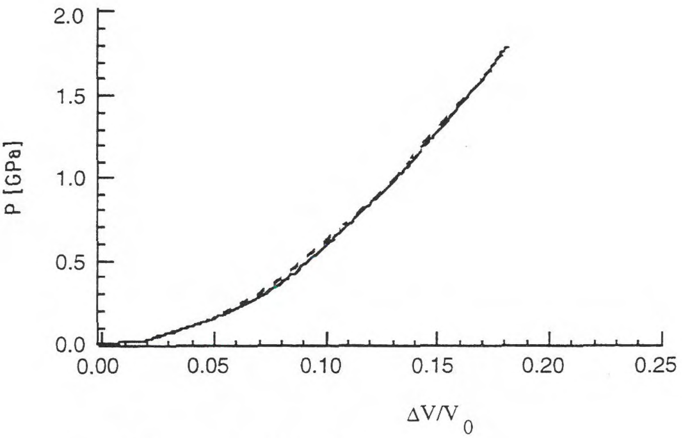

Fig. 7 Two loading curves of 5P4E.

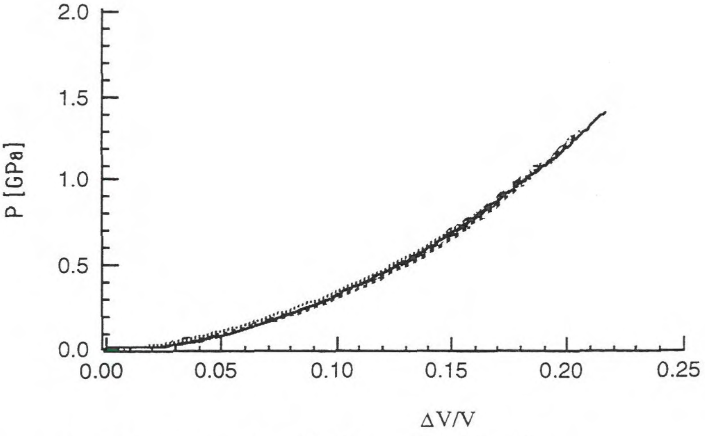

Fig. 8 Six loading curves of the naphthenic oil.

It is worth noting that no particular knee at a point where the liquid transforms to a solid like state can be found for any of the two tested oils. Such a knee could have been expected considering the results presented by Hamrock et al (1987). Feng and Ramesh (1993) discuss the possibility of a knee in their data obtained by the Kolsky bar method but due to scatter it was very difficult to quantify such a transition. The absence of a transition knee may be explained by the temperature increase associated with the adiabatic compression.

In figure 9 it can be seen that there is a significant difference in compressibility between the two types of oil. The 5P4E shows a lower compressibility, i.e. a higher stiffness than the naphthenic oil. This is in accordance with previous results by Feng and Ramesh (1993).

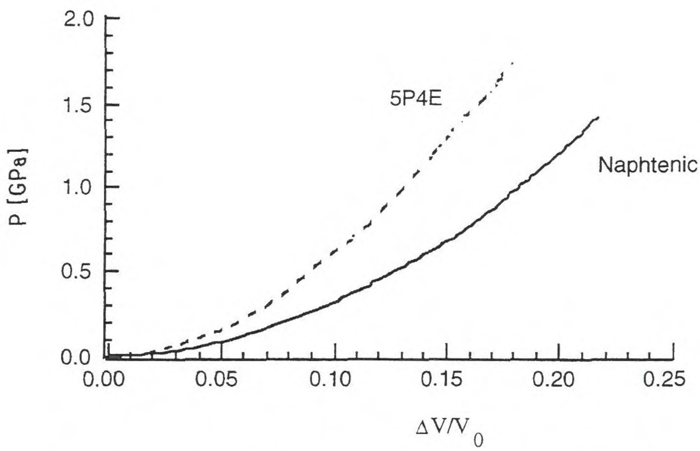

Fig. 9 A comparison of the measured dilatation-pressure relation (the loading phase) for the two oils.

To establish an empirical model, a polynomial equation of the form

$$p = c_1 \frac{\Delta V}{V_0} + c_2 \left(\frac{\Delta V}{V_0} \right)^2 \tag{7}$$

has been fitted to the experimental data using the method of least squares. The empirical model is almost identical with the original measured curve.

The three dilatation-pressure relations, equations (2), (3) and (7) are presented in table 2 together with suggested parameters.

	Dilatation-Pressure relation	Type of oil and Constants
Dowson & Higginson	$p = \dfrac{\frac{\Delta V}{V_0}}{k_1 - k_2 \frac{\Delta V}{V_0}}$	Mineral oil: k_1=0.6 [1/GPa] k_2=2.3 [1/GPa] (Shell HVI650)
Feng & Ramesh	$p = \dfrac{K \frac{\Delta V}{V_0}}{\left[1 - a \frac{\Delta V}{V_0}\right]^2}$	Mineral: K=1.4 [GPa] a=3.5 Synthetic: K=4.3 [GPa] a=1.0
Present investigation	$p = c_1 \dfrac{\Delta V}{V_0} + c_2 \left(\dfrac{\Delta V}{V_0}\right)^2$	Mineral: c_1=1.0 [GPa] c_2=22.4 [GPa] Synthetic: c_1=1.1 [GPa] c_2=49.1 [GPa]

Table 2. Pressure-dilatation relation. The Dowson and Higginson, Feng and Ramesh and present investigation.

For <u>mineral</u> oil static measurements were made up to about 400 MPa by Dowson and Higginson (1966). Feng and Ramesh (1993) have made dynamic measurements up to about 1 GPa. In figure 10 their results are plotted together with the results from the present investigation. The Dowson and Higginson relation has been extrapolated to 1.5 GPa as it is often used up to these pressures.

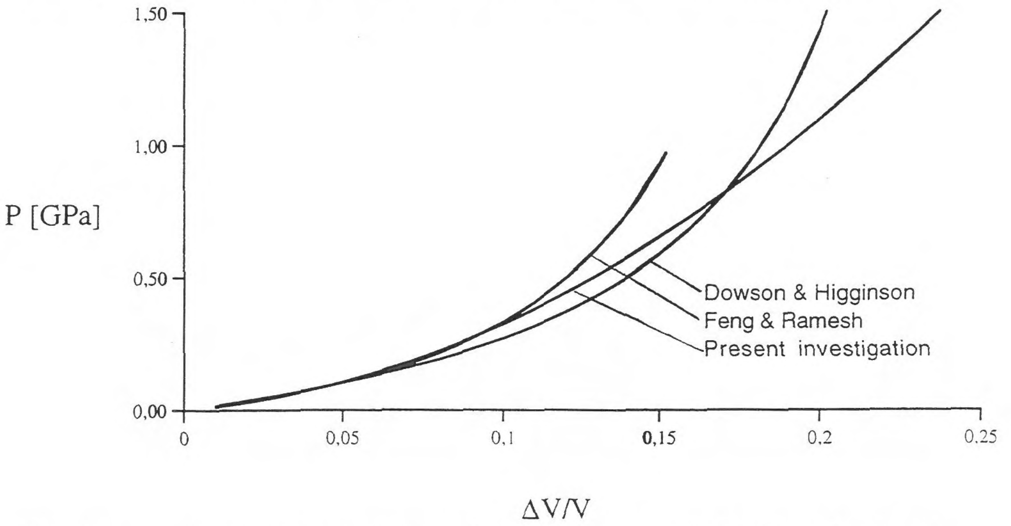

Fig. 10 A comparison of the dilatation-pressure relationship of mineral oils, equation (2), (3) and (7).

As seen in figure 10 the present investigation gives approximately the same results as the Feng and Ramesh investigation up to 400 MPa. However, the curve is not so steep at higher values of dilatation indicating a less progressive dilatation-pressure relation.

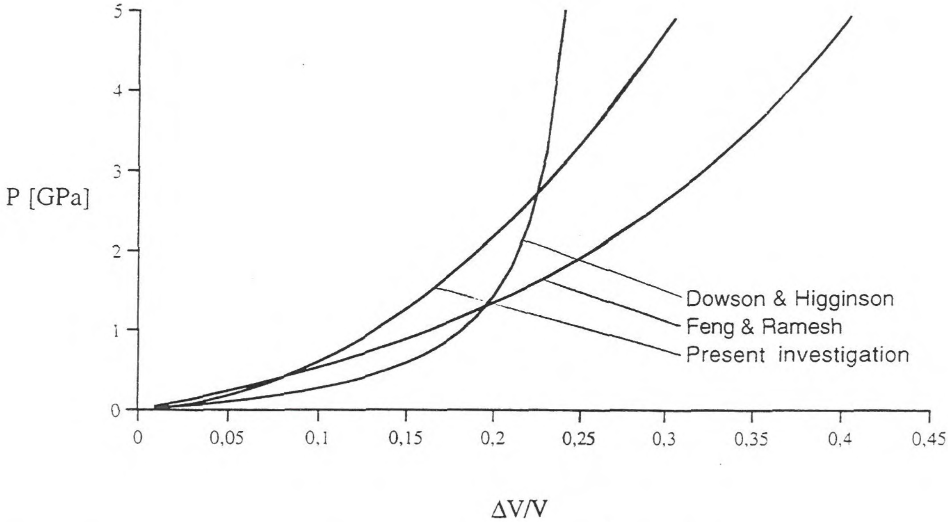

Fig. 11 A comparison of measurements by Feng and Ramesh, Dowson and Higginson and the present investigation on the synthetic oil 5P4E, equation (2), (3) and (7).

A comparison of the three models for the synthetic oil 5P4E, can be seen in figure 11. In the present investigation measurements have been made to 1.9 GPa. Feng and Ramesh have presented results from measurements on the synthetic oil 5P4E with two different methods in two different pressure regions. They measured up to 1 GPa with loading times of 10 μs, Feng and Ramesh (1993), using the Kolsky bar method and from 1 GPa to almost 5 GPa, Ramesh (1991), using the plate impact method which generates loading times of 1 μs. These loading times, 1 and 10 μs, are quite short for a real contact in a bearing or a gear.

The results of the present investigation and the Dowson and Higginson results have been extrapolated using equation 2 and 7 to make it possible to compare the three models at pressures of 2-5 GPa. As can be seen from figure 11 the present investigation shows a significantly stiffer behaviour compared to the Feng and Ramesh results.

The loading times in the present investigation, 100 μs, are more representative for a real EHD-contact than in the investigation by Feng and Ramesh (1993).
From the expressions in table 2 it can be seen that the relation suggested by Dowson and Higginson has an asymtotic limit at a dilatation of 26 %. The Feng and Ramesh expression has similar asymtotes at 29 % for mineral oil and 100 % for synthetic oil. The suggested relation in the present investigation has no asymtotes at all. From a physical standpoint an asymtote at 26 or 29 % has no relevance.

4. CONCLUSIONS

The use of the modified split-Hopkinson pressure bar method makes it possible to determine the dilatation-pressure relation to high pressures in one single experiment. Dilatation-pressure relationships can be determined up to pressures of 2 GPa and with loading times comparable to those found in a lubricated contact in a bearing or a gear, 100-300 μs. Experiments were performed up to 1.9 GPa for two tested oils, a synthetic 5P4E and a naphthenic mineral oil. A leakage of only 3-5 % of the total enclosed oil volume occurred during the experiments. The accuracy and the repeatability for the presented method is within a few per cent considering dilatation. A mathematical model of the form

$$p = c_1 \frac{\Delta V}{V_0} + c_2 \left(\frac{\Delta V}{V_0} \right)^2 \qquad (7)$$

has been adapted by curve fitting.

The results give a relation between the dilatation and pressure that is weaker than the model suggested by Feng and Ramesh (1993) for dynamic compression of lubricants. The present model is more adopted to different kinds of lubricant and is based on a method that gives a more realistic loading time. A good accuracy is verified by the calibration procedure and the possibility to monitor the leakage.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	area of the pistons	[m^2]
a	dimensionless material constant	
c_1	material constant	[GPa]
c_2	material constant	[GPa]
E	index extension side	
F	force	[N]
K	material constant	[GPa]
k_1	material constant	[1/GPa]
k_2	material constant	[1/GPa]
L	length of the oil column	[m]
M	index main side	
p	pressure above atmospheric	[GPa]
t	time	[s]
u	displacement	[m]
v	particle velocity at the piston-oil interface	[m/s]
V	volume at pressure p	[m^3]
V_0	volume at atmospheric pressure	[m^3]
ΔV	change in volume, $V-V_0$	[m^3]
ρ	density of oil at pressure p	[kg/m^3]
ρ_0	density of oil at atmospheric pressure	[kg/m^3]

Dynamic Density Measurement and Dilatation-Pressure Relation for Lubricating Oils and Greases

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ABSTRACT

The relation between dilatation and pressure is a basic characteristic relation for lubricants which is of importance for modelling of elastohydrodynamically loaded conjunctions. A modified split-Hopkinson pressure bar (SHPB) system has been used to determine the dilatation-pressure relation of lubricating oils and greases. The test conditions are similar to those encountered in a real contact; loading and unloading times of about 100 and 300 μs respectively and pressures up to 2.1 GPa. An empirical model has been stated for each of the tested lubricants to mathematically describe the density's dependence of pressure.
Seven oils and two greases have been tested in order to investigate the relation between molecular structure and dilatation-pressure relation. The chosen greases are made from the tested naphthenic and PAO base oils. Long straight molecules like in rape seed oils, polyglycols and polyalphaolefines give a waek dilatation-pressure behaviour whereas in naphthenic or paraffinic oils where ring shaped molecules can be found, give a stiffer behavior. The synthetic oil 5P4E, which molecules have a principal shape of a chain with very compact lumps on, has the stiffest behaviour.
The thickener in a grease, in this case Li-12-OH, also seem to influence the dilatation-pressure relation.

1. INTRODUCTION

In a highly loaded elastohydrodynamically lubricated (EHL) contact the lubricant is often subjected to pressures of several GPa during a short loading and unloading time, typically 100-300 μs. These conditions can be found where two nonconformal surfaces are separated by a thin film of lubricant, e.g. in rolling element bearings, gears or cam-followers. To be able to calculate film thickness, pressure distribution and friction it is important to know, among other data, the dilatation-pressure relation or density's pressure relation for the lubricant.

Many investigations have been made under static conditions. Dowson and Higginson (1966) measured up to 400 MPa and their well known relationship

$$\frac{\rho}{\rho_0} = 1 + \frac{0.6p}{1 + 1.7p} \qquad (1)$$

is still in use. The unit of pressure in their formula is GPa. Statically performed investigations do not take into account the rapid loading time or the influence from the possible pressure induced temperature rise in the EHL contact which may have an effect on the dilatation-pressure behaviour. The increase in temperature due to the more or less adiabatic compression will decrease the lubricant stiffness and counteract the pressure induced increase.
Investigations have been made dynamically up to 5 GPa by Ramesh (1991) which led Feng and Ramesh (1993) to suggest the relationship

$$p = \frac{K\left\{1 - V / V_0\right\}}{\left[1 + a\left\{V / V_0 - 1\right\}\right]^2} \qquad (2)$$

Equation (2) is based on results from two different kinds of experiments, plate impact and Kolsky bar experiments. The loading times were 1 and 10 μs respectively, which is quite short compared to contact times in real EHL contacts. The measurements gave only one result per experiment and therefore a lot of experiments were required to ensure reliability over a large span of pressures.
Equation (2) can be rewritten to give a relation between pressure and density. If the mass of the tested lubricant is considered constant the density's dependence on pressure can be expressed as

$$\frac{\rho}{\rho_0} = \frac{1}{1 - \frac{1}{2a^2 \frac{p}{K}} [1 + 2a\frac{p}{K} - \sqrt{1 + 4\frac{p}{K}}]} \tag{3}$$

Lindqvist et. al. (1996) developed an experimental technique and performed dynamic measurements on two types of lubricating oils using a modified split-Hopkinson set-up, originally developed by Färm and Sundin (1994). These measurements gave the entire dilatation-pressure relation up to maximum pressure in one single experiment. Pressures up to 2 GPa were applied and the loading-unloading time (400μs) was chosen to simulate a real lubricating situation. A curve fit was made for the dilatation-pressure relation based on a second degree polynomial,

$$p = c_1 \frac{\Delta V}{V_0} + c_2 \left(\frac{\Delta V}{V_0} \right)^2 \tag{4}$$

which can be rewritten to a density-pressure equation expressed as

$$\frac{\rho}{\rho_0} = \frac{1}{1 + \frac{c_1}{2c_2} [1 - \sqrt{1 + \frac{4c_2 p}{c_1^2}}]} \tag{5}$$

The aim of the present paper is to investigate and establish empirical relations between pressure and density for lubricating oils and greases of different chemical structure, and also to compare the results with presently used models. Another purpose is to relate the dilatation-pressure relation to the molecular structure of the lubricants.

2. EXPERIMENTS

2.1 Set-up

The equipment used in this investigation, see figure 1, is a modified split-Hopkinson pressure bar (SHPB) set-up for confining and compressing the lubricant. It has been described in detail in Lindqvist et. al. (1996). The set-up consists of a container and two pistons. The pistons are connected to bars with conical adapters made of cemented carbide.
All surfaces are in contact, secured by a small external axial force.
The length of the confined lubricant volume in the container has been chosen to 2-5 mm to achieve pressures found in real EHL contacts.
A cylindrical projectile fired from an air gun impacts the main rod, and generates a compressive wave that propagates through the main rod and the conical adapter, reaching the lubricant specimen. A part of the wave is reflected and another part is transmitted to the extension rod.
Strain gauges measuring axial strain are attached at two cross sections on both main and extension rod. The amplified signal is recorded by a transient recorder and taken over to a computer for evaluation.
Pressure, dilatation and dilatation rate in the specimen are determined from measured strain histories in the rods.

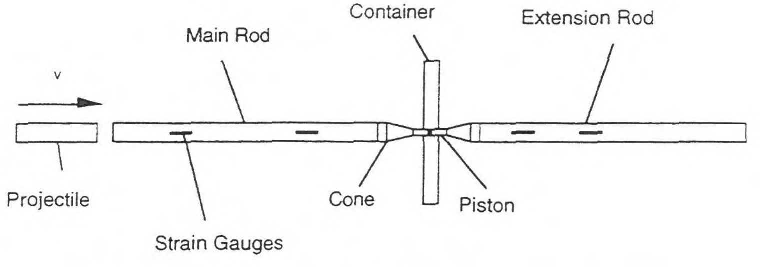

Fig. 1 Schematic picture of the mechanical parts for the experimental set-up.

2.2 Tested lubricants

Seven lubricating oils and two greases were tested at room temperature, 20°C. Two of the oils were also tested at 70°C. The atmospheric viscosity and density data for the oils and greases are shown in table 1. The oils were chosen to have different molecular structure. Two greases consisting of base oil and thickener without additives, have been tested. These measurements were made to investigate how the thickener affects the dilatation-pressure behaviour.
The two greases were specially manufactured from the same base oils as two of the tested oils.

Type of oil or grease	Name	Viscosity (20°C) [mPas]	Viscosity (40°C) [mPas]	Viscosity (70°C) [mPas]	Density (15°C) [kg/m^3]
Mineral Oil	Naphthenic base oil	66	24	7.5	894
Mineral Oil	Paraffinic base oil	71	29		870
Synthetic Oil	Poly-phenyl Ether 5P4E	4400	385		900
Synthetic Oil	Polyalpha-olefin PAO base oil	85	36	14	829
Synthetic Oil	Santotrac traction fluid	86	30		907
Synthetic Oil	Rape seed oil (68%) + synthetic ester (32%)	100	46		926
Synthetic Oil	Polyglycol hydraulic fluid	128	41		981
Mineral Grease NLGI 2	Naphthenic base oil+ Li-12-OH (13.2%)	2594 base oil	90 base oil	5 base oil	900
Synthetic Grease NLGI 2	Polyalpha-olefin base oil+ Li-12-OH (18.2%)	789 base oil	86 base oil	10 base oil	856

Table 1. Properties of the oils and greases.

2.3 Experimental Procedure

All surfaces in contact, the two pistons and the cylindrical hole in the container were carefully cleaned with alcohol solvent and put together. Before every measurement, a position reading including the complete system with no lubricant in the container was made to determine the reference position. After that the extension piston, the cone and the rod were removed during the filling of lubricant and afterwards put back again. Great care was taken to avoid air in the enclosed oil volume. A small axial force was applied on the extension rod to secure good contact between the surfaces. An axial leakage of oil through the radial clearance between the piston and the cylindrical hole in the container was caused by this external axial force. When the lubricant column had reached a desired length of 2-5 mm the projectile was fired.

Each oil and grease were tested several times to make sure that the measurements were repeatable. To investigate possible influence from the test rig, two different pairs of cones, pistons and projectiles were used. Different lengths of the oil columns were also used for the same reason.

3. RESULTS AND DISCUSSION

The pressure, dilatation and dilatation rate in the rapidly loaded oil specimen are evaluated from the force and the particle velocity at the piston-oil interfaces, Lindqvist et. al. (1996). In figure 2 a comparison of the dilatation-pressure relation is shown for the 7 different oils.

The 5P4E is the stiffest oil which agrees with the Feng and Ramesh (1993) results. The paraffinic and the naphthenic mineral oils follow each other well. The three synthetic oils, the rape seed + ester, the PAO and the polyglycol have virtually the same dilatation-pressure relation. Santotrac has a dilatation-pressure relation similar to that of the mineral oils but at higher pressures it shows a stiffer behaviour.

If there is air in the confined oil volume the pressure-dilatation relation shows a flat initial part were the dilatation increases while the pressure is close to zero. When the air has been dissolved in the oil the curve starts to rise, e.g. the oil is being compressed.

In the evaluation this was compensated for by shifting the curve in the horizontal direction.

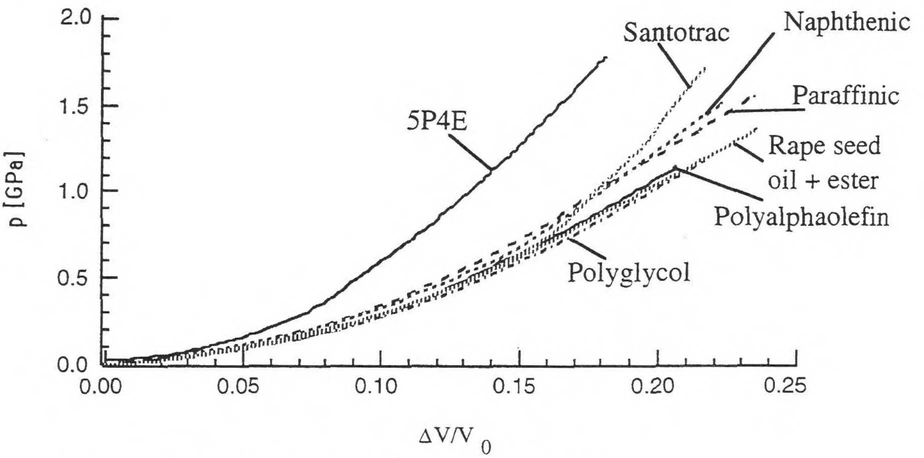

Fig 2. A comparison of measured dilatation-pressure relations for the seven tested oils at 20°C.

Figure 2 indicates that there is a correlation between the dilatation-pressure relation and the molecular structures of the oils. Oils with straight long molecules like rape seed oil, PAO and polyglycols show a relatively weak behaviour. Well refined mineral oils like the naphthenic or the paraffinic oils can be expected to have less possibility to adopt different configurations and therefore should have a stiffer behaviour than the polyglycol, PAO and rape seed oils. The synthetic 5P4E has a more compact molecular structure and consequently it also shows the stiffest behaviour of the tested oils.

Grease consists of a two phase system of a base oil, a thickener, and usually some additives. The tested greases consist of only the base oil and the thickener without additives.

A comparison between grease and the corresponding base oil is shown in figures 3 and 4. The grease with 13.2 % thickener and naphthenic base oil shows a stiffer behaviour compared to the base oil. The grease with 18.2 % thickener in a polyalphaolefinic base oil, figure 4, exhibits a weaker behaviour, at least for smaller values of dilatation, compared to the base oil. No explanation of the influence from the thickener on the dilatation-pressure relation has been found for the two tested graes.

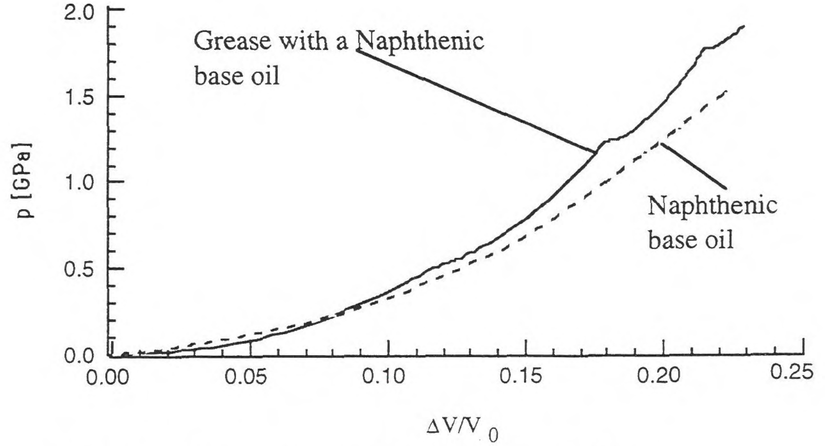

Fig 3. Dilatation-pressure curves for grease made from naphthenic base oil and the base oil itself.

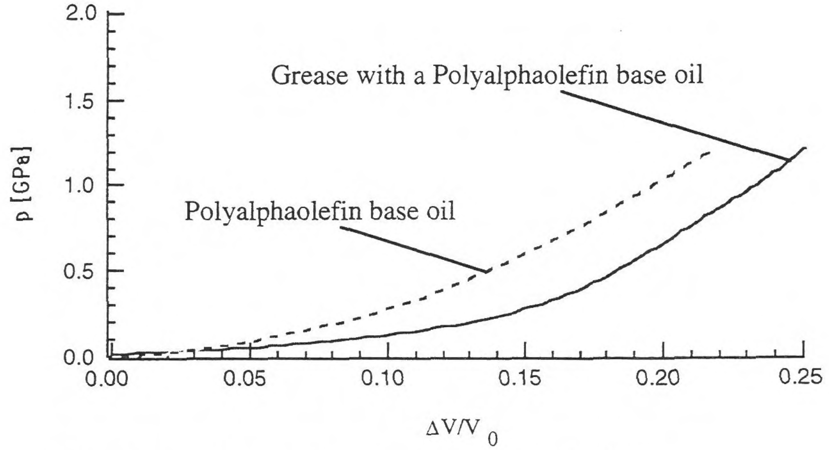

Fig 4. Dilatation-pressure curves for a grease made from polyalphaolefin base oil and the base oil itself.

An increased temperature decreases the stiffness. This behaviour can be seen in figures 5 and 6. The naphthenic oil shows an approximately 30% weaker behaviour at 70°C compared to 20°C. No such connection could be found for the synthetic oil polyalphaolefin.

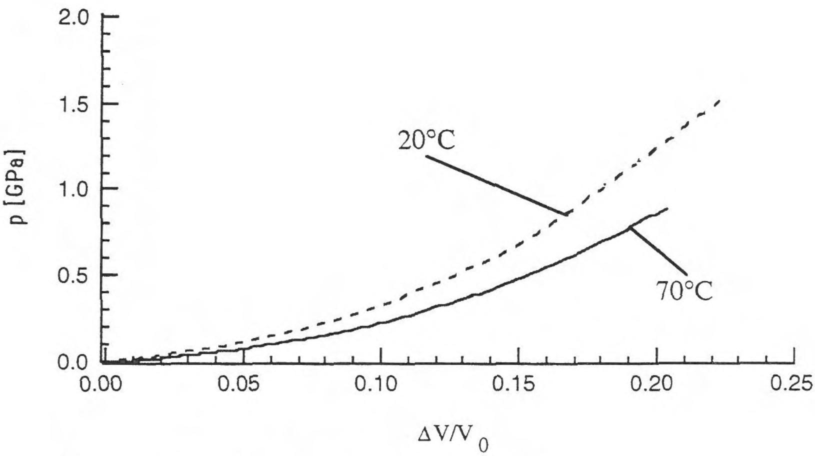

Fig 5. Measured dilatation-pressure curves for a naphthenic mineral oil, at 20 and 70 °C.

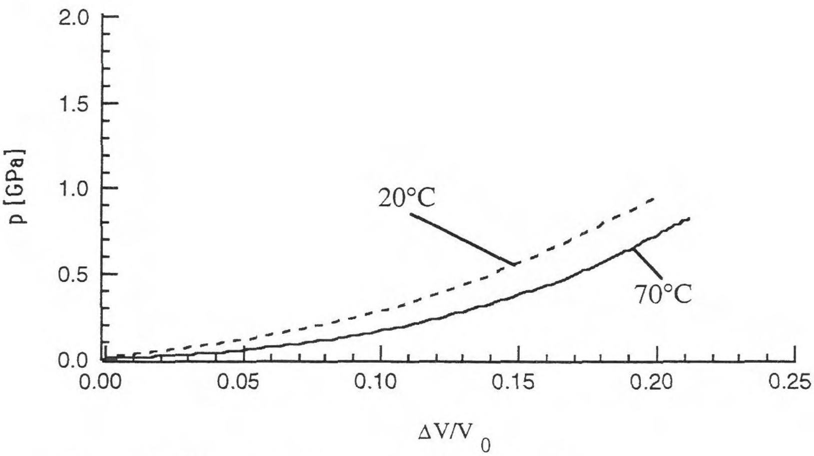

Fig 6. Measured dilatation-pressure curves for the polyalphaolefin, at 20 and 70 °C.

A second order polynomial curve fit, equation (4), has been adapted to all measured dilatation-pressure data. Constants from the curve fit are presented in table 2.

Type of oil or grease	Name	Temp [°C]	Pressure p1 [MPa]	Pressure p2 [MPa]	Constants [GPa] up to pressure p1 c_1 c_2 c_3	Constants [GPa] between pressure p1 and p2 c_1 c_2 c_3
Mineral Oil	Naphthenic base oil	20	500	1500	1.0 22.4 --	-0.2 32.3 --
Mineral Oil	Naphthenic base oil	70	1000		0.2 22.0 --	
Mineral Oil	Paraffinic base oil	20	1000		1.7 19.7 --	
Synthetic Oil	Poly-phenyl Ether 5P4E	20	1800		1.1 49.1 --	
Synthetic Oil	Polyalpha-olefin PAO base oil	20	1200		0.7 19.5 --	
Synthetic Oil	Polyalpha-olefin PAO base oil	70	1000		1.0 19.5 --	
Synthetic Oil	Santotrac traction fluid	20	450	1900	0.9 20.6 --	-16.6 90.7 1.1
Synthetic Oil	Ester rape seed oil (68%) + synthetic ester (32%)	20	900		0.6 23.6 --	
Synthetic Oil	Polyglycol hydraulic fluid	20	1200		0.3 27.1 --	
Mineral Grease NLGI 2	Naphthenic base oil+ Li-12-OH (13.2%)	20	2100		0.5 33.0 --	
Synthetic Grease NLGI 2	Polyalpha-olefin base oil+ Li-12-OH (18.2%)	20	140	2100	0.2 9.2 --	-6.7 39.7 0.4

Table 2. Results of the polynomial curve fit for the constitutive constants for all tested lubricants.

For three of the tested lubricants the second order polynomial equation (4) has been completed with a constant term c_3, resulting in equation (6)

$$\frac{\rho}{\rho_0} = \frac{1}{1 + \frac{c_1}{2c_2}[1 - \sqrt{1 + \frac{4c_2(p - c_3)}{c_1^2}}]} \qquad (6)$$

to better describe the relation at pressures higher than p_l in table 2.

Equations 1,3 and 6 are presented in table 3 expressed in both pressure as a function of dilatation and density as a function of pressure.

	Pressure-dilatation relation	Pressure-density relation	Type of oil and Constants
Dowson & Higginson	$p = \dfrac{\frac{\Delta V}{V_0}}{0.6 - 2.3\frac{\Delta V}{V_0}}$	$\dfrac{\rho}{\rho_0} = 1 + \dfrac{0.6p}{1 + 1.7p}$	Mineral oil: (Shell HVI650)
Feng & Ramesh	$p = \dfrac{K\{1 - V/V_0\}}{[1 + a\{V/V_0 - 1\}]^2}$	$\dfrac{\rho}{\rho_0} = \dfrac{1}{1 - \frac{1}{2a^2\frac{p}{K}}[1 + 2a\frac{p}{K} - \sqrt{1 + 4\frac{p}{K}}]}$	Mineral: K=1.4 [GPa] a=3.5 Synthetic: K=4.3 [GPa] a=1.0
Present investigation	$p = c_1\dfrac{\Delta V}{V_0} + c_2\left(\dfrac{\Delta V}{V_0}\right)^2 + c_3$	$\dfrac{\rho}{\rho_0} = \dfrac{1}{1 + \frac{c_1}{2c_2}[1 - \sqrt{1 + \frac{4c_2(p - c_3)}{c_1^2}}]}$	See table 2

Table 3. A comparison of the Dowson & Higginson, Feng & Ramesh and present investigation expressions for both the dilatation-pressure relation and the density-pressure relation.

The present investigation gives results for different types of oils and greases. It is also based on a method which gives a large number of measured values for every loading-unloading cycle. These two aspects make the results more reliable and more adopted to different lubricants than the two other models, Dowson and Higginson (1966) and Feng and Ramesh (1993). The Feng and Ramesh measurements up to almost 5 GPa show no dramatic change in behaviour at higher pressures. Thus there should be no problem to extrapolate the presented equations, (5) and (6) up to higher pressures than used in the present experiments.

In figure 7 the relative density as a function of pressure can be seen. A mineral oil has been chosen in comparing the three models since this is the only oil type used in all threee investigations.

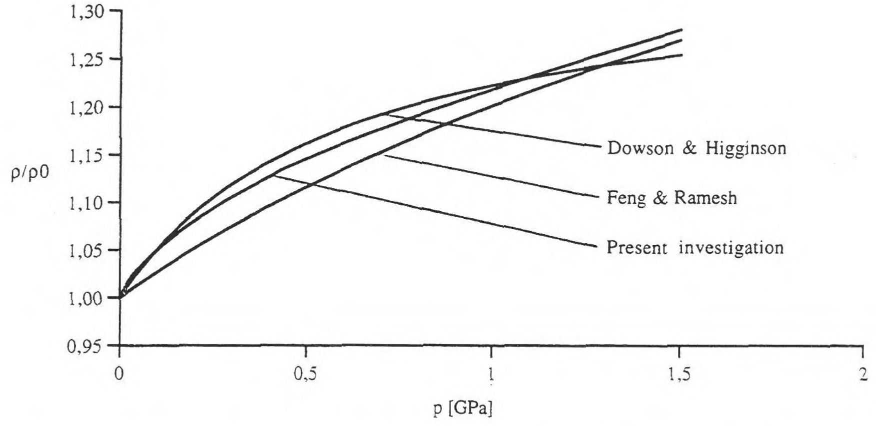

Fig. 8 Relative density as a function of dilatation for mineral oil.

4. CONCLUSIONS

The use of the modified split-Hopkinson pressure bar (SHPB) makes it possible to determine the dilatation-pressure and calculate the density-pressure relations of lubricating oils and greases up to pressures of 2.1 GPa and with loading and unloading times of 100 and 300 μs respectively. Similar situations are found in a lubricated contact in a bearing or a gear. A second degree polynomial curve fit has been adapted to measured data for 7 oils and 2 greases to describe the pressure-dilatation relation. Higher temperature gives a weaker behaviour for the two tested oils. Long straight molecules like in rape seed oils, polyglycols and polyalphaolefins give a weaker behaviour. Naphthenic or praffinic oils, where ring shaped molecules can be found, show a stiffer behaviour. The 5P4E which has the most compact molecular structure consequently also has the stiffest behaviour. There is a need for further investigations concerning grease to be able to determine the relation between the thickener structure and the dilatation-pressure relation.

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