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DETERMINATION OF THE VISCOSITY PARAMETERS FOR AN ULTRA THIN LIQUID LAYER IN LUBRICATION

WYZNACZANIE PARAMETRÓW LEPKOŚCI CIECZY W ULTRACIENKICH WARSTWACH SMARUJĄCYCH

Key words:

ultra thin liquid layer, viscosity measurements, new method

Słowa kluczowe:

supercienka warstwa cieczy, pomiar lepkości, nowa metoda

Summary

This paper presents a new method for the estimation and, consequently, a new method of liquid viscosity measurements for non-Newtonian liquids retained in ultra thin layer. Essentially the test stand consists of a Piezoelectric Tuning Fork (PTF) and an Atomic Force Microscope (AFM). This method is to be based on the measurements of the amplitude values of PTF vibrations inside the

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liquid region using AFM and other devices described in this paper. Vibration implies a share rate in liquid and this implies changes of the apparent viscosity of non-Newtonian liquids. During measurements, the ultra thin layer of liquid is laying on the solid substratum. This solid substratum imitates the superficial layer on cooperating bearing surfaces. Experimental measurements prove that the physical properties of superficial layers have a significant influence on the liquid viscosity in ultra thin liquid layers.

Viscosity changes within ultra thin layer in relation to height.

INTRODUCTION

The behaviour of liquids is different for large volumes and for thin layers [**L. 1, 2**]. Generally, two types of liquids are distinguished: Newtonian and non--Newtonian. Non-Newtonian liquids can be time independent and time dependent (thixotropic and rheopectic) [**L. 3**]. The dynamic viscosity of oil depends on adhesion forces between fluid particles and cells on the micro-bearing surface; therefore, oil-dynamic viscosity changes in ultra thin micro-bearing gap in the height direction. In such cases, bearing gap height is smaller than 1 μm.

Non-Newtonian properties of oil lead to the changes of the hydrodynamic pressure in the super thin micro-bearing gap height direction. This phenomenon can be described by the new non-classical hydrodynamic theory of lubrication, where we obtain a three-dimensional hydrodynamic pressure distribution in micro-bearing gap. Such phenomenon has been unsuitable in the hydrodynamic theory of lubrication.

For comprehensive studies of the viscosity parameters and for a recognition of the type of liquid, it is necessary to have a technique that will allow changing the shear rate, time, and height of fluid [**L. 2, 3**]. In this case, it is very promising to use a combination of atomic force microscopy (AFM) and an Piezoelectric Tuning Fork (PTF) [**L. 4**] for ultra thin layers of liquid.

The present work is focused on the implementation of a special technique that combines AFM and PTF and allows the measuring of the viscosity parameters for Newtonian and non-Newtonian liquids that are presented as the thin layer and the ultra thin layer.

DEVICES FOR VISCOSITY MEASUREMENTS

To present the non-conventional method of viscosity determination, we will begin by describing the new devices for measurements.

Function ***«Viscosity»*** has been realised on a commercial AFM unit (NT-206, Belarus) using a PTF fixed in special holder illustrated in **Fig. 1**. An oscillation of PTF is created by the AFM generator that is typically used for the dynamic mode. Feedback control for this complex technique has been designed using the criteria of the output amplitude of PTF. A laser system of AFM was not used for measurements.

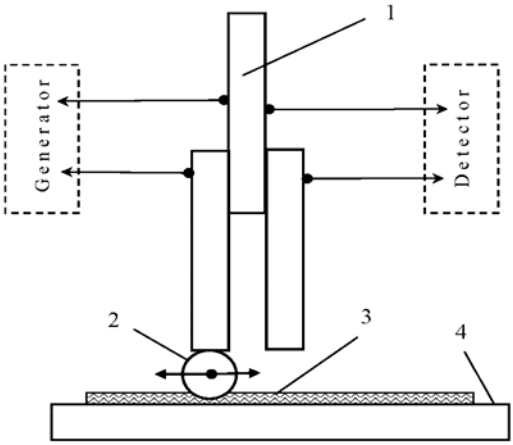

Fig. 1. General scheme of viscosity measurement using the tuning fork technique: 1 – PTF; 2 – probe; 3 – thin layer of liquid; 4 – solid substratum

Rys. 1. Ogólny schemat pomiaru lepkości techniką kamertonową: 1 – PTF; 2 – próbka; 3 – cienka warstewka cieczy, 4 – podkład ciała stałego

The main window of the viscosity control software is shown in **Figure 2**, and it consists of five panels. Panel I includes the buttons ***Load exp. settings…***, ***Save exp. settings…***, and textual field ***text.*** Button ***Save exp. settings…*** allows saving all settings for viscosity measurements in a special file for follow-up using. Button ***Load exp. settings…*** is used for loading of the saved settings.

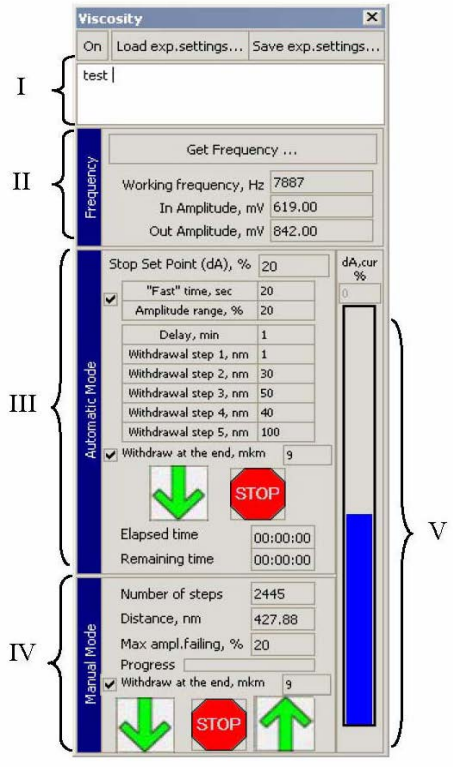

Fig. 2. Main window of viscosity control software: I – general content menu; II – tuning frequency and amplitude; III – automatic mode; IV – manual mode; V – panel of amplitude indicator

Rys. 2. Główne okno pomiarowe komputerowego sterowania lepkością: I – ogólna zawartość menu, II – Częstotliwość i amplitudy kamertonu; III – proces automatyczny; IV – proces ręczny,V – panel automatycznego odczytu

SET UP PARAMETERS OF PTF

Panel II **(Fig. 2)** includes functions for adjusting the PTF before measurements. Parameters presented by buttons ***Working frequency***, ***In Amplitude*** (A_{in}) and ***Out Amplitude*** (A_{out}) are used to set up the working properties of PTF. Button ***Get Frequency*** activates and loads a special panel ***Frequency Sweep*** showed in **Fig. 3** to specify PTF frequency sweep. This graph is used for fixing the PFT resonance frequency in the same way as for AFM dynamic mode. The slider ***Amplitude*** on the right side of **Fig. 3** is used for set up the input amplitude of PTF. The user can also type the value in the box below the amplitude indicator. Input amplitude should be an interval of ***Frequency Sweep***.

Fig. 3. Frequency sweep panel for tuning the PTF
Rys. 3. Panel odczytu częstotliwości kamertonu

The check-box ***Legend*** switches on/off descriptions of plotted parameters. The red line is the output amplitude of PTF, and the green line is the phase curve. Button ***Save*** allows one to save the current graph in BMP format or the data as TXT file. Buttons ***Working frequency***, ***In Amplitude*** and ***Out Amplitude*** indicated in **Fig. 2**, Panel II, are automatically set up after closing of the ***Frequency Sweep*** panel. After that, the system is ready for automatic or manual measurements

AUTOMATIC MEASUREMENT PROCESS

Panel III depicted in **Fig. 2** denotes the Automatic Mode and includes controls for presetting the measurements parameters. Parameter ***Stop Set point (dA)*** denotes the criteria of finding the set point. Button dA_{cur} on the right side of Panel III indicates current amplitude in percentages of input amplitude. The parameter presented by button ***Fast time*** sets up the period for decreasing and increasing of the input amplitude (***In Amplitude***) on the fixed value (***Amplitude Range***) in percentages. The parameter presented by button ***Delay*** is the time that is used for measurements with a constant input amplitude.

Button ***Elapsed time*** shows the time of measurements. Button ***Remaining time*** determines the estimated time before ending measurements. Measurement starts after pressing the button  and can be interrupted at any instance of time by pressing the button ***Stop***.

At the beginning of measurement, the system fixes the AFM piezoelectric scanner in the middle position for Z range. This Z range describes the height of the thin layer of the liquid. Then, the PTF approaches the sample surface using AFM stepper motor by checking of amplitude decrease at each step. If the result of checking is that the PTF approaches the sample surface by

- dA_{cur} > ***Stop Set point (dA)***, then the step motor realises the next step for the movement of PTF;
- dA_{cur} = ***Stop Set point (dA)***, then system stops the step motor and starts the measurements;
- dA_{cur} < ***Stop Set point (dA)***, then system stops the step motor, switches off feedback of the piezoelectric scanner and runs it for setting up dA_{cur} = ***Stop Set point (dA)*** by the withdrawal movement of PTF.

The system shows the message for 5 seconds that PTF has reached the solid substrate. All further withdraw movements for automatic measurements can be done very accurately using only the AFM piezoelectric scanner. The AFM step motor is not involved in this stage of measurements. The piezoelectric scanner starts ***Withdrawal step 1.*** Then, after completing this step, the system automatically decreases and increases the ***Input Amplitude*** of PTF on the value of ***Amplitude Range*** for time ***Fast time***. The next stage of the measurements is done with permanent input amplitude for time ***Delay.*** After that, the system repeats the same procedure for ***Withdrawal step 2, 3, 4 and 5.*** Figure 4 shows the graphical results of measurements of viscosity performed for the glycerin layer under room temperature (20 degrees Celsius). The obtained results are depicted in the form of a visualisation window, the Viscosity Graph, illustrated in **Fig. 4.** The measured results are then represented by the following parameters: Input amplitude of vibration (A_{in}), Output amplitude (A_{out}), Z position of PTF, i.e. height of thin layer of the liquid and time with a step of 0.1 second. According to [**L. 3, 5**], the PTF technique allows one to measure simultaneously and independently both the dynamic viscosity and density

of liquid: a) viscosity – though the changing of amplitude in mechanical impedance and b) density – though the changing of the resonant frequency in air and the measured liquid.

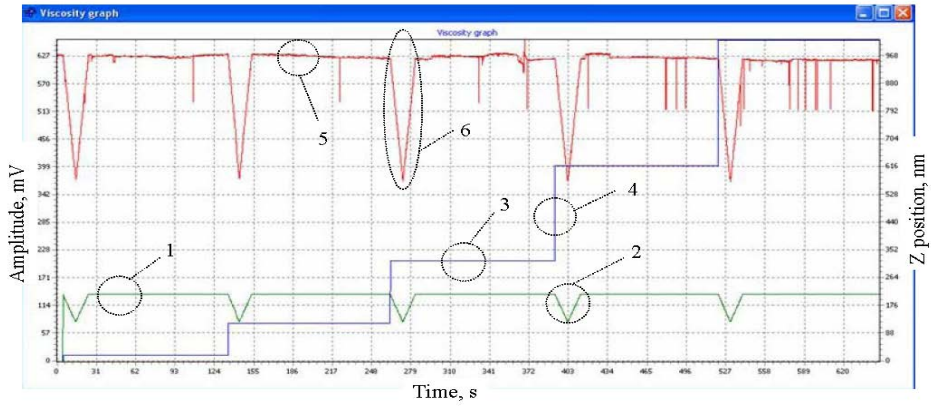

Fig. 4. Visualisation window of viscosity measurements results: 1 – A_{in} = const; 2 – A_{in} is variable; 3 – Z position of PTF above the sample; 4 – Changing of Z position of PTF; 5 – A_{out} under A_{in} = const; 6 – A_{out} under variable A_{in}

Rys.4. Wizualizacja rezultatów pomierzonej lepkości: 1 – A_{in} = stała; 2 – A_{in} zmienna; 3 – Z lokalizacja PTF względem próbki; 4 – Zmiany Z dotyczące położenia PTF; 5 – A_{out} dla A_{in} = stałego; 6 – A_{out} dla zmiennego A_{in}

If check box ***Withdraw at the end*** presented in Panel III, **Fig. 2**, is on, then the step motor will withdraw the PTF from sample based on the distance in micrometers indicated in the section, and measurements of the viscosity parameters in automatic mode will be completed.

MANUAL MEASUREMENT MODE

Panel IV **(Fig. 2)** enables one to perform the Manual Mode and contains the controls for manual measurements. All measurements are performed only using vertical motion of PTF by the AFM step motor in the direction of approach. The main difference between the manual and automatic modes is that AFM piezoelectric scanner is not use for the manual mode and all graphs and data are measured only in the approach to the surface of the sample.

The parameter ***Number of steps*** sets up the number of steps for step motor. ***Distance, nm*** is automatically calculated via number of steps. The user can specify ***Distance*** or ***Number of steps***. Parameter ***Max ampl. falling*** sets up the maximum value for decreasing the PTF amplitude. The system will stop the approach of PTF after reaching the maximum. This regime is mainly used for safety reason to prevent possible damage to the instrument. Measurements start

by pressing the button  according to the specified parameters (Panel II and IV, **Figure 2**). The indicator will show the progress for one cycle (number of steps). The indicator ***Progress*** represents the progress in measurements. The process of measurements can be interrupted at any moment by pressing button ***Stop***. Withdraw of the PTF from the sample starts by pressing the button  . Accordingly to Panel IV (**Fig. 2**) each user can set up the distance of withdraw in micrometers.

DISCUSSION

Shear rate depends on the linear velocity of the probe that is moving into a liquid. The PTF vibrates and, consequently, the probe executes a reciprocal motion into the liquid. Regime 2 (**Fig. 4**) shows that increasing the input amplitude leads to the increasing of the linear velocity of the probe at the same frequency of PTF. The vibration frequency influences the value of the linear velocity as well. Thus, the developed technique allows changing the shear rate through the variation of the input amplitude and frequency of PTF.

Non-Newtonian time-dependent liquids can be characterised by measurements of the parameters over a period of time under the permanent input amplitude and frequency of PTF (constant shear rate). Changes in the behaviour of the liquid can be recognised by the increasing or decreasing of the output amplitude of PTF in time. In this way, non-Newtonian liquids can be separated into two types: thixotropic and rheopectic fluids.

Atomic force microscopy has unique possibilities for the precise movements of the sample using the build-in piezoelectric scanner with an accuracy about 0.1 nm for the Z coordinate. This opens the door to great possibilities for the measurement of the exact changes of the thickness of liquid and the investigation of layers with heights even less than one nanometer.

CONCLUSIONS

It is proposed to use a combination of atomic force microscopy and a piezoelectric tuning fork for measurements of the viscosity parameters of the ultra thin layer of Newtonian and non-Newtonian liquids. The algorithm and software have been developed and tested. Software has been incorporated into commercial AFM control software SurfaceScan. A new function is available in version 210 or higher of the SurfaceScan program and compatible with all AFM NT-206 scanning units (Microtestmachines Ltd., Belarus) without any changes in the control unit.

We believe that proposed technique has very promising application for practical tribology, primarily for investigations of the boundary and mixed lubrication regimes under micro contact interaction. The changes of non--isotropic material coefficients, such as the module of the elasticity of the

texture of the substrate and probe (in applications superficial layer lying on the micro bearing surface) have an influence on the gap height changes. This fact leads to the oil velocity changes what produces the share rate changes of the oil flow and consequent dynamic viscosity changes of the oil. Therefore, there are many options to change the roughness and texture of the substrate and probe. The substrate and probe materials can vary in a rather broad range. The measurements are performed for various shapes of the samples, taking into account the various geometric shapes, e.g., spheres, cylinders, plates or wedge bars. Moreover, the sample can be studied in a vacuum or under height pressure, and the substrate material and liquid can be additionally heated or vibrated.

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Streszczenie

Niniejsza praca przedstawia nową metodę oszacowania wartości, a w konsekwencji pomiaru wartości lepkości nie newtonowskiej cieczy w ultracienkich warstwach. Stanowisko badawcze składa się zasadniczo z dwóch części: piezoelektrycznego kamertona widelcowego (PTF) oraz mikroskopu sił atomowych (AFM). Polega ona na zastosowaniu pomierzonych wartości amplitudy mikrodrgań PTF z mikroskopem sił atomowych oraz na wykorzystaniu odpowiedniego oprzyrządowania. Drgania wywołują wzrost prędkości ścinania, a te zmieniają lepkość cieczy. W trakcie pomiarów warstwa badanej cieczy zalega na podkładce materiałowej ciała stałego imitującej warstwę wierzchnią współpracujących powierzchni w węzłach tarcia ślizgowego. Materiał podkładki można zmieniać w trakcie badań. Tak pomyślana metoda badań może mieć duże zastosowanie w praktyce projektowania mikrołożysk, ponieważ badania eksperymentalne wykazały, że w ultracienkich warstwach cieczy smarującej własności materiałowe warstwy wierzchniej, a zatem podkładki mają wpływ na kształtowanie się

wartości lepkości cieczy smarującej. Lepkość cieczy smarującej w ultracienkich warstewkach zmienia się wraz z grubością warstwy.

Prezentowana metoda pomiaru lepkości cieczy ma szczególne znaczenie w przypadku cienkich warstewek cieczy o właściwościach nie newtonowskich, czyli takich, gdzie zmiany prędkości deformacji w trakcie przepływu smarującego mają wpływ na wartość lepkości. Kamerton wykonuje mikrodrgania, których amplitudy mierzy się z użyciem AFM. Drgania powodują zmiany prędkości deformacji cząsteczek cieczy w trakcie przepływu. W konsekwencji uzyskuje się zmiany wartości lepkości, które zostają uchwycone w trakcie opisanej w pracy procedury pomiarowej. Procedura pomiaru została w niniejszej pracy szczegółowo opisana. Według informacji autorów badania takie mogą mieć duże zastosowania w projektowaniu mikrołożysk HDD.