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RHEOLOGICAL CARACTERISATION OF VISCOUS FLUIDS IN OSCILLATORY SQUEEZING FLOWS

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Lucrarea prezentă este dedicată analizei reologice a unui fluid pur vîscos supus unei solicitări periodice de expulzare între două plăci paralele. Analiza experimentală este realizvată cu ajutorul prototipului Micro Fourier Rheometer 2100 iar simulările numerice au fost obtinute prin intermediul software-ului Fluent, folosind o geometrie a cărei discretizare permite deformarea sa în timp. Pentru plaja de frecvențe testate, 0.5 Hz < f < 50 Hz, rezultatele arată o bună corelare între măsurătorile experimentale şi simulările numerice, respectiv o limitare a valabilită□iii formulei analitice numai în domeniul amplitudinilor foarte mici.

The study is dedicated to the investigations of a pure viscous fluid in oscillatory squeezing flow between two parallel discs. The experiments are performed using the Micro Fourier Rheometer prototype MFR 2100 and the numerical simulations of the flow are obtained with the deformation mesh procedure implemented in the FLUENT code. For the tested frequency range, 0.5 Hz < f < 50 Hz, the results confirm a good prediction of the experiments by the numerical solutions and limited validity of the theoretical formula at small amplitudes.

Keywords: Fluid mechanics · Squeezing flow · Oscillatory rheometry · Viscous Fluids

1. Introduction

A common definition of "squeezing" phenomenon is the large deformation (or a flow) of a soft material (or a viscous fluid) between two nearly solid surfaces approaching each other. Consequently, the gap between surfaces is changing in time and the sample is ejected from the gap. In many applications the gap is small in comparison to the other dimensions of the surfaces, so squeezing flow is mainly associated to thin film hydrodynamics, lubrication and rheology of complex fluids. The squeezing flow has both extensional and shears components, but in the limit of small gap and low relative velocity the shear is considered dominant. For a given geometry, the approaching velocity, $V = \partial h/\partial t$ and the force thrust F are

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the only parameters to be determined in this case, see Fig. 1. Therefore, squeezing flow is often used for the determination of rheological proprieties of different types of materials, from pure viscous fluids to perfect elastic bodies and between, viscoelastic and viscoplastic (yield stress fluids) samples [1, 2].

The study is dedicated to the investigations of a pure viscous fluid in oscillatory squeezing flow [3-5] between two parallel discs, in order to establish the validity domain of the theoretical formula used to determine the viscosity of the tested sample. The experiments are performed using the Micro Fourier Rheometer prototype MFR 2100 (designed by GBC Scientific, Australia) and the numerical simulations of the flow are obtained with the deformation mesh procedure implemented in the FLUENT code. The results confirm, for the whole tested domain, a good prediction of the experiments by the numerical solutions. The theoretical formula is found valid only at small amplitudes and limited frequency range.

2. Formulation of problem

The squeezing flow between two parallel discs is presented in Fig. 1. The lower disc is at rest and the upper has a continuous or oscillatory motion. If the velocity V of the upper disc is continuous and the ratio h/R is very small, the radial velocity of the fluid can be considered almost a symmetric parabola, which proves that v_z velocity component within the gap h can be neglected.

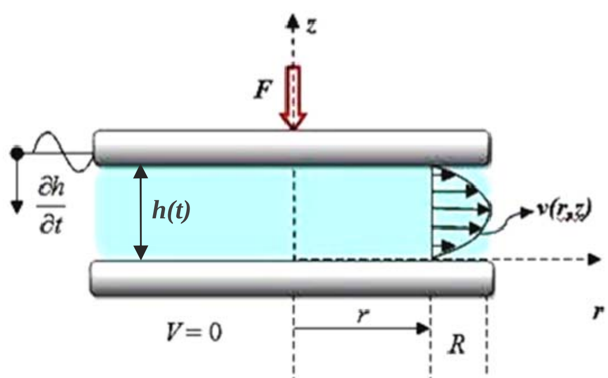

Fig. 1. Radial fluid velocity in squeezing flow.

In a first approximation, the description for the squeezing flow is given by the Navier Stokes equation, a particular form of the momentum conservation written for an incompressible Newtonian fluid:

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t}+grad\mathbf{v}\,\mathbf{v}\right]=\rho\mathbf{b}-\nabla p+\eta_0\Delta\mathbf{v} \quad (1)$$

where $\boldsymbol{v}$ is the velocity ($div\boldsymbol{v} = 0$), $\boldsymbol{b}$ is the specific mass force, p is the pressure, ρ and η_0 being the density and Newtonian viscosity, respectively. Using the necessary assumptions for thin layer approximation, one obtains the Reynolds equation for lubrication, which is common to describe and to model the squeezing flow, [6].

Considering that the upper plate velocity is much smaller then the fluid radial velocity and the gap is small enough to be neglected comparison to the plate radius, the Reynolds equation in cylindrical coordinates becomes:

$$r\frac{d}{dr}\left(\frac{1}{r}\frac{\partial p}{\partial r}\right)+2\frac{1}{r}\frac{\partial p}{\partial r}=12\eta_0\frac{1}{h^3}\frac{\partial h}{\partial t} \tag{2}$$

and the expression of the thrust force is founded to be [6,7]:

$$F(t)=-\frac{3\pi\eta_0 R^4}{2h^3}\frac{\partial h}{\partial t} \tag{3}$$

For a given time variation of the h function and R value, formula (3) is normally used in the rheological measurements based on squeezing: the force (F) and the gap (h) are measured and the viscosity (η_0) of the sample is computed [2].

3. Experimental setup

The experimental measurements were performed on the Micro Fourier Rheometer (MFR) using parallel plate geometry (see Fig. 2 and Fig. 3).

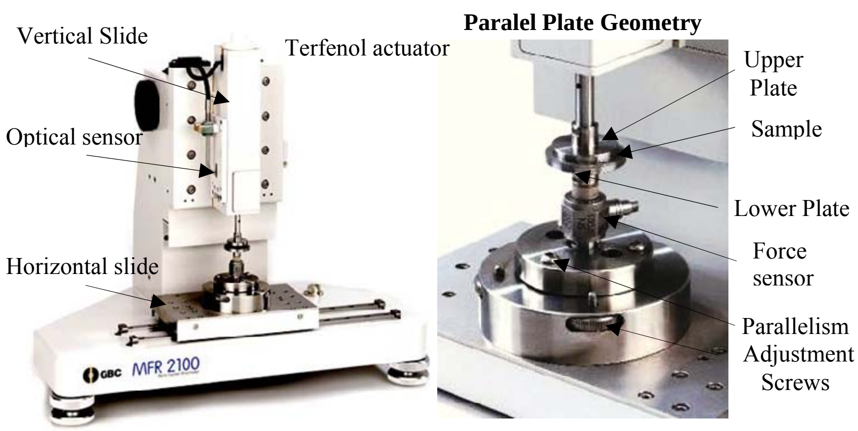

Fig. 2. Micro Fourier Rheometer 2100 - GBC Scientific (general view).

Rheometer's mechanism induces a multi-frequency signal to the sample by the upper plate oscillations, covering the frequency range $f \in [0.1, 100]$ Hz. The device is usually capable to give amplitudes of the displacement up to 25 μm and the force sensor (fixed on the lower plate at rest) has a range of $F = \pm 44$ *N*. Plate parallelism is highly important [1, 2] and it is assured by performing small angular adjustments to the bottom plate and using a provided ruby spacer as etalon for the gap. The upper and lower plates are concentric discs with diameter D = 25 *mm* and manufactured from stainless steel. The device was set on a thick granite plate sustained by several elastic balls, inside a metallic case with rubber seats, in order to isolate the system from the surrounding vibrations.

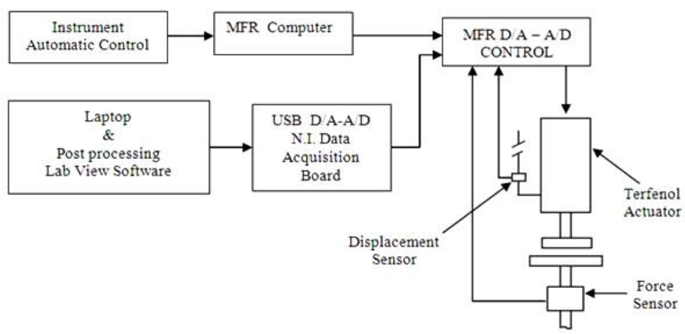

Fig. 3. Experimental setup and instrumentation.

The MFR D/A-A/D Control system of the input oscillation (displacement and frequency) of the upper disc is connected to the MFR computer, together with the force sensor transducer, see Fig. 3. In parallel, a National Instruments Data Acquisition Board transfer the imposed and measured signals to another PC for data post-processing with *Origin 8* software.

4. Experimental results and correlation with theory

The test fluid is a mineral Newtonian oil with dynamic viscosity $\eta_0 = 0.15$ $Pa{\cdot}s$ at $20°C$, measured on the stress-controlled rheometer Physica Anton Paar MCR301. The present analyze is focused to the study of the amplitude influence of the sinusoidal input signal on the measured force. Experiments are performed for a gap of $h = 300$ μm, constant frequency of $f = 10$ Hz and amplitudes up to $\varepsilon = 1$ μm. Due to technical limits and probably environmental influences, the signals captured with the data acquisition board are slightly noisy, especially in the case of the force signal. However, the disturbances are quite small compared to the base signal, so after the Fourier filter was applied the measured signal became a uniform continuous wave, see Fig. 4.

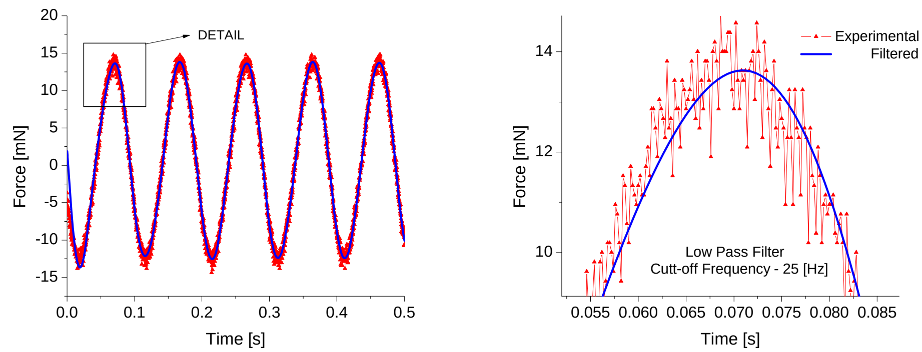

Fig. 4. Force measured signal with *Fast Fourier Transform Filter* (f = 10 Hz, $\varepsilon = 0.45 \mu m$, $h = 300 \mu m$).

In order to have a good interpretation and correlation of the experimental measurements with the theoretical modeling, the input signal for the displacement of the upper plate was chosen to be a sine wave, i.e. $h(t) = \varepsilon \cdot \sin(\omega \cdot t + \delta)$, where δ is the phase shift between the input sine displacement and the output sine force. Since the sample is pure viscous, the output force is normally delayed with $\pi/2$. In our experiments the input frequency is not always maintained constant during the whole test period, so δ value might varies with time, see Fig. 5.

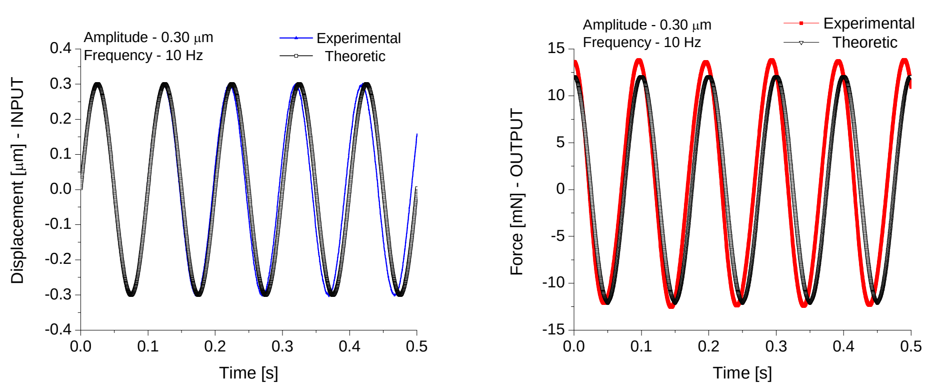

Fig. 5. Displacement (INPUT) and force (OUTPUT); experimental and theoretical results at $h = 300 \mu m$. At longer experimental times, the shift phase between the experimental signals and theoretical ones is increasing. Note that on the onset of the flow the shift angle is exactly $\pi/2$.

One can observe from Fig. 5 that recorded magnitude of the force fits fair also quantitatively the theoretical prediction of formula (3). The influences of the input amplitude magnitude on the differences between the measurements and theoretical predictions are shown in Fig. 6. It is evident that the absolute difference between measurements and prediction is increasing with increasing the amplitude of oscillations (we remark that always the measured amplitude is larger than the theoretical value).

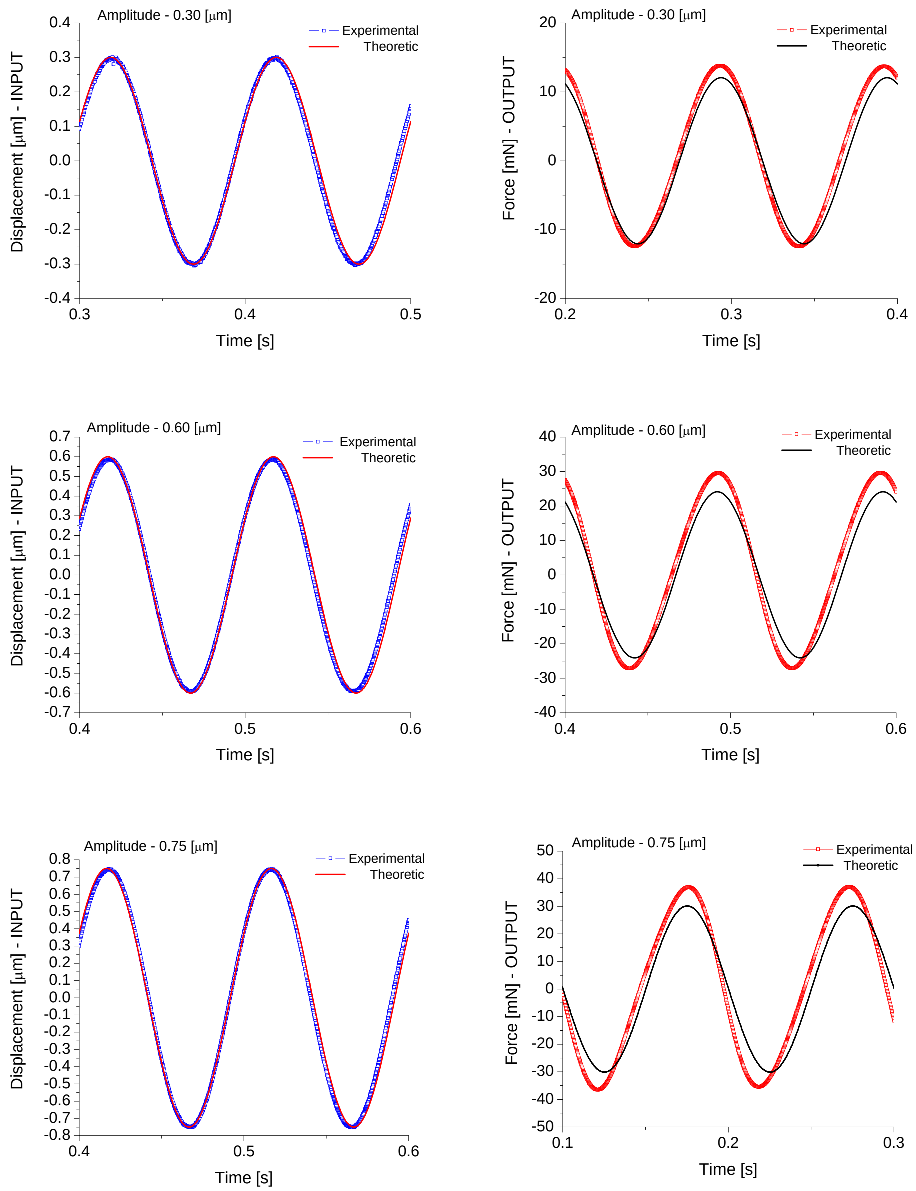

Fig. 6. Experimental and theoretical displacements and forces at $f = 10$ *Hz*, $h = 300 \mu m$; amplitude oscillation influence.

5. Numerical simulation

In order to perform the numerical simulations with the CFD software *Fluent*, first we reconstruct the parallel plate geometry using the pre-processor *Gambit*. The 2D geometry was created in axial-symmetric construction reduced with a scale of 6.25, ($R_{simulation}$ = 5 *mm*, R_{real} =12.5 *mm*), in order to decrease the simulation time, but still keeping a fine mesh (450.000 cells) with an acceptable cell ratio (the mesh is built using quad elements). In order to increase the accuracy of the computations, the mesh was chosen to be refined nearby the plates (walls) and less refined throw the middle of the gap.

Under these working conditions, the dimensionless force |F| must be amplified with *k*-constant , the correction factor defined as:

$$k = \left(\frac{R_{real}}{R_{simulation}} \right)^4 = 39.0625. \tag{9}$$

The simulations were made at a constant frequency and different amplitudes by defining a movement profile for the upper wall of the geometry (dynamic deformable mesh module from *Fluent* is used). The results shown in Fig. 7 and Fig. 8 prove a good qualitative correlation with the theoretical prediction of relation (3) and also a fair good quantitative fit of the measured data.

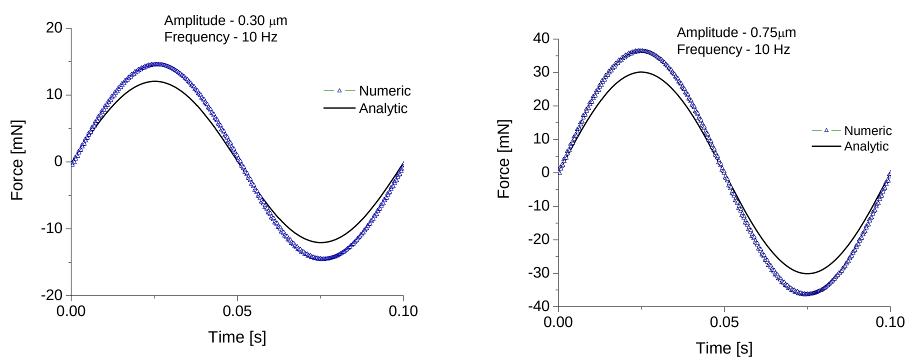

Fig. 7. Numerical calculus and theoretical prediction for force at *h* = 300μm. See Fig. 6 for comparison with the experimental measurements.

6. Conclusions

Analyzing the results presented in this work, we can conclude that the numerical simulations predict very well the experimental measurements, for the whole range of tested amplitudes. The results also show that theoretical formula (3) is valid only at very small applied amplitudes. Fig. 8 shows that force magnitude computed numerically is direct proportional with the amplitude variation, exactly how theory predicts. When amplitude value increases, the difference between numeric/experimental and theoretic results becomes more obvious.

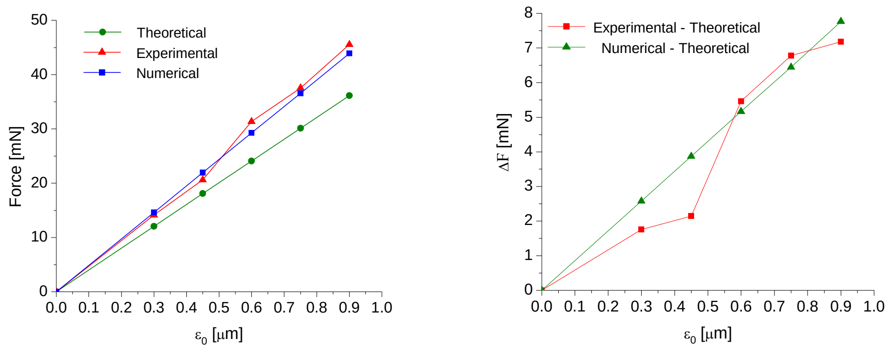

Fig. 8. Comparison between numerical, theoretical and experimental force magnitude (a) and amplitude difference between forces (b) vs. amplitude.

As a final conclusion, this study proves the value of numerical solutions for the analyzed oscillatory squeezing flow and the limit of the theoretical formula in appreciation of the normal thrust force. Further work will be dedicated to the investigations of viscoelastic fluids, the oscillatory squeezing procedure being able to evidence also the elastic component within the liquids.

Acknowledgements

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