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Prediction of Fluid Density & Viscosity Using Dynamic Characteristics of a Cantilever Beam

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***Abstract**: In physics, liquid is characterized as a substance that consistently twists under a connected shear stress. Viscosity and density of any liquid are the most essential rheological properties to characterize its behavior and other parameters related to many engineering applications. The estimation of Viscosity and density, i.e., rheological properties, has been utilized for a long time to precisely anticipate the stream conduct of numerous flow behavior including lubricants, blood, mucus, adhesives, paint, fuels and others. Ostensibly these liquids assume a critical part in numerous designing applications in acoustics, streamlined features, power era, cryogenic science, water powered hardware, maritime models and others. Thus, there is a developing enthusiasm for the utilization of MEMS gadgets to gauge the rheological properties, particularly with a point of empowering high throughput. These gadgets incorporate weight sensors, optical tweezers. In numerous studies directed some time recently, the scientists have performed constrained hypothetical computation notwithstanding the exploratory estimations. Be that as it may, the utilization of extremely prominent and successful limited component demonstrating plan is not embraced to improve the examination outline. In this study, the use of a 7cm stainless steel cantilever beam to accurately measure the rheological properties of viscous fluid is explored. First the resonance frequency of the cantilever beam in air is calculated by the use of software analysis. Then resonant frequency of the same beam is measured in air using the experimental technique. Experimental result is compared with the software analysis to validate the accuracy of the experimental setup. Once the test is calibrated well, the resonant frequency measurement is repeated by partially (half) submerging the beam tip in water. Finally, the finite element analysis (FEA) software ANSYS WORKBENCH 16.0 is used to model the partially submerged cantilever beam. Once the FEA results are validated, the fluid properties such as viscosity and density are varied to study their effects on resonant frequency.*

***Index Terms—** Viscosity, Density, Mode Frequencies, Resonance, Laser vibration sensor, MESCOPE.*

1. Introduction

Liquid is a substance that ceaselessly twists under a connected shear stress. Thickness and thickness of any liquid are the rheological properties to acquire its conduct. The estimation of thickness and consistency has been utilized to precisely anticipate the stream conduct of numerous liquids, for example, greases, blood, powers and so on. Thickness and thickness estimation of liquids have applications in different fields like acoustics, streamlined features, cryogenic science, water driven hardware and so forth. Depend upon the estimation of thickness and thickness of different liquids.

In past studies, they performed restricted hypothetical computation and exploratory estimations. The utilization of exceptionally powerful limited component displaying plan is not embraced to streamline the investigation outline.

In this study, the utilization of a 7cm stainless steel cantilever bar to precisely quantify the rheological properties of gooey liquid is investigated. To begin with the reverberation recurrence of the cantilever shaft in air is computed by the utilization of programming investigation. At that point thunderous recurrence of the same pillar is measured in air utilizing the exploratory strategy. Test result is contrasted with the product examination with accept the precision of the exploratory setup. Once the test is aligned well, the full recurrence estimation is rehashed by mostly (half) submerging the bar tip in water. At long last, the limited component investigation (FEA) programming ANSYS WORKBENCH 16.0 is utilized to display the halfway submerged cantilever bar. Once the FEA results are accepted, the liquid properties, for example, consistency and thickness are shifted to contemplate their impacts on resounding recurrence.

Consistency and thickness of a liquid are two essential parameters as they are the pointers of some predefined norms of the concerned liquids in some predetermined application. Seemingly liquids assume an imperative part in all significant building applications beginning from vehicles to biofilm. Consistency is frequently thought as the liquid's erosion, imperviousness to stream or the liquid's imperviousness to shear when the liquid is in movement. The thickness of a liquid is regularly spoken to as a coefficient that portrays the dissemination of energy in the fluid. The estimation of thickness has been utilized for a long time to screen and test greases, blood, bodily fluid, glues, paint, powers and different liquids. Thusly monitoring the dynamical conduct of these liquids (i.e., rheology) is fundamental as they experience worldly changes.

[1] John Elie Sader, the vibrational qualities of a cantilever shaft are surely understood to firmly rely on upon the liquid in which the bar is drenched. In this paper, we display a nitty gritty hypothetical examination of the recurrence reaction of a cantilever pillar that is submerged in a thick liquid and energized by a subjective main thrust. Because of its reasonable significance in application to the nuclear power magnifying instrument (AFM) they consider in point of interest the uncommon instance of a cantilever shaft that is energized by a warm main thrust. This will join the presentation of express investigative formulae and numerical results, which will be of quality to the clients and creators of AFM cantilever bars.

[2] James W. M. Chon and Paul Mulvaney, John E. Sader, Definite estimations of the recurrence reactions of a progression of rectangular nuclear power magnifying lens AFM! Cantilever shafts, inundated in a scope of liquids, have been performed to test the legitimacy and precision of the late hypothetical model of Sader. This hypothetical model gives the recurrence reaction of a cantilever shaft that is inundated in a gooey liquid and energized by a subjective main thrust. Good assertion between trial estimations and hypothetical counts is found for all liquids considered. Besides, a basic evaluation of the surely understood inviscid model is displayed, which exhibits that this model is not pertinent to AFM cantilever pillars when all is said in done.

[3] S. Boskovic, J. W. M. Chon and P. Mulvaney, J. E. Sader, the utilization of micro cantilevers in rheological estimations of gasses and fluids is illustrated. Densities and viscosities of both gasses and fluids, which can run more than a few requests of size, are measured at the same time utilizing a solitary micro cantilever. The micro cantilever procedure tests just moment volumes of liquid 1 nL and empowers in situ and quick rheological estimations. This is in direct differentiation to build up techniques, for example, "cone and plate", which are limited to estimations of fluid thickness, require extensive specimen volumes, and are unequipped for in situ estimations. The proposed method likewise defeats the limitations of past estimations that utilization micro cantilevers, which are constrained to fluid consistency just, and require autonomous estimation of the fluid thickness. The method introduced here just requires learning of the cantilever geometry, its resounding recurrence in vacuum, and its direct mass thickness. A basic yet powerful alignment strategy is depicted to decide the last two parameters, from a solitary estimation of the full recurrence and quality element of the cantilever in a reference liquid, for example, air if these parameters are obscure.

[4] Christian Bergauda and Liviu Nicu Exploratory examinations have been led to concentrate on the multimode dynamic reaction of composite cantilever bars in different thick media and to decide their thickness. Hypothetical eigen frequencies are processed utilizing the diagnostic model proposed by Sader in light of the investigation of the hydrodynamic capacity of cantilever shafts. A decent understanding is found amongst hypothesis and trial for the initial two thunderous frequencies of composite shafts worked in air and in water. The same trial methodology is utilized to decide the thickness of ultrapure ethanol. In this way, it is set up that Sader's model speaks to an exact option for the determination of fluid consistency in little volumes around 50 ml which may be of extraordinary significance for microfluidics applications. At long last, the points of confinement of the technique are underlined by checking the dynamic reaction of cantilever shafts in silicon oil.

[5] Naser Belmilouda and Isabelle DuFour, Annie Colin, Liviu Nicu, the point of this paper is to show that vibrating miniaturized scale cantilevers can be utilized to evaluate liquid properties, for example, thickness and consistency. In opposition to traditional rheological estimations utilizing miniaturized scale cantilevers, the advancement of the proposed smaller scale rheometer depends on the estimation of liquid properties over a scope of vibration frequencies, without fundamentally being confined to resounding wonders. To this end, a systematic model is actualized and, when joined with estimations, permits the determination of the consistency as an element of recurrence. The preparatory results are empowering for the improvement of a valuable small scale rheometer on a silicon chip for microfluidic applications.

[6] Murali Krishna Ghatkesar, Thomas Braun, Viola Barwich, Jean-Pierre Ramseyer, Christoph Gerber, Martin Hegner, and Hans Peter Lang, an investigation of Nano-mechanical cantilevers vibrating at different resounding modes in fluid is exhibited. Full recurrence range with 16 very much determined flexural modes is gotten. The quality component expanded from 1 at mode 1 to 30 at mode 16. The hypothetical evaluation of eigen-recurrence

utilizing the Elmer–Dreier model F.J. Elmer and M. Dreier, J. what's more, Sader's developed gooey model C. A. Van Eysden and J. E. Sader, J. coordinated well with the test information. The clear mass of the fluid comoved by the wavering cantilevers diminished asymptotically with mode number.

[7] Kyungsuk Yum, Zhaoyu Wang, Abhijit P. Suryavanshi, and Min-Feng Yu, the damping impact in the nanoscale mechanical bar resonators worked under encompassing conditions was examined. Test estimation of the thick air damping in the nanowire cantilever resonators was done utilizing the electric-field-actuated reverberation technique; and a hypothetical model, which represents the impacts of measurement and material property of the nanowires and the air thickness of the earth, was produced for depicting the mechanical reverberation and damping. The study demonstrated that the damping impact in the nanoscale shaft resonators worked in air could be as high as that in the microscale resonators worked in fluids, and scaled with the geometric measurement of the concentrated on nanowire cantilevers.

[8] Christophe Castille, Isabelle Dufour, and Claude Lucat, report on the creation of a self-activated resounding micro sensor, taking into account a thick-film piezoelectric cantilever, devoted to either bio-substance discovery in vaporous or fluid media or liquid portrayal. The point of this paper is to show that longitudinal modes can be utilized as a part of exceedingly thick situations. Lower levels of liquid strong association in examination with established flexural modes are normal from the aftereffects of our diagnostic model of a cantilever swaying in a liquid. For instance, in different liquid extending from air to a Newtonian liquid of 300 cP consistency, measured quality variables for the principal longitudinal mode range from 300 to 20.

[9] F. R. Blom, S. Bouwstra, M. Elwenspoek, J. H. J. Fiuitman A test investigation of damping and recurrence of vibrating little cantilever bars in their most minimal Eigen state is exhibited. The cantilever bars are created from monocrystalline silicon by method for micromachining strategies. Their size is a couple of millimeters long, a couple of 100 Ilm in width, and a couple 10 pm in thickness. Damping and reverberation recurrence are concentrated on as a component of the encompassing weight p (1-105 Pa) and the geometry of the pillar. The reason for this exploration was to get outline rules for sensors utilizing vibrating pillars. The examination of the test results as far as a semi-subjective model uncovers that one can recognize three systems for the weight reliance of the damping: thick, atomic, and characteristic. For gooey damping a turbulent limit layer rules the damping at high weights (105Pa), while at littler weight laminar stream overwhelms. In the last area, this prompts a level for the quality element Q and in the previous to Q a V p. The weight Pc at which the move from laminar stream ruled damping to turbulent stream overwhelmed damping happens relies on upon the geometry of the pillars. Pc is autonomous on the length and abatements with both, the width and the thickness of the shafts.

2. Experimental work

A piezoelectric-energized cantilever bar is a two-layer composite structure built from a piezoelectric material bound to a stainless steel layer. Both layers are a couple of centimeters long and the stainless steel layer is of longer measurement, see Fig. 3.1. The Piezo-patch layer was poled in the z-direction and in this way, the utilization of a substituting current parallel to the poling bearing causes the Piezo-patch to recoil pivotally (x-direction) and extend horizontally. Alternately, as the extremity of the present turns around, the PZT layer extends pivotally and contracts along the side.

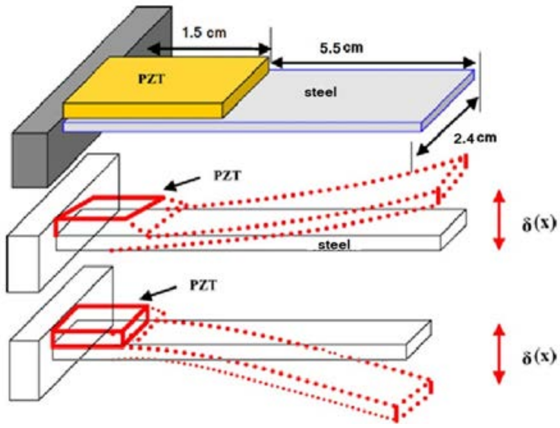


Fig.2 1. A 3D view of the experiment setup

2.1. Density Measurement

The inertia due to mass loading of the liquid on the sensor was responsible for the resonant frequency shift in going from air to liquid. Because inertial forces due to viscous drag of the liquid were negligible as a result of the high Reynolds number (Re). For Re>>1 the frequency response of a rectangular cantilever in an inviscid fluid is given by

$$\frac{\omega_{f,n}}{\omega_{v,n}} = \left(1 + \frac{\pi\rho 0W}{4\rho ct}\text{Real}\left[\Gamma\left(\omega f, n\right)\right]\right)^{-1/2} \quad (1)$$

Can be rearranged as

$$\rho_0 = \frac{1}{B}\left(\left(\frac{f_{v,n}}{f_{f,n}}\right)^2 - 1\right) \quad (2)$$

Where $B = \pi W/4\rho_c t$ is a constant. Because the cantilever thickness is not uniform due to two-layer construction, a shape factor is needed to accurately determine density using Eq. (2).

Therefore, modify Eq. (2) as

$$\rho_0 = \frac{1}{\alpha B}\left(\left(\frac{f_{v,n}}{f_{f,n}}\right)^2 - 1\right) \quad (3)$$

Where α is a constant. Using published value of density of water at 25 ◦C, and measured values of resonance frequency in vacuum and in water, the parameter αB was determined at each of the excitation voltages from 0.01Vto 1V. The parameter αB varied. Averaging them and find yielded αB. Density of unknown solution was then determined from the following which was derived from Eq. (3)

$$\rho_g = \frac{1}{\alpha B}\left(\left(\frac{f_{v,n}}{f_{a,n}}\right)^2 - 1\right) \qquad (4)$$

Where $f_{g,n}$ is resonance frequency in unknown solution and ρ_g is density of unknown solution

2.2. Viscosity Measurement

The viscous effects of the various glycerol solutions on the second resonant mode were determined as dissipative losses due to drag force of the liquid. Kirstein reported the following to determine the viscous damping coefficient, C_v:

$$C_v = \frac{2\pi f_{f,n}(M_e + m_{ae})}{Q} - C_s \qquad (5)$$

Where C_s is the intrinsic damping coefficient, which depends on the material of construction and is determined from Eq. (5) by setting $C_v = 0$ and the resonance frequency in vacuum. The viscous damping coefficient depends on the peak shape (Q-value) and the added mass of liquid, m_{ae}.

$$\omega = \frac{1}{8}\left(\sqrt{9(K\mu\rho)^4 + 64{\omega_0}^2} - 3(K\mu\rho)^2\right) \qquad (6)$$

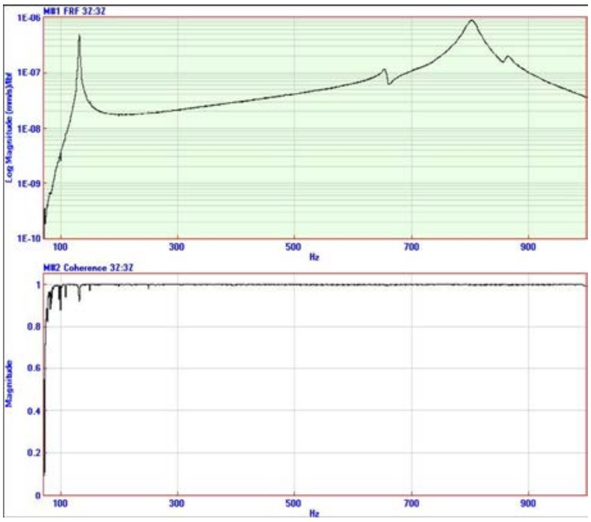
Where, ω is the 1st mode frequency of damped cantilever in viscous medium
K is a constant having value 3.1635
µ is dynamic viscosity of fluid in mPa.s
ρ is the density of liquid in g/cm3
ω_0 is the 1st mode frequency of damped cantilever in vaccum.
By using this relation, we can easily find the dynamic viscosity of the unknown fluids.

2.3. Experimental setup

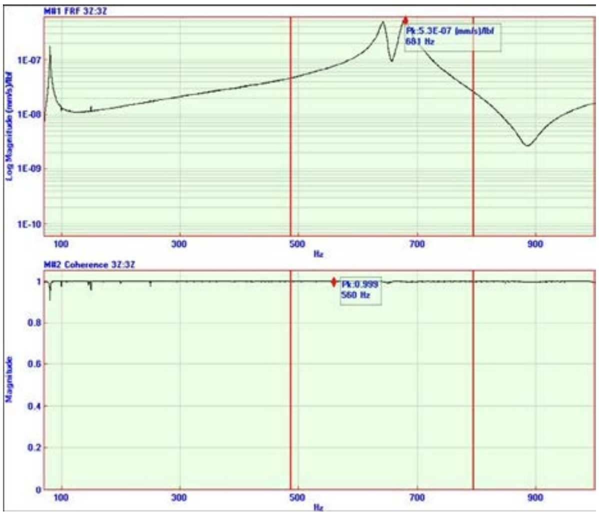
Fig 2.2 Testing in water

2.4. Results

2.4.1. Bode plot for beam in air

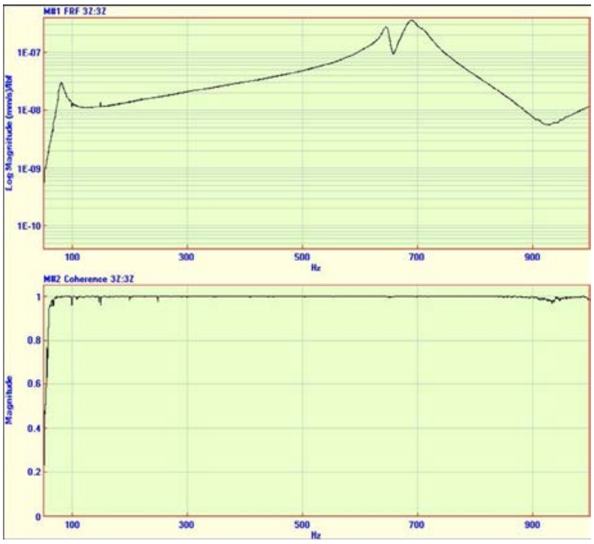


2.4.2. Bode plot for beam in water



2.4.3. Bode plot for beam in MANUAL GL 4

2.4.4. Bode plot for beam in 20W 40



2.4.5. Bode plot for beam in POWER 2T

2.4.6. Bode plot for beam in AXLE 140

2.5. Modal Frequencies and Damping Values

Fluid	1^{st} mode (frequency)	2^{nd} mode (frequency)	1^{st} mode Damping (%)	2^{nd} mode Damping (%)
Air	132	779	0.675	0.162
Water	80.1	645	0.945	0.771
Manual GL 4	82	647	4.29	1.04
20W 40	82.1	659	5.54	3.52
Power 2 T	82.8	663	3.48	2.37
AXLE 140	81.7	646	9.91	7.13

2.6. Density Measurement

Fluid	Density (kg/m^3)
Water	1043
MANUAL GL 4	942
20W 40	936
Power 2 T	901
AXLE 140	957

2.7. Viscosity Measurement

Fluid	Dynamic viscosity (mPa.s)
Water	0.9607
MANUAL GL 4	1.0295
20W 40	1.034
Power 2 T	1.0608
AXLE 140	1.0187

3. Software Analysis

The viscosity and density are measured by the guide of software analysis. Here ANSYS WORKBENCH 16.0 is utilized to demonstrate the test. In this software a fluid structure interaction module is created and the work is done.

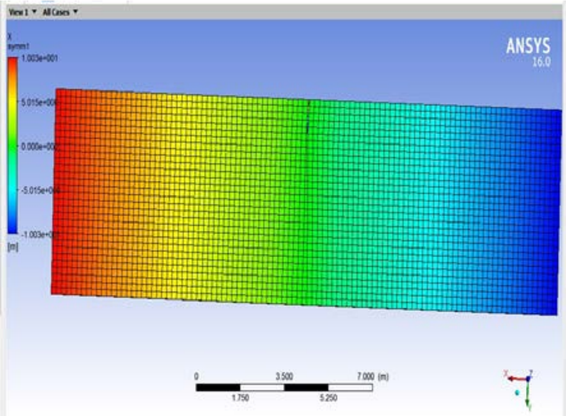


Fig 3.1 Nodal displacement

3.1. RESULTS

3.1.1. MODAL FREQUENCIES

Fluid	1st Mode (Frequency)	2nd Mode (Frequency)
Air	132	720
Water	80.79	680
Manual GL 4	82.85	640
20w 40	83	643
Power 2 T	83.31	659
Axle 140	82.56	641

3.1.2. DENSITY MEASUREMENT

Fluid	Density (Kg/M^3)
Water	1005
Manual GL 4	898
20w 40	891
Power 2 T	876
Axle 140	913

3.1.3. Viscosity Measurement

Fluid	Dynamic viscosity (mPa.s)
Water	0.988
MANUAL GL 4	1.0635
20W 40	1.069
Power 2 T	1.0809
AXLE 140	1.0398

4. CONCLUSION

In this work a new model for measuring the density and viscosity of unknown fluids is proposed. The modal is based on vibration on a cantilever beam. Different mode frequencies are measured from the experiment and using that data density and viscosity of various fluids are found. The obtained values are compared with a ANSYS WORKBENCH 16.0 model. A similar tendency is obtained from the ANSYS WORKBENCH 16.0 model.

4.1. Density Measurement Comparison

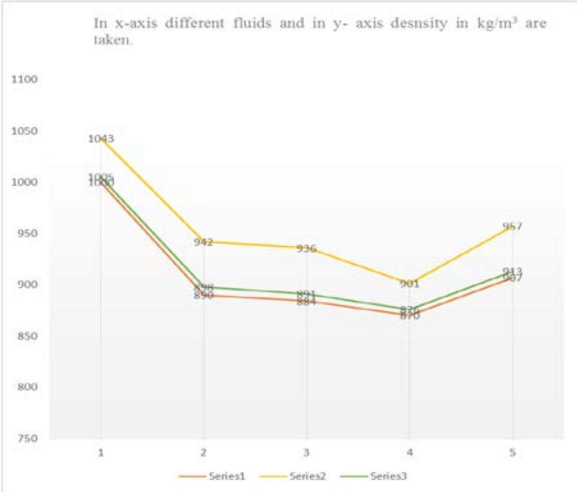


Fig 4.1 Density Measurement Comparison

Here the yellow line represented the experimental data green line represented the software data and red line represented the actual theoretical value. From the chart I can understand that software data and actual theoretical values are in close match but there is a shift had scene in the experimental data. But all the three data are in same manner so I concluded that my assumptions are right.

4.2. Viscosity Measurement Comparison

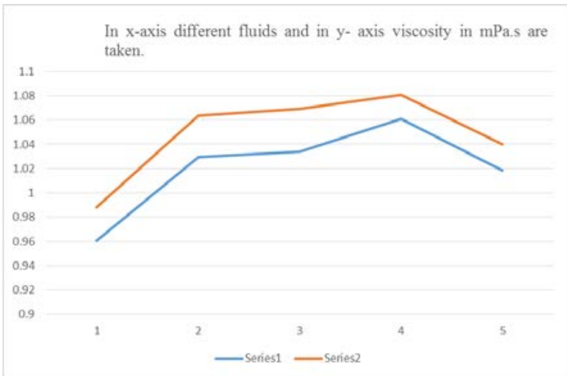


Fig 4.2 Viscosity Measurement Comparison

Here the blue line represented the experimental data and red line represented the software data. From the chart I can understand that software data and experimental values are in same manner.

From these comparisons I can conclude that the proposed work is good enough to measure the density and viscosity of unknown fluids.

5. References

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[6] A. A. H. Phdua, M. N. A. Fareleira. C. G. Calado, and W. A. Wakeham – "Validation of an Accurate Vibrating-Wire Densimeter: Density and Viscosity of Liquids Over Wide Ranges of Temperature and Pressure"

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