A New Approach of Blood Viscosity Measurement

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I. Introduction

In the medical research, chemical composition of blood, such as cholesterol and triglyceride levels, has been focused exclusively and related to various cardiovascular diseases. While blood chemistry is absolutely important, studies have shown that physical properties—such as viscosity—may play a critical role in predicting possible diseases as well. Physical properties of blood directly affect blood flow, and sufficient blood flow is essential for the health of all organs. Since blood supplies oxygen and nutrients needed for living cells and removes the cells' waste products, when blood flow is impeded in any way, medical problems arise, ranging from heart attacks and strokes to kidney disease and blindness. Perhaps the aging process in general is affected as well.

A new method for viscosity measurement is proposed by Kensey[1], who uses a capillary tube to measure whole blood viscosity at different shear rate without the use of anticoagulants. His device markets on pharmaceutical companies and medical researches, which investigate the correlation between the viscosity and various diseases.

The method we proposed is not a research-oriented product, but a consumable diagnostic tool. We change the capillary tube to a cantilever beam, which eliminate the capability of measuring blood viscosity at different shear rates, but retain the blood-handling system, which is biocompatible and does not need anticoagulant. We expect a cost-effective fabrication of our device, which is capable of performing quick blood viscosity tests.

Not much research has been done regarding the quantitative dependence of various diseases on blood viscosity levels. However we can foresee that atherosclerosis, heart attack, strokes, and kidney disease will be monitored by measuring the blood viscosity in the near future.

II. Estimated Market Size

According to the World Bank, there were about 60 million deaths worldwide in 1990's attributable to cardiovascular disease, and, contrary to the perceptions of many, deaths are expected to continue to increase. In addition, there are about 60 million people suffer at least one form of cardiovascular disease in the U.S. [American Heart Association]. The total spending in the U.S. on diagnostic system in blood testing is expected to exceed $300 million. A research shows that more frequent testing can reduce the incidence of these cardiovascular diseases from 12 to 14 percent per patient-year to less than two percent per patient-year. According to the American Heart Association, 40,000 strokes could be prevented each year among atrial fibrillation patients in the U.S. alone if warfarin were not under prescribed due to the current elevated complication rates. Current test strips priced at $4.50 and a meter priced at $750. Therefore, if our blood viscometer can perform a quick testing, and easy-to-use characteristics with medical suggestion of frequent tests (once a week [avocetmedical corporation]), there is a potential market in the blood testing market (17 billion market [2]).

III. Theories of Operation[3]

Damping in a structure is the ability of the structure to dissipate energy thus reducing the amplitude of vibration and shifting the natural frequency. Damping occurs in structure due to fluid dynamic drag, viscous dissipation (fluid damping), friction, and impact between the part of the structure (structural damping) and internal energy dissipation of materials (material damping). In a fluid dynamic model, the damping is the dissipation of energy by viscous and pressure drag due to motion of the structure relative to the fluid. The total damping coefficient is the sum of the fluid damping, structural damping, and the material damping. In flow-induced vibration, the damping is dominated by the fluid-damping component of the total damping coefficient. The damping ratio ζ is obtained from the damping factor, which is the fraction of the total energy of vibration that is damped out in one cycle.

The most widely used and practically useful model for damping forces on the structures is the ideal damper. This damper opposes structural motion with a force proportional to velocity:

$$F_d = -c\frac{dy}{dt} = 2M\zeta\omega_n\frac{dy}{dt} \quad (1)$$

where y(t) is the displacement of the structure, c is proportionality constant with units of force per unit velocity, and F_d is the damping force.

Vibration in a fluid is damped by the surrounding viscous fluid. Fluid damping is the result of viscous shearing of the fluid at the surface of the structure and flow separation. The drag force per unit length on the structure is

$$F_y = F_d = \frac{1}{2}\rho|U_{rel}|U_{rel}DC_D \quad (2)$$

where ρ is the fluid density, D is a characteristic dimension used in non-dimensionalizing the drag force, C_D is the drag coefficient, and U_{rel} is the relative velocity between the structure and the body of the fluid. For a still fluid which is in the sensor's design, U_{rel} is the result of motion of the structure alone, $U_{rel}=-\dot{y}$, and the equation of motion is

$$m\ddot{y} + 2m\zeta_s\omega_n\dot{y} + ky = F_y = -\frac{1}{2}\rho|\dot{y}|\dot{y}DC_D \quad (3)$$

The mass per unit length m includes the effect of added mass and ζ_s is the structural damping factor that would be measured if the fluid were absent. This nonlinear equation can be solved for the fluid damping factor. If the structural motion is harmonic with amplitude A_y, $y(t) = A_y \sin \omega t$, then the nonlinear term on the right-hand side of Eq (6) is expanded in a Fourier series,

$$|\dot{y}|\dot{y} = A_y{}^2\omega^2|\cos\omega t|\cos\omega t \approx \frac{8}{3\pi}A_y{}^2\omega^2\cos\omega t = \frac{8}{3\pi}\omega A_y\dot{y} \qquad (4)$$

So, we can get the following equation of motion:

$$m\ddot{y} + 2m\omega_n[\zeta_s + \frac{2\rho D C_D A_y\omega}{3\pi m\omega_n}]\dot{y} + ky = 0 \qquad (5)$$

which implies the fluid contribution to damping of the structure is

$$\zeta_f = \frac{2}{3\pi}\frac{\rho D^2}{m}\frac{A_y}{D}\frac{\omega}{\omega_n}C_D \qquad (6)$$

This equation gives the still fluid damping for a known drag coefficient.

The drag coefficient derived by Stokes in 1843 is[4]:

$$C_D = \left(f\frac{D}{\dot{y}_{\max}}\right)\left(\frac{3\pi^2}{2}\right)\left(\frac{\mu}{\rho\pi f D^2}\right)^{\frac{1}{2}} \qquad (7)$$

Therefore, the laminar fluid damping coefficient can be approximated by

$$C_f = \left(4\pi^3 f D^2\mu\rho\right)^{1/2} \qquad (8)$$

The fluid damping then becomes proportional to the square root of the viscosity μ. Based on the fluid damping coefficient, and neglecting the structural damping, the peak vibration amplitude, $y_{\max}$, is

$$y_{\max} = \frac{Fl[1-\cos(\pi h/l)]/\pi}{(4\pi^3 f D^2\mu\rho_l)^{1/2}\omega_0} \qquad (9)$$

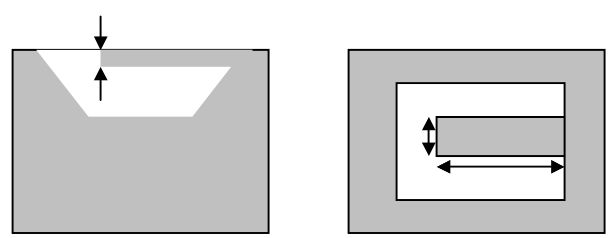
where F is the driving force of mechanical structure, h is the length of the structure immersed in the fluid, and l and the length of the structure.

In order to measure displacement, we suppose two methods to detect it. One is to coat PZT film on the beam as a strain gauge, which can be integrated in the same chip along with the related circuit. However, we worry about the sensitivity of this piezoelectric device because the displacement could be in the range of sub micron (It depends on the thickness and length of the PZT thin film).

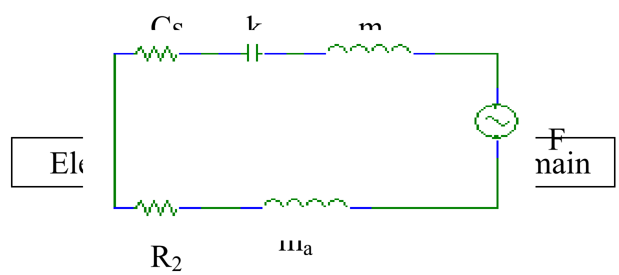
The other approach is to detect the shift of laser beam reflected from the surface of cantilever beam. Like it works out in atomic force micrometer, the deflection is enlarged by the ratio of distance from beam to detector and deflection itself. Obviously, in this case we have to fabricate another device and increase our cost drastically.

IV. Evaluation of sensor's performance

In this section, we use "lumped circuit model" to calculate resonant frequency, quality factor and viscosity coefficient. There are some approaches able to cope with this issue as well[5], but obviously lumped circuit model is one of the most convenient and quickest to work out.



Equivalent lumped circuit



R_1	Cs
C	1/k
L_1	M
R_2	C_f
L_2	m_a

Where,

1. Cs: damping coefficient of beam, which describe internal losses
2. k: spring constant of beam
3. m: mass of beam
4. C_f: damping coefficient of fluid
5. m_a: added mass, proportional to the displaced mass of the fluid m_d and given by

$m_a = C_m*m_d = C_m*m_d = C_m*\rho_f*V$

1. Resonant frequency

From the above lump element circuit, total impedance for this series circuit is

$$Zt= R+j X = (R_1 +R_2) +j (X_{L1} +X_{L2} -X_C) \quad (10)$$

Series resonance will occur when imaginary part equals to zero, thus,

$(X_{L1} +X_{L2} -X_C) =0$, $\omega L_1+ \omega L_2 -1/(\omega C)=0$,

therefore,

$$\omega(L_1+ L_2)= 1/(\omega C),\ \omega^2=1/(L_1+ L_2)C \quad (11)$$

$$\omega = \sqrt{1/(L_1 + L_2)\,C} \quad (11.a)$$

or

$$f=\frac{1}{2\pi}\sqrt{1/(L_1 + L_2)\,C} \quad (11.b)$$

recast (11) into mechanical domain, so

$$\omega = \sqrt{k/(m + m_a)} \quad (12)$$

for rectangle beam,

$$k= \frac{3EI}{L^3} = \frac{3E}{L^3} * \frac{WH^3}{12} = \frac{EWH^3}{4L^3} \quad (13)$$

Substituting into (13), we obtain the following

$$\omega=\sqrt{\frac{EWH^3}{(m + m_a)L^3}} \quad (14)$$

2. The quality factor Q

The quality factor of a series resonant circuit is defined as the ratio of the reactive power of either the inductor or the capacitor to the average power of the resistor at resonance; that is,

Q= (reactive power/ average power), as a result,

$$Q= \frac{I^2 X_L}{I^2 Z} = \frac{X_L}{R} = \frac{\varpi(L_1 + L_2)}{(R_1 + R_2)} \quad (15)$$

Again, in mechanical domain,

$$Q= \frac{\varpi(m + m_a)}{(C_s + C_v)} = \frac{\varpi}{\Delta\varpi} \quad (16)$$

3. Figure out C_f

Compare the quality factors measured in fluid and atmosphere,

$$\frac{Q_f}{Q_a} = \frac{(m + m_a)}{(Cs + C_f)} / (\frac{m}{Cs}) =$$

$$(\frac{m + m_a}{m})(\frac{Cs}{Cs + C_f}) \quad (17)$$

From (13), we can obtain

$$\frac{\varpi_f}{\varpi_a} = \sqrt{\frac{m}{(m + m_a)}} = \frac{f_f}{f_a} \quad (18)$$

Rewrite (17), then

$$\frac{Q_f}{Q_a} = (\frac{m+m_a}{m})(\frac{Cs}{Cs+C_f}) = \frac{f_a}{f_f} * \frac{1}{1+\frac{C_f}{Cs}} \quad (19)$$

Right now, measuring these data in cases of atmosphere and fluid, we can know $\frac{Q_f}{Q_a}$, $\frac{f_a}{f_f}$ and Cs. Accordingly, by means of (19), we can calculate the value C_f.

4. Discussion

From (15) and (17), quality factor can be expressed as:

Q=

$$\frac{\varpi(m+m_a)}{(C_s+C_f)} = \sqrt{\frac{\mathrm{EWH}^3}{(\mathrm{m}+\mathrm{m}_\mathrm{a})\mathrm{L}^3}} \times \frac{(m+m_a)}{(C_s+C_f)} =$$

$$\sqrt{\frac{\mathrm{EWH}^3(m+m_a)}{\mathrm{L}^3}} \times \frac{1}{(C_s+C_f)} \quad (20)$$

Because m_a is less than m, so we can ignore m_a. Furthermore, substituting m=ρV=ρHLW. Into (20),

$$\mathrm{Q}=\sqrt{\frac{\mathrm{EWH}^3(\rho\mathrm{HLW})}{\mathrm{L}^3}} \times \frac{1}{(C_s+C_f)} = \frac{WH^2}{L}$$

$$\frac{\sqrt{\rho}}{(C_S+C_f)} \propto \frac{WH^2}{L} \quad (21)$$

As a result, we should design a cantilever beam thicker, wider and shorter to avoid noise during sensing.

Conclusion

A new way to measure the viscosity of blood using cantilever beam is presented. The sensor appears feasible from the theoretical analysis. The measure technique of the sensor is based on the knowledge from our class. There are, however, several important issues need to be addressed before this technique can become a practical alternative to established methods.

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