Sensor For Viscosity and Shear Strength Measurement

**Topical Report
August 1, 1995 - October 30, 1996**

**By:
M. A. Ebadian; W. Kinzy Jones
J. E. Moore, Jr.; J. Dillon**

Work Performed Under Contract No.: DE-FG21-95EW55094

**For
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880**

**By
Florida International University
Hemispheric Center for Environmental Technology (HCET)
Center for Engineering & Applied Sciences
10555 West Flagler Street
EAS-2100
Miami, Florida 33174**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owed rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

LIST OF FIGURES	iv
NOMENCLATURE	v
EXECUTIVE SUMMARY	vii
1. INTRODUCTION	1
1.1 BACKGROUND	1
1.2 MAJOR ACCOMPLISHMENTS.....	1
2. DEVELOPMENT OF THE OSCILLATING CYLINDER VISCOMETER.....	2
3. DEVELOPMENT OF THE MAGNETOSTRICTIVE WAVE GUIDE VISCOMETER.....	8
3.1 ACOUSTIC WAVES ON CYLINDRICAL RODS AND WAVE GUIDES.....	8
3.1.1 Acoustic Waves	8
3.1.2 Generation of Acoustic Waves.....	9
3.1.3 Propagation of Acoustic Waves	9
3.1.4 Reception of acoustic waves.....	9
3.2 INSERTION OF WAVE GUIDES IN A VISCOUS MEDIUM.....	10
3.2.1 Effect on These Waves by the Insertion of the Wave Guides in a Viscous Medium.....	12
3.2.2 Error analysis.....	12
4. ALTERNATIVE CONFIGURATIONS.....	13
4.1 TWO TRANSDUCER TRANSMISSION MODE MEASUREMENTS	13
4.2 FOUR-TRANSDUCER TRANSMISSION MODE MEASUREMENTS	13
5. FIRST GENERATION ELECTRONIC INSTRUMENT	15
5.1 THE KEY CIRCUIT.....	15
5.2 MEASUREMENTS AND REPEATABILITY	16
5.3 OTHER FEATURES	16
5.4 INSTRUMENT DESIGN.....	20
5.5 ELECTRONIC CIRCUITS NOT YET DESIGNED.....	31
5.6 STATUS OF FABRICATION	31
6. EXPECTED FUTURE WORK NEEDED ON THIS INSTRUMENT	32
REFERENCES	33

LIST OF FIGURES

- Figure 1. Illustration of the Oscillating Cylinder Viscometer.
- Figure 2. Phase angle vs. viscosity for $\rho = 1.5 \text{ g/cm}^3$.
- Figure 3. Phase angle vs. density for $\nu = 16.67 \text{ cm}^2/\text{sec}$.
- Figure 4. Amplitude ratio vs. viscosity for $\rho = 1.5 \text{ g/cm}^3$.
- Figure 5. Amplitude ratio vs. density for $\nu = 16.67 \text{ cm}^2/\text{sec}$.
- Figure 6(a) One-transducer configuration used in reflected mode measurement;
(b) Experimental setup for reflective mode measurements.
- Figure 7. The test result for aluminum wave guide.
- Figure 8. Configurations in transducers, rods, and wave guides.
- Figure 9. Initial gate generator.
- Figure 10. Oscilloscope.
- Figure 11. Signal list for the viscosity instrument.
- Figure 12. Gate comparitor.
- Figure 13. Boards and switches.
- Figure 14. Final gate generator.
- Figure 15. 100 MHz oscillator/time base.
- Figure 16. Fast printed circuit board.
- Figure 17. Slower counter.
- Figure 18. Counter board.
- Figure 19. Viscometer cables.
- Figure 20. Viscometer power supply.
- Figure 21. Silk screen overlay for the Fastboard PCB.
- Figure 22. Top side of Fastboard PCB.

NOMENCLATURE

a	Moving cylinder acceleration amplitude (cm/s ²)
D	Moving cylinder inner diameter (cm)
F	Force amplitude generated by solenoid to move cylinder (dyne)
i	Imaginary number $\sqrt{-1}$
L	Length of the moving cylinder (cm)
m	Mass of the moving cylinder (g)
r	Radial position (cm)
t	Time (s)
α	Womersley parameter $\frac{D}{2} \sqrt{\frac{\omega}{\nu}}$
Φ	Amplitude ratio of F/p
ϕ	Phase angle between F and p
ν	Fluid kinematic viscosity (cm ² /s)
ρ	Fluid density (g/cm ³)
τ	Shear stress at inner wall of moving cylinder (dyne/cm ²)
ω	Angular frequency of oscillation (radians/s)

EXECUTIVE SUMMARY

Measurement of the physical properties (viscosity and density) of waste slurries is critical in evaluating transport parameters to ensure turbulent flow through transport pipes. The environment for measurement and sensor exposure is extremely harsh; therefore, reliability and ruggedness are critical in the sensor design.

The work for this project will be performed in three phases. The first phase, carried out in FY96, involved 1) an evaluation of acoustic and other methods for viscosity measurement; 2) measurement of the parameters of slurries over the range of percent solids found in tanks and transport systems; 3) a comparison of physical properties (e.g., viscosity and density) to percent solids and composition; and 4) the design of a prototype sensor. The second phase (FY97) will involve the fabrication of a prototype hybrid sensor to measure the viscosity and mechanical properties of slurries in remote, high-radiation environments.

Two different viscometer designs are being investigated in this study:

- A magnetostrictive pulse wave guide viscometer
- An oscillating cylinder viscometer

In FY97, the Hemispheric Center for Environmental Technology (HCET) at Florida International University (FIU), which has printed circuit, thick film, thin film, and co-fired ceramic fabrication capability, will fabricate five probes for demonstration after technology selection and evaluation.

1. INTRODUCTION

Viscosity and strength (e.g. compressive, tensile, shear) are the physical properties which are crucial for the in-situ analyses and monitoring of tank waste removal. Measuring viscosity is critical in evaluating transport parameters for slurries to ensure turbulent flow when the slurry is processed through transport tubes. The primary methods for viscosity measurement are 1) the interaction between two moving physical objects (rotating cylinders, spindles, or screws), 2) the movement of an object through a fluid (falling ball or rising bubble), or 3) the damping effects of a fluid on the forced vibration of an object. Although the first method is predominant, its mechanical characteristics restrict long-term reliability in the severe environments found in storage tanks and transport structures. The second method is impractical as an in-situ process. The use of acoustically driven test methods, although more restricted in commercial applications, seems to provide a possible solution for viscosity measurements in the harsh, high-viscosity environments found in storage and transport structures.

1.1 BACKGROUND

This project began with an evaluation of new and novel technologies for the measurement of the viscosity of tank slurries in transport pipes [(viscosity < 30 Centipoises (cps)] and tank structures (viscosity 1000-10,000 cps). Techniques capable of measuring a range of viscosities from 20 to 20,000 cps were investigated. Other evaluation factors included robustness, radiation tolerance (10^7 total dose), and the ability to be inserted either inline or used as part of a probing instrumentation package. Additionally, the sensors must have a high chemical resistance for application in highly caustic environments. A complete literature search (see References) and a vendor search for commercially available suppliers of viscometers or related apparatus was completed. The results of this investigation, coupled with the design constraints, have led to the development of two sensor technologies.

The first, the Torsional Wave Sensor, is an adaptation of a torsional wave guide. The main challenge confronted in developing this technique is in the electronic control and signal processing of the emitted and received signals. The second approach, the Oscillating Cylinder Viscometer, involves measuring the force necessary to move a cylinder in an oscillatory fashion in the direction of its axis. This is a new concept which shows promise for use in tanks and pipelines. Many of the details of the design of the Oscillating Cylinder Viscometer will remain confidential until a patent application can be completed.

1.2 MAJOR ACCOMPLISHMENTS

The theoretical development of the oscillating cylinder design for the measurement of the viscosity and density of Newtonian fluids has been completed. The components for the fabrication of a prototype have been ordered, and testing of the prototype is scheduled for the upcoming year.

2. DEVELOPMENT OF THE OSCILLATING CYLINDER VISCOMETER

The design principle upon which this viscometer is based implements a hollow cylinder that oscillates back and forth in the direction of its axis (see Figure 1). This design can be immersed in a tank of the fluid of interest and send the necessary information back to the operator remotely via wireless or wire communications devices. This design can also be modified to permit mounting in a pipeline.

Figure 1. Schematic of the oscillating cylinder viscometer (F represents the force amplitude; a , the acceleration magnitude; and z , the displacement amplitude).

The cylinder movement is to be driven by a solenoid or similar electrical device surrounding the hollow cylinder. Following proper calibration, the amount of alternating current supplied to the solenoid should provide a direct representation of the force, F , applied in moving the cylinder. The solenoid will reside between the moving cylinder and an external housing that will provide protection from corrosive components of the fluid. This external housing should possess a feature that restricts its movement inasmuch as it must remain stationary while the cylinder oscillates. Large, circumferentially oriented fins should suffice.

Assuming that there are no internal friction forces, a force balance on the moving cylinder results in the following equation:

$$mae^{i\omega t} = Fe^{i\omega t} - \pi DL \tau e^{i\omega t} \quad (1)$$

A key assumption in this equation and all that follow is that the movement of the cylinder is periodic and sinusoidal with only one frequency of oscillation. In principle, more complex movements with several harmonics could be used, but the analysis would be much more complex. The force amplitude, F , that provides the movement of the cylinder is known from the current supplied to the solenoid. The acceleration magnitude, a , can be measured directly with an accelerometer or indirectly with a displacement transducer.

As will be seen later, the velocity of the cylinder will need to be quantified as well. All subsequent equations will be derived assuming the displacement of the cylinder is known. The equations could also be expressed in terms of cylinder acceleration or velocity. The remaining term in Equation 1 is the amplitude of the shear stress on the inner surface of the moving cylinder, τ . The shear stress can be related to the displacement amplitude of the cylinder through an equation that involves the viscosity and density of the fluid. What remains is an equation relating F to the displacement of the cylinder, with the viscosity and density remaining to be determined.

The governing equations for fluid flow (Navier-Stokes equations) can be written so that the frame of reference follows the moving cylinder. Assuming the fluid is incompressible (constant density) and Newtonian (constant viscosity) and that the effects of the ends of the cylinder on the flow patterns are negligible, the axial momentum equation can be written as

$$i\omega v = \nu \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial v}{\partial r} \right) + \omega^2 z \quad (2)$$

The solution to this equation is the velocity amplitude of the fluid as a function of radial position (Moore et al. 1994), or

$$v = i\omega z \left[1 - \frac{J_0 \left(i^{3/2} \alpha \frac{2r}{D} \right)}{J_0 \left(i^{3/2} \alpha \right)} \right] \quad (3)$$

The first derivative of the velocity amplitude (with respect to radial position) evaluated at the wall is the shear stress, τ . This is expressed as follows:

$$\tau = i\omega \frac{2\rho\nu}{D} i^{1/2} \alpha \left[\frac{J_1(i^{3/2} \alpha)}{J_0(i^{3/2} \alpha)} \right] z \quad (4)$$

Substitution into Equation 1 gives the following relationship between the force amplitude, F , and the displacement amplitude, z

$$F = \left[\frac{2\pi^{3/2} \alpha \omega \rho \nu L J_1(i^{3/2} \alpha)}{J_0(i^{3/2} \alpha)} - m\omega^2 \right] z \quad (5)$$

Considering that F and z are amplitudes of complex periodic functions, the quantity in brackets in Equation 5 is complex and can be expressed as a magnitude and complex exponential phase angle, or

$$\frac{2\pi^{1/2}\alpha\omega\rho v L J_1(i^{1/2}\alpha)}{J_0(i^{1/2}\alpha)} - m\omega^2 = \Phi e^{i\phi} \quad (6)$$

The magnitude, Φ , is simply the ratio of F to z . The phase angle, ϕ , represents the lag between the sinusoidal wave forms for the force and displacement. If the first term in brackets in Equation 5 is much greater than the second term (i.e., if the mass of the moving cylinder is relatively small), the phase angle, ϕ , will be predominantly determined by the first term, representing the viscous flow contribution.

As an illustration of the dependence of Φ and ϕ on fluid density and viscosity, the following parameters were chosen:

$$m = 10 \text{ grams}$$

$$D = 10 \text{ cm}$$

$$L = 20 \text{ cm}$$

$$\omega = 2\pi \text{ rad/s}$$

To determine the relationship between the phase angle, ϕ , and viscosity, a representative value of the fluid density, $\rho = 1.5 \text{ g/cm}^3$, was chosen. The resulting graph is shown in Figure 2.

Figure 2. Phase angle vs. viscosity for $\rho = 1.5 \text{ g/cm}^3$.

To demonstrate the relationship between ϕ and ρ , a representative value of the viscosity equivalent to 2500 cps was chosen ($\nu = 16.67 \text{ cm}^2/\text{s}$). The resulting graph is shown in Figure 3.

Figure 3. Phase angle vs. density for $\nu = 16.67 \text{ cm}^2/\text{sec}$.

It is evident that the phase angle, ϕ , depends strongly on viscosity, but hardly at all on density. Thus, the phase angle between F and z can be used to determine viscosity, independent of density.

The dependence of the amplitude ratio, Φ , on fluid viscosity and density was derived using the same indicative values. The amplitude ratio versus viscosity plot in Figure 4 reveals a non-linear dependence.

Figure 4. Amplitude ratio vs. viscosity for $\rho = 1.5 \text{ g/cm}^3$.

As might be ascertained from Equation 5, Φ depends linearly on ρ , as shown in Figure 5.

Figure 5. Amplitude ration vs. density for $\nu = 16.67$ cm^2/sec .

The procedure for determining fluid viscosity and density is as follows. Using the measured phase angle between the applied force and cylinder displacement, the viscosity is determined from the curve shown in Figure 2. Then, this value is applied to determine the exact slope of the line in Figure 5. The density can then be determined. It would be desirable to repeat this measurement at several different oscillation frequencies to increase the reliability of the measurement.

In review, the assumptions made in the development of this viscometer are:

- The fluid is Newtonian (i.e., it has a constant viscosity);
- The fluid is incompressible (i.e., it has a constant density);
- The force applied to move the cylinder and the movement itself are periodic and sinusoidal, with only one frequency;
- The effects of the ends of the cylinders on the flow patterns are negligible; and
- No internal friction forces exist.

The assumption that the fluid is Newtonian is likely the most tenuous. There is no way to determine whether this is case without first measuring the viscosity with a well-established method. It might be possible to derive the fluid properties of a viscoelastic fluid using this Oscillating Cylinder Viscometer. This possibility will be investigated in future work.

The remainder of the assumptions should be relatively safe. Most liquids are very nearly incompressible, especially over the range of flow situations encountered in normal plant operations. The solenoid can be carefully chosen and calibrated to produce precise sinusoidal movement. The effects of the ends of the cylinder would be expected to be minor. This could be verified using computational fluid dynamics methods. The validity of the assumption of no internal friction forces will depend on the exact design of the viscometer. If any other friction

forces are present, they can be easily incorporated into Equation 1, most likely without a significant change in the final results.

The design presented in Figure 1 was developed with the aim of dropping the sensor into a static tank of fluid. The design may also be modified to permit mounting in a pipeline. The measurement procedure would be like that described above if there is no flow through the pipe. The possibility of measuring fluid viscosity and density of a fluid that is flowing through a pipe is currently being investigated from a theoretical point of view. The components needed to construct a working prototype of this viscometer have been ordered, and testing is scheduled for FY97.

3. DEVELOPMENT OF THE MAGNETOSTRICTIVE WAVE GUIDE VISCOMETER

The Torsional Wave Sensor is based upon the retardation of the transmission of a torsional sound wave through a solid by the surface interaction of the transmitted wave with the viscous fluid in contact with the solid. Transmission time is based on the elastic properties of the rod and the shape of the rod. The design uses the difference in transmission between two equivalent rods, one of which is immersed in the fluid to be tested. The rods are excited by the same pulse into the magnetostrictive transducers, and the time of flight difference in the signals, which represents the retardation due to the viscous drag on the rod immersed in the fluid, is compared. This time difference, when measured versus a known clock frequency, can be related to the viscosity and density of the fluid (Kim and Ban 1989). The use of two different shape rods (a cylinder and a rod) will allow the separation of density and viscosity to allow independent measurement of these two parameters. Initial testing indicates that this method should allow the measurement of viscosities over the range of 20 to 10,000 cps to an accuracy of 1 percent.

3.1 ACOUSTIC WAVES ON CYLINDRICAL RODS AND WAVE GUIDES

3.1.1 Acoustic Waves

Pulse excitation of a magnetostrictive transducer generates a magnetic field which causes the solid but thin magnetostrictive rods to vibrate acoustically. Unfortunately, the elongations during vibration of a solid rod are much less than with a hollow cylinder; hence, the rod does not interact sufficiently with an acoustic medium. To obtain greater elongations, a hollow wave guide is mechanically attached to the far end of the rod so that the rod's acoustic energy is coupled to it (see Figures 6a and 6b). This wave guide is inserted in the viscous medium.

Figure 6a. One-transducer configuration used in reflected mode measurements.

Fig. 6b. Experimental setup for reflective mode measurements.

3.1.2 Generation of Acoustic Waves

Panametrics manufactures equipment for acoustic non-destructive testing. Panametric's Model 5055PR is a Magnetostrictive Pulser-Receiver that generates up to a 350 volt negative pulse that shock excites the transducer. It does so with adjustable amplitude, pulse repetition rate, and damping. When pulsed, the Panametric KT-55 magnetostrictive transducer rings at its characteristic frequency (100 KHz). The 5055PR can also process the received reflections.

3.1.3 Propagation of Acoustic Waves

There are two modes of acoustic propagation—extensional (longitudinal) or torsional. In extensional propagation, particles of the rod move parallel to the rod's center axis. This vibration is in a wave train that moves down the rod. In torsional propagation, the rod's particles rotate primarily around the center axis even though the acoustic wave train still travels down the rod, but at a different propagation velocity. The same transducer can generate either mode of propagation by means of the selection of different rods and the optional use of a transducer magnet.

As either type of wave propagates down the rod, the juncture between the rod and wave guide represents an acoustic impedance mismatch. Some energy is reflected back to the sending end, while the rest travels to the end of the wave guide before reflecting back. This second energy can differ from the first, so the two wave shapes can have different amplitudes.

3.1.4 Reception of Acoustic Waves

In the reflective mode of measurement, the same transducer is used both for generation and reception. However, due to the reflected energies, the received wave trains are in millivolts. There are therefore three wave shapes of interest: the huge original excitation pulse and the small reflected wave trains from the two ends of the wave guide. The 5055PR is complex, with clippers, attenuators, and amplifiers so as to clip the transmit pulse at the T/R terminal and generate a usable receiver output at a separate terminal (see Figure 6b). The sync output announces the beginning of the excitation pulse cycle.

Typical pulse trains at 5055PR's signal output are shown in Figure 7. The first significant pulse is the residue from the negative transmit pulse after clipping and attenuation. The second and third pulse trains are the ones of interest in measurement. We measure time between these two pulse trains as the round-trip flight time, defined as t , between the ends of the wave guide. Typical values are 230 microseconds for torsional waves. Reflections continue to bounce back and forth from both ends of the rod and wave guide, generating a mishmash of following signals.

Hence, the signals before and after the interval from the second and through the third pulse trains are visually ignored or need to be eliminated. Unfortunately, the reflected wave shapes are altered significantly by the value of damping resistance placed across the transducer.

3.2 INSERTION OF WAVE GUIDES IN A VISCOUS MEDIUM

Each wave train has several cycles; that is, each is under-damped or can be considered to be amplitude modulated. In the frequency domain, this modulation has a wide bandwidth of around 40 percent of the carrier frequency (100KHz). The Remandur magnetostrictive rod has to be long enough so that it can introduce propagation delays that separate each wave train. Hence, this rod length cannot be reduced by more than a factor of two or so when used with 100 KHz transducers.

The following wave guides, each with a length of 300 mm, were evaluated:

- Solid copper, with diameters of 1.6, 2.4, and 3.2 mm;
- Hollow copper, with diameters of 1.6, 2.4, 3.2 and 6.4 mm;
- Solid aluminum, with diameters of 2.4 and 6.4 mm;
- Hollow aluminum, with diameters of 1.6, 2.4, 3.2, and 6.4 mm; and
- 1.6 mm with a length of 6".

The hollow aluminum wave guide of 3.2 mm OD worked the best (see Figure 7 for typical wave forms as recorded on an expensive digital Tektronix Time Domain Reflectometer, TDR).

Figure 7. Test result for the aluminum wave guide ($\varnothing 3.2 \times 300$ mm, in air and glycerin).

3.2.1 Effect on These Waves by the Insertion of the Wave Guides in a Viscous Medium

Sound propagating down a wave guide in a viscous medium has its propagation velocity degraded due to viscous drag. The change in round-trip flight time (defined as Δt) due to different viscous mediums can be measured, and from this, the viscosity can be calculated. For aluminum, and with air as the reference medium,

$$\nu = 2(\Delta t / t)^2 \omega a^2 \quad (6)$$

where ν is the kinematic viscosity, ω is the wave frequency, and a is the wave guides' characteristic dimension of the cross section.

3.2.2 Error analysis

Accurate values for viscosity then requires that all four measured variables be obtained with precision and accuracy. An ordinary analog oscilloscope cannot measure Δt , t , or ω with sufficient precision for viscosity instrumentation. It is even difficult to achieve repeatable results with a digital TDR.

If the wave guide's length is cut in half, both Δt and t are cut in half. Unfortunately their ratio, while independent of the wave guide's length, is small, typically around 1 percent for glycerin at room temperature. This is a differential flight time of around 2 microseconds on a 300 mm wave guide. To measure this time difference with around 1 percent accuracy means measuring with 10nS precision. Cutting the wave guide's length is half doubles the error or requires measurement with 5nS precision to maintain the accuracy of around 1 percent. In the simple configuration in Figure 6, this time difference is obtained from the difference of separate time measurements from different wave trains from the two viscous media by successive immersions.

Another reason is the difficulty of identifying the beginning of a wave train by visual inspection. This is complicated by the dramatic effect of damping on the wave trains. Since the 5055PR has continuously variable damping, it is difficult to achieve repeatability. Repeatability would be improved by switchable damping resistance.

Reflective mode measurements require a complex transmitter/receiver. The difficulty in processing received millivolts at the same terminal which, microseconds before, had hundreds of volts produced a 5055PR which gave inconsistent results for different attenuator settings. These inconsistencies went away under transmission mode measurements.

4. ALTERNATIVE CONFIGURATIONS

4.1 TWO-TRANSDUCER TRANSMISSION MODE MEASUREMENTS

Transmission mode measurements require separate transducers for transmit and receive (see Figure 8 for the two-transducer option). The receive transducer never sees the transmit pulse. This mode simplifies the receiver measurement process substantially since there is no large transmit pulse to attenuate. The raw receive transducer output is about 140 mV p-p open circuit. The signal-to-noise ratio is excellent, and there is no 60 Hz hum.

A pre-amp will produce a larger signal to evaluate and provide a means to dynamically vary the gain so that the two wave trains show the same amplitudes. However, two separate (in both space and time) measurements of time are required, and the difference between them is calculated before being used in the calculation of the viscosity. Any calculated difference between measured values has the potential for degradation in accuracy, particularly when the measured values are close to one another.

4.2 FOUR-TRANSDUCER TRANSMISSION MODE MEASUREMENTS

It is possible to measure the differential flight time, Δt , directly if two transmit and receive transducers are used (see Figure 8). The same transmit pulse is supplied to two identical transmit transducers. The wave propagates down two identical rods to two identical wave guides. When both wave guides are in air, the receive wave trains should be identical; if not, this can be compensated for. Then, one wave guide is inserted in the viscous medium under test, and the difference in time is measured directly. This method is not likely to be feasible until the other difficulties mentioned above are dealt with. Nonetheless, below we show how that they can be resolved to make this approach feasible. It is the preferred approach from an accuracy standpoint, but may not be from a standpoint at probe bulk.

Fig. 8. Configurations in transducers, rods, and wave guides.

5. FIRST GENERATION ELECTRONIC INSTRUMENT

An electronic instrument has been designed

- a) With solutions for the receiving difficulties mentioned above;
- b) That can be used with any of the above configurations;
- c) Which directly measures digitally all the electronic variables needed for the viscosity calculation, with 10nS resolution; and
- d) With switches to monitor all relevant signals on an inexpensive oscilloscope.

Electronic research has resulted in validated circuits for

- a) Suppression of the transmit pulse waveform, even if already attenuated, plus all of the wave trains after the first two desired reflections;
- b) Detection of the point in time when each of the two pulse trains begin (positive slope of the first positive cycle) by a method that is automated (not dependent on human skill), digital, robust, repeatable, and accurate;
- c) Generation of a digital gate signal whose width is the accurate time difference between these two beginnings, (this is the round-trip flight time);
- d) The measurement of the time of this gate width with 10nS resolution; and
- e) The direct measurement of the differential time Δt due to viscous drag if the four-transducer configuration is used.

5.1 THE KEY CIRCUIT

Figure 9 depicts the first circuit developed by which the gate signal is generated from the receiver output(s). It has been prototyped and has proven to work as intended. An improved version is used in the instrument. The comparator output is high whenever the received signal is greater than the manually adjusted threshold. It is low when the signal is below. The threshold is set above the noise level. The comparator is very fast, generating a clean and sharp square pulse for each of the positive half cycles of packets two and three. It clips off the negative half and the noise. The following retriggerable single-shot functions as an envelope detector which holds on the pulse output to turn the pulse train of each of the first two received packets into single pulses. The two resultant pulses toggle high and then low the first flip-flop. This flip-flop is very fast and generates a sharply defined gate for the counter. The second flip-flop suppresses every packet after the first two received packets. The delay on single-shot multivibrator generates a low pulse of adjustable width which disables the comparator output before the first received packet arrives.

Figure 9. Initial gate generator.

5.2 MEASUREMENTS AND REPEATABILITY

In addition to the direct measurement of roundtrip flight time and the differential time due to viscous drag, the instrument can switch to measure the period of each cycle in the wave train. This is approximately 10 microseconds. The wave frequency is the reciprocal of this period. These measurements are all required for calculation. For repeatability, the instrument will also measure the period of the sync pulses plus the pulse width of hold-on and delay-on. Time can be measured with four precisions: 10, 100, and 1000 nS or a time specified by an oscillator connected to a back panel connector.

5.3 OTHER FEATURES

The instrument also includes receive transducer preamplifiers with manually adjustable values of gain that can be varied between the first and second wave trains to achieve equal display amplitudes for the comparator/oscilloscope. This minimizes slope error. It also has two analog coax cable drivers to send analog or digital signals to a two-channel oscilloscope and switches to select the signals to go to each. The back panel holds 7 BNC jacks and a power strip. The instrument block diagram is shown in Figure 10. Figure 11 lists all the signals.

Figure 10. Oscilloscope.

SIGNAL LIST FOR VISCOSITY INSTRUMENT

NET	USAGE	AC	SRCE	DESTINATIONS
SW0	Output of flip-flop which shows differential time interval.	H	U19A-5	SW5A
SW1	Inverted SYNC.	L	U6	
SW2	DP before second digit from right DP2	H	SW2A	L7-9
SW3	DP before third digit from right DP3	H	"	L5-4
SW4	DP before fourth digit from right DP4	H	"	L5-9
SW5	DP before fifth digit from right DP5	H	"	L4-4
SW6	When low, enables the 100 MHz clock to CLOCK	L	SW5B	U8C-10
SW7	When low, enables the 10 MHz clock to CLOCK	L	"	U8D-13
SW8	When low, enables the 1 MHz clock to CLOCK	L	"	U8B-4
SW9	When low, enables the alternate oscillator clock to CLOCK	L	"	U8A-1
SW10	BLANK/ for counters	L	SW5B	U13,U14 pin 4
SW11	Delay_On when active high. U3a enabled when low	H	U2A-13	SW4
SW12	Inverted form of SW11. Delay_On/	L	U2A-4	SW5A
SW13	Inverted pulses of the second wave train, for scope CH2		U6	SW4
SW14	These pulses converted into a pulse for counter. Hold_On	H	U2B-5	SW4
SW15	Inverted form of SW14. Hold_On/	L	U2B-12	SW5A, SW5B
SW16	Inverted version of gate to counter, for scope	H	U6	SW4
SW17	Second envelope detector similar to hold on	H	U16A-13	SW4
SW18	Output of switch SW 4. Input to amplifier to scope CH 2		SW4	
SW19	Output of first flip-flop	H	U17B-9	SW5A
SW20	Output of SW 5A. The GATE into the counter.	H	SW5A	U11-2,7
SW21	Period; the output of the first gate.	L	U3A-12	
SW22	BNC of transducer 1; into preamplifier one			
SW23	T/R of 5055, from the BNC			
SW24	BNC of transducer 2, into preamplifier two			
SW25	Output of SW5B; flips first FF which then generates GATE			
SW26	Output of Receiver 1 preamplifier;			
SW27	Output of Receiver 2 preamplifier			
SW28	Output of SW3A into first comparitor and CH1 driver			
D11	Driver output of 7 segments of display of fastest counter--A	H	U13-13	J11
D12	B		U13-12	J13
D13	C		U13-11	J14
D14	D		U13-10	J17
D15	E		U13-9	J19
D16	F		U13-15	J21
D17	G		U13-14	J23
D21	Driver output to 7 segments of display of next fastest counte--Ar	H	U14-13	J24
D22	B		U14-12	J27
D23	C		U14-11	J29
D24	D		U14-10	J31
D25	E		U14-9	J33
D26	F		U14-15	J35
D27	G		U14-14	J37
50MHZ	Output of the crystal oscillator			
100MHZ	Frequency doubled, for both counter chains			
10MHZ	Output of the first time base decade counter			

Figure 11. Signal list for the viscosity instrument.

1MHZ	Output of the second time base decade counter			
CLOCK	Selected from one of the above four; permits different precisions			
GATE/10	Output of first decade of count of time interval			
GATE/10	Output of second decade of count of time interval; into 4534			
Q0	Least bit of 4 bits of counter digit. From 4534		U25-20	U20,U21,U22,U23,U24
Q1			U25-19	
Q2			U25-18	
Q3	Most significant of 4 bits of counter digit.		U25-17	
Q4	Inverted LE4 of 4534 when not floating. drives active low LE of 451	L	U18-5	U21-5
Q5	Inverted LE5 of 4534	L	U18-7	U22-5
Q6	Inverted LE6 of 4534	L	U18-9	U23-5
Q7	Inverted LE7 of 4534	L	U18-11	U24-5
Q8	LT (lamp test for 7 seg. displays	L		Pin 3 of U20 to U24, U13, U14
Q9	PUP (pull-up for permanently high inputs)	H	RP1-8	
Q10	BLANK for 4534. Inverted form of SW10	H		
Q11	SCAN for 4534 clock--timing resistor Ra of 555A		RP1-10	U25-7
Q12	SYNC signal to system reset the 4534. Inverted form of SW1	H		
Q13	Inverted LE3 of 4534 when not floating	L	U18-3	U20-5
Q14	Alternate oscillator time base. Useful for test		J7	
Q15	Threshold of first comparator; goes to the pot that adjusts it			
Q16	Threshold of second comparator; goes to the pot that adjusts it			
Q17	Output of CH1 driver; to BNC			
Q18	Output of CH2 driver; to BNC			
Q19	To pot of first single-shot that holds off until first reflection			
Q20	To pot; adjusts gain for the second reflected pulse train for main			
Q21	To pot; adjusts gain for the second reflected pulse train for Rcvr2			
Q22	To JFET that switches in parallel resistance to up the gain			

Figure 11. Signal list for the viscosity instrument (continued).

5.4 INSTRUMENT DESIGN

The receive and counter circuit design is complete, including all its switches. The schematic design given by Figures 10 through 20 passes all CAD design rule checks. This design is partitioned between internal cabling, power supply, panel switches/controls/connectors, and two boards, a Fastboard and a Counter.

The Fastboard, shown in Figures 21 through 22, is a four-layer printed circuit board which handles all the highest speed and time critical circuitry. There are separate power and ground layers plus two signal layers. The highest speed circuits use Small Outline ICs. Nothing over 1 MHz leaves this board. Front panel selection of high-speed options is done indirectly. The front panel switches merely control an on-board multiplexer with different high-speed signal inputs, and which routes the high-speed option.

The critical high speed circuitry (up to 100 MHz) on the Fastboard was laid out manually to insure minimum lead lengths, good shielding, adequate by-passes, and low-inductance power and ground. Then, the rest of the layout except for J8 was completed with limited assistance from a CAD autorouter. The assignment of signals to J8 pins was made manually so as to give minimal trace length. Finally, the J8 signal allocations was back annotated to the schematics. The layout passes all CAD design rule checks and has been submitted to a commercial PCB fabricator. Two blank boards will be procured.

A large connector (J8) is used on the Fastboard for compatibility with Dr. Dillion's ARK tester and because 69 allocated connector pins are needed on this board alone. The board houses two potentiometers for adjustment of the two hold-on pulse widths. All resistors used with the comparitors and linear amplifiers are discrete and capable of easy replacement during tests and refinements. The minus 5 volt supply regulator for the comparitors and linear amplifiers is on the Fastboard to provide minimum power inductance.

The Counter board, while complex, handles only lower speed circuits. It includes the seven-digit, seven-segment displays and five latches, decoders and drivers. This gives up to seven digits of time precision. It also includes the five lower speed decimal counters. The upper two and their latch/decoder/drivers are on the Fastboard. The worst-case current requirements to illuminate all 49 segments is about 0.7 ampere. This heavy current is supplied by a separate 5 volt regulator circuit on the counter board so that heavy current surges do not affect the power to the critical timing measurement circuits.

Figure 12. Gate comparator.

Figure 13. Boards and switches.

Figure 14. Final gate generator.

Figure 15. 100 MHz oscillator/time base.

Figure 17. Slower counter.

Figure 19. Viscometer cables.

Figure 21. Silk screen overlay of Fastboard PCB.

Figure 22. Top side of Fastboard PCB.

5.5 ELECTRONIC CIRCUITS NOT YET DESIGNED

The design is not yet completed for the digital measurement of the threshold voltage or the digital measurement of the probe temperature, all on the same display. However, the switches in the first generation instrument have been designed for upgrading in the second generation instrument to allow for routing these measured values to the digital displays when included on another board.

Presently, the 5055PR will be used to drive the transmit transducer. Eventually, it is anticipated that the transmit circuitry can be added to the second generation instrument on a third board with additional controls for damping, pulse repetition rate, and pulse energy.

5.6 STATUS OF FABRICATION

The 3-voltage power supply for the system has been built in a metal cabinet, leaving room for the rest of the circuits. All switches and connectors have been installed. The critical electronic circuits have been breadboarded and tested. They work. The counter board is being constructed using soldering and a perf board. Construction is almost complete. Components and specialized tools for future fabrication are almost all in place. This includes a pick and place machine for placement of the Small Outline ICs, several infrared ovens, and a robot for mechanical routing and drilling of alternate boards or modifications.

6. EXPECTED FUTURE WORK NEEDED ON THIS INSTRUMENT

- Wiring of permanent cables between panels and boards.
- Fastboard integrated assembly and test in stages.
- A formal statement of the theory of measurement, with the definition of variables, equations, and a spreadsheet to simplify calculation.
- Documentation on its operation.
- Investigation of alternate wave guides with better acoustic coupling to the viscous medium so as to induce greater viscous drag and delay.
- Design of a robust probe assembly to be used close to this instrument.
- Local evaluations as the surrogate solution with refinements as needed.
- Field trials at Oak Ridge National Laboratory (ORNL) (July 1997).

REFERENCES

- "A Better Way to Measure Viscosity," 1994, *Machine Design (Mechatronics)*, Vol. 66, pp. 60-62.
- Bailey, P. and Gillies, D., 1991, "New Low Cost Electroviscometer," *Measurement of Science Technology*, Vol. 2, No. 8, pp. 735-739.
- Benes, E. and Groschl, M., 1995, "Sensors Based on Piezoelectric Resonators," *Sensors and Actuators*, Vol. 48, No.1, pp. 56-60.
- Beyer, R.T. and Letcher, S.V., 1969, *Physical Ultrasonics*, Academic Press, New York.
- Borner, M. and Murphy, M., 1995, "Ultrasonic Measurements with Micromembranes," *Sensors and Actuators*, Vol. 46-47, pp. 62-65.
- Cutrone, L., 1984, "Use of the Brookfield Viscometer to Predict Rheological Performance of Coatings," *Journal of Coatings Technology*, Vol. 56.
- Duncan, B.L, 1994, "Density and Viscosity of Concentrated Aqueous Solutions of Potassium Hypochlorite," *Journal of Chemical and Engineering Data*, Vol. 39, pp. 863-864.
- Gaglione, R. and Attane, P., 1993, "A New High Frequency Rheometer Based on the Torsional Wave guide Technique," *Review of Scientific Instruments*, Vol. 64, No. 8, pp. 2326-2333.
- Gahletner, M. and Sobzak, R., 1988, "A New Apparatus For Measuring High Viscosities," *Journal of Physics, E, Scientific Instruments*, Vol. 21, pp. 1074-1077.
- Garza, J. and Glazmer, D., 1995, "A Fast and Easy Way to Measure Viscosity," *Chemical Engineering*, Vol. 102, pp. 133.
- Giacomin, J. and Thomas, V., 1994, "A Rheometer to Measure the Viscoelastic Properties of Polymer Melts at Ultrasonic Frequencies," *Review of Scientific Instruments*, Vol. 65, No. 7, pp. 2395-2401.
- Gladkii, V. and Gerlanets, I., "Analysis of Errors of Liquid Viscosity Measurement with a Vibration Viscometer," *Measurement Technology*, Vol. 34, No. 6, 1991, pp. 593-596.
- Golden, J.M. and Graham, G.C., 1989, "A Proposed Method of Measuring the Complex Modulus of a Thick Viscoelastic Layer," *Rheologica Acta*, Vol. 28, No. 5, pp. 414-416.
- Guozhen, Z. and Laoli, X., 1985, "Measurements of Viscosity and Density by a Vibrational Sphere," *Review of Scientific Instruments*, Vol. 56, No. 8, pp. 1639-1642.
- Hertz, T.G. and Dymling, S., 1990, "A Non-Invasive Ultrasonic Method for Viscosity Measurements," *Ultrasonics Symposium Proceedings*, Vol. 1, pp. 299-302.
- Heywood, N., 1985, "Selecting a Viscometer," *The Chemical Engineer*, n.v., pp. 16-23.
- Hitchcock, C.D. and Hammons, H.K., 1994, "The Dual-Capillary Method for Modern-Day Viscometry," *American Laboratory*, n.v. pp. 1-6.
- Hood, J. and Mignona, B., 1995, "Determination of Elastic Moduli in Anisotropic Media From Ultrasonic Contact Measurement," *Ultrasonics*, Vol. 33, No.1, pp. 45-54.

- Houmady, M. and Bastien, F., 1991, "Acoustic Wave Viscometer," *Review of Scientific Instruments* Vol. 62, pp. 1999-2003.
- Huilgol, R., 1975, "Continuum Mechanics of Viscoelastic Liquids," Hindustan Publishing Corporation, New York, Halsted Press.
- Jackman, M., 1991, "In Line Viscometers Help Achieve Perfect Products," *Food Technology*, Vol. 45, pp. 92-96.
- Josse, F., 1994, "Acoustic Wave-Liquid-Based Microsensors," *Sensors and Actuators*, Vol. 44, No. 3, pp. 199-208.
- Kim, Jin O. and Bau, H., 1989 "Instrument for Simultaneous Measurement of Density and Viscosity," *Review of Scientific Instruments*, Vol. 60, No. 6, pp. 1111-1115.
- Kimura, M. and Shirane, K., 1988, "Method for Measurement of Viscosity and Density of Liquid with a Slowly Rotating Column," *Review of Scientific Instruments*, Vol. 59, pp. 967-970.
- Krigman, A., 1985, "Viscosity Measurement: Still Sticky but Stopping Ahead Steadily," *Intech*, Vol. 32, n.p.
- Lansagan, R.M., 1991, "Viscosity, Density and Composition Measurements of Certain West Texas Oil Systems," *Society Petroleum Engineers, Inc.*, pp. 157-174.
- Leyh, C. et al., 1984, "New Viscosity Measurement: the Oscillating Magnetically Sphere," *Review of Scientific Instruments*, Vol. 55, pp. 570-577.
- Lynnworth, L., 1988, *Ultrasonic Measurements for Process Control: Theory, Techniques, Applications*, Academic Press, San Diego.
- Martin, Bret A., 1989, "Viscosity and Density Sensing with Ultrasonic Plate Waves Transducers," *Proceedings of the 5th International Conference on Solid State Sensors and Actuators and Eurosensors III*, pp. 704-708.
- Moore, J.E.J., Guggenheim, N., Delfino, A., Doriot, P.A., Dorsaz, P.A., Rutishauser, W., and Meister, J. J., "Preliminary Analysis of the Effects of Blood Vessel Movement on Blood Flow Patterns in the Coronary Arteries," 1996 *ASME Journal of Biomechanical Engineering*, 116, pp. 302-306.
- Park, N. and Thomas I. 1988, "Measurements of Rheological Fluid Properties with the Falling Needle Viscometer," *Review Of Scientific Instruments*, Vol. 59, pp. 2051-2058.
- Rajakovic, L.V., 1991 "Mediation of Acoustic Energy Transmission from Acoustic Wave Sensors to the Liquid Phase by Interfacial Viscosity," *Analytical Chemistry*, Vol. 63, pp. 615-621.
- Rosenberger, F. and Ivan, J., 1992, "Gravimetric Capillary Method for Kinematic Viscosity Measurements," *Review of Scientific Instruments*, Vol. 63, pp. 4196-4199.
- Saad, E., 1989, "Modeling the Viscosity of Glasses Used in the Immobilization of High-Level Liquid Nuclear Waste," *Nuclear Technology*, V. 86, pp. 66-69.
- Santra, L. and Bhaumick, D., 1988, "Development of a Differential Viscometer," *Journal of Physics*, Vol. 21, pp. 896-898.

- Shackleton, M. and Green, R., 1993, "On-Line Viscometer for Measurement in the Range 1 To 100 Pa's," *Measurement Science and Technology*, Vol. 4, No. 3, pp. 395-404.
- Shana, A. et al., 1994, "Quartz Crystal Resonators as Sensors in Liquids Using the Acoustoelectric Effect," *Analytical Chemistry*, Vol. 66, No. 13, pp. 1955-1964.
- Stokisch, T. and Radtke, D., 1991, "Instrument for Precise Measurement of Viscoelastic Properties of Low Viscosity Dilute Macromolecular Solutions of Frequencies from 20 to 500 KHz," *Journal of Rheology*, Vol. 34, No. 4, pp. 1195-1210.
- Suryanarayana, C., 1992, "Propagation of Ultrasonic Waves In Liquids: A New Model" *Ultrasonics*, Vol. 30, No. 20, pp. 104-106.
- Thomas, V. and Giacomini, A., 1995, "Measuring the Viscoelastic Properties of an Ethylene-Tetrafluor Ethylene Copolymer at Ultrasonic Frequencies," *Polymer Engineering and Science*, Vol. 35, pp. 1053-1060.
- Tozaki, K. and Miyatani, T., 1993, "Instrument for Measuring Viscosity and Shear Modulus under Steady Shear Stress," *Japanese Journal of Applied Physics*, n.v. pp. 2892-2894.
- Wang, J., 1993, "Piezoelectric PH Sensors: At-Cut Quartz Resonators with Amphoteric Polymer Films," *Analytical Chemistry*, Vol. 65, pp. 2553-2562,.
- Winkel, V. and Oliveira, J., 1995, "Acoustic Wave Propagation in Piezoelectric Fibers of Hexagonal Crystal and Symmetry," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 42, No. 5, pp. 949-955.