Sensor for Viscosity and Shear Strength Measurement

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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.

Two different viscometer techniques are being investigated in this study, based on:

- Magnetostrictive pulse generated acoustic waves
- An oscillating cylinder

Prototype sensors have been built and tested which are based on both techniques. A base capability instrumentation system has been designed, constructed, and tested which incorporates both of these sensors. It requires manual data acquisition and off-line calculation. A broad range of viscous media has been tested using this system. Extensive test results appear in this report. The concept for each technique has been validated by these test results.

This base capability system will need to be refined further before it is appropriate for field tests. The mass of the oscillating system structure will need to be reduced. A robust acoustic probe assembly will need to be developed.

In addition, in March 1997 it was made known for the first time that the requirement was for a deliverable automated viscosity instrumentation system. Since then such a system has been designed, and the hardware has been constructed so that the automated concept can be proved. The rest of the hardware, which interfaced to a computer, has also been constructed and tested as far as possible. However, for both techniques the computer software for automated data acquisition, calculation, and logging had not been completed before funding and time ran out.

1.0 INTRODUCTION

BACKGROUND

The introduction consists of topics needed to introduce this year's work, but which are not strictly parts of this year's work. In the Appendix appear definitions of nomenclature, some principles of viscosity, and the details on last and this year's instruments and waveforms. While some of this work in the Appendix began in the prior year, the theoretical background, summary, and analysis of it spilled over into the present year. It is placed in the Appendix to make clear that the main body includes only this year's results.

The main body of this report covers this year's original research in Sections 2.0-5.0. It is presented top-down:

Section 2.0 summarizes the history of the research this year. It describes the base capability instrumentation system that was used to obtain the measurements that demonstrated proof of concept. Section 2.0 presents the sub-systems in greater detail. The first two subsystems consist of the instrumentation probes/apparatus and the principles on which they work. Then follows a summary of the electronics used to process the signals in a base capability sufficient to validate the concept.

The Proof of Concept results are given in Section 3.0 (Oscillating Cylinder) and Section 4.0 (Acoustics).

Section 5.0 discusses the electronics in greater detail. The electronics used to prove the concept is a subset of a larger automated instrumentation system that has been designed and most of which has been implemented.

Two papers on which this research was based are "Instruments for simultaneous measurement of density and viscosity" by Jin O. Kim and Haim H. Bau [1989] and "Method for the calculation of velocity, rate of flow and viscous drag in arteries when the pressure gradient is known," by J.R. Womersely.

These two articles about viscosity sensor principles and designs became the theoretical basis for further research and development at Florida International University:

The contents of the two articles will be briefly summarized in the next two sub-sections. Details follow on these two approaches.

In the first mentioned article, an on-line, real-time instrument for the simultaneous measurement of fluid density and viscosity is discussed by Kim and Bau. The discussion focuses on Newtonian fluids. It was anticipated that a similar methodology could be used for non-Newtonian fluids.

Consider a torsional stress wave traveling in a waveguide with a uniform cross-section and a density of ρ_s submerged in a liquid with a fluid density ρ_f . The solid-liquid interface will be accelerated and decelerated as the wave travels through the waveguide. Consequently, the inertia which needs to be overcome by the torsional pulse is a combination of the solid waveguide's

inertia I_s and the adjacent liquid's apparent inertia I_f . The torsional wave speed, which is in direct correlation with the viscosity of the fluid, can be calculated as follows:

$$c = K (G/\rho_s)^{1/2} \cdot (1 + \rho_f I_f / \rho_s I_s)^{1/2}$$

where c is the torsional wave speed, G is the shear modulus of the solid, $K = \sqrt{\frac{D}{I_s}}$, and D is the torsional rigidity.

If the flight time in air is t_0 and t is the flight time in liquid at the same temperature, $\Delta t = t - t_0$ describes the difference in the delay in the transmission times of a torsional wave in a waveguide submerged in liquid and one in air. It has been demonstrated that for a waveguide with a circular cross-section of radius a ,

$$I_f/I_s = (8\nu/\omega a^2)^{1/2},$$

where ω is the wave's frequency and ν is the kinematic viscosity. It has been shown that the inner radius of a hollow circular waveguide does not influence the measurements, so the same theory was applied in the design of the waveguide sensor.

FIU Professor James Moore extended a concept discussed in Womersely's article. Moore has defined the second approach for a mechanical sensor rather than acoustic. Based on Womersely's article, Moore developed a new theory for finding the viscosity of Newtonian and non-Newtonian fluids. The system consists of an outer stationary housing that approximates a static case moving against an oscillating inner cylinder. Measurements of the displacement and shear force allow the viscosity to be calculated. This type of device is designed with no open bearings and is shielded by the connecting pipes and local shielding from some harsh environments like the tank slurries.

PROJECT TEAMS AND TASKS

Last year the acoustic and mechanical methods of measurement of viscosity were investigated in independent projects. Dr. W. Kinzy Jones was the principal investigator on both. Dr. Jerry Dillion and Liana Pernes, a Mechanical Engineering Masters student, worked with Dr. Jones on the acoustic project. Dr. James Moore and Alan Santamarina, a Mechanical Engineering Masters student, worked on the mechanical project.

The acoustic project consisted of parallel developments on an acoustic probe and in the associated electronics. Ms. Pernes and Dr. Jones worked on the acoustic probe, and Dr. Dillion worked on the electronics.

SUMMARY OF FY96 RESULTS FOR THE OSCILLATING CYLINDER PROJECT

The oscillating cylinder project achieved the following: a) theoretical derivations resulting in usable Bessel function equations to calculate viscosity from amplitude, force, and phase shift; b) the development of Mathcad software to perform the calculations; and c) an investigation of a

drive mechanism for an oscillating cylinder. A linear drive was investigated, based on the same principle as the voice coil in a loudspeaker, with a restraining spring. The driving force was to be inferred indirectly from a measurement of coil current.

REVIEW OF FY96 RESULTS FOR THE ACOUSTIC PROJECT

In the acoustic project, a literature search was conducted and equipment was assembled. The experimental setup developed by Kim and Bau was duplicated using a magnetostrictive pulser/receiver. Torsional waves were generated using a circumferentially magnetized piezo-magnetic Remendur wire. However, the use of high modular (stainless steel) waveguides, in addition to problems with the generation of the torsional waves, did not allow the duplication of results for water or glycerin in water.

Generation of acoustic waves

A Panametrics Model 5055PR generates the acoustic waves. This Pulser-Receiver generates up to a 350 volt negative pulse that shock excites the transmit transducer located at the beginning of the delay-line. It does so with adjustable amplitude, pulse repetition rate, and damping. When the Panametric KT-55 magnetostrictive transducer is pulsed, it rings at its characteristic frequency (100 kHz). The 5055PR can also process the received reflections. Each wave train has several cycles; that is, each is under-damped or can be considered amplitude modulated. In the frequency domain, this modulation has a wide bandwidth of around 40 percent of the carrier frequency (100kHz). The Remendur magnetostrictive rod moves due to the transmit transducer in which it is inserted. This 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.

Unfortunately, the flexures during vibration of a solid rod are much less than with a hollow cylinder; hence, the rod does not interact efficiently with an acoustic medium and the delay times are very small. To obtain greater flexure, a hollow waveguide is mechanically attached to the far end of the rod so that the rod's acoustic energy is coupled to it (Figures 1 and 2). This waveguide is inserted in the viscous medium.

Propagation of acoustic waves

The propagation of the acoustic wave is in the torsional mode. Particles of the rod rotate primarily around the center axis although the acoustic wave train still travels down the rod, but at a different propagation velocity. The same transducer can generate either mode of propagation (it will alternately be a transducer and a receiver) 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 waveguide represents an acoustic impedance mismatch. Some energy is reflected back to the sending end, while the rest travels to the end of the waveguide before reflecting back. This second energy can differ from the first, so the two wave shapes can have different amplitudes.

Reception of acoustic waves

If the configuration is of one transducer and one delay line (i.e., the reflective mode), as shown in Figure 1 and 2, typical received waveforms are shown by Figure 3.

Figure 1. One-transducer configuration used in reflected mode measurements.

Figure 2. Experimental setup for reflective mode measurements.

Figure 3. A typical waveform for an aluminum waveguide ($\varnothing 3.2^* 300$ mm, in air or glycerin).

The peaks are received at the transducer in the following order:

- The first (negative and positive) peak corresponds to the residue of the transmit pulse, although clipped and attenuated.
- The second (positive) peak is due to the acoustic impedance mismatch at the interface between the delay line and waveguide.
- The third peak is from the end of the waveguide.

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 τ , between the ends of the waveguide. A typical value for torsional waves is 230 microseconds. Reflections continue to bounce back and forth from both ends of the rod and waveguide, 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.

In the reflective mode of measurement, the same transducer was used for both generation and reception. However, due to the attenuation of reflected energies, the received wave trains at the transducer are in the range of millivolts. The 5055PR is complex, with clippers, attenuators, and amplifiers. It clips the 350V transmit pulse at the T/R terminal and generates a usable receiver output at a separate terminal (see Figure 2). The sync output is also provided, which annunciates the beginning of the excitation pulse cycle.

Waveguides

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

- Solid copper, with outside 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
- An aluminum waveguide of 1.6 mm OD with a length of 6 in.

The hollow aluminum waveguide of 3.2 mm OD worked the best.

The key equation for calculating viscosity from acoustic measurements

According to the test data, when the diameter is between 1.6 and 3.2 mm, the viscosity exhibits the following relationship that is the fundamental equation used to calculate viscosity:

$$\nu = 18(\Delta t/t)^2 \omega a^2 \quad (\text{for copper})$$

$$\nu = 2(\Delta t/t)^2 \omega a^2 \quad (\text{for aluminum})$$

where ν denotes kinematic viscosity; Δt is the time difference of the times of propagation in air and in the viscous medium; ω is the wave frequency (angular velocity) or its reciprocal, the wave period; and a is the characteristic dimension of the cross section. With a fixed, there are then three time variables to be measured. Note the sensitivity of viscosity to the time measurements.

Two-transducer transmission mode measurements

Different electrical configurations of possible transducers, rods, and waveguides were also identified. There were advantages to going from one transducer towards two or four. Transmission mode measurements require separate transducers for transmit and receive (see Figure 4 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.

However, two separate (in both space and time) measurements of time are required, and the difference between them is calculated before being used to calculate the viscosity. Any uncorrected difference between measured values has the potential for degradation in accuracy, particularly when the measured values are close to one another.

Four-transducer transmission mode measurements

It is possible to measure directly the differential flight time, Δt , if four transducers are used. The same transmit pulse is supplied to two identical transmit transducers. The wave propagates down two identical rods to two identical waveguides. When both waveguides are in air, the receive wave trains should be identical; if not, this can be compensated for. Then, one waveguide 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, we show how they can be resolved to make this approach feasible. For accuracy, it is the preferred approach, but may not be as accurate at probe bulk.

Figure 4. Configurations in transducers, rods, and waveguides.

Error analysis when measuring with an oscilloscope

Accurate values for viscosity requires that all 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 Time Domain Reflectometer (TDR).

If the waveguide's length is cut in half, both Δt and t are cut in half. Unfortunately, their ratio, while independent of the waveguide's length, is small, typically around one percent for glycerin at room temperature. This is a differential flight time of around two microseconds on a 300-mm waveguide. To measure this time difference with around one percent accuracy implies measuring with 10nS precision. Cutting the waveguide's length in half doubles the possible error or requires measurement with 5nS precision to maintain the accuracy of around one percent. In the simple configuration of Figure 4, this time difference is obtained from the difference of separate time measurements from different wave trains obtained from the two viscous media by successive immersions.

Another reason for the difficulty in obtaining accurate values 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 also difficult to achieve repeatability. Repeatability would be improved by a switchable damping resistor.

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 resulted in a 5055PR that gave inconsistent results for different attenuator settings. These inconsistencies were resolved under transmission mode measurements.

FY97 research in acoustic electronics

The associated research in acoustic electronics was for a laboratory instrument that was to be used in proximity to the acoustic probe. It allowed for direct measurement of roundtrip flight time and the differential time due to viscous drag. It also can switch to measure the period of each cycle in the wave train. Each cycle period is approximately ten microseconds. The wave frequency is the reciprocal of this period. These measurements are all required for calculation. For repeatability, the instrument can 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.

The instrument also had 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 channel. The back panel holds seven BNC jacks and a power strip.

Electronic research has resulted in validated circuits for the following:

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

This instrument was designed to measure automatically and display in turn one of the three needed time delay values. These time values were to be read and written down. Then, the viscosity could be calculated off-line. The principle on which it worked was to have the instrument select automatically the voltage reference points, then measure the time difference between these points automatically using an electronic counter.

Further details on both the oscillating and acoustic projects appear in Section 2.0 and in the FY96 Year-End Report.

2.0 FY97 ACCOMPLISHMENTS AND PROJECT STATUS

CONTINUATION UP TO MARCH, 1997

Measurement of viscosity using an oscillating cylinder

This year both projects were independently conducted through March. Dr. Dillion, however, assisted with some preliminary cylinder drive electronics design and testing. A low-frequency power amplifier was designed and built to drive a coil with a moving internal rod core. The internal rod in turn drove the cylinder. However, the voice coil approach proved unsuccessful. The displacement could not easily be held constant or stable, the relationship between the drive voltage and displacement was not linear, the conversion between coil current and force was not easy to calibrate, and too much audio power was required.

Acoustic probe structures

Some structures to house the acoustic probe(s) were investigated. A promising two-transducer structure is shown below as Figure 5. This structure has the advantage of isolating the 350V excitation pulse supplied to the left (transmit) transducer from the millivolt signals generated by the receive transducer on the right. However, the design and construction of such a structure proved difficult. The difficulty was in providing a good seal and sufficient mechanical strength in support of the transducers, rod, and waveguide while not dampening the acoustic waves.

Isolating the transmit and receive transducers permits the use of a simple but high performance receive preamplifier located in the probe housing. The preamplifier can drive by a low-impedance source a possibly long line with high-level signals, to minimize the effect of noise. This preamplifier could be designed with sharp cut-off below 30 KHz, to reduce 60 Hz hum pickup. Such a preamplifier was built and was used for measurement and, therefore, did yield proof of concept.

Figure 5. A promising acoustic probe assembly.

Acoustic electronics

By March, the acoustic counter instrument had been constructed and tested as much as it could be without a working acoustic probe.

THE NEW REQUIREMENTS IN MARCH, 1997

At a March ORNL meeting, definitive requirements were given for the first time specifying the requirements for the evaluation on-site of various approaches to the measurement of viscosity. Explicit in these requirements was that each approach include automated and unattended data acquisition, calculation, and data logging. This implied for the first time that the need was to develop a whole automated instrumentation system. In addition, this system was required to be functional and delivered in a few weeks.

DECISIONS MADE IN MARCH

In response to these requirements the following decisions were made:

- Change from a research mode with emphasis on investigating the feasibility of new and innovative methods to measure viscosity. These research activities were not complete, but the results at this time demonstrate the promise of both the acoustic and oscillating cylinder approaches.
- Change into a development mode to provide an operational system with basic capability for field tests as soon as possible.
- Since the data logging and computer configurations would be the same for both the acoustic and oscillating approaches, design a joint system that will support both the acoustic and oscillating cylinder methods. Design the system in its entirety, but so that the implementation can be staged to provide a basic capability for tests as soon as possible, with fuller features to follow.
- Due to the short time frame, the base capability will incorporate the features most readily available, hence, which can be implemented most quickly.

THE BASE CAPABILITY VISCOSITY INSTRUMENTATION SYSTEM

Features of the probes

The base capability instrumentation system is shown at the left of Figure 6.

Figure 6. The complete automated viscosity instrumentation system.

Features of the oscillating cylinder sub-system:

- A variable DC motor controller and a DC-motor is used to actuate the oscillating cylinder rather than a voice-coil since it is the approach that can be implemented most quickly. It also implies a cylinder position that can be known with high precision. The motor controller and its power supply are mounted at the motor, with only low-powered signals running between it and the electronics.
- The position of the cylinder is sensed by a Linear Variable Differential Transformer (LVDT).
- The shear force needed to move the cylinder in the viscous medium is sensed by a pressure transducer.
- The motor controller includes a precise digital readout of RPM. Knowing the gear reduction ratio enables the angular velocity of the oscillating cylinder to be calculated with high accuracy.
- A digital oscilloscope with ensemble averaging capability is required to recover clean signals.

Structure of the oscillating cylinder

The side view of the structure of the prototype oscillating cylinder is diagrammed in Figure 7. Figure 8 is a top-view photograph. An AC electric motor turns the crank gear through a belt drive. The crank arm, A, is attached to the crank gear two inches from its center of rotation. Arm B transmits the motion through a pivot point to Arm C, which is attached to the moving cylinder.

Figure 7. Illustration of the prototype oscillating cylinder viscometer.

The motion of the cylinder is guided by a linear bearing assembly. The force that moves the cylinder is measured with a strain gauge force transducer located in Arm C. The motion of the cylinder is measured with a Linear Variable Displacement Transducer (LVDT), located adjacent to the cylinder. These components are contained within a sealed, open-top aluminum box. The connection between the cylinder and the box is accomplished with a sealed bellows.

Figure 8. Top View of the oscillating cylinder structure.

The features of the acoustic probe in this version of the system include:

- A two transducer structure is used, but without a housing.
- A Panametrics 5055 Pulser Receiver drives the transmit transducer.
- A 30X preamplifier boosts up the received signal before sending it to the oscilloscope.
- A high-bandwidth oscilloscope is required to display accurately the sharply rising pulses in the received pulse train.

System electronics

Both the acoustic and oscillating structures are placed at the remote site of the viscous medium. At this site, one remote box houses the electronics and connectors. It requires only one either short or long cable to go back to a control site where a custom enclosure and oscilloscope are located (see Figure 6).

In a custom enclosure there is additional electronics, including drivers for an oscilloscope. This is all the electronics needed for the basic capability system.

The basic capability system was constructed, and it works. As such, it is sufficient to demonstrate basic capability, but it uses manual measurement and data recording.

AN AUTOMATED VISCOSITY INSTRUMENTATION SYSTEM

The computer

The more complete automated instrumentation system adds one laptop PC with a PCMCIA data acquisition interface card from National Instruments (NI). The computer additions are shown on the right of Figure 6. This laptop can be situated in the control room at some distance from the viscous media. It runs NI LabView software. The software will control the processes, acquire data, signal condition, calculate, and monitor for out-of-bounds condition, display, and log data. Most of this software has been written and debugged.

The custom enclosure

The electronics which customize the laptop interface for automating both the acoustic and oscillating cylinder measurements is housed in this custom enclosure. This includes the high-speed counters and gates needed to work with automated measurement in a four-transducer system. It runs one short cable to the laptop's PCMCIA interface card. The connectors and electronics are designed so that the custom unit could also be used with a larger desktop computer with an internal NI Lab PC-interface card. While the nominal specifications are the same for the PC+ and PCMCIA interface cards, there are subtle differences for default levels that made the design for the custom unit complex. The custom unit also includes all the regulated DC voltages needed, plus switches.

All this system hardware, including the two probes, has been built and tested as far as possible without having a four-transducer acoustic probe assembly in the housing.

PROJECT STATUS

Acoustic method

We have completed our proof of the concept of measuring viscosity by acoustics. There were recurring apparatus limitations. These limitations prevented automated data acquisition, but sufficient acoustic time delay data has been obtained manually from representative solutions. This data has been used to calculate viscosity, and the results check with good accuracy from 5 cP to 2000 cP on several mixtures—sugar, glycerin, and glycerol—across a broad temperature range. Non-Newtonian fluids can also be measured for particle sizes of less than one millimeter.

A robust four-transducer probe assembly still needs to be developed.

The electronics hardware for an automated instrumentation system has been constructed. However, substantial additional effort and corresponding funding will be required for software development and testing to complete a stable automated instrument.

Oscillating cylinder method

We have completed our proof of the concept of measuring viscosity using an oscillating cylinder. The force and displacements transducers and their signal conditioners work, as observed on a storage oscilloscope. With only limited time available, a manual approach was used for data acquisition and recording. All the required averaged force and displacement waveforms were captured and documented using a camera. Data was read and recorded manually from the screen and camera pictures for various solutions and mixtures with various cylinder oscillation frequencies. From this manual data, the viscosity was calculated using MATHCAD and Bessel function equations from fluid mechanics. The process works.

However, the mass and power of the present prototype oscillating structure is too large for the opposing viscous drag to modify sufficiently to obtain laboratory-quality precision. A reduced mass, second-generation structure is called for.

To produce a stable automated instrument some LabView programs will need to be developed. In addition, some means must be found to either link these programs to MATHCAD so that data is transferred automatically, or to embed corresponding calculations within LabView.

3.0 PROOF OF CONCEPT FOR THE OSCILLATING CYLINDER METHOD

EXPERIMENTAL LIQUIDS

The properties of some liquids tested are presented in Table 1.

Table 1.
Thermophysical properties of the experimental fluids

Adjacent Fluid	Density (g/cm ³)	Viscosity (cPs)
water	0.987	1
25% sugar-75% water	1.1	2.42
40% sugar-60% water	1.1765	6.1625
50% sugar-50% water	1.2295	10.27
60% sugar-40% water	1.28	45.46
45% sugar-45% water-10% sand	1.25	24.673

The first five data from the table are from "The Manufacturing of Sugar Products," by G. Nicolescu. The last information on the multi-component fluid sugar-water-sand was provided from previous experiments developed at Oak Ridge National Laboratories.

WAVEFORMS

Introduction

The goal was to prove the feasibility of measuring the viscosity of an adjacent fluid by an oscillating cylinder. According to the theory developed last year, with the mass m and the displacement fixed, viscosity can be calculated if three variables are measured: the angular velocity ω , the force x the cylinder exerts on the viscous medium, and the phase lag between them.

The accuracy of the calculated viscosity depends on the accuracy with which these measured values are determined. In addition, since force is implied by voltage from a load cell, calibration is required to interpret this voltage as the force x . The calibration can be extended to include the calculation of the term $m\omega^2x$ that is proportional to x . Therefore, the key factors affecting accuracy are the accuracy of this term and the measurement of phase angle. A least-squares fit will be used to come up with mathematical models for both, and the correlation for each fit is an objective measure of the validity—hence, accuracy of each. Raw data on which these linear fits

were performed were obtained from the waveforms. Waveforms follow for force and position of some tested liquids.

The need for ensemble averaging

A substantial noise was detected in the force waveform but was eliminated by using ensemble averaging over 150 cycles. The LabView software was not completed sufficiently to include its capability for ensemble averaging for noise reduction. In order to prove the feasibility of this approach, a Hewlett Packard 500 MHz storage oscilloscope was used. Figure 9 shows both the noisy shear force and displacement transducer waveforms in air. The force signal is not stable and varies within a certain range. A closer look at both waveforms is presented in Figure 10. In Figure 11, the force waveform was ensemble averaged over 150 cycles by the oscilloscope.

Comparing waveforms in air and water

The waveforms obtained in air and in the first tested fluid (water) are compared in Figures 12, 13. The force peak amplitude is higher in water than in air. Frequencies in Figures 12, 13 correspond to the same electronic settings. Most likely due to the non-sinusoidal nature of the force waveform, the frequencies are close to each other in value, but never the same. The displacement waveform remained in the same range of 2.750V- 2.781V for all the tested liquids.

Figure 9. Waveforms in air at 2.849 Hz.

Figure 10. Detail of the waveforms for a frequency of 2.849 Hz.

Figure 11. The same waveforms as shown in Figure 10, but using ensemble averaging.

Figure 12. Waveforms in air for 2.604 Hz.

Figure 13. Waveforms in water for 2.604 Hz.

Figure 14. Waveforms in air for 2.750 Hz.

The effect of frequency on waveshape

Figures 14, 15 represent waveforms obtained in air for two different frequencies: 2.813 Hz and 2.750 Hz. The force waveforms change with the frequency of oscillation. The waveforms become more stable as the frequency increases, and the signal can be triggered more easily if the frequency of oscillation is higher than 2.5 Hz.

Figure 15. Waveforms in air for 2.813 Hz.

EXPERIMENTAL RESULTS

Calibration

The calibration of the device is done in air, where viscous fluid forces are negligible. The force amplitude is represented through $m\omega^2x$. By using a least square-approximation one obtains a straight line with the corresponding equation and correlation factor. The equation obtained from the calibration $y = 7.7824x + 3.6504$, is used later for calculating the measured force (N). In Figure 16, the x value is replaced by the force value (V), which is the voltage displayed on the oscilloscope screen.

Figure 16. Calibration in air.

The obtained curve fit is linear for a force corresponding to a 0.5-3.5V range. In the experimentally calculated force it is assumed that this approximation can be extended for magnitudes greater than 3.5V.

Table 2.
Experimental data for calibrating the oscillating cylinder sensor in air

Force (V)	$m\omega^2x$ (N)
1.0	9.330943
1.0	12.5116
1.75	17.97802
2.031	19.98008
2.344	22.21299
2.938	26.93487
3.438	29.45601

In Table 2, $m\omega^2x$ represents the calculated experimental force using the calibration provided data. This value will be referred to as the 'measuring force'.

Measured data in water

After obtaining the calibration diagram, the device is immersed in 40 liters of water. The fluid dynamic effects at the extremities of the moving cylinder are considered negligible. Table 3 shows the force in volts obtained from the oscilloscope, the measured, and the predicted force in Newtons. By considering the density, viscosity and frequency of cylinder movement, the force amplitude and the phase angle are predicted with accuracy. The measured experimental force is obtained by using the calibration curve with the X value replaced by the force amplitude. The predicted force amplitude was obtained by using a Mathematica program (see Figure 17).

Table 3.
Force peak amplitude and the corresponding frequencies for water as the adjacent fluid

Frequency (Hz)	Reading force (V)	Measured force (N)	Predicted force (N)
1.98	1.625	16.2968	14.078
2.105	1.937	18.72491	15.9062
2.227	2.219	20.91955	17.8062
2.347	2.594	23.83795	18.7629
2.469	2.969	26.75635	19.7796
2.538	3.063	27.48789	20.8049
2.597	3.188	28.46069	22.5025
2.66	3.438	30.40629	23.6711
2.725	3.625	31.8616	24.8103
2.841	4.125	35.7528	26.0347
2.976	4.5	38.6712	27.8067
3.091	5	42.5624	30.3708

Figure 17. Predicted force versus measured force for water.

Data for 25% sugar mixtures

The experimental fluids are mixtures with the same properties and behavior as the waste tank slurries.

Their initial aqueous mixtures were designed with sucrose instead of sugar. Due to the high cost, the sucrose was replaced with sugar. For a 60% sugar–40% water, 80 lbs. of sugar was needed to acquire the desired percentage.

The next adjacent experimental fluid is 25% sugar–75% water. Table 4 shows the data for the measured force obtained from the calibration equation. The predicted force obtained from the Mathematica program is plotted versus the measured force in Figure 18.

Table 4.
Experimental data for 25% sugar–75% water

Frequency (Hz)	Reading force (V)	Measured force (N)	Predicted force (N)
2.237	2.344	21.89235	17.905
2.358	2.688	24.56949	18.8691
2.481	2.938	26.51509	22.034
2.532	3.188	28.46069	22.485
2.604	3.313	29.43349	22.9511
2.66	3.438	30.40629	23.601
2.732	3.625	31.8616	24.7977
2.849	4.125	35.7528	26.0183
2.976	4.625	39.644	27.8683
3.077	5.000	42.5624	30.3622
3.145	5.125	43.5352	32.799
3.268	5.625	47.4264	34.6676

Figure 18. Predicted force versus experimental force for 25% sugar–75% water solution.

Results for 40% sugar mixtures

The next experimental fluid measured was 40% sugar–60% water. In Figure 19, the predicted force is represented versus the experimental force (obtained using the calibration curve obtained in air).

Figure 19. Predicted force versus measured force for 40% sugar–60% water solution.

Results for 50% sugar

The magnitude of the peaks corresponding to the force signal in the 40% sugar–60% water and 50% sugar–50% water are different. It can be seen that as the frequency increases the peak amplitude corresponding to the more concentrated aqueous solution is bigger in magnitude than the one in the lower concentrated solution. Figure 20 is the plot.

Figure 20. Predicted force versus measured force for a 50% sugar–50% water solution.

Data for 60% sugar

The next experimental fluid is a 60% sugar–40% water solution. See Table 5 and its plot Figure 21. The sugar particles in this solution were not completely dissolved because this solution is supra-saturated. There is a phase change between this solution and the 45% sugar–45% water–10% sand (presented in the next section).

Table 5.
Experimental data for 60% sugar–40% water

Frequency (Hz)	Reading force (V)	Measured force (N)	Predicted force (N)
2.237	2.563	23.59669	17.2314
2.358	2.844	25.78355	18.1407
2.481	3.406	30.15725	19.1695
2.604	4.000	34.78	20.1457
2.732	4.437	38.18091	22.2751
2.849	4.937	42.07211	24.5559
2.976	5.375	45.4808	26.8984
3.077	5.875	49.372	29.3263
3.125	6.406	53.50445	31.7093

Table 5.
Experimental data for 60% sugar–40% water (Continued)

Frequency (Hz)	Reading force (V)	Measured force (N)	Predicted force (N)
4.04	10.31	83.88694	49.5325
4.228	10.63	86.37731	54.7151
4.556	12.66	102.1756	59.486
4.773	13.44	108.2459	67.1034

Figure 21. Predicted force versus measured force for 60% sugar–40% water solution.

Data for 25% sugar, 45% water, and 10% sand

The last experimental solution is 45% sugar–45% water–10% sand. See Table 6 and its plot, Figure 22. This solution is a multi-component phase fluid. During the measurements, the solution was permanently mixed manually to maintain the sand particles as a suspension within the sugar–water solution.

Table 6.
Experimental data for 45% sugar–45% water–10% sand

Frequency (Hz)	Reading force (V)	Measured force (N)	Predicted force (N)
2.358	3.188	28.46069	19.4894
2.481	3.625	31.8616	20.4905
2.604	4.000	34.78	21.5916
2.732	4.687	40.12651	22.6462
2.849	5.062	43.04491	24.955
2.976	5.562	46.93611	27.3238
4.367	11.72	94.86013	55.4449
4.566	12.81	103.3429	62.0909

Figure 22. Predicted force versus experimental measured force for 45% sugar–45% water–10% sand solution.

PHASE ANGLES

Introduction

Dr. Moore's theoretical derivations predicted phase shifts between the force and displacements that vary with viscosity. Such phase shifts were found to occur, but the correlations are weak for

low viscosities. Figures 23-28 present the predicted and calibrated (calculated) phase angles for the various solutions tested.

Phase angles for water

Phase angles for 40% sugar

Figure 25. Predicted phase angle versus measured angle for 40% sugar-60% water solution

Phase angles for 50 % sugar

Figure 26. Predicted phase angle versus measured phase angle for 50% sugar-50% water solution.

Phase angles for 60% sugar

Figure 27. Predicted phase angle versus measured phase angle for 60% sugar-40% water solution.

Table 7 compares the calculated and predicted phase angles for 45% sugar, 45% water, and 10% sand.

Table 7.
Predicted and calculated phase angles
for 45% sugar-45% water-10% sand solution

Calculated phase angle	Predicted phase angle
-152.798	-178.32
-156.303	-178.274
-154.678	-178.362
-157.363	-178.319
-158.974	-178.36
-160.704	-178.404
-180.794	-178.669
-189.032	-178.659

Figure 28. Predicted phase angle versus measured phase angle for 45% sugar-45% water-10% sand solution.

Summary Results

The results for force, displacement amplitudes and phase lag for the different solutions tested are summarized in Tables 8, 9.

Table 8.
Comparative measured-predicted force results for the fluids measured

Solution	Linear fit Measured-Predicted Force	Correlation factor
25% sugar – 75% water	$0.6307x + 4.2311$	0.9775
40% sugar – 60% water	$0.6148x + 1.6565$	0.9615
50% sugar – 50% water	$0.6278x + 0.5743$	0.9649
60% sugar – 40% water	$0.5933x + 0.8415$	0.9911
45% sugar – 45% water – 10% sand	$0.5788x + 1.1203$	0.9944

Table 9.
Comparative measured-predicted phase lag results for the fluids measured

Solution	Linear fit Measured-Predicted Phase lag	Correlation factor
25% sugar – 75% water	$0.0027x - 179.09$	0.6109
40% sugar – 60% water	$0.0035x - 178.62$	0.4521
50% sugar – 50% water	$0.0060x - 177.84$	0.3754
60% sugar – 40% water	$0.0141x - 175.19$	0.4303
45% sugar – 45% water – 10% sand	$0.0111x - 176.60$	0.9232

4.0 CONCLUSIONS

OSCILLATING CYLINDER DESIGN

The prototype of the oscillating cylinder viscometer succeeded in predicting the force necessary to move the cylinder in a viscous medium. There was a clear dependence of the force on the frequency of the movement, as was predicted by the theory. This design will be able to accurately measure fluid viscosities, provided some design changes are made.

Suggested design changes for the next version include measures to reduce the noise generated by the force transducer and making the moving cylinder carriage much lighter. In the prototype experiments, the noise from the force transducer was reduced by ensemble averaging. Although this technique was successful, the time required to make a single measurement is on the order of one minute. This may need to be reduced for some applications. The ability of this design to measure viscosity will be significantly enhanced if the mass of the moving cylinder carriage is reduced. The mass of the prototype design was too large to allow a large phase angle to develop between the applied force and the resulting displacement. Neither of these design changes is difficult to overcome.

Finally, some distinct advantages of this design must be noted. It was considered desirable to be able to measure the viscosities of slurry mixtures that are being pumped from one storage facility to another. This viscometer is ideal for such an application, because it measures the force necessary to move the fluid as a whole. It measures a sample volume of fluid that is similar in size to the pipeline used to convey the slurry mixtures. Therefore, the values of viscosity obtained with the oscillating cylinder design will be more applicable than those obtained with ultrasonic methods that only measure a sample volume within a few millimeters of the probe.

5.0 PROOF OF CONCEPT FOR THE ACOUSTIC VISCOMETER

EXPERIMENTAL PROCEDURES

System configuration

While all the electronic hardware was constructed, only the basic system capability to the left of the dotted line in Figure 6 was used for proof of concept. A four-transducer configuration was used. Data was read off the Tektronix TDR and recorded manually. As Figure 29 indicates, time measurements were made at the peak amplitude of the first pulse in each of the second and third wavetrains on the received waveform. This TDR had storage and sweep magnification to increase the precision of time measurement

Calibration

The first fluids considered were water and a solution of 25% sugar-75 % water. After evaluating the results obtained from a computer program, it was concluded that an acoustic viscometer as described in [H1] would be able to take measurements for a viscosity higher than 5 cPs. In addition, calibration was considered necessary by the literature. The results imply a calibration factor of 10 for a viscosity higher than 500 cPs.

Solutions

Several sucrose-water solutions with different concentrations of sucrose were considered. See Table 10. The viscosity for these fluids can be found in *Perry's Chemical Engineer Handbook*, 6ed, page 3-254. Solutions 4, 5, and 6 were studied mainly for seeing if the waveguide sensor data are valid for a multi-phase component fluid. The obtained data were compared with the data provided by CTPSM Instrument Developers and the existing literature.

Table 10.
Some experimental fluids

Number	Sugar %	Water %	Kaolin %	Sand %	Gravel %
1	40	60	0	0	0
2	50	50	0	0	0
3	60	40	0	0	0
4	45	45	10	0	0
5	45	45	7.5	2.5	0
6	10	45	45	7.426	0.099

Experimental tasks

Tasks used to determine viscosity by acoustic means were as follows:

- Calibration of the waveguides in air.
- Recording the time values (CS1) in air for the second peak for both waveguides.
- Insertion of the waveguide 1 (the shorter waveguide) in a confined space (in this case a 750 ml cylinder) containing the fluid to be measured.
- Reading again the time value (CS2) of the second peak for Waveguide 1 in the solution of interest.
- Calculation of Δt (CS2 – CS1).
- Calculating the viscosity of the fluid.

EXPERIMENTAL DATA

Waveforms

Figure 29 shows typical waveforms for the four-mode transducer configuration. The first two peaks are the peaks of interest. The first peak corresponds to the interface between delay line and waveguide. The second peak corresponds to the reflection at the end of the waveguide. To prove these two peaks are the ones of interest, the time between them and the published torsional speed (3015 M/S) implies a calculated propagated distance that is double the length of the aluminum waveguide. This is expected for a round-trip.

Figure 29. Waveforms in the four-transducer transmission mode.

To improve the precision of measurement, the sweep can be expanded. Figures 30 and 31 show expanded displays of peaks in air and glycerin, respectively.

Figure 30. Detail of the second peak in air.

Figure 31. Detail of the second peak in glycerin at 45°C.

Initial tests of sucrose-water solutions at room temperature

Table 11 shows Δt for various solutions. The position CS1 corresponding to the reference peak in air is needed for calculating the ratio I_f/I_s .

Table 11.
Initial results for water and sucrose-water solutions

Sugar (%)	Water (%)	Kaolin (%)	Sand (%)	Gravel (%)	Delta τ (μ s)	Conditions of measurement
0	100	0	0	0	.04	3 μ s/div
						150 mv/div
						333.6 MP
						333.64 CS1
						333.72 CS2
						20 ns Acc
62	38	0	0	0	2.68	3 μ s/div
						150 mv/div
						333.6 MP
						333.64 CS1
						336.32 CS2
						20 ns Acc
70	30	0	0	0	2.88	3 μ s/div
						150 mv/div
						333.6 MP
						333.64 CS1
						336.52 CS2
						20 ns Acc

The first solution presented in Table 11 is for Solution 1. The time difference air-liquid is about 1 μ s. Calculated results do not correspond with the value found in the literature. Several other solutions were investigated: 10% sucrose-90% water, 20% sucrose-80% water, 10% glycerine-90% water, 15% glycerine-85% water. The conclusion was that this device has a lower usable limit of 5-7 cPs.

A very good correspondence to literature data was obtained for a 50% sucrose-50% water solution and for a 60% sucrose-40% water solution. Figure 32 shows the curves obtained for Solutions 1, 2, and 3.

Temperature sensitivity of sucrose for solutions 1, 2, and 3 (sugar-water solutions)

After taking the measurements at room temperature, the solution was heated to 50°C. The solubility of sucrose increases as the temperature increases (see Tables 12 and 13). Table 14 calculated the kinematic viscosity for solutions 1, 2 and 3.

Table 12.
How the solubility of sucrose increases with temperature

Temperature (°C)	Dissolved sucrose in 100 ml water (g)	Temperature (°C)	Dissolved sucrose in 100 ml water (g)	Temperature (°C)	Dissolved sucrose in 100 ml water (g)
0	179.2	35	228.4	70	320.5
5	184.7	40	238.1	75	339.9
10	190.5	45	248.8	80	362.1
15	197.0	50	260.4	85	386.8
20	208.9	55	273.1	90	415.7
25	211.4	60	287.3	95	448.6
30	219.5	65	302.9	100	487.2

Table 13.
Raw data (shift in peak position) as a function of temperature for solutions 1, 2, and 3

Temperature (°C)	Solution 1 Cursor position (μs)	Solution 2 Cursor position (μs)	Solution 3 Cursor position (μs)
55	540.42	540.46	540.54
54	540.24	540.40	540.50
53	540.06	540.16	540.42
52	540.05	540.10	540.38
50.5	540.03	540.05	540.32
49.5	540.00	540.049	540.22
48.7	539.94	540.047	540.16
46	539.92	540.045	540.12
45	539.70	540.04	540.06
44	539.68	540.04	540.02
43	539.58	539.86	540.00

Table 13.

Raw data (shift in peak position) as a function of temperature for solutions 1, 2, and 3 (Continued)

Temperature (°C)	Solution 1 Cursor position (μs)	Solution 2 Cursor position (μs)	Solution 3 Cursor position (μs)
42	539.54	539.74	539.94
41	539.44	539.72	539.92
38	539.34	539.68	539.90
37	539.24	539.62	539.90
35.5	539.14	539.56	539.88
30	539.06	539.44	539.86
22	538.18	538.08	539.00

Table 14.

Calculated kinematic viscosity for solutions 1, 2 and 3

Temperature (°C)	Solution 1 v (cSt)	Solution 2 v (cSt)	Solution 3 v (cSt)
5.50E+01	7.10E+01	9.90E+01	1.10E+02
5.40E+01	6.40E+01	8.80E+01	1.10E+02
5.30E+01	6.10E+01	7.80E+01	1.00E+02
5.20E+01	5.70E+01	7.80E+01	1.00E+02
5.10E+01	5.40E+01	7.70E+01	9.60E+01
5.00E+01	5.20E+01	7.50E+01	9.00E+01
4.90E+01	4.60E+01	7.20E+01	8.70E+01
4.60E+01	4.40E+01	7.10E+01	8.50E+01
4.50E+01	4.00E+01	6.00E+01	8.10E+01
4.40E+01	3.70E+01	5.90E+01	7.90E+01
4.30E+01	3.50E+01	5.50E+01	7.80E+01
4.20E+01	3.20E+01	5.30E+01	7.50E+01
4.10E+01	3.10E+01	4.80E+01	7.40E+01
3.80E+01	2.90E+01	4.40E+01	7.30E+01
3.70E+01	2.70E+01	4.00E+01	7.30E+01
3.60E+01	2.50E+01	3.70E+01	7.20E+01
3.00E+01	2.30E+01	3.40E+01	7.10E+01
2.20E+01	3.10E+00	9.90E+00	3.40E+01

The peak shift was measured from the oscilloscope screen. This raw data was logged manually. Then a Fortran program calculated the viscosity.

Figure 32. Kinematic viscosity for Solutions 1, 2, and 3 for temperatures from 20°C - 50°C.

Figure 33. The effect of % sucrose on the viscosity of Solutions 1, 2, and 3.

Note this interesting phenomenon: the viscosity increased as the temperature increased. The reason was that small sucrose particles were in suspension. In addition, during the experiments it was observed that sugar particles were deposited on the waveguides' surfaces. This deposition was hard to remove.

After evaluating the experimental data and comparing the results with the existent data, it was concluded that Solution 1 represents the lower range of viscosity for this device.

The data for Solution 1 was close to data in the literature (5.238 cSt). The lower range for this viscometer was determined to be 5-7 cSt. A 40% (weight percent) sucrose solution weighing 500 grams contained 200 grams of sucrose and 300 grams of water.

Multi-component fluids

The results for Solution 4 (sugar, kaolin, and water) are presented in Table 15. The corresponding plot appears in Figure 34. Solution 4 was a multi-component fluid because the clay particles could not be dissolved. As the solution was heated up, the particles of sugar dissolved in the water. Solution 4 is a multi-phase component fluid. A comparison of these results with published data shows this acoustic sensor is capable of measuring the viscosity without taking into consideration a second phase existing as a suspension. The sand particle size was less than 5 μm . When the sucrose is completely dissolved the percent solids are estimated to be around 10%.

Table 15
Viscosity as a function of temperature for solution 4

Temp ($^{\circ}\text{C}$)	Sol. # 4 $\nu(\text{cSt})$
5.50E+01	1.20E+02
5.40E+01	1.20E+02
5.30E+01	1.20E+02
5.20E+01	1.20E+02
5.10E+01	1.20E+02
5.00E+01	1.10E+02
4.90E+01	1.10E+02
4.60E+01	1.20E+02
4.50E+01	1.00E+02
4.40E+01	1.00E+02
4.30E+01	1.00E+02
4.20E+01	1.20E+02

Table 15
Viscosity as a function of
temperature for solution 4 (Continued)

Temp (^o C)	Sol. # 4 v(cSt)
4.10E+01	1.10E+02
3.80E+01	1.00E+02
3.70E+01	8.80E+01
3.60E+01	7.50E+01
3.00E+01	7.30E+01
2.20E+01	4.20E+01

According to previous tests performed at ORNL and Hanford, the viscosity was 12.5 cSt, if the sucrose was completely dissolved. A solution of 50% sucrose-15% water has a viscosity of 12.55 cSt. The presence of sand particles and probably sucrose particles generates some differences. See Figure 35 for a comparison between Solution 2 and 4 showing the effect of particles. There is a clear difference, both at room and high temperatures. It can be concluded that this device would be capable of sensing presence of particles less than 5 μ m.

Another solution (7) was also tested, with the sand particles mixed in the sucrose water mixture. The sand did not have any influence in modifying the viscosity. The viscosity for solution 6 was found to be 42.7 cSt (54.459 cPs). Glycerin and glycerol solutions were also studied and the results were very close to the available data. For Solution 5, the density of the fluid was calculated to be 1275.2 kg/m³ and the kinematic viscosity of 42.7068 cSt. This result did not coincide to the result obtained by CTPSM Instrument Developers. However, the result was encouraging because it showed that the instrument was capable of detecting existing solids. For multiphase component fluids with particle size above 5 μ m, like Solutions 5 and 6, the design and the shape of the waveguide' cross section should be modified.

Viscosity of Glycerin

Data for glycerin was obtained for room temperature and for temperatures up to 50^oC. Figures 36 and 37 show typical waveforms. The waveform in glycerin has lower amplitude than the one in air.

Figure 34. Viscosity (cSt) versus temperature (°C) for Solution 4.

Figure 35. Comparison between the viscosities of solutions 2 and 4.

Tables 16 and 17 give the raw and calculated data, respectively, and Figure 38 shows the plot. These results are in agreement with published data. In Table 16, the time value at the second peak is for the waveguide immersed in the glycerin. The reference (first) peak position was 336.02 μs and the first waveguide peak position (in air) was 323.52 μs . The reference peak is the cursor position in air of the waveguide to be emerged in the experimental fluid. This value is necessary for further calculation for the kinematic viscosity. According to the results, the viscosity of glycerin decreased as the temperature increased. This demonstrates that this sensor is valid for measurements involving liquids or liquids mixtures (glycerol solutions). For all mixtures, a 650-ml cylinder was used. The smaller the space around the waveguide, the better the accuracy of the results.

Figure 36. Waveforms when both waveguides are in air.

Figure 37. Waveforms when waveguide 1 is in air and waveguide 2 is in Glycerin at 20°C.

Table 16.
Raw data as a function of temperature for 68% glycerin–32% water solution

Cursor position (µs)	Temperature (°C)
340.44	45
340.48	44
340.64	43
340.68	42
340.68	41
340.70	40
340.72	38
340.76	37
340.80	36
340.84	35
340.96	34
341.30	30
342.96	20

Table 17.
Calculated viscosity versus the temperature for 68% glycerin-32% water solution

Temperature (°C)	Viscosity (cSt)
4.50E+01	4.96E+02
4.40E+01	4.98E+02
4.30E+01	5.00E+02
4.20E+01	5.00E+02
4.10E+01	5.10E+02
4.00E+01	5.10E+02
3.80E+01	5.20E+02
3.70E+01	5.30E+02
3.60E+01	5.40E+02
3.50E+01	5.40E+02
3.40E+01	5.70E+02
3.00E+01	6.50E+02
2.00E+01	1.10E+03

As seen in Table 16, changes in time are small. Still, Table 17 shows they produce a significant difference in viscosity. This is because viscosity varies as the square of Δt . Data with less randomness could be obtained with a temperature-controlled bath and a permanently homogenization process.

Figure 38. Viscosity (cSt) versus temperature (°C) for Glycerin.

Viscosity of Glycerol

Glycerol ($\text{CH}_2\text{OHCHOHCH}_2\text{OH}$) solutions were measured. Tables 18 and 19 present the raw and calculated data respectively. Figure 39 is the plot. As the temperature increases, the viscosity of the solutions decreases. A solution of 68% glycerin–32% water is close to the range of this apparatus; the change in viscosity is very small. The experimental data obtained for temperatures higher than room temperatures are compared with the results reported by Jin Oh Kim (1989, page 196).

Table 18.
Raw data of glycerol solutions versus temperatures

Temperature (°C)	68%G-32%W Cursor Position	80%G-20%W Cursor Position	92%G-8%W Cursor Positions
50	342.1	342.24	345.46
45	342.12	342.4	345.48
40	342.16	343.08	345.50
35	342.18	344.3	345.58
30	342.24	344.46	345.68
20	342.42	345.02	346.42

The symbol 'G' represents glycerin and the symbol 'W' represents water. The results obtained at room temperature agree with published data. The viscosity of 68% glycerin–32% water solution remained almost the same as the temperature increased. This was due to the low viscosity of this solution. As the percent glycerin increases, the viscosity increased in magnitude. This made the variation of this parameter more visible as the temperature varied between 20°C and 50°C.

Table 19.
Calculated viscosity as a function of temperature for glycerol.

Temperature (°C)	Solution 68%G-32%W ν (cSt)	Solution 80%G-20%W ν (cSt)	Solution 92%G-8%W ν (cSt)
5.00E+01	8.20E+00	9.50E+00	1.60E+02
4.50E+01	8.40E+00	1.10E+01	1.70E+02
4.00E+01	8.80E+00	1.90E+01	1.70E+02
3.50E+01	9.00E+00	3.80E+01	1.80E+02
3.00E+01	9.50E+00	4.10E+01	1.90E+02
2.00E+01	1.10E+01	5.30E+01	3.00E+02

Figure 39. Viscosity (cSt) versus temperature (°C) for different glycerol solutions.

Summary Data

Summary results for the principal experimental fluids are presented in Table 20, with comparison to the data from *Perry's Chemical Handbook*. The symbols used are "G"-glycerin; "W"-water; "S"-sucrose.

CONCLUSIONS

Both reflective and transmission mode testing have been conducted with both torsional and longitudinal acoustic waves. A four-transducer version works the best. 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. The difference in the time of flight is directly measurable. This difference is due to the retardation caused by the viscous drag on the rod immersed in the fluid. This time difference can be related to the viscosity and density of the fluid, as predicted by Kim and Bau (1989).

Table 20.
Summary of experimental data for the tested solutions, compared to published data

Liquids	Density ($\times 10^3 \text{ kg/m}^3$)	Published data for ν (cSt)	Experimental data for ν (cSt)
Water	0.982	1.005	-
40% S - 60% W	1.17	5.238	3.2
50% S - 50% W	1.2295	12.55	9.9
60% S - 40% W	1.2864	45.46	34.0 - 47.4
Glycerin	1.2611	1181.3	1100
68% G - 32% W	1.1755	11.73	11.0 - 13.24
80% G - 20% W	1.2085	49.57	53.00
92% G - 8% W	1.2404	310.0	300.0 - 374.1

Acoustic tests were successful on the following solutions:

- sucrose-water solutions above 7 cPs
- sugar, kaolin, and water mixtures
- glycerin solutions
- glycerol solutions

While the results obtained manually on the base capability system have more randomness than published data, the trends are good, and they are sufficient to prove the concept of an acoustic method. The automated system described in the next section when implemented completely will provide improved repeatability, precision, and accuracy.

6.0 FLORIDA INTERNATIONAL UNIVERSITY'S AUTOMATED VISCOSITY INSTRUMENTATION SYSTEM

REQUIREMENTS

Principles

Incorporate two independent and innovative approaches to the measurement of viscosity. One approach is to use an acoustic pulse whose propagation along a probe is retarded by the viscous medium in which it is inserted. The other approach is to measure the mechanical interaction of a cylinder oscillating in the viscous medium.

The acoustic approach

Use a four-transducer configuration with two waveguides, one in air and the other in the viscous medium under test. Measure the round trip and differential flight time directly and automatically. Calculate the viscosity automatically.

The oscillating cylinder approach

Measure automatically the shear force and cylinder displacement using electronic sensors and signal conditioners. Calculate the viscosity automatically.

Test and control sites

Place the acoustic and oscillating cylinder sensors at a remote site adjacent to the viscous media under test, along with a remote junction box housing local signal conditioners, DC regulators, and line drivers. Link this by a cable that could be quite long to a larger electronics complex in a control room.

Computer control

Control and process instrumentation data using an IBM compatible computer such as a laptop in the control room, with a commercial instrumentation card. Use another enclosure that will customize the interface between this card and the remote electronics. plus provide DC power supplies, and support diagnostic circuits.

The processing of data is to include automated data acquisition, calculation, data logging, data display, and system monitoring.

Computer software

Use National Instrument's LabView software, running as an application under Windows 95, and possibly other specialized mathematical programs.

PHYSICAL DESCRIPTION

Physical configuration

The system's physical configuration shown before in Figure 6 is repeated in this section for convenience as Figure 40. Items to the left of the cable are placed at the remote site in the room with the tanks and piping. A long shielded cable carries only low-level signals for control, instrumentation, and DC power. Items to the right of the cable are to be placed in the control room. The unit customizes (via the cable) the remote site to the National Instruments instrumentation interface card. All data is acquired through this card. The oscilloscope is used only for setup and monitoring. The custom unit is designed so that the laptop and PCMCIA card can be placed on top of it, with the oscilloscope behind. However, a rack-mount installation is possible. Unregulated plus and minus DC power is sent to the remote unit where local regulators supply precise and noise-free plus and minus voltages to all electronics there and in the probe assembly.

Probe assembly

The assembly includes the transducers, probes, receive preamplifier, and the cylindrical housing. The probes are inserted in the tank holding the viscous medium. In this (generation three) system, an external commercial pulser is used. Generation four's probe assembly will house also the high-power pulser output circuit, driven by a low-level signal from the custom unit.

Motor controller

The motor controller is a commercial AC Inverter (Model 1C93C) from Dayton. The 3-phase 207-v 60 Hz AC power is supplied directly at the remote site to this inverter. It, in turn, controls the motor through the modified AC it sends to the motor. Three-phase power is used because it is more effective and efficient for speed control. This inverter offers sophisticated control and, in turn, communicates by low-powered signals with the control room. A set of low-powered slowly varying digital signals can be and is used to set basic operating modes for the motor. The speed of the motor can be adjusted over a range of about 2 to 30 Hertz.

Figure 40. The FIU/HCET automated viscosity instrumentation system.

Motor

The industrial standard 1/3 HP AC motor is coupled to the oscillating cylinder.

Oscillating cylinder and transducers

The oscillating cylinder is immersed in the viscous medium under test. In the same structure is a Linear Variable Differential Transformer (LVDT), attached to the cylinder that senses the cylinder position. In addition, a Load Cell is interposed between the motor and the cylinder to sense force.

Remote unit

The oscillating cylinder electronics of the remote unit includes the signal conditioners for LVDT and Load Cell outputs, supplying high-level analog signals P (position) and F (force) to the long cable. Acoustic electronics in the remote unit consists of a receiver that drives the pulser's sync input with a pulse when it receives one pulse from the custom unit. Each sync pulse supplied to the pulser causes one transmit pulse to be sent to the transmit transducer. This, in turn, generates

one acoustic wave, which is sent on the long cable back to the custom unit, where high-speed circuits capture one value of raw data at a time, but automatically.

Custom unit acoustic electronics

The custom unit includes:

- DC power supplies of +5, +9V, +16V, -5V, -9V, and -16V for its own and all the remote electronics.
- Simple digital line drivers between the low-current digital signals from the NI instrumentation card and the long cable.
- Sophisticated acoustic electronics for processing the received acoustic pulse signals to give the digital data required which the instrumentation card and computer can at its leisure calculate the viscosity. This includes the Fastcard that is described in last year's report.
- Electronics that processes the force (F) and position (P) signals to give continuous values indicating peak amplitude, period, and time-shift.
- Circuits for waveform and DC voltage monitoring.

The custom unit in the fourth generation version will also contain a high-voltage power supply and low-powered pulser circuits, including the driver to a high-power pulse output circuit in the probe assembly. It might also include a commercially available oscilloscope sub-system. There is sufficient room in the enclosure for these.

FUNCTIONAL DESCRIPTION

See Appendix

Appendix B contains additional details on the system electronics. The details below are included because they help in the understanding of the software.

Digital counter function allocation for the instrumentation card

See what is denoted Figure 41 for the connection of instrumentation card circuits to the custom and remote units. Counter B's three 16-bit counters are used as follows:

- B0 measures directly the time difference between the oscillating cylinder's zero crossings of position and force, counting one-half microsecond pulses.
- B1 measures one half the period of oscillation of the cylinder in counts of one-half microsecond pulses.
- B2 measures the remainder of the time of one of the three quantities needed for viscosity calculation in counts of one microsecond per clock pulse. Hardware counters in the custom unit preceding B2 measure the lower two digits of count of time in units of 10 and 100 nS.

Figure 41. Signal flow for the automated instrument.

Parallel digital function allocation for the instrumentation card

The parallel capability of the instrumentation card is based on Intel's classic 24-bit Peripheral Parallel Interface (PPI) chip, the 8255A. In this system its three digital ports are allocated as follows:

- Port A (i.e., PA) is not now used.
- PB is used in input mode 0 only to pick up quickly one value from one of the three 8-bit fast counters in the custom unit.
- There are two separate parts of PC, whose functions depend on the mode selected for PA and PB. Since mode 0 (simple input without handshaking) is selected for PA and PB, then PC <7..0> is free to be used for independent purposes. Note that these bits can be independently set (logic one, or a high) or reset (logic zero or a low).

PC1 and PC0 are encoded to specify the counter address of the acoustic quantity whose time is to be digitally measured:

Table 21.
How to select the time quantity to be measured

PC1, 0	Q	QUANTITY
00		No measurement of time is performed
01	Q(1)	Differential flight time Δt
10	Q(2)	Round-trip flight time T
11	Q(3)	Wave-train period

This is the address of one of the three 8-bit-high-speed counters in the custom unit, each of which contains two digits of one count of time. Hence, to select the time quantity to be measured, send the appropriate byte out to port PC.

The function of PC2 is to control the acquisition of one time measurement value. It is described in the Appendix. PC5, PC4, and PC3 are yet unspecified.

The upper two bits PC7, PC6 of PC are used to generate individually the two software inverted control signals going to the motor controller to individually control the two control terminals of the motor controller.

ACOUSTIC DATA ACQUISITION, REDUCTION, ANALYSIS, LOGGING, AND DISPLAY

Data acquisition

Acoustic data acquisition is a joint software and hardware process. The hardware collects raw time counts with high precision. The precision is such that three bytes are needed to portray one measured time value.

Software selects the three acoustic quantities in turn. Let us begin with Q(1). Software then: a) signals the hardware to trigger one pulse train, b) wait a while (TIME DELAY) for counts to accumulate, and c) read the three bytes from the counters. These three bytes are stored in main memory in a temporary one-dimensioned array.

This process is repeated for the other two quantities, Q(2), Q(3); as detailed below.

Data reduction

Each of these three bytes of one quantity is converted into a 32-bit-integer-type measurement quantity. From these three 32-bit numbers (defined as one scan), one double-precision floating-point value of viscosity is calculated. This single calculated value is stored in another temporary main memory one-dimensioned array called VISC of length IMAX.

Then the process is repeated as fast as possible IMAX times, to give IMAX scans of the computed values of viscosity and fill the array VISC.

Data analysis

One set of the statistics of viscosity (mean, standard deviation, minimum, and maximum) are calculated from the entire array of values in VISC. These values in one set are converted to ASCII text and stored in main memory in the one-dimensioned string array REC. Date and time stamp and measured values of threshold voltage are also stored in REC. In the next generation system, temperature and radiation level would also be added.

Data logging

REC is appended to a hard disk file as one record.

The entire process above is repeated at scheduled points in time. This requires an additional timed delay.

Summary of processes

While the final need mentioned above is for a process that results in systematic data logging, there are three other processes required for setup, test, etc. The four processes with their features are summarized in the table below. The adjust process is used when the system is first powered up, check power supply voltages, and to adjust the delay times and threshold voltages while monitoring waveforms on the oscilloscope. The test process is used to check for the production of raw data, thus verifying the low-level hardware processes. The single-step process checks also for the proper functioning of the software, or to just obtain one value of calculated viscosity. The full process includes all functions.

Table 22.
The four processes of the acoustic virtual instrument

FEATURE	ADJUST	TEST	SINGLE-STEP	FULL
L (Case index)	1	2	3	4
Trigger mode	Repetitive	Single	Single	Repetitive
Raw data acquisition	No	Yes	Yes	Yes
Raw data display	No	Yes	Yes	No
Data reduction	No	No	Yes	Yes
Data analysis	No	No	No	Yes
Data logging	No	No	No	Yes

Algorithms

Algorithms for all four of these processes are expressed in pseudo-code in Appendix C.

Pseudo-code is used below because it is a convenient way to clearly present iterative processes without use of a particular programming language. It is probably the place to begin for those more familiar with computer programming than with LabView. In addition, it presents an alternative discussion to that embedded in the LabView virtual instruments (vis), if there is any question as to what the vis are doing. However, the pseudo-code requires and defines some variables that LabView handles internally and automatically.

TOP LEVELS OF THE LABVIEW SOFTWARE FOR THE VIRTUAL ACOUSTIC INSTRUMENT

Introduction

National Instrument's (NI) LabView v 4.1 was used to write a series of programs which turn the hardware described above into an acoustic viscometer virtual instrument (vi). It implements the algorithms in Appendix C. The programs are over half completed. Only some top-level programs are included below. These are included to show the potential power of the instrument, and as graphic documentation of the algorithms. A corresponding program for an oscillating cylinder has not yet been written.

LabView software principles

Each Virtual Instrument (vi) in LabView is high level self-documenting software with a front panel, signal flow diagram, and associated routines. It is likely that one signal flow diagram will include lower-level "vi"s, down ultimately to a subset from the set of vis available for each of NI's instrumentation cards. A compiler translates this high-level software into run-time code. The Front Panel handles all input and output for the "vi".

Each signal flow diagram shows how its corresponding front panel inputs are processed to yield that front panel's outputs. Note it is NOT properly a control flow-chart. Transfer of control is implicit; there is not a single "token" which is located at only one point and progresses a step at a time through the diagram as do the tokens in the board game Monopoly. As soon as conditions permit, any operation shown can commence, and this might be independent of another operation. In other words, usually operations run in parallel. However, sequential constraints can be imposed, if needed. The virtual instruments below are presented with little comment. The complete documentation can be made available to those with a need to know.

Some front panels and signal flow diagrams

Figure 42. Selecting process options from the top-level panel of the virtual instrument.

The top-level instrument runs continually. When the mouse clicks on the select mode bar in the left panel in Figure 42, the four process options shown on the right appear. When one process is selected, its program will be launched and its panel will appear showing only those inputs (controls) and outputs (indicators) for that process. The Figure 42 panel has only one control, and no indicators. Its diagram counterpart is shown in Figure 43. Only part of the diagram is shown because the top-level instrument includes what would be called in computer science a case statement. Only one of the cases can be and is shown at a time.

Figure 43. Part of the signal flow diagram for the top-level instrument.

Selecting the “Full Instrument” option on the Figure 42 panel causes Figure 44 to appear. This is the operational panel after some initial settings are made.

Selecting the “Adjust” option on Figure 42 causes the Adjust sub-instrument panel of Figure 44 to appear. Adjust is used while DC threshold voltages are adjusted manually using the custom unit’s potentiometers. The Figure 45 panel has two outputs (indicators)—showing the exact current value of the two threshold voltages. This instrument will run until the “return” button is pressed.

Figure 44. Front panel for the Full Instrument sub-sub vi.

Figure 45. The Adjust sub-instrument panel.

Selecting the “Single Step” option on Figure 42 causes the Step sub-instrument panel of Figure 46 to appear. Step is used to obtain and display (output) only one calculated value of viscosity. The diameter of the waveguide and the calibration constant must first be supplied (input) by the operator. Every time the one-test button is pressed, the three time values are read and viscosity is calculated. The Step signal flow diagram is given in Figure 47.

Figure 46. The Step sub-instrument panel.

Figure 47. The Step signal flow diagram.

Selecting the "Test" option on Figure 42 causes the Test sub-instrument panel of Figure 48 to appear. The operator selects which of the three time values is to be displayed. Every time the

“one-test” button is depressed, one time value is acquired and displayed. It then loops waiting for the next time this button is depressed, until the “return” button is depressed.

Figure 48. The Test sub-instrument panel.

Status of software development

A low-level vi still needs to be debugged. It sends one byte out to a single output port. The problem is to disengage the cumbersome overhead that LabView exacts for digital I/O for such a simple task. LabView tries to first initialize (clear) the port every time a byte is to be sent. This prevents single bit twiddling. Other than that, all upper level and digital I/O vis have been developed and tested, as has viscosity calculation.

Analog I/O has been written but not tested for both the acoustic and oscillating cylinder vis.

Data reduction and logging have yet to be developed for both the acoustic and oscillating cylinder vis.

7.0 RECOMMENDATIONS FOR FUTURE WORK

IF THE ACOUSTIC PROJECT IS CONTINUED

Acoustic transducer/rod/waveguide

Investigate making our own transducers. The transducer is just a coil. Our Panametrics coils were intended merely for proof of concept and training. They are encapsulated in a plastic cylinder that doubles its diameter. It also places a BNC connector off the side, not the end. This doubles again the effective diameter, so the resulting housing must be much larger and bulkier than necessary. In addition, their coils are not shielded. Since we wish to place two coils side-by-side, shielding would be desirable.

A stable magnetic transducer/rod is needed which generates only torsional waves. This will entail a visit to Panametrics with all our rods, transducers, and pulsers, to have them make them work more reliably together. Possibly, different rods and waveguides need to be investigated. Coating the waveguide with a non-wetting material might improve the sensitivity of the waveguide and eliminate some effects like adherence over time of elements in the fluid to the surface of the waveguide. Research teams who had published results using circular waveguides have since abandoned the use of circular cross-sections.

Acoustic probe assembly

The receive transducer preamplifiers are presently mounted on a small board hung between the transmit and receiving transducers. For robustness, protection against corrosion, to simplify the cable layout, and to allow easier access for maintenance the board should be moved to a disc at the rear (top) of the assembly. See Figure 5. This disc would also include the I/O connectors and a high-voltage pulse driver (to remove the need for the Panametrics Pulser/Receiver).

A temperature sensor for measurement of temperature close to the insertion rod should be designed.

Probe housing should be designed, built, and tested. Both acoustic and environmental tests should be performed. If the probe is to be used in caustic or high-radiation environments, the design and test should reflect this with suitable additional sensors. The housing should be liquid-proof and provide both acoustic isolation between the rods and from the coils to the support structure. If additional sensors are added, the support electronics will probably require preamplifiers/signal conditioners in the probe assembly or in the remote unit box.

Acoustic electronics/software

Once there are reliable and high-amplitude waveforms from both receive transducers, the few remaining timing circuits and switch settings in the control unit which require both receive signals can be tested.

The LabView initialization, system test, and data acquisition software needs to have one bug corrected.

The data analysis and data logging software needs to be developed.

Then the LabView software needs to be developed using a GPIB interface card and bus to transfer oscilloscope waveforms to monitor and document them (not measure) into the computer report files.

The instrument needs to be field tested, and modified if problems are found.

IF THE OSCILLATING CYLINDER PROJECT IS CONTINUED

Oscillating cylinder structure

The size of the structure needs to be scaled down to reduce the mass. Leaks in the tank need to be repaired.

The nature of the noise and harmonics in the force waveform needs to be investigated. This is probably due to the friction and non-sinusoidal nature of the drive linkage.

Electronics/software

The transmission mode for motor controller pulse noise needs to be identified and corrections implemented.

LabView software needs to be developed for data control, acquisition, ensemble averaging, calculation (using Bessel functions), data logging, and waveform data transfer using the GPIB oscilloscope link.

IF EITHER PROJECT IS CONTINUED, ADDITIONAL WORK IS WARRANTED

Sensors

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

Remote unit

The prototype board inside the remote unit box that mounts the electronics is fragile and difficult to maintain. It should be redone as a printed circuit board along with additional circuits added. The printed circuit layout for this board has already been completed, but will have to be augmented if additional sensors are required.

Custom unit

The two printed circuit boards in the custom unit have suffered much revision as the design objectives were clarified. If they were combined, much connecting cable would not be necessary. The component count could be less, noise rejection could be improved, and potentiometers and

switches could be mounted on it. Most of the smaller power-supply components now mounted separately could be placed there as well. The net result of these improvements would be a more robust and portable system for field tests.

The viscous media solutions

More accurate measurements require a temperature-controlled bath.

The time taken for preparing the solutions is now excessive and a better mixer is needed. An electronic mixer was used for better homogenization of the sucrose or clay, but due to the speed of mixing, air bubbles were added.

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APPENDIX A

VISCOSITY PRINCIPLES

VISCOSITY PRINCIPLES

Definition of variables

The measurement of the viscosity of liquids first requires the definition of variables. All fluids possess a definite resistance to change of form, and many solids show a gradual yielding to forces to change their form. This property, an internal friction, is called viscosity. The units of absolute (dynamic) viscosity are dyne-seconds per cm^2 or poises. If the tangential force per unit area τ , exerted by a layer of fluid upon one adjacent layer is one dyne for a tangential velocity (shear rate) γ of unity, the dynamic viscosity η is one poise. A hundredth of a poise, or centipoise (cP), is commonly used because it avoids fractional values. The viscosity of water is around 1 cP.

Isaac Newton was the first to express the basic law of viscometry. He described the flow behavior of an ideal liquid by the means of dynamic viscosity η and shear rate γ :

$$\text{Shear stress} = (\text{viscosity}) * (\text{shear rate}) \qquad \tau = \eta * \gamma \qquad \text{or} \qquad \eta = \frac{\tau}{\gamma}$$

Another unit of viscosity is Pascal-seconds. One milli Pascal-second is one cP.

Another common type of viscosity is kinematic. Kinematic viscosity ν and dynamic viscosity η of a fluid are linked by the density ρ of the liquid:

$$\nu = \frac{\eta}{\rho} \qquad [\text{mm}^2/\text{s}]$$

The unit of measurement used for kinematic viscosity is centi Stokes or Stokes:

One $[\text{mm}^2/\text{s}]$ is one [cSt].

Magnetostriction

The term magnetostriction is defined as the change in the dimension of a ferromagnetic material when it is placed in a magnetic field. Magnetostriction is available in the ferromagnetic materials such as nickel, iron, cobalt, Remendur 27 (48% Co, 3%V, Fe), and Hiperco50 (49% Co, 2% V, Fe).

Magnetostriction effects are classified as follows:

- **Widen Effect.** In the Widen type magnetostrictive delay-line, the introduction of a direct current through the transmitting coil develops a circumferential field around the ferromagnetic wire that goes through the coil. The introduction of a current pulse into the transmitting coil causes a changing axial field that twists the wire. This effectively starts a shear stress pulse, which will be detected later by the receiving coil, by the virtue of the Inverse Widen Effect.
- **Joule Effect (joule and Widen effects—tzannes).** In 1966, Tzannes conducted a study that developed a new understanding of the Widen effect and its relationship to the basic Joule effect. His study included theoretical development and experimental verification of the phenomena of simultaneously producing two different stress pulses in magnetostrictive

materials. The Joule effect, often called longitudinal magnetostriction, was studied under the condition of dynamic excitation.

If a changing current is introduced into the transmitting coil—consequently the ferromagnetic wire located in the coil will cause the material to change its length. This abrupt change in the length of the ferromagnetic wire generates a stress wave that propagated down the wire and into the receiving coil. This stress wave simultaneously travels toward both ends of the wire at the speed of sound within the material. The stress pulse will be extinguished when it reaches the damping pad on the sending end. When the stress pulse reaches the receiving coil, it generates a changing flux in the axial direction because of the Inverse Joule effect or Villari Effect. The changing flux links the turns of the receiving coil and generates an output voltage because of Faraday's law.

- **Wertheim Effect.** When a wire is placed in a longitudinal magnetic field and is twisted, there will be a transient voltage difference between the ends of the wire.

Magnetostrictive delay lines—(From the theory of magnetostrictive delay lines—by Roscoe Williams)

Magnetostrictive delay lines are passive networks that can transiently store a number of dc or ac pulses. This can be a simple structure of two coils and a magnetostrictive rod. The basis operation of the line is dependent upon three principles:

- The magnetostrictive effect (Joule Effect)
- The propagation of sonic energy in an elastic medium
- The Villari effect.

The following are some of the properties characteristic of delay lines:

- The maximum pulse repetition frequency is independent of the total delay.
- The insertion loss varies between 40 and 60 dB.
- The end-to-end delay time is a function of the length of the line.

The basic assumption is that the variables concerned in magnetostriction, inverse magnetostriction, elasticity, and magnetism are linearly dependent. This requires the presence of biasing magnets at both the transmitting and receiving coils to insure that the operating points lie in the linear regions of the static characteristics of strain versus magnetic intensity. Small signal (linear) analysis will then apply, since the input magnetic field is assumed small in comparison to the saturation value of the magnetic field.

Newtonian and Non-Newtonian fluids – concept definition

Most common fluids such as water, air, and gasoline are Newtonian under normal conditions: If one considers the deformation of two different Newtonian fluids, say glycerin and water, one recognizes that they will deform at different rates under the action of the same applied shear

stress. Glycerin exhibits a much larger resistance to deformation than water, so we say it is much more viscous. If a fluid is Newtonian, then it will follow Newton's law of viscosity:

$$\tau = \mu \frac{du}{dy}$$

Dimensionally: shear stress in the x-y direction = (dynamic viscosity) * (rate of deformation). Thus, a fluid element when subjected to shear stress experiences a rate of deformation given by

$\frac{du}{dy}$. Fluids in which shear stress is directly proportional to rate of deformation are Newtonian fluids. The term non-Newtonian is used to classify all fluids in which shear stress is not proportional to shear rate. Most non-Newtonian fluids fall in the class of pseudoplastic (or shear thinning) fluids. Examples include polymer solutions, colloidal suspensions, and paper pulp in water. If the apparent viscosity increases with increasing deformation rate, the fluid is termed dilatant (or shear thickening). Suspensions of starch and of sand are examples of dilatant fluids.

The *Daniel Costel et al.* Paper

In the article "Ultrasonic viscosity measurement of molten liquid," Daniel Costel et al. describe a sensor able to take viscosity measurements in the 7 to 500 cP range with two different calibration liquids. A versatile system has been developed in which either torsional or extensional waves can be excited and detected in thin rods made of magnetostrictive materials. Under the influence of a magnetic field, the magnetostrictive material will deform. The deformation depends on the polarization of the magnetic domains within the material and the alignment of the external magnetic field. When a current passes through a magnetostrictive rod, the domains are aligned circumferentially within the rod. A twist in the rod is produced if the rod is then subjected to an external axial magnetic field. If the external field is transient, then the twist propagates as a torsional wave down the length of the rod (Wiedemann effect). The axial magnetic field is produced by passing current through a coil that is wrapped around the wire (transducer). The detection of torsional waves is accomplished via the inverse - Wiedemann effect, in which the torsional wave produces a current in the wire. The magnetostrictive rod can be attached by either solder or glue to another rod made of a different material, such as stainless steel. Waveguides of circular cross-section are used to determine viscosity. Waveguides of noncircular cross-section are used to determine liquid density. In two-phase fluids, such as particulate suspensions or liquid-vapor mixtures, density can be measured by using elliptical or rectangular cross-section. Both types of waveguides can be used to determine temperature and liquid level. For a waveguide with a circular cross-section immersed in a viscous fluid, it has been shown that both the attenuation and the velocity of the torsional waves depend on the ratio of the density to the viscosity. When the surface of the waveguide is in contact with a viscous fluid, shear stresses will be produced at the surface which oppose the motion in the solid rod. These stresses or viscous drag will cause the torsional wave to attenuate; the phase velocity will decrease as well. The decay in amplitude could be represented as a function of dimensionless numbers:

$$A_2 / A_1 = f \left(\frac{\lambda}{L}, \frac{a}{L}, \frac{c}{Lf}, \alpha \frac{T}{L}, \beta L, \frac{\eta}{LLf\rho} \right)$$

where A_2 and A_1 are the amplitudes of the torsional wave at two different points, c is the speed of the wave, T is the temperature, a is the radius and L is the length of the rod, α is the coefficient of thermal expansion for the material immersed in the fluid, β is the attenuation in nepers or dB per meter, f is the frequency, λ is the wavelength, ν and ρ are the kinematic viscosity and density of the fluid, c is the torsional wave speed in the rod and refers to the lowest mode of torsional wave speed. The frequency of the torsional wave pulses is under 100 KHz. It has been shown that the speed of torsional waves in the material is a function of temperature. Secondly, the rod will elongate along with the increase of the temperature, so the torsional pulse will have a longer distance to travel. The viscosity was related to the time difference between air and liquid.

APPENDIX B

FUNCTIONAL DESCRIPTION OF THE CURRENT AUTOMATED INSTRUMENTATION SYSTEM

FUNCTIONAL DESCRIPTION OF THE CURRENT AUTOMATED INSTRUMENTATION SYSTEM

Receiver electronics

Signal flow is shown on by a diagram in Figure 1. Receive preamplifiers in the probe assembly boost the receive transducer's 100 KHz signals and drive a long line with a 50 ohm source resistance. The higher amplitudes and low impedances minimize noise pickup. The frequency response of the preamplifiers cut off below 30 KHz to reject 60 Hz hum. These signals wire directly through the remote unit without interception.

Figure 1. Signal Flow for the FIU Viscometer.

Remote unit wiring for the motor controller

Seven control terminals are provided on the motor controller (AC inverter) by the designer to allow for remote control. Five terminals are for digital and two are for analog. Since there is never a need to reverse the motor direction of rotation and the RPM of the motor is controlled only by the analog signal sent to it, only two of the digital signal terminals are used. The signals these two digital terminals require originate on the instrumentation card, are sent on the long cable to high-voltage open-collector drivers in the remote unit, and then to the two input control terminals on the motor controller. The controller has at each of these two input control terminals

an internal pull-up resistor to + 13 V DC. One driver in the remote unit has the function of pulling one of these terminals low (as if a contact closure occurred to the common pin CM) to make the function associated with that terminal to occur. For example, to make the motor run in the forward direction, keep the FWD terminal low (contact closure). The motor will continue to run as long as this low condition is supplied. When the contact is opened (signal allowed to be pulled high by the internal resistor) at FWD, the AC power will be removed from the motor and the motor will coast to a stop. The default condition is no action during power on and off, or instrumentation card poor programming, or protection against cable noise. However, to achieve this default of "no action" an inverter needs to be inserted the custom unit. This means that a logic "one" or high must be issued by the software/instrumentation card for a pull-down (contact closure, logic "zero") to appear at the appropriate inverter and subsequent control terminal.

One of the two analog terminals is an input receiving from the instrumentation card DC (0-10 V) so that this instrumentation card can control the RPM of the motor. The second is an output analog value that the controller issues which is indicative of actual motor RPM. Unfortunately, this is a pulse whose average value is what must be obtained by calculation in LabView. Such a process is complex, and the result will be a value of less accuracy than the period measured by Gate B1. Hence, while the capability is provided to monitor period by analog voltage, this is not expected to be the method of choice.

Remote unit dc power

The receive preamplifiers require regulated DC of plus and minus 5 volts. Therefore five-volt regulators are located in the remote unit and driven by unregulated plus and minus 9-volt wires in the long cable. Any noise or hum picked up on these 9-volt wires is removed by the regulators.

A + 16 volt unregulated DC voltage is sent down the long cable to drive a + 10-volt regulator in the remote unit and send it to the motor controller. This powers the motor controller's analog amplifiers. Also plus and minus 16 volts are provided to the remote unit to power the load cell signal conditioning module placed inside the remote unit. The LVDT signal conditioner comes with its own power supply, and must be supplied with 120 V ac 60 Hz.

Custom unit acoustic electronics

There are three quantities whose values are used in calculation of viscosity by acoustic means:

- The quantity $Q(2)$, the flight time T in air for an acoustic pulse train to traverse the probe and return,
- The quantity $Q(1)$, the differential flight time Δt between flight time T in air and the flight time in the acoustic medium, and
- The quantity $Q(3)$, the period of the pulse train—approximately 100 KHz.

Each of these is measured in turn by an accurate 100 MHz clock and decade counter string. The counter string begins with the first two (fastest) decade counters in the custom unit. The rest of the count is read by the 16-bit counter B2 in the instrumentation card. The quantity to be measured is selected remotely by the instrumentation card and computer software. The software reads the four bits from each of the two fast counters using 8-bit digital port B on the card.

Custom unit electronics for the oscillating cylinder

The high-level conditioned analog signals of position and force are sent back to the control unit as inputs to peak and zero crossing detectors, plus an AND which generates a gate whose width is indicative of phase shift time between the two zero crossings.

Digital counter function allocation for the instrumentation card

See what is denoted Figure 1 for the connection of instrumentation card circuits to the custom and remote units.

Counter B's three 16-bit counters are used as follows:

B0 measures directly the time difference between the oscillating cylinder's zero crossings of position and force, counting one-half microsecond pulses.

B1 measures one half the period of oscillation of the cylinder in counts of one-half microsecond pulses.

B2 measures the remainder of the time of one of the three quantities needed for viscosity calculation in counts of one microsecond per clock pulse. Hardware counters in the custom unit preceding B2 measure the first two digits of count of time in units of 10 and 100 nS.

Parallel digital function allocation for the instrumentation card.

The parallel capability of the instrumentation card is based on Intel's classic 24 bit Peripheral Parallel Interface (PPI) chip, the 8255A. In this system its three digital ports are allocated as follows:

- Port A (i.e., PA) is not now used
- PB is used in input mode 0 only to pick up quickly one value from one of the three 8-bit fast counters in the custom unit
- There are two separate parts of PC, whose functions depend on the mode-selected for PA and PB. Since mode 0 (simple input without handshaking) is selected for PA and PB, then PC <7.0> is free to be used for independent purposes. Note that these bits can be independently set (logic one, or a high) or reset (logic zero or a low).

PC1 and PC0 are encoded to specify the counter address of the acoustic quantity whose time is to be digitally measured:

PC1, 0	Q	QUANTITY
00		No measurement of time is performed
01	Q(1)	Differential flight time Δt
10	Q(2)	Round-trip flight time T
11	Q(3)	Wave-train period

This is the address of one of the three 8-bit counters that contains the count of this time. Hence, to select the time quantity to be measured, send the appropriate byte out to port PC.

The function of PC2 is to control the acquisition of one time measurement value. It is described below. PC5, PC4, and PC3 are yet unspecified.

The upper two bits PC7, PC6 of PC are used to generate individually the two software inverted control signals going to the motor controller to individually control the two control terminals of the motor controller.

Consider now why we need software to invert these signals, (i.e., why inverters were required in the custom unit), so that a software inversion is necessary to compensate for the required inverters. **THIS IS VERY IMPORTANT!** The Oki version of this 8255 differs in two important respects from the Intel version. See pages D-9 and D-10 of the PC+ manual.

A computer normally generates a RESET signal to all its I/O circuits during power-up or when the front panel Reset push-button is depressed. This includes the National Instruments Instrumentation card. On this card's Oki 8255 such a reset causes all output latches to be cleared to zero and the mode set automatically to mode zero. This means all 24 pins of the three ports A, B, and C will have on them a "low" voltage, close to zero volts. These zero values can be verified with a DC voltmeter. However, we do not want any of the motor controller functions to be affected, so a zero (low) out of the 8255 must result in highs (contacts open) at the controller input digital terminals. The inverters in the custom unit perform this inversion.

On page D-10 note it says "The output registers for ports A and C are cleared to zero each time data is written in the command register and the mode is changed." This means zeros are placed on the cable going to the custom unit. We do not want the motor controller's input digital terminal values to go to zero when this programming operation happens, so this is another occasion when we need the inverters in the custom unit.

PCi out of NI	Interpretation of the Signal out of the NI card	Control Unit Output	Motr. Contr. Terminal	Motor operation when this motor control terminal is connected to (i.e., has contact closure to) CM.
PC7	RST/BX*	RST/BX-C	RST/BX	External reset signal and/or coast-to-stop command
PC6	FWD*	FWD-C	FWD	Forward operation command

* The asterisk after the letters of the name denotes an inverted value.

Input allocation for Analog to Digital Conversion (ADC) on the instrumentation card

The eight Analog input Channels (ACH <7..0>) are assigned as follows:

- ACHj **APPLICATION**
- ACH7 Motor frequency, 0-10v

- ACH6 Spare—(radiation level in generation four)
- ACH5 Spare—(temperature in generation four)
- ACH4 Comparitor 1 threshold
- ACH3 Peak amplitude of force
- ACH2 Comparitor 2 threshold
- ACH1 Peak amplitude of position
- ACH0 Reserved as a guard channel to go along with ACH1

**Output allocation for Digital
to Analog Conversion (DAC) on the instrumentation card**

Only one (DAC1 OUT) DAC output is currently allocated, to route to the motor controller to control motor RPM in analog fashion.

APPENDIX C

ALGORITHMS FOR INSTRUMENTATION SYSTEM SOFTWARE

ALGORITHMS FOR INSTRUMENTATION SYSTEM SOFTWARE

Definition of Variables

L	Index of the Case option, selecting one of the four processes listed in the table above.
TMP	One-dimensioned temporary byte array with index J. TMP stores one set of raw binary counter data.
J	Index number of one of three bytes acquired for one quantity. $0 < J < 4$
Q	One-dimensioned temporary single-precision floating-point array with index K. It stores the three decimal values needed for one calculation of viscosity.
K	Index which defines which of the three quantities Q(K) is being referred to.
Q(1)	Differential flight measurement. It is denoted d in LabView.
Q(2)	Round-trip flight time. It is denoted T in LabView.
Q(3)	The period of the individual cycles in the acoustic wave-train. It is denoted p in LabView.
v	One calculated double-precision floating-point value of viscosity.
k	An experimental constant, based on the type of material such as aluminum used in the waveguide.
a	The cross-sectional area of the waveguide.
VISC	One-dimensioned double-precision floating-point array with index I and length IMAX. Stores the calculated values of viscosity v.
IMAX	The total number of scans acquired before one set of statistics is calculated to give one record of logged measurement.
I	The index number for a particular scan. $0 < I < IMAX + 1$
RECD	One-dimensioned ASCII string array of eight fields. One record of data to be logged.
STOP	Push-button that, when depressed, stops the process. Is normally off (FALSE), and reverts to TRUE when depressed.
thr1	The DC threshold voltage of comparitor 1
thr2	The DC threshold voltage of comparitor 2
dly1	The value in milliseconds that is somewhat greater than the sum of delay on and gate width. If we delay this long, the time raw data will be in the counters and counter.
dly2	The rate at which one record of final data is logged, in seconds.

Procedure main;

Begin

Call subroutine initialize

Switch (L)

case 1: /* Generates an acoustic waveform repetitively for adjustment of threshold. */

Call subroutine adjust

case 2: /* Acquires raw data and decimal displays one time measurement in microseconds. */

Call subroutine test

case 3: /* Acquires and displays in decimal one value of viscosity. */

Call subroutine step

case 4: /* Automatically acquires, reduces, calculates, and logs viscosity. The full instrument. */

Call subroutine full

default: report error

Return

End of main

Subroutine adjust

Begin

Set up a front panel display of threshold voltages thr1, thr2

Call subroutine getthresholds (thr1, thr2)

Define dly1 as one millisecond.

WHILE STOP = False then trigger continuously while the waveforms are monitored and threshold is

manually adjusted by the operator. Do not acquire, save, reduce, analyze, log.

Call subroutine wave

End of while

Return

End of subroutine adjust

Subroutine test

Begin

Input an index for the desired quantity for which raw data is to be displayed.

Call subroutine wave

Input the one packed decimal byte from the 74374 register through the 8255 Port B and store in TMP.

Display the decimal value of this byte on the front panel as the least two significant Figures.

Input the two packed-decimal bytes from counter B2 in the instrumentation card and store in TMP.

Display the decimal value of these two bytes on the front panel as the most significant four Figures.

Return

End of subroutine test

Subroutine step

Begin

Call subroutine raw3

Calculate viscosity

Output viscosity to front panel

Return

End of subroutine step

Subroutine full

Begin

Call subroutine parameters

Call subroutine getthresholds (thr1, thr2)

Get date

recd(1) = date

Get time

recd(2) = time

sum = 0 = max = var

min = $2 \times (2^{30} - 1)$

For I = 1, IMAX

Call raw3

Call subroutine calcvisc

```

sum = sum + visc(I)
If visc(I) > max then max = visc(I)
If visc(I) < min then min = visc (I)
    Next I
    avg = sum/imax
    recd(3) = ASCII(avg)
    Calculate standard deviation stddev
    recd(4) = ASCII(stddev)
    recd(5) = ASCII(max)
    recd(6) = ASCII(min)
    Call subroutine logrcd
Return
End of subroutine full

```

```

Subroutine raw3
Begin
For K = 1,3—which of the three quantities
    Output the value K to PC<1,0>
    Call subroutine rawdat(vraw)
    Q(K) = vraw
Next K
Return
End of subroutine raw3

```

```

Subroutine rawdat (vraw)
Begin
    Call test
    Convert to one decimal 32-bit number vraw .
Return
End of Subroutine rawdat

```

```

Subroutine wave

```

Begin

Call subroutine trigger

Call subroutine delay (dly)

Call subroutine trgrst

Return

End of subroutine wave

Subroutine trigger

Begin

Reset the count in DAQCard-1200 counter B2 to all ones (max count), since it counts down.

Output a one to PC2. (PC2) = 1. This causes the following to occur, in order:

The high-speed counter's clear* signal will be deactivated, so that a count can build up. However, the count will not yet begin.

At the remote pulser, the sync signal will rise to a one, which will cause one high-voltage transmit pulse to be sent to the transmit transducers. These transducers will generate an acoustic wavetrain.

Return

End of subroutine trigger

Subroutine dly (dely)

Begin

Delay by an amount of time in microseconds given by dely

This subroutine is called by two different routines. The first calls to delay about 600 uS between triggering and raw time data acquisition. The other is to delay about 60 seconds between successive data loggings.

In the first application, the acoustic wavetrain will propagate down the rod/waveguide, with reflections. The reflections will be picked up at a later time by the receive transducers as a series of wavetrains.

In the fastboard the gate NAND will need to wait until the first of the two receive wavetrains is detected. This wait needs to be slightly more than the time DELAY-ON which is manually set by the operator by manual observation. The instant the first wavetrain is detected the counter gate will "open". The gate will stay "open" until the second wavetrain begins. At this point in time the gate will "close". If time data is to be acquired, the value is the time the gate is open (i.e., the gate pulse width).

The value dely should be specified manually on the front panel at a value somewhat more than the sum of delay-on and gate width.

Subroutine trgrst

Begin

During the time the counter gate is open the series of counters will count the 10 nS pulses from the 100 MHz crystal oscillator. The two low-order counter digits change the fastest and are counted by the fast counters on the Custom1 board. The slower output from these two goes to DAQCard-1200 counter B2.

When the gate closes all the counters will hold their combined count of 10 nS pulses. In other words, the time in nanoseconds that the gate is open is ten times the count in the counters.

Output a logical zero to PC2. This causes the following to occur, in order:

The 4-bit counts in each of the two fast Custom1 counters will be loaded in parallel into the 74F374 register, where they will be retained until a new value is loaded in.

After the 74F374 register is loaded a clear* signal will go to the fast counters, freezing their count at zero.

Counter B2 will retain its count until retriggering causes reset.

Therefore the count values are now ready to be read, if desired.

Return

End of subroutine trgrst

Subroutine calcvisc

Begin

Calculate viscosity

Store in array visc

Return

End of subroutine calcvisc

Subroutine initialize

Begin

Hardware and LabView Initialize:

During power-up LabView clears all DAQCard-1200 counters and registers automatically. The initial conditions for the 8255 are: Mode 0 for Ports A, B. Ports A, B, and C are initialized to high-impedance inputs, but supplying a zero output voltage on its port pins due to a default values sent to the output registers.

LabView configures and initializes the ADC channels and DAC channel 0.

Then specify the following configuration to the 8255 by means of a byte sent to Port D (Port 3):

Port A (i.e., port 0) is ignored, but defaults to input.

Port B (port 1) set to input

Port C (port 2) set to output

Output to Port C the following initial contents:

Bit(s)	Value	Significance
0,1	0,0	No measurement of time is being performed
2	0	Initial state of the trigger pulse is zero, fast counter is cleared. (PC2) = 0
3,4,5	0,0,0	Unused bits, default is zero
6	0	No action on the motor
7	0	No reset of the motor

Set up a front-panel push-button STEP that steps through the succeeding sub-routines.

Return

End of subroutine initialize

Subroutine parameters

Begin

Define by input from the operator the following initial parameters as global variables:

- a) IMAX, the number of scans
- b) How often the logged data is obtained, in seconds
- c) The path and file name it is stored in.

Return

End of subroutine parameters

Subroutine logrcd

Begin

Save string rec by appending to filename

Return

End of subroutine logrcd

Subroutine getthresholds is not yet implemented