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INJURY BIOMECHANICS RESEARCH
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Sonomicrometry in Impact Biomechanics

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ABSTRACT

Sonomicrometry is the science of measuring distances and changes in distances through the sending and receiving of ultrasonic energy between piezoelectric crystals. The robustness of sonomicrometry as pertaining to high frequency response is investigated. The principles behind the physics of sonomicrometry are discussed and the advantages and weaknesses of this measuring system are overviewed. By comparing a known displacement input to the measured output of a sonomicrometry system, the accuracy and sensitivity of this system to input frequencies and data sampling rates are discussed. Recommendations for current and potential use are offered.

INTRODUCTION

Sonomicrometry is the measurement of distances using sound energy. As applied to biomechanics, sonomicrometry can enable the scientist to accurately measure real-time displacements in the body with minimal surgical intrusion. Within the last ten years, the size of the transducers has significantly decreased and the accuracy of the resulting displacements have substantially increased, allowing detailed analysis of the deformation of soft tissue over a large strain range.

The concept behind sonomicrometry is based upon the use of piezoelectric crystals that oscillate at a predetermined frequency when electrically charged. Conversely, these crystals generate an electric current when oscillated. These oscillations travel at the speed of sound though an aqueous media, from which the distance between two crystals can be calculated by measuring the time taken for an impulsive peak to travel between crystals.

Using the latest sonomicrometry technology, it is possible for these crystals to be simultaneously both transmitters and receivers of sound energy. These *transceivers* make it possible to obtain multiple measurements between all crystals when several are imbedded in the specimen. This ability to directly measure the relative displacements between points of interest in a tissue sample is a clear advantage over strain-gage measurements in which a fair idea of the geometry of the specimen must be known in order to calculate the relative displacements from the supplied data. In addition, most strain gauging techniques require a relatively hard surface on which to apply the

gauge. In contrast, sonomicrometry crystals may be embedded in soft or aqueous media and strain with the local soft tissue.

It is of interest to the biomechanical community to be able to directly measure multiple displacements in a specimen during impact loadings. Because of the small size and minimal intrusive characteristics of the sonomicrometry crystals, a more complete picture of tissue response is now possible, providing local details of tissue behavior.

RESEARCH

Biomechanical research using sonomicrometry has primarily concentrated on measuring physiological heart functions, including myocardial contractility, wall motion, and chamber volume at physiological rates of strain. In a study by Barbier *et al.* (1999), regional myocardial shortening was measured in the mid anterior wall and the basal lateral wall of an anesthetized pig using the sonomicrometry system considered in this study (Sonometrics Corp.). In a study to determine the effects of transient local coronary artery occlusion on regional systolic function, ultrasonic dimensioning transducers were used to derive percent systolic shortening (Brown *et al.*, 1999).

Another innovative use for sonomicrometry involved measurements of mitral valve dynamics (Gorman *et al.*, 1996). In this study, sixteen transducers were mounted around the mitral valve annulus, at the tips and bases of both papillary muscles, at the ventricular apex, across the ventricular epicardial short axis, and on the anterior chest wall in anesthetized sheep, in order to understand the three-dimensional motion of the valve. The unique characteristics and accurate data derived from the sonomicrometry allow the three-dimensional imaging of the valve throughout the cardiac cycle.

The accuracy of sonomicrometry allows the technique to be utilized as a reference method for other strain measuring devices. Urheim *et al.* (2000) measured myocardial strain using Doppler echocardiography as the time integral of regional velocity gradients, comparing the results against sonomicrometry data. Similarly, Gorcsan *et al.* (1997) computed changes in fractional shortening and shortening velocity due to changes in TDI peak systolic velocity using sonomicrometry.

The bulk of the studies performed and documented in the literature use sonomicrometry in biomechanical cases where the loadings are either quasistatic or loaded in the 0.5 to 2 Hz range. In the case of high-rate impact loadings, there appears to be little research using sonomicrometry, though the capabilities of the system appear adequate to perform high rate displacement.

DIGITAL SONOMICROMETER

Conventional, or analog, sonomicrometers have been used to measure small displacements in tissue samples (c.f Moores *et al* (1984)). This technology measures the elapsed time for an impulsive ultrasonic signal to travel between a pair of crystals using an analog capacitive charging circuit. It is the resulting voltage that becomes a measure of distance, and is recorded for later analysis in analog form. These distances can only be measured using dedicated transmitting-receiving pairs, with additional distances requiring additional crystal pairs.

Digital sonomicrometry (c.f. Gorman *et al* (1996)) allows computer acquisition of the ultrasonic signals which allows automated analysis of the sensor time histories. In the system considered in this study (Sonometrics Corp.), any single crystal may act as both a transmitter and receiver, thus allowing more measurements using fewer crystals. The possible number of unique distances measured is a function of the number of crystals, N, and can be calculated:

$$distances = \frac{N!}{2 \cdot (N-2)!}$$

For a redundancy check on data, it is possible to set all crystals to alternatively send and receive signals (transceiver mode), thus having two separate measurements between any two crystals. A crystal is shown in Figure 1.

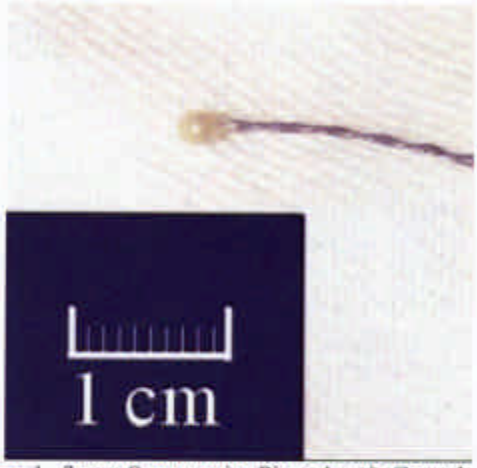

Figure 1. 2-mm Sonometrics Piezoelectric Crystal.

The measuring process begins with a fast rising transmit pulse being sent to the transmitting crystal, causing it to oscillate. The length of this transmitted pulse is user defined and must be set under the considerations of signal strength (depending on the medium being measured) and the distance being measured. The maximum practical distance that can be measured by the sonomicrometry system is 196 mm at a rate of 64 MHz. The smallest distance that can be measured at the 64 MHz rate is 0.024 mm.

Each transceiver is allowed to transmit an energy pulse according to the set cycle time allotted to each transceiver. The total sampling duration is user defined and can range from 28μs to 2044μs, in increments of 16μs. Resultant sample frequencies are shown in Table 1. This frequency must be carefully set as the time needed to transmit a signal across the medium must be long enough so that the signal can actually arrive at the receiving crystal. In addition, more time may be needed to dissipate the acoustic energy before the next transmit cycle is started. The crystals are activated sequentially as shown in

Figure 2. Two and three-dimensional relative position may be calculated using standard triangulation techniques.

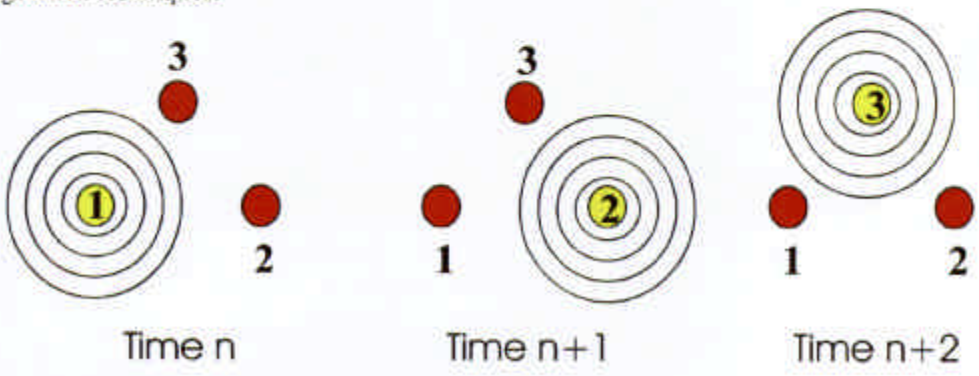

Figure 2. Activation Sequence of Sonomicrometry Crystals with Three Transmitter/Receivers

Each set of crystals must be sampled individually during a portion of the duration allotted for a given sampling rate. So, if four transmitters are used, the time available for sampling each crystal is only one forth time total time available. So, the sample frequency, the number of transmitting crystals and the sound speed in the medium set limits on the distance between crystals. The sound speed in aqueous biological materials averages approximately 1540 m/s in soft tissues, approximately 1480 for water. For an unknown tissue, this value can be obtained from a calibration using crystals a known distance apart. Using the sound speed of 1540 m/s a set of guidelines for maximum distance between crystals may be developed as shown in Figure 3. One crucial issue is the attenuation of the acoustic reflections. These must be substantially attenuated to prevent the sensor from recognizing a reflection as a pulse leading edge. This is influenced by the size of the specimen and the ultrasonic attenuation in the tissue. A practical limit of approximately 50 mm of travel is needed to sufficiently attenuate the pulse in most biological tissues (attenuation 1-2 db/cm). Further, the current practical limit of crystal separation is approximately 30 mm at 11 kHz sampling rate for two transmitters.

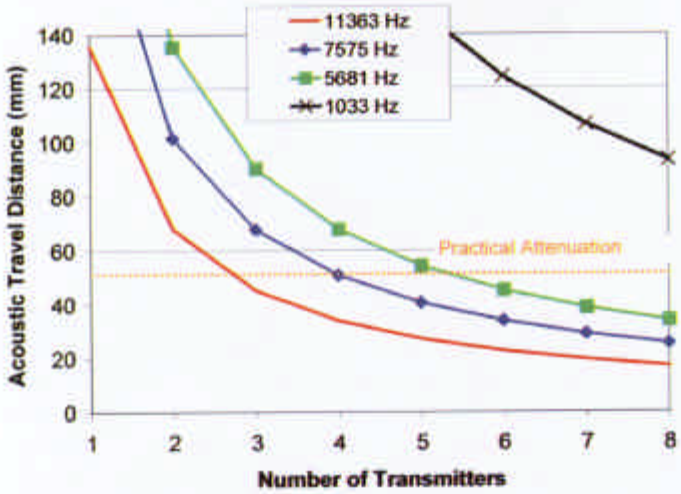

Figure 3. Acoustic Travel at 1540 m/s Sound Speed Against Number of Transmitters for Various Sampling Frequencies

Several parameters may be varied in the system to account for circumstances of the measurement. These may include local surfaces with nonattenuating characteristics (bone) and multiple reflections. These parameters are shown in Table 1. The pulse strength is related to the transmitted pulse duration. The duration ranges from almost to 62.5 ns to approximately 2 ms. Increasing the pulse duration increased the pulse strength at the expense of increasing the duration of the ringing of reflections that must die down to allow the transmission of additional pulses. The inhibit delay varies from 0.5 mm to 202.3 mm, and is the timed distance over which a pulse reception is not considered a true pulse. This prevents the electromagnetic pulse excited in the piezoelectric sensor from being considered to be the signal. In addition, the reception peak sensitivity may be selected to optimize the level at which a received pulse is considered to be a signal.

Table 1. AVAILABLE PARAMETERS FOR SONOMICROMETRY SYSTEM (SONOMETRICS CORP.)

Parameter	Max Value	Min Value
Sample Frequency (Hz)	11363	15.2
Transmit Pulse Duration (ns)	1968.8	62.5
Inhibit Delay (mm)	202.3	0.5
Peak sensitivity	Varies	0

The Sonometrics system has the ability to digitize external analog signals from other instruments, maintaining a synchronized record with the sonomicrometry data. The accompanying data acquisition system can store up to 5000 blocks of data at a rate of 200 Hz. The data is transferred in a packed-binary format at a rate of 12 bits per sample to a computer hard drive.

The following potential sources of error to the system are (c.f. Sonometrics,2000):

The accuracy of the underlying time measurement. A 64 MHz crystal oscillator is currently being used and is not considered a significant source of error.

The addition or subtraction of an offset to the calculated distance. An offset value resulting from known system delays and crystal geometry can be a source of error, but only to the quasistatic absolute distance measurement between two crystals, not to the change in distance (maximum error estimated to be 1.5 mm or less).

Variations in the speed of sound. Depending on the density of the transmitting medium, the speed of sound can be a source of error. Factors including temperature and tissue moisture content will affect the speed of sound though it, thus altering the calculated distance measured. It is important to determine the speed of sound of the medium that is being tested, and entered into the measuring system. There is a potential for higher speed of sound tissues (e.g. bone) to transmit significant signal to the receiver crystal in advance of that through the acqueous medium. In practice, this does not appear to be a significant issue.

The reception of the signal at the receiving crystal. The main source of error in the current Sonometrics system lies in the strength of the received signal. The signal strength consisting of a number of cycles of a sine wave builds over the course of the first several cycles, reaching maximum strength by the third or fourth cycle. The detection circuitry in the receiver has a detection threshold that the receiving signal must pass, filtering out any ambient noise. In the case of a weak signal, the detection circuitry may alternate between the first, second, or third cycle, resulting in a shift in the measured distance based on the cycle time.

CURRENT APPLICATIONS

One of the current applications for high-rate sonomicrometry involves measuring the displacement of the human brain under ballistic impact loads. Along with the human brain model shown in Figure 4 (Ivarsson, 1999), a pneumatic-driven gas gun is used to accelerate a polycarbonate cylinder in order to simulate a non-lethal projectile hitting the head. This brain model is comprised of an aluminum chamber in the approximate cross section of the human brain, filled with a 5% (by volume) mix of ballistic gelatin. The projectile enters the model through access holes where a latex "dura", and either a Nylon 6/6 cranial bone surrogate, or a hydraulic impact cylinder is located.

Figure 4. Brain surrogate model

Figure 5 shows the setup for the direct impact tests utilizing the nylon cranial bone surrogate. Impacts from the projectile contact this "skull", which in turn transmits the energy through the dura to the brain matter.

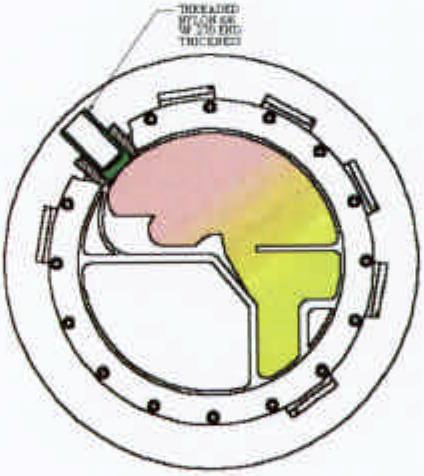

Figure 5. Schematic of brain model showing surrogate cranial bone interface.

Figure 6 shows the test setup using the hydraulic impact cylinder. In this case, the projectile impacts the piston, thus driving the energy through the saline solution, resulting in a uniform pressure wave being applied to the dura.

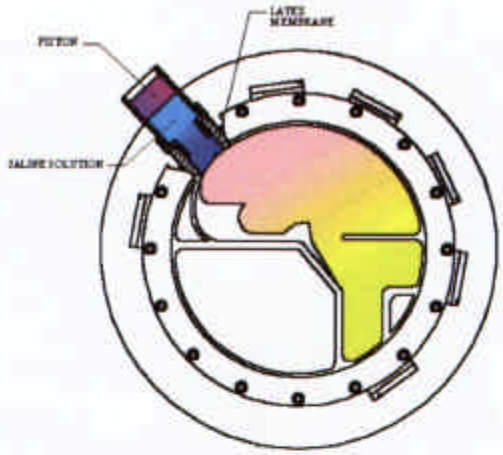

Figure 6. Schematic of brain model showing hydraulic impact cylinder.

The velocities of the projectiles are in the range of 100-150 m/s. The resulting pressure wave is transferred to the brain matter (ballistic gelatin), and the relative displacement of an array of points is obtained from the placement of the sonomicrometry crystals.

An example of this experiment shows the results of two different projectile velocities impacting the nylon cranial bone interface, and the corresponding strain occurring in the brain (ballistic gelatin). For the 120 m/s projectile, the nylon interface did not fracture and the strain in the brain matter is low (< 1%). The higher energy projectile (200 m/s) fractured the nylon interface, but did not penetrate past the "dura". This higher energy projectile resulted in much higher strains in the brain cavity (–8%).

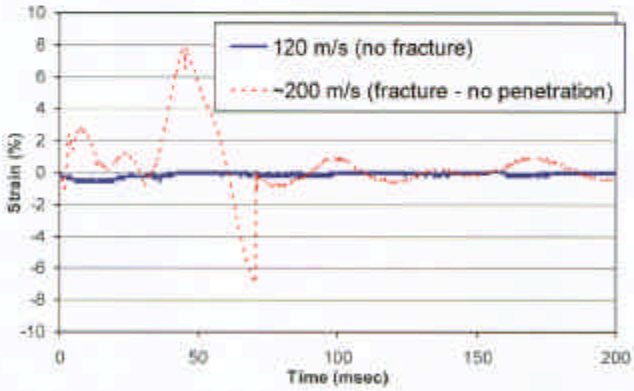

Figure 7. Strain History Trace Resulting From Projectiles (120 m/s And 200 m/s) Impacting The Nylon (Simulated Cranial Bone) Interface.

LIMITATION OF SONOMICROMETRY

To determine the ability of the sonomicrometry system to measure high-rate impacts, a series of tests were performed where a known input is compared to the measured change in dimension. In this experiment, two Sonometrics crystals were mounted a small distance apart, one to a fixed

surface and the other to the end of a linear shaker, and submerged in a tray of water as shown in Figure 8. A sine-wave signal generator causes the crystals to oscillate apart. The resulting displacement data is obtained through the Sonometrics system and compared to the output of a displacement transducer (LVDT) connected to a separate high-speed data acquisition system. These experiments were conducted with a variety of forcing frequencies and a variety of sampling rates from within the Sonometrics data acquisition system.

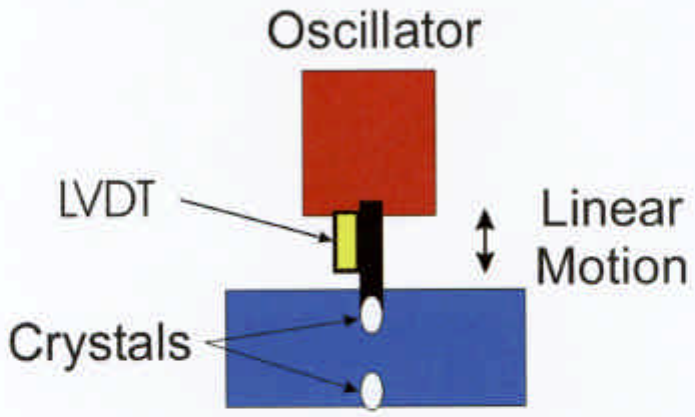

Figure 8. Oscillatory Comparison Test Setup

The first case analyzed involves a 10 Hz input frequency from the shaker, with the Sonometrics system acquiring data at a rate of 498 Hz. As can be seen in Figure 9, the agreement between the LVTD (sampling at 21978 Hz) and the Sonometrics data is excellent at this low rate input and low Sonometrics sampling rate.

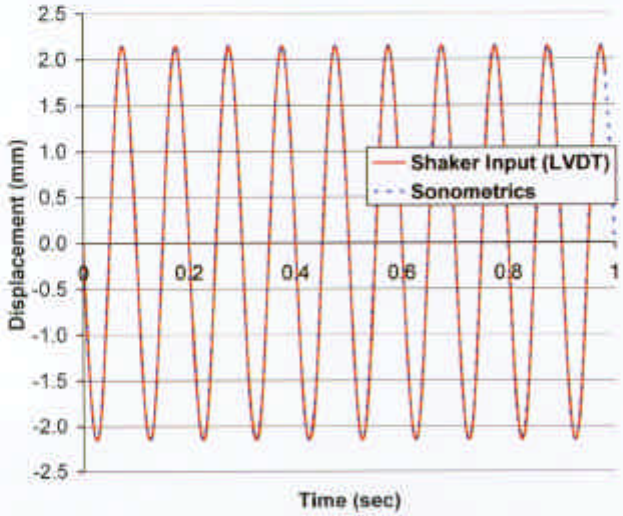

Figure 9. Comparison of displacement traces from the LVDT acquiring at 21978 Hz, and the Sonometrics system acquiring at 498 Hz. Input displacement frequency is 10 Hz.

For the input frequency of 200 Hz, and a Sonometrics sampling rate of 5434 Hz, some deviation between results is seen as shown in Figure 10, especially in the number of dropped data points in the traces.

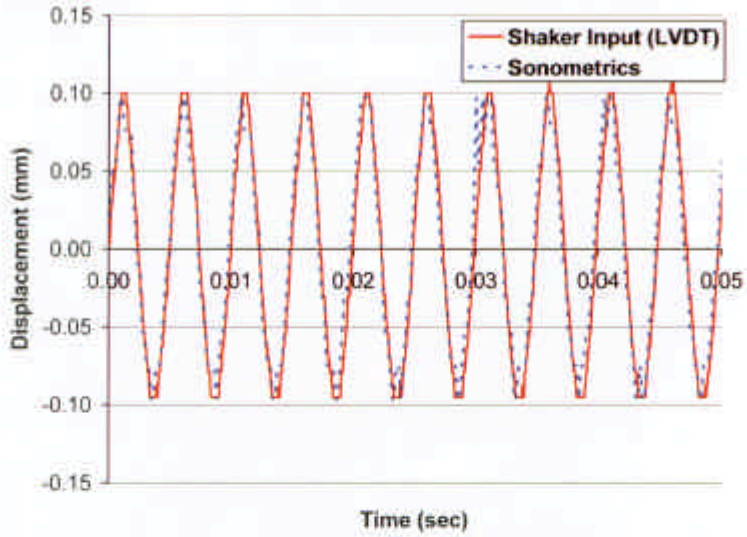

Figure 10. Comparison of displacement traces from the LVDT acquiring at 21978 Hz, and the Sonometrics system acquiring at 5434 Hz. Input displacement frequency is 200 Hz.

With an input frequency of 100Hz and a Sonometrics sampling rate of 11363Hz, significant discrepancies between the input trace and the measured output becomes apparent as seen in . Several phase shifts are seen over the trace; a result of data points missing from the Sonometrics recording.

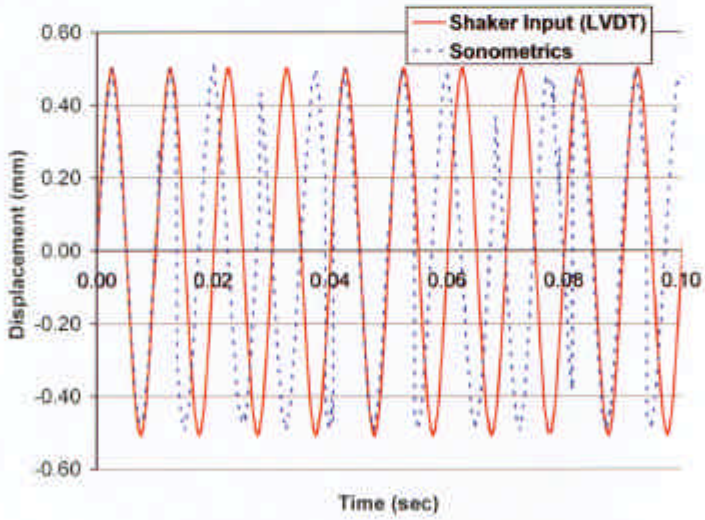

Figure 11. Comparison of displacement traces from the LVDT acquiring at 21978 Hz, and the Sonometrics system acquiring at 11363 Hz. Input displacement frequency is 100 Hz.

This dropping of data points is exacerbated by the increase in the input frequency to the system. In Figure 12, the input frequency is doubled to 200 Hz while maintaining the Sonometrics sampling

rate of 11363 Hz. In addition to the apparent shifting of phase due to the dropping of data points, the magnitude of the displacements also deviates substantially from the LVTD data.

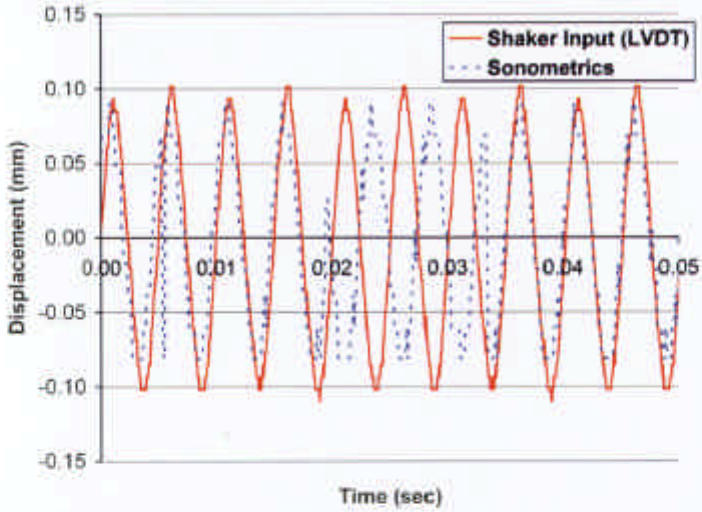

Figure 12. Comparison of displacement traces from the LVDT acquiring at 21978 Hz, and the Sonometrics system acquiring at 11363 Hz. Input displacement frequency is 200 Hz.

DISCUSSION

The sonomicrometry distance measurement system is investigated for the frequency range of high-rate impact loads. Originally, the sonomicrometry system was developed to measure the dynamic motion of a beating human heart at physiological rates. At this low rate of motion, this system has shown to be unique in calculating distances between crystals directly, with robost performance.

When this system is pushed to higher limits, certain aspects of these parameters become more critical. With the sampling rate at 11363 Hz, the total distance between crystals become critical, as the signal from the transmitting crystal must have time to reach the receiving crystal. Therefore, as sampling frequency gets higher, it is necessary that the crystals be spaced closer together.

Signal strength can also be troublesome, as the ultrasonic sound energy can be reflected by certain surfaces, resulting in multiple signals arriving at the receiving crystal. In an enclosed container such as the brain model, sorbothane polyurethane was used as a lining in order to minimize the reflection of energy, causing a cleaner, more readable signal. For best results, a smooth, fluid pathway between crystals is desirable, with the nearest reflective surface several lengths away. While there are certain difficulties at higher sampling rates, with practice high rate sonomicrometry can be an efficient and accurate tool to directly measure displacements, particularly with a noninvasive sensor[1].

[1] Note: The version of Sonometrics that allows an 11363 Hz sampling rate is in a non-commercially available package obtained directly from Sonometrics for experimental purposes only.

ADDENDUM

Since completing this study, the Sonometrics Corporation has modified their current data acquisition system to address several of the issues discussed in this paper. Currently, they have a version of their measurement software that acquires data from 2 transmitting and 6 receiving crystals at 11363 Hz for over 9 seconds without any loss of data. This modification is yielding much cleaner signals between crystals, and has virtually eliminated the apparent phase shifts seen previously. In addition, the crystals are currently less dense than typical biological tissues. The sensors may be weighted to obtain neutral buoyancy for impact conditions.

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DISCUSSION

PAPER: **Applicability of Sonomicrometry in High-Rate Impact Testing**

PRESENTER: ***Rob Salzar, ASL, University of Virginia***

QUESTION: *Pat Kaiker, PSKN*

Have you determined exactly how close these crystals have to be before they lose their accuracy?

ANSWER: The maximum distance is about 200 millimeters. They've got to be closer than that. The faster you sample, and I don't understand why they've linked the sampling rate in with what's going on with the crystals, but the faster you sample the closer they are going to have to be. What you saw, all the tests that I did; generally they were about five, six millimeters apart, which is pretty darn close. If you are sampling at a lower rate you're not so worried about catching a bullet and what the frequency of that bullet comes in at, they can be up to, you know, a couple centimeters without any problem.

Q: *Guy Nusholtz, Daimler Chrysler*

How difficult are they to work with in terms of putting into biological tissues? Groups that normally work with cadavers you can't be too gingerly because you've got all sorts of other instrumentation that you're putting on, you're time constrained because if you sit there and "putschky" with the things you could take days and they will decay.

A: These things are pretty tough. You can bang them on the table you're not breaking them. They come with a variety of different connectors. The ones I have pictured here have those little spider legs in there for some applications. They also come with suture loops. If you have some sort of a scope that you can kind of wind your way into the heart, wind your way into the brain you can place them really easily and not worry about losing a crystal.

Q: So, someone who is doing an experiment could just stick it on or sew it on or loop it on or however they put it on and not have to worry about it?

A: Actually that's been the least of our problems.

Q: As long as you know the distance between the two crystals?

A: It will give you the distance between the two crystals.

Q: It will give you distance between two crystals?

A: Yes.

Q: As long as you're not beyond your distance?

A: Exactly. You got it.

Q: Thank you.