High frequency signal acquisition using a smartphone in an undergraduate teaching laboratory: Applications in ultrasonic resonance spectra

Blake T. Sturtevant, Cristian Pantea, and Dipen N. Sinha

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High frequency signal acquisition using a smartphone in an undergraduate teaching laboratory: Applications in ultrasonic resonance spectra

Blake T. Sturtevant,[a] Cristian Pantea, and Dipen N. Sinha
Materials Physics and Applications, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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A simple and inexpensive approach to acquiring signals in the megahertz frequency range using a smartphone is described. The approach is general, applicable to electromagnetic as well as acoustic measurements, and makes available to undergraduate teaching laboratories experiments that are traditionally inaccessible due to the expensive equipment that are required. This paper focuses on megahertz range ultrasonic resonance spectra in liquids and solids, although there is virtually no upper limit on frequencies measurable using this technique. Acoustic resonance measurements in water and Fluorinert in a one dimensional (1D) resonant cavity were conducted and used to calculate sound speed. The technique is shown to have a precision and accuracy significantly better than one percent in liquid sound speed. Measurements of 3D resonances in an isotropic solid sphere were also made and used to determine the bulk and shear moduli of the sample. The elastic moduli determined from the solid resonance measurements agreed with those determined using a research grade vector network analyzer to better than 0.5%. The apparatus and measurement technique described can thus make research grade measurements using standardly available laboratory equipment for a cost that is two-to-three orders of magnitude less than the traditional measurement equipment used for these measurements.
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I. MOTIVATION AND INTRODUCTION

The study of acoustics bridges many sub-fields of physics, including continuum mechanics, thermodynamics, condensed matter physics, and electrodynamics, among others.[1,2] Due to this breadth of classical physics topics, the inclusion of acoustics resonance experiments in undergraduate teaching laboratories presents many different teaching and learning opportunities including standing waves, resonances, wave polarizations, tensor notation and analysis, technological applications (e.g., proximity sensors and biomedical), and radio frequency (RF) measurement techniques, to name just a few. Acoustic resonance measurements in laboratories offer special advantages because they allow for a general discussion of resonances in almost any field of science. Previous authors have noted that acoustic resonance measurements provide higher precision and accuracy than an equivalent time of flight measurement.[3] Most traditional undergraduate physics curricula, however, limit acoustics experiments to measurements in the audible range and in air (e.g., Helmholtz resonators, organ pipe resonators, musical instrument sound boards). The absence of acoustics experiments in liquids and solids in undergraduate physics curricula, despite the significant learning opportunities enabled by them, is at least partially (and likely largely) due to the cost of the necessary equipment. For example, research grade RF analysis equipment can currently cost well upward of $10 K[4] for entry level equipment and more than $100 K for high end models. Similarly, commercially available broadband piezoelectric transducers can cost up to $1000 for a single transmitter–receiver pair.

The present work is largely motivated by the desire to make the study of ultrasonic resonances in liquids and solids, and the corresponding learning opportunities, affordable and accessible to students and instructors of undergraduate teaching laboratories. Given that nearly all undergraduate students have access to a smartphone, this powerful and portable computer provides a compelling alternative to conventional RF analysis equipment. Over the past ten years, much has been written about the use of smartphones for acoustic measurements[5–14] and scientific measurements in general.[15–20] Due to the ease of interfacing with the internal microphone and the limited bandwidth of the smartphone analog-to-digital converter (ADC), the studies mentioned above have focused almost exclusively on the use of the internal microphone to make measurements of sound in air and in the audible frequency range. In Refs. 17 and 19, the bandwidth of possible measurements is extended below 20 Hz to enable slower measurements (e.g., EKG readings), but not to frequencies above the audible range. In this study, a simple and inexpensive diode mixer is used, together with a local oscillator, to down-convert a high frequency analog signal into the audible range so measurements can be recorded through the smartphone's audio jack. Additionally, expensive commercial ultrasonic transducers are replaced by basic piezoelectric PZT disks which can be easily and inexpensively

[a]Electronic mail: bsturtev@lanl.gov

acquired. Though the specific case of ultrasonic measurements is highlighted in this work, the described approach is applicable to the acquisition of *any* data signal with frequencies above the limits of a smartphone ADC (typically ~20 kHz). The instrumentation described here is intended to demonstrate the approach as clearly as possible but is not the only way of accomplishing this. For example, inexpensive integrated circuits can be used to build the mixer or the local oscillators.

Prior to employing the described measurement technique in a teaching laboratory, students should have a working knowledge of the concept of down-conversion using a frequency mixer or multiplier. In an ideal mixer, a radio frequency (RF, with frequency f_{RF}) signal (i.e., the signal used for the experiment) is multiplied with a local oscillator (LO, with frequency f_{LO}) signal and the mixer outputs intermediate frequencies (IF, with frequency f_{IF}) as shown in Fig. 1. The IF signal consists of the sum and difference frequencies, $f_{RF}+f_{LO}$ and $|f_{RF} - f_{LO}|$, respectively. The relationship between the input RF and LO frequencies and the output IF frequencies can be explained as the multiplication of two sine waves using a standard trigonometric identity:

$$\sin(u) \times \sin(v) = \frac{1}{2}\left[\cos(u-v) + \cos(u+v)\right]. \quad (1)$$

In this case, $u = 2\pi \times f_{RF} \times t$ and $v = 2\pi \times f_{LO} \times t$. Thus, experiments will be made at the RF frequencies and a suitable LO frequency will be chosen such that the difference frequency is in the audible range (20–20 000 Hz). While, in principle, the ADCs in smartphones are usable slightly above 20 kHz,[17] it has been found in practice that most apps available for download limit the measurements to 20 kHz and so that is the practical upper limit assumed in this work.

Section II describes the general hardware setup and the technique for making measurements as well as the piezoelectric transducers used for the specific examples presented here. Section III explains the measurement procedure and shows some example spectra. Section IV presents results and analyses of ultrasonic resonance data collected in liquids and solids using the described technique. Section V presents a brief discussion of caveats for using smartphones in an undergraduate teaching laboratory as well as possibilities for advancing this technique. Finally, Sec. VI concludes the paper.

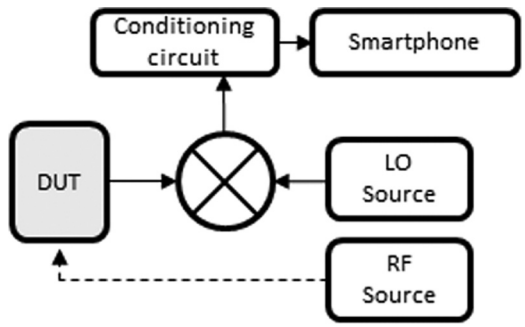


FIG. 1. Schematic of the hardware setup used for making high frequency measurements using a smartphone. For active measurements, an RF signal is applied to the input port using the cable denoted by the dashed line. For passive measurements, where the RF signal is collected from ambient fields (e.g., radio wave measurements), the cable denoted by the dashed line is omitted.

II. EXPERIMENTAL SETUP

A. General hardware for reading a high frequency signal using a smartphone's audio jack

Figure 1 shows a schematic of the hardware required to acquire a high frequency data signal through the audio jack of a smartphone. Passive mixers, such as the one used in this work (model ZAD-3+, www.minicircuits.com), are commercially available and inexpensive. A detailed discussion of mixers in general, along with circuit diagrams for both passive diode ring and active transistor-based mixers, can be found in Ref. 21, which is freely downloadable.[22] For experiments requiring an active source (e.g., ultrasonic resonance or time of flight measurements, electromagnetic Doppler measurements), an RF source is supplied at the desired frequency using a basic sine wave generator, commonly found in teaching laboratories. The LO frequency is supplied independently, either by a separate channel on a multiple channel sine wave generator or by another sine wave generator. A number of online vendors sell suitable inexpensive dual channel function generators. For example, a 6 MHz dual channel arbitrary waveform generator made by KKmoon (part # JRQ7936245905505MG) can be purchased on Amazon.com for $79.99. It is worth mentioning that it is not necessary to have a pure sine wave source. Other input waveforms, such as square waves or triangular waves also suffice since the resonance phenomenon itself works as a narrow band-pass filter and naturally filters out the higher harmonics from sources that are not pure sine waves. While it is desirable for each laboratory working group to have its own RF signal generator, it should be noted that multiple groups can share a common LO signal since this signal will remain fixed for relatively extended periods. Thus, if only single channel function generators are available to n separate work groups, only $n+1$ and not $2*n$ sine wave generators are required. An adaptor is also necessary to split the three signal carrying components of the audio jack into separate cables for the headphones ($\times 2$), and the microphone which will be used as the input for these experiments. Smartphones with an external microphone input utilize a standard 3.5 mm TRRS (Tip-Ring-Ring-Sleeve) audio jack,[17] not to be confused with the also common 3.5 mm TRS (Tip-Ring-Sleeve) audio jack which only supplies headphone output audio and does not accept a microphone input. The conditioning circuit shown in Fig. 1 serves two purposes: (1) it provides a resistive load that alerts the smartphone that it should switch from the internal to the external microphone, and (2) it provides DC isolation between the smartphone and the experiment since the phone's microphone supplies a DC voltage that is meant to power a preamp in an external microphone. The specifics of the resistive load required and the DC voltage supplied to the microphone jack vary from phone-to-phone. Details for the iPhones used in this work are provided below but practitioners should check the documentation for their own phones. A spectrum analyzer app, many of which are currently available for download on all major mobile

software platforms, is used to determine the spectral content and magnitude of the input signal.

B. Measurement procedure

The frequency range to be investigated, $f_{min} \leq f \leq f_{max}$, should be determined prior to the experiment based on reasoned assumptions about the system being studied. This frequency range is then divided into n local oscillator windows where $n = \text{ceiling}[(f_{max} - f_{min})/40\ \text{kHz}]$ since a single LO frequency will enable measurements 20 kHz above it and 20 kHz below it. The ceiling function rounds the quotient in the argument up to the nearest integer value. The first LO frequency used is then $f_{LO} = f_{min} + 20\ \text{kHz}$ and, in active measurements where an RF signal is applied as an input, this is used to measure RF signals $f_{min} < f_{RF} < f_{min} + 40\ \text{kHz}$. The second LO frequency used is then $f_{LO} = f_{min} + 60\ \text{kHz}$ and is used to measure RF signals from $f_{min} + 41\ \text{kHz} < f_{RF} < f_{min} + 80\ \text{kHz}$, and so on. For active systems, the RF signal is applied to the input port of the device under test (DUT), the output port of the DUT is connected to the RF port of the mixer, and the LO signal from the sine wave generator is connected to the LO port of the mixer. The IF port of the mixer is then connected to the smartphone through the conditioning circuit and the audio jack adapter. Using a spectrum analyzer app, the magnitude of the IF frequency can then be determined and recorded. The next data point is collected by changing the RF frequency by the desired measurement resolution and recording the magnitude of the next IF frequency. This process is repeated, adjusting the LO frequency every 40 kHz, until data have been collected over the entire frequency range of interest. A typical data collection entry in a laboratory notebook is shown in Table I, where a measurement range of $980\ \text{kHz} \leq f_{RF} \leq 1060\ \text{kHz}$ is used as an example. Prior to data collection, such a table can be established and the magnitudes of the recorded signals can be filled in as the experiment progresses.

For passive measurements not requiring an RF source (e.g., measuring the amplitudes of ambient radio waves), the data acquisition process is slightly different. For a given LO frequency, one can collect an entire 40 kHz bandwidth at one time, identifying one or more IF frequencies using a spectrum analyzer app at a single time. The IF frequency is then adjusted by 40 kHz and the next frequency band is collected. An important consideration in this technique is the ambiguity of the frequency being measured. As an example, if a resonance peak is determined at an IF frequency of 4 kHz, and the LO frequency is set to 1000 kHz, the RF frequency being observed can be either 1004 or 996 kHz, since both of these will yield a difference frequency of 4 kHz. To determine unambiguously, the LO frequency can be changed by a small amount, such as 1 kHz. A second measurement with a LO frequency of 1001 kHz will then show a resonance at an IF frequency of either 3 or 5 kHz, removing the ambiguity in the first measurement.

TABLE I. Example of a data collection table.

f_{RF} (kHz)	f_{LO} (kHz)	f_{IF} (kHz)	Magnitude (dB)
980	1000	20	
981	1000	19	
⋮	1000	⋮	
1019	1000	19	
1020	1000	20	
1021	1040	19	
1022	1040	18	
⋮	1040	⋮	
1059	1040	19	
1060	1040	20	

C. Transducer specifications and preparations

The remainder of this paper focuses on a specific application of making high frequency measurements with an iPhone 4s, that of ultrasonic resonances in liquids and solids. Two piezoelectric transducers are typically used to measure ultrasonic resonances. One transducer serves as a transmitter that excites the resonant fluid-filled cavity (or media) and the other is a receiver to determine the response of the system. To replace the expensive commercial products mentioned in the introduction, this work utilized a pair of 50 mm diameter 1 MHz PZT disks with a coaxial electrode configuration which were purchased for $19 (Steiner & Martins, Inc., Doral, FL). For signal input/output, coaxial cables were soldered onto the electrodes as seen in Fig. 2.

III. EXPERIMENTAL PROCEDURE FOR ULTRASONIC RESONANCE MEASUREMENTS

A. Liquids

In a liquid-filled 1D cavity, measurement of successive resonance frequencies, f_n, can be used to determine sound speed, c, in the liquid through the relationship

$$c = 2L\frac{df_n}{dn}. \tag{2}$$

FIG. 2. (Color online) 50 mm diameter PZT disks assembled with coaxial cables.

Here, L is the distance between the walls, in this case the transducers, that create the resonant cavity, and n is the harmonic number.[23] This relationship follows from the fact that sound speed equals the product of frequency and wavelength for any n ($c = f_n \lambda_n$), and that the boundaries of the resonant cavity must be nodes of the displacement wave ($\lambda_n = 2L/n$).

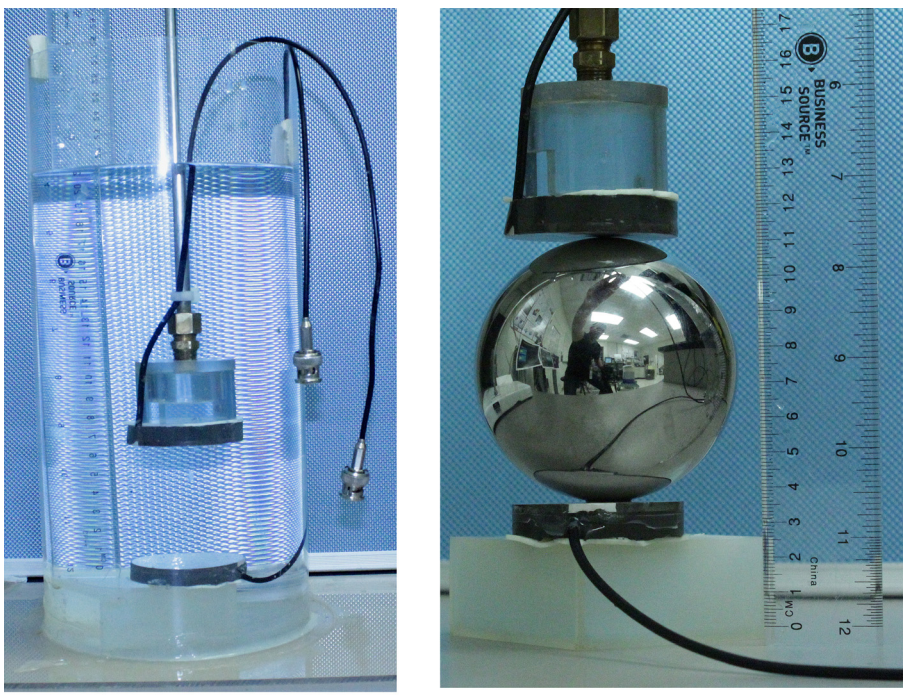
In this work, the transducers described in Sec. II C were submerged in the liquid of interest with their faces opposing each other [Fig. 3(a)]. The faces of the transducers were aligned by eye to be as parallel as possible, which is a critical consideration in resonance experiments. The distance between the transducers was measured using a ruler with a precision of ± 0.5 mm. The two transducers comprised the DUT in Fig. 1, thus the transmitting transducer was connected to the RF signal coming from the sine wave generator and the receiving transducer was connected to the RF port on the mixer.

Using the procedure described in Sec. II B, data were collected over a 140 kHz bandwidth with a step size of 1 kHz in distilled water and also in Fluorinert FC-43 (3 M Company, Maplewood, MN), both at a temperature of 24 °C. For the water measurements, the frequencies measured were $600 \leq f_{RF} \leq 740$ kHz, while the Fluorinert measurements were carried out over a frequency range of $900 \leq f_{RF} \leq 1040$ kHz. Each spectrum, consisting of 140 measurement points, took approximately 15 min to collect using the smartphone technique. The measurement results from water, with a resonant cavity length $L = 118$ mm, are shown in Fig. 4(a), compared to a spectrum over the same frequency range collected with a commercial vector network analyzer (VNA, model: Bode 100, Omicron Electronics Corp., Houston, TX). It can be seen from the figure that, while the resolution of data points is less in the smartphone case than in the VNA case, all of the resonances are easily identified and the spacing between resonance peaks, important for determining sound speed, are essentially the same. Figure 4(b) shows data collected in Fluorinert with two different resonance cavity lengths, $L = 34$ mm and $L = 74$ mm. The purpose of these measurements was to demonstrate the inverse relationship between L and df_n/dn described by Eq. (2). Clearly, for the longer resonance cavity length, $L = 74$ mm, adjacent resonance frequencies, f_n, are spaced more closely in the frequency domain.

B. Solids

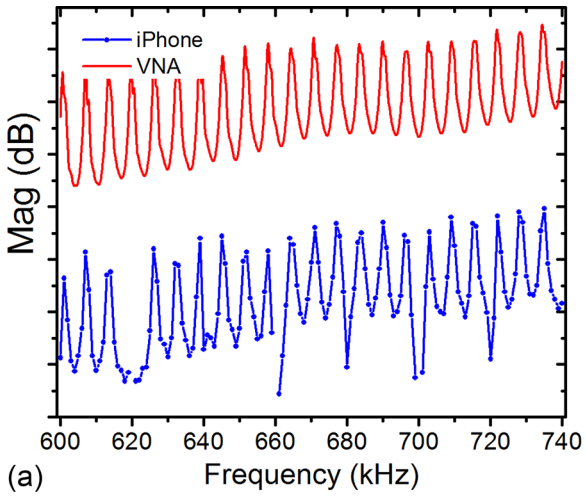
Solids can support many different types of normal modes (e.g., longitudinal, shear, torsional, bending), making the resonance spectra considerably more complex than in the case of liquids. Consequently, there is no relationship analogous to Eq. (2) for solids. However, ultrasonic resonances in solids, combined with knowledge of a sample's crystallographic symmetry and measurements of the mass density and sample dimensions, can be used to determine the elastic moduli of solid samples using theory provided by Resonant Ultrasound Spectroscopy (RUS).[3] The determination of elastic moduli is accomplished through an inverse calculation and implemented using freely downloadable software available at Ref. 24.

For the solid measurements performed in this work, the transducers described in Sec. II C were placed in point contact with a 3-in. diameter stainless steel sphere as shown in Fig. 3(b). Data were collected between 32 and 55 kHz with a step size of 50 Hz. Figure 5 qualitatively compares the spectrum collected using a smartphone to that collected using a commercial VNA. The lowest five resonance frequencies, identifiable in both data sets, are identified with arrows in the figure. Compared to the liquid measurements, a smaller frequency step size was required to ensure that the resonances, which are considerably sharper in the solid sample, were able to be resolved. Using the smartphone technique,



(a) (b)

FIG. 3. (Color online) Experimental geometries for making liquid and solid ultrasonic resonance measurements. (a) Transducers immersed in a liquid of interest. The opposing and aligned transducers comprise the 1D resonance cavity. (b) The same transducers used to make point contact with a solid sample, in this case a 3-in. diameter stainless steel sphere.



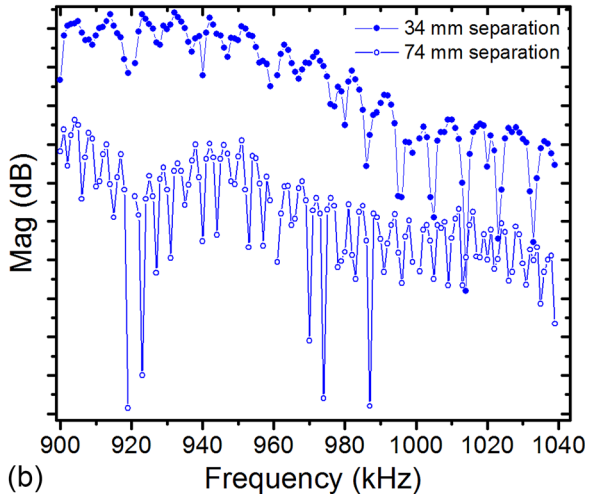


FIG. 4. (Color online) Resonance spectra collected in liquid samples. (a) Spectra collected in 24 °C distilled water with a resonance path length $L = 118$ mm. Spectra were collected over the same range using a smartphone (marker and line) and with a commercial vector network analyzer (solid line) and the important features of the spectrum, peak position and peak spacing, are seen to be the same. (b) Spectra collected in 24 °C Fluorinert FC-43 using a smartphone with two different resonance path lengths, $L = 34$ mm (filled circle data marker) and $L = 74$ mm (open circle data marker). The inverse nature of L and df_n/dn can be clearly seen.

the 461 data points were collected in roughly 45 min, a time that is entirely possible in a teaching laboratory.

IV. ANALYSIS AND RESULTS

A. Liquids

Equation (2) was used to calculate the speed of sound in the liquids. For the water measurements shown in Fig. 4(a), the resonance frequencies were selected by identifying the frequencies having the highest magnitude and plotting them vs cycle number. No peak fitting procedure was implemented and thus a very rough estimate of the uncertainty in these resonance frequencies would be ±0.5 kHz. However, by plotting many of these resonances and fitting a straight line to them as shown in Fig. 6(a), the important parameter df_n/dn can be determined with relatively high precision. From the 21 peaks plotted in Fig. 6(a), df_n/dn was determined to be

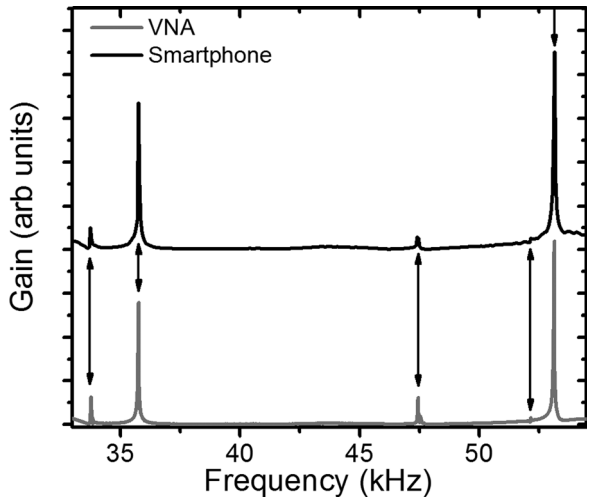


FIG. 5. Resonance spectra collected from a 3-in. diameter stainless steel sphere using a smartphone (black trace) as well as a commercial vector network analyzer (gray trace). The five resonances with the lowest frequencies, observable in each spectrum, are identified with arrows.

6.37 ± 0.01 kHz. Combined with the length measurement $L = 118$ mm, a sound speed of 1504 ± 2 m/s was determined. A sample of the same water was measured in a commercial sound velocity meter (DSA 5000 M, Anton-Paar GmbH) which determined a sound speed of 1497.4 m/s. Thus, the smartphone technique achieved a precision, determined by

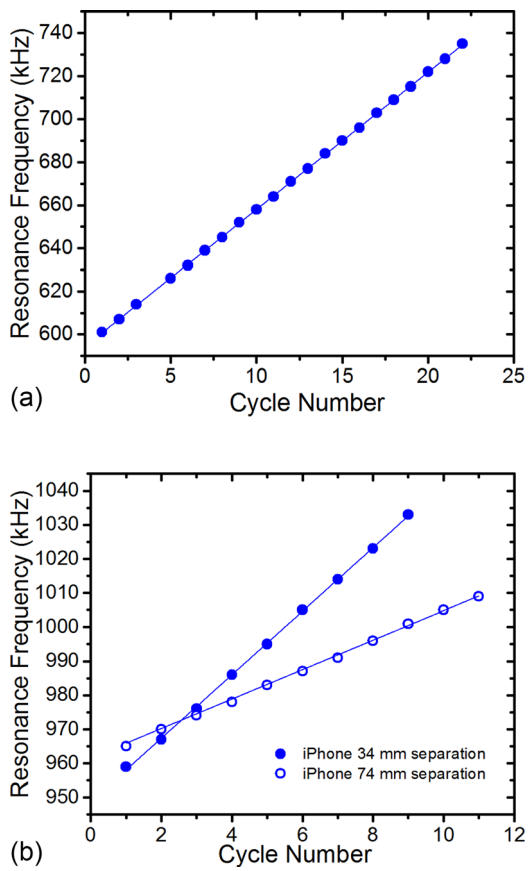


FIG. 6. (Color online) Linear fits to resonance frequencies vs cycle number, used to determine sound speed in liquids. (a) Linear fit to 21 resonances in liquid water. (b) Linear fit resonances in Fluorinert FC-43 with two different path lengths: $L = 34$ mm and $L = 74$ mm.

the linear fit to f_n vs n, better than 0.2% and an accuracy, referenced to the commercial sound velocity meter, better than 0.5%. Together with the mass density, the sound speed in liquids can also be used to calculate the bulk modulus, K, through the relationship $K = \rho c^2$. For the measured sound speed in water, with a density of approximately 1000 kg/m^3, $K = 2.26$ GPa.

For the Fluorinert data shown in Fig. 4(b), the minima rather than the maxima were selected for the calculation of df_n/dn since they have the same periodicity as the maxima and are significantly more well-defined. Nine and 11 resonances were selected from the $L = 34$ mm and $L = 74$ mm data, respectively. These resonances were plotted against the cycle number, n, and a linear fit was performed to determine df_n/dn [Fig. 6(b)]. The frequency spacing for the $L = 34$ mm and $L = 74$ mm data were found to be $df_n/dn = 9.32 \pm 0.07$ kHz and $df_n/dn = 4.41 \pm 0.04$ kHz, respectively. These frequency spacings imply sound speeds in the liquid of $c = 635 \pm 5$ m/s and $c = 652 \pm 6$ m/s. The precision of these measurements, reported from the standard error of the linear fit, is better than 1%. The reason for the reduced precision when compared to the water data discussed above, is likely due to the reduced number of resonances used in the Fluorinert analysis. In previously reported work,[25] the temperature behavior of Fluorinert FC-43 was characterized and the sound speed at 24 °C was found to be 648.98 m/s using the commercial sound velocity meter mentioned above. When compared to this value, the smartphone data at both resonance cavity lengths are accurate to better than 2%.

B. Solids

The first five measured resonances of the stainless steel sphere, denoted with arrows in Fig. 5, were used together with a measured mass density of 7804 kg/m^3, to calculate the elastic moduli using the computer code downloaded from Ref. 24. The fit to the smartphone-measured data determined bulk and shear moduli of 168.2 and 81.5 GPa, respectively. The root-mean-square error (rmse) from the fit was 0.07%. A VNA was used to measure the first 16 non-degenerate resonance frequencies and these were also fit assuming the same mass density as mentioned above. From the VNA data, bulk and shear moduli of 169.1 and 81.1 GPa, respectively, were determined with an rmse of 0.12%. Students can also use the bulk and shear moduli to calculate other material properties of interest such as Young's modulus (E), Poisson's ratio (σ), or the Lamé constants (λ, μ). As was the case with the fluid measurements, the elastic moduli determined here show that the simple smartphone method yields research grade results that are within 0.5% of commercial RF analysis equipment.

V. CAVEATS AND IDEAS FOR IMPROVEMENT

As mentioned in Sec. II A, it is possible to use a square or triangular wave as an RF frequency source in place of a pure sine signal. However, it should be kept in mind that such signals naturally carry harmonic content and can thus excite higher order resonance modes. If the frequencies of interest are low enough, the higher harmonics could be captured as separate peaks on the spectrum analyzer within the same 40 kHz window. In designing laboratories, instructors should select sample dimensions and LO frequency ranges to mitigate this potential source of confusion.

Smartphones' microphone jacks supply a DC voltage that is used to power the preamp in an external microphone. For many measurements using the technique described above, it is desirable to remove this DC component. In this work, DC isolation was accomplished by using a simple iron core transformer between the phone and the measurement apparatus. A capacitor circuit will also suffice, and there are many such circuit designs available online. Additionally, a resistive load will need to be placed across the microphone jack and ground so that the phone knows to switch from the internal to external microphone. The iPhone 4 s and 5 s were studied in this work and the load required for microphone switching was found to be 1.6 kΩ, though students should find the specifications for the specific phone that they will be using. Also, care should be taken to ensure that the signal that is input into the phone does not damage the phone. An instructor should test an apparatus before the start of the lab to determine appropriate RF input voltages that will yield output signals that are strong enough to be detected, but not so strong that they damage students' phones. For the case of the iPhones mentioned above, the A/D saturates at voltages >40 mV and this is readily apparent in the measurement as harmonics of the IF suddenly appear. At the first sign of this in an experiment, the RF input power should be reduced.

One possibility for improvement on the technique described above would be to use a swept frequency, chirped, or noise signal as the input rather than a single frequency RF signal. This offers the advantage of enabling the measurement of multiple frequencies at once and in a continuous manner, rather than stepping through RF frequencies manually. However, care must be taken to ensure that the bandwidth of the input signal does not exceed 20 kHz and that it is entirely either above or below the frequency of the local oscillator. These steps will ensure that there is no ambiguity in the signal being studied, as described in Sec. II B above. Smartphones output a voltage to the headphone jacks that is high enough to use the phone as a source as well as a receiver. In the case of the iPhone models mentioned above, the phone outputs ~3.5 V peak-to-peak when set to full volume. Since the digital-to-analog converter in smartphones is also limited to roughly the audible range, using the smartphone as a source requires first up-converting the signal from the audible range into the desired measurement frequency. The experiment would then be made at high frequency and the remainder of the measurement process would be the same as described earlier. This experimental setup requires an additional mixer and an additional local oscillator. The frequencies of the local oscillators used for up-conversion and down-conversion should be slightly different to remove the ambiguity in the frequencies being studied.

VI. CONCLUSIONS

A simple and inexpensive technique for making high frequency measurements using a smartphone has been

presented. The technique has been applied to the measurement of acoustic resonances in liquids and solids above the audible range and up to 1.04 MHz. From the measured resonances, material properties of interest (i.e., sound speed and elastic moduli) were determined and found to be in close agreement with those determined using commercial research grade instrumentation. The described technique makes high frequency measurements, and many learning opportunities, available to students in undergraduate teaching laboratories.

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