Laboratory Studies of the Impact of Fish School Density and Individual Distribution on Acoustic Propagation and Scattering

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LONG-TERM GOALS

The long-term scientific objective of this project is to increase our understanding of acoustic propagation and scattering in the presence of schools of fish, the effects of which can potentially overshadow all other acoustic mechanisms in shallow water. This in turn benefits sonar operation and acoustic communication in shallow water, and will increase the accuracy of acoustically-based fisheries surveys. This study will utilize both one- and three-dimensional acoustic resonator techniques, previously developed by the author under ONR [1, 2] and industry [3] sponsorship, and free-field measurement techniques to study the low-frequency (50–10000 Hz) acoustics of collections of model fish, large (≈10 cm diameter) encapsulated bubbles and schools of real fish in the laboratory.

OBJECTIVES

In this study, existing apparatus design and techniques are being leveraged to accurately measure and quantify, under well-controlled laboratory conditions, the effect of fish number density and the effect of the distribution of individuals and motion of individuals within an aggregation on sound propagation and attenuation through aggregations, at frequencies spanning swim bladder resonance. We will ultimately interface with the biologists working under this BAA topic to identify the species of fish to be investigated and to specify their arrangement within aggregations used in the proposed experiments. These measurements will be used to verify and guide the development of existing and future models, as well as provide a means to characterize the effective acoustic properties of different species. An example of the former would be to determine the number density of fish of a particular species at which a transition from single- to multiple scattering acoustic behavior is observed, as a function of frequency (spanning the swim bladder resonance) and depth, and to quantify the acoustic effects of this transition. An example

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of the latter would be to infer the effective acoustic properties (sound speed and attenuation) of an aggregation of a particular species at frequency ranges that span the swim bladder resonance. Both of these examples can be useful to either verify forward physics-based models, or to obtain inputs for empirically-based models.

Although significant previous work has been done on multiple scattering in fish schools (Refs. [4, 5] are examples), there is less work on modeling and measurement of attenuation through fish schools, especially at low frequencies. For example, Furusawa [6] reported *insignificant* attenuation through schools of several species, in both lab and ocean measurements, using both direct and indirect techniques, but at frequencies ranging from 25 kHz to 420 kHz, with a focus on the attenuation's effect on abundance determination. Diachok [7] reported very different results, finding between 15 dB and 35 dB, at swim bladder resonance frequencies (1 kHz to 3 kHz), indirectly observed via shallow water ocean waveguide measurements. The present work seeks to provide state-of-the-art measurements of the low frequency (trans-swim-bladder-resonance) sound speed and attenuation in aggregations of live fish in conjunction with state-of-the-art characterization of the physical parameters of the fish.

It is difficult or impossible to achieve the above in nature for a variety of reasons: 1) The long wavelengths at these frequencies require the control and understanding of a large volume of the environment. 2) The effect of the surrounding environment is difficult and expensive to separate from the effect of an aggregation of fish, due to the required environmental knowledge, such as sound speed gradients, bathymetry, sediment properties and layering, ocean surface effects, etc. 3) It is difficult or impossible to obtain ground-truth information on the aggregation being studied, such as species, number density, spatial distribution, individual size distribution, etc. The resonator technique used here overcomes these difficulties. The technique allows one to conduct low frequency measurements in a reasonably-sized (inexpensive) laboratory apparatus, because only a quarter- or half-wavelength is needed at the lowest frequencies. The resulting test environment (the 1- and 3-D resonators) is well-known and well-characterized, hence all of the observable acoustic effects can be confidently attributed to the material of interest, the fish. The fish species, number density, spatial distribution, individual size distribution and even individual motion can be controlled. The physical morphology of the fish can be measured in house using an available micro-X-ray computed tomography system [8].

APPROACH

This section contains the statement of proposed work in two parts: Waveguide/resonator measurements intended to verify and guide model development of sound propagation through aggregations of swim bladder fish, and free field scattering measurements intended verify and guide model development of scattering from aggregations of swim bladder fish. In both cases the measurements will be conducted in laboratory environments to provide the highest degree of control over the experimental conditions, and frequencies spanning swim bladder resonances will be used.

Propagation Measurements The techniques described above are being used to measure the effective sound speed and attenuation within collections of live fish, of a wide variety of species of interest and in collections of artificial fish, namely air bubbles with elastic shells. Fresh and salt water fish can be used inside the 1-D resonator, and the resonator can be filled with water appropriate for the survival of the fish. The fish have to be contained within a bag of appropriate fresh or salt water for use in the large outdoor tank, because of the chlorine treatment of the tank water. Model fish are also used in all cases, too. The density and individual distribution of fish inside the aggregations can be varied and the resulting acoustic effects observed. All of these acoustic measurements will be compared to existing and developing models of sound speed and attenuation within the aggregations. Close control and characterization of the individuals within the aggregation and of the aggregation itself can be achieved in these laboratory measurements. This includes the use of micro-X-ray computed tomography to accurately characterize the morphology of the fish used in the proposed work. We envision close collaboration with other modeling efforts under this BAA topic such that the measurements can guide the modeling and vice versa.

More direct propagation measurements are also conducted using the artificial fish at UT's Lake Travis Test station. In this case, a sound source (Navy J-13) is surrounded by a collection of artificial fish and acoustic measurements are obtained and compared to the receive levels in absence of the artificial fish. From that data the phase speed and attenuation of sound waves within the artificial fish school can be extracted.

Scattering Measurements We also plan to measure the free field acoustic scattering properties of the same aggregations of fish and artificial fish described above. These measurements would proceed as those described in Ref. [5], but will be conducted in the laboratory conditions provided by the Lake Travis Test Station (LTTS) of the Applied Research Laboratories. LTTS is located in a large fresh water lake near ARL:UT and the test station is specifically designed to support and conduct target scattering measurements, as well as to perform source and receiver calibration measurements, at frequencies as low as 2 kHz. We also measure scattering from single objects in a small tank using a subtraction technique.

The personnel for this project are: Preston S. Wilson serves as PI and is an Associate Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Associate Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Craig N. Dolder is a UTME Ph.D. student who contributes to all aspects of the project. ARL:UT Post-doctoral fellow Kevin M. Lee has assisted with conducting measurements and analysis. Laura M. Tseng is an physics student at UT Austin and serves as an undergraduate research assistant on this project.

WORK COMPLETED

Objective 1—Propagation Measurements: Despite years of study and use by this PI, the graduate student working on this project, Craig Dolder, made significant advances in the understanding and use of the resonator method, as well as improvements in the modeling used to extract acoustic properties from the measurements. One of the advancements included the additional modality of scanning the waveguide along its length, whereas past usage was limited to single point measurements. Apparatus was constructed for the scanning measurements. Using these advancements, precise measurements of sound speed have been made across a range of frequencies for both artificial and real swim bladder fish. Due to Dolder's advancements, the frequency range of this technique has been significantly increased to well above the individual bubble resonance frequency (IBRF). In the past, the technique had been limited to frequencies below IBRF.

In addition to the improvements referred to above, the measurements obtained this year (presented below), are the result of improvements to the protocol for use of live fish. Our animal use protocol was modified using a painstaking and slow trial and error process that required a live animal test to be conducted, results to be obtained, guesses made as to how improvements could be achieved, modifications to the animal use protocol made and approved by the UT animal use committee, test and repeat, etc. Because of this difficulty, significant effort was also expended trying different ways to make more acoustically realistic artificial fish. Several months of student time was expended on the activities describe in this and the preceding paragraph.

Larger-scale open water measurements of both sound speed and attenuation were made using artificial fish (rubber-shelled air balloons) over a range of bubble sizes and shell thicknesses at ARL:UT's Lake Travis Test Station (LTTS).

Most of the available models for sound propagation and scattering in fish schools, in collections of bubbles and shelled bubbles have been coded and are now being used to compare with measurements.

Objective 2 — *Scattering Measurements*: Apparatus for the large-scale, open water scattering measurements was constructed and deployment scenarios were tested at LTTS. Single artificial fish scattering measurements were conducted in an indoor tank to study a range of swim bladder sizes and shell properties.

RESULTS

Objective 1—Propagation Measurements: One of our acoustic waveguides, set up as a one-dimensional resonator, is shown in Fig. 1. This apparatus and others of different lengths are used in this work to measure the acoustic phase velocity in model and real fish schools. In the current project, we had to modify our existing equipment to be approved for use with live fish, which included constructing a filtration, water treatment and aeration system. All of the fish husbandry aspects of this work are now complete. The apparatus to scan the hydrophone along the length of the resonator is now in place

The advancements in using the resonator method are illustrated in Fig. 2. Models of the phase speed (upper) and the resonance spectrum (lower) inside a bubble- or fish-and water-filled 1-D resonator are shown. The upper curve also contains strait lines of constant wave number. The lines start on the left with a half wavelength filling the resonator, and proceed left-to-right increasing by one-half wavelength. The second line is two half-wavelengths, the third line is three half-wavelengths, etc. Notice the strait lines intersect the phase speed curve at multiple locations. Each time a particular strait line intersects the phase speed curve, a mode is indicated. Each mode associated with one strait line has the same number of half-wavelengths filling the resonator, but because the phase speed inside the tube is highly dispersive, each mode of constant wave number has a different frequency. Therefore, there can be, for example, using the first line on left (the green line), three modes are found (indicated by three green stars in the upper plot) that posses a single half wave length inside the tube at each of three independent frequencies (indicated by three green stars in the lower plot). In this way, each frequency peak of the resonance spectrum can be associated with its correct mode and therefore phase speed can be extracted across the entire range of frequencies. Like-colored stars in both the upper and lower plots indicate association with a particular constant wave number line.

Fig. 3 shows an example of this technique for artificial fish in a loosely packed aggregation. The void fraction was 2.5×10^{-4} and the bubble radius was 7.6 mm. Lines of constant wave number are also shown to illustrate the new technique used to extract additional phase speed measurements from spectra. Several models for sound propagation in collections of bubbles are also shown. The effect of the finite-impedance waveguide walls has also been incorporated. The best model here is the Kargl model [11], which is the only model shown that incorporates multiple scattering, and hence is the only model (of those shown) appropriate for high void fractions and hence densely packed schools. Note that the Kargl model does not incorporate the effects of a shell, which can be included. It was not included here, because very thin-shelled balloons were used, and the effect of the shell is small. Some fish (rockfish larvae, for example) have such large swim bladders, that they are nearly like free bubbles, so the Kargl model may be appropriate for these types of fish that appear mostly like free bubbles. Another key point shown here, is that a much more wide frequency range of data is now available from our resonator measurements. About twenty data points are present spanning both sub- and super-resonance regimes. Compare this to data collected last year, shown in Fig. 4, where only a few data points have been extracted.

The improved resonator technique was used with our improved fish protocol to obtain sound speed measurements in collections of fish of varying number. A photograph of the resonator filled with fish is shown in Fig. 5. Waveguide resonances and extracted phase speeds are shown for one through five fish filling the waveguide in Fig. 6. We consider these results to be preliminary, and have not yet been compared to models, but the expected behavior is seen. Sound speed is reduced below resonance, and increases above resonance and there are a few data points that exhibit supersonic (relative to bubble-free water) sound speed. Further, the effect of increasing fish density is as expected. The sub resonance sound speed (below about 1 kHz) *decreases* with increasing fish density (or void fraction). This effect is predicted by all models. There is some small *increase* in the sound speed above resonance (above about 1 kHz), which is also predicted by all bubble models. This data has not yet been compared to models, but that is forthcoming. X-ray micro-computed tomography scans were also conducted on the fish used in this experiment. Fish and swim bladder volumes can be extracted from this data, as well as tissue density inferences. An example of the μ-CT data is shown in Fig. 7.

Free field sound speed and attenuation measurements conducted at Lake Travis Test Station (LTTS) on model fish schools consisting of rubber-shelled, air-filled balloons were obtained. The apparatus is shown in Fig. 8. The apparatus used to measure the free field sound speed and attenuation in a model fish school. The model fish were rubber-shelled air-filled balloons. The school was held together with a metal frame and netting. A source (Navy J-13) was placed in the middle of the model school. A five-element hydrophone array was used to receive the wideband signals from the source. Various fish school densities and swim bladder sizes were used. A typical attenuation measurement is shown in Fig. 9. Three models are also shown: CP is the Commander and Prosperetti model [12], Kargl [11] and Church [10]. Finally, a modified Church model (still under development by our group) is shown. The CP model does not account for shells (fish flesh) or multiple scattering. The Kargl model accounts for multiple scattering but no shell. The Church model accounts for shells but no scattering. The modified Church model accounts for the shell and uses the Kargl approach to account for multiple scattering. It is clear that the shell must be accounted for, but in this data, it is not clear that the multiple scattering is even encountered, as the Church model does a good job describing the data.

The results for a variety of school densities and swim bladder sizes are shown in Fig. 10. Only the Church [10] (black curves) and modified Church models (blue curves) are shown. N represents the number of model fish in the school, β is the void fraction, and a_1 is the mean radius of the swim bladder. Changes in swim bladder volume with depth are ignored. As expected, attenuation increases with fish school density (increasing N), and frequency shifts with swim bladder size. In most cases, it appears that ignoring multiple scattering effects (the Church model) does a better job of describing the data.

Phase speeds associated with two of the cases shown in Fig. 10 were extracted from the measured data and are shown in Fig. 11. Data (circles) and the Church model (lines) for the 7.96 cm (red) and 6.08 cm (blue) model swim bladders are shown. These correspond with the attenuation data from Fig. 10(e), VF = 0.0047, and (f), VF = 0.0053, respectively. We are using a new technique to extract this phase speed data, and we consider these results to be preliminary. The technique did not work as well on the other cases from Fig. 10.

Objective 2 — *Scattering Measurements*: The apparatus shown in Fig. 8 will also be used for free field scattering measurements planned for the next FY. For now, the results of measurements of the scattering dynamics of single model swim bladders can be shown. These results were obtained in a tank, using a subtraction technique from the literature. [13] The apparatus is shown in Fig. 12. The scattered field from a single artificial swim bladder is shown in Fig. 13. Physical parameters are shown within the figure. Resonance frequencies and quality factors can be extracted. In the future, we will compare these measurements to scattering models but for now, we have concentrated on just the resonance frequencies, and the effect of the shell on the resonance frequency. Measurements of the resonance frequencies of artificial swim bladders composed of rubber-shelled, air-filled bubbles are shown in Fig. 14. These measurements were extracted from the peak of scattering curves like those shown in Fig. 13. Blue and red curves are the Church model for resonance frequency. As the shell gets thicker (data around blue curves) the effect of the shell is large, and CP model (gray curves) greatly under-predicts the resonance frequency. For thin shells, the Church model (red curves) still does a better job than the CP model, but the effect of the shell is not as large. Circled data points indicated likely experimental bias, as described in the text box within the figure.

IMPACT/APPLICATIONS

Our results to date indicate that the Church model [10] does a good job of describing fairly closely packed fish schools. I use these words more from a bubbly liquid point of view, where the void fractions here would be considered very high for bubbly liquids. These may not be considered very high densities for fish schools. We will be continuing to increase the density in the next year. Both effective sound speed and attenuation of the artificial fish schools considered as an effective medium are well described by the Church model. [10] Also included in this model, and also equally successful is how well it describes the resonance frequency of artificial swim bladders.

TRANSITIONS

No transitions at this time.

RELATED PROJECTS

This work is part of a Basic Research Challenge project, and hence there are several other ONR-sponsored projects that are related.

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PUBLICATIONS

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HONORS/AWARDS/PRIZES

No honor/awards/prizes.

FIGURES

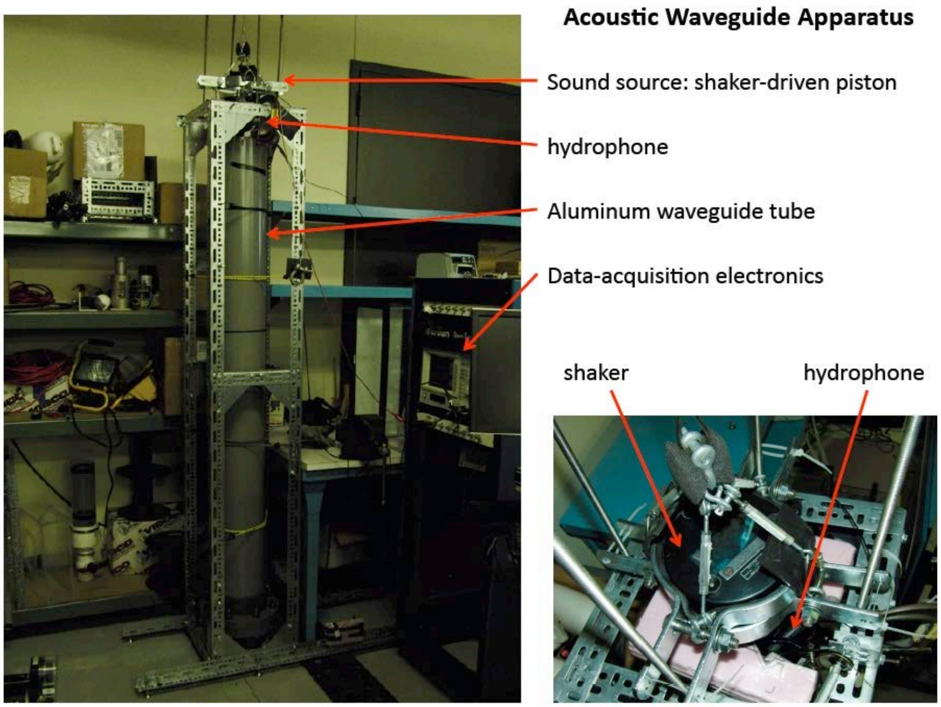

Fig. 1. The image on the left shows one of the 1-D acoustic resonators that we use to measure the phase velocity in model and real fish schools. The image on the lower right shows a view of the system from the top, which includes the shaker sound source and the still-hard-to-see hydrophone.

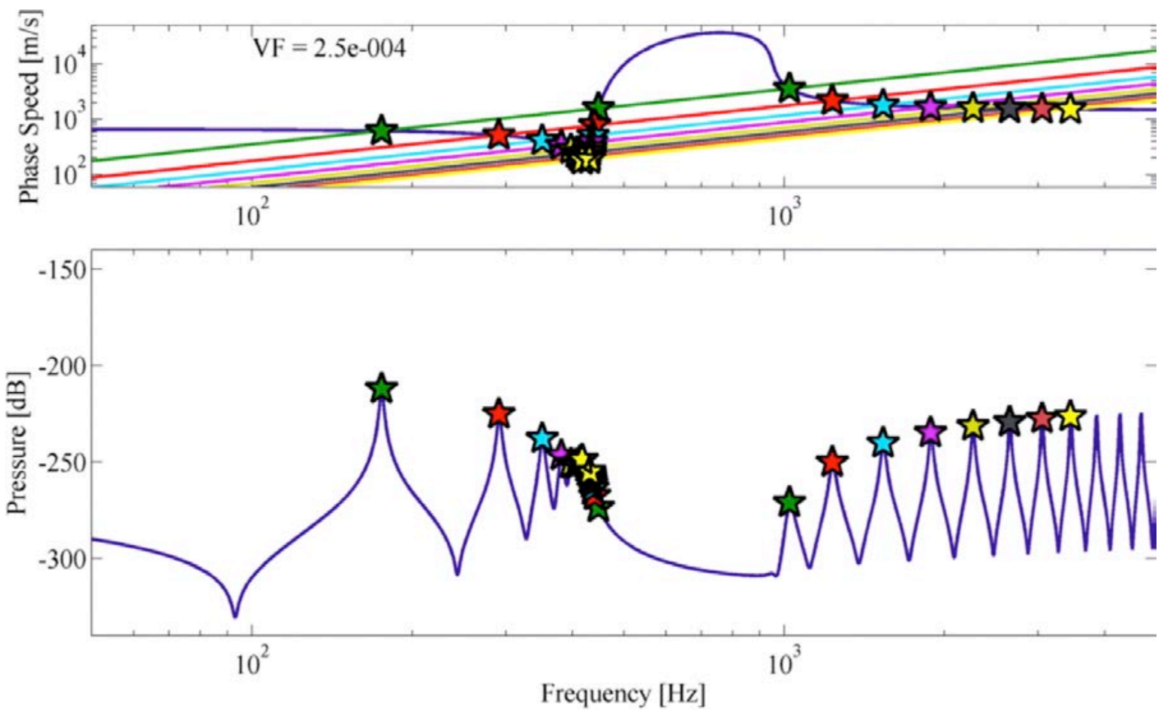

Fig. 2. Models of the phase speed (upper) and the resonance spectrum (lower) inside a bubble- or fish-and water-filled 1-D resonator are shown. The upper curve also contains strait lines of constant wave number. The lines start on the left with a half wavelength filling the resonator, and proceed left-to-right increasing by one-half wavelength. The second line is two half-wavelengths, the third line is three half-wavelengths, etc. Notice the strait lines intersect the phase speed curve at multiple locations. Each time a particular strait line intersects the phase speed curve, a mode is indicated. Each mode associated with one strait line has the same number of half-wavelengths filling the resonator, but because the phase speed inside the tube is highly dispersive, each mode of constant wave number has a different frequency. Therefore, there can be, for example, using the first line on left (the green line), three modes are found (indicated by three green stars in the upper plot) that posses a single half wave length inside the tube at each of three independent frequencies (indicated by three green stars in the lower plot). In this way, each frequency peak of the resonance spectrum can be associated with its correct mode and therefore phase speed can be extracted across the entire range of frequencies. Like-colored stars in both the upper and lower plots indicate association with a particular constant wave number line.

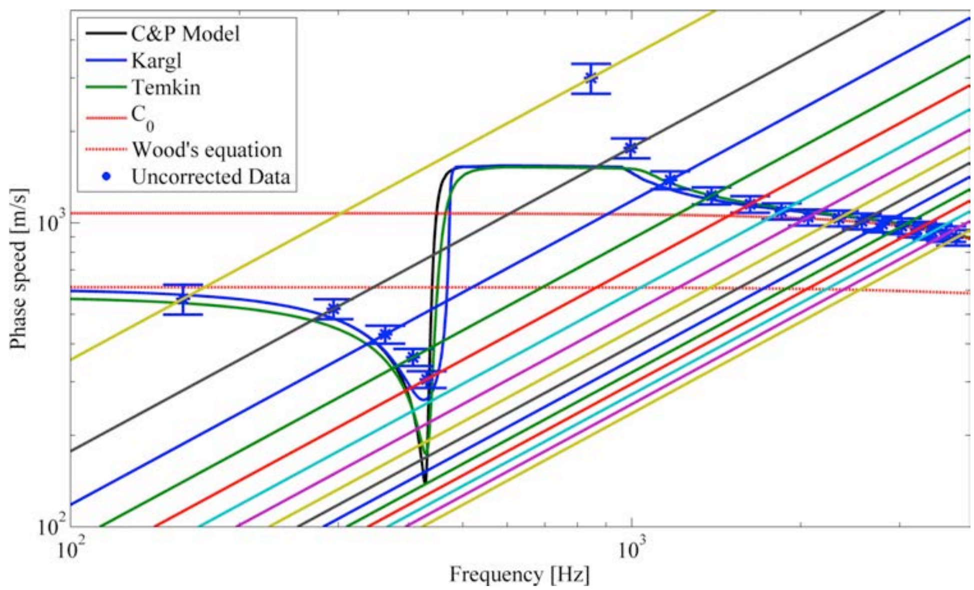

Fig. 3. Measured phase velocity in a model fish school made of encapsulated bubbles with thin rubber shells is shown. Bubble radii was 7.6 mm and void fraction was 2.5 x 10^{-4}. Lines of constant wave number are also shown to illustrate the new technique used to extract additional phase speed measurements from spectra. Several models for sound propagation in collections of bubbles are also shown. The effect of the finite-impedance waveguide walls has also been incorporated. The best model here is the Kargl model, which is the only model shown that incorporates multiple scattering, and hence is the only model appropriate for high void fractions and hence densely packed schools. Error bars represent measurement uncertainty due to resonator length uncertainty and finite frequency resolution.

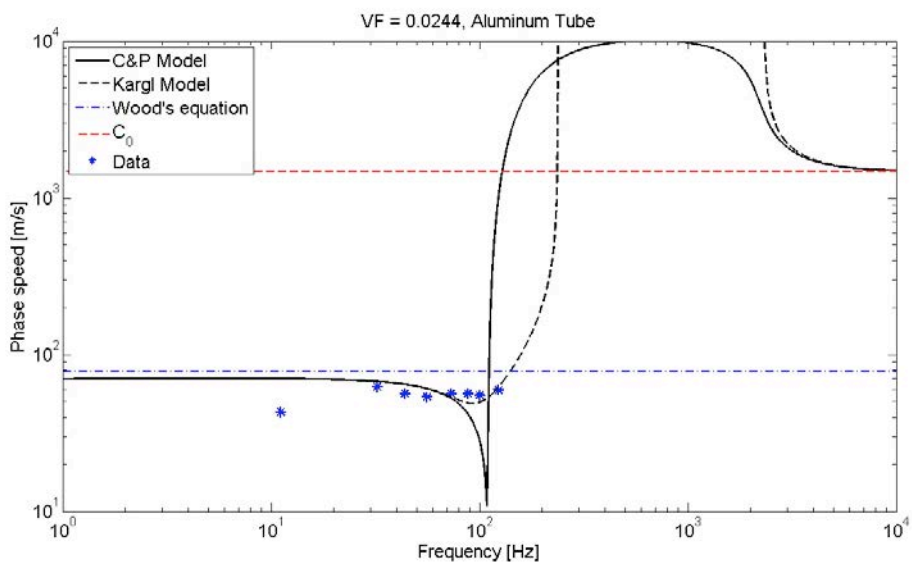

Fig. 4. A plot similar to that shown in Fig. 3, from last year's report is shown. This plot illustrates the advancement that has been made this year using our improved resonator technique. Note that in Fig. 3, using the new technique, about 20 data points have been obtained, both above and below the individual bubble resonance. Here, only about 8 data points have been obtained, all below resonance.

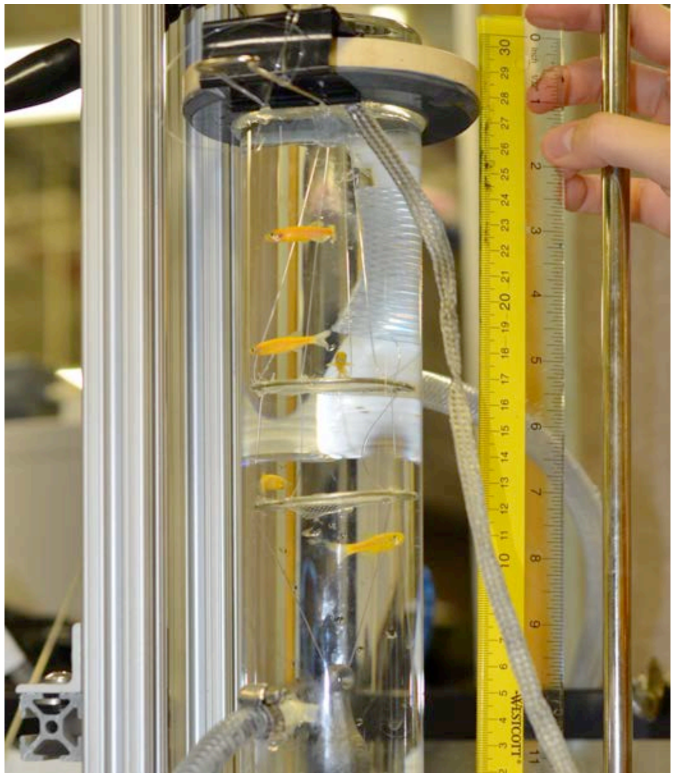

Fig. 5. The 1-D acoustic resonator with live zebra fish (*Danio rerio*).

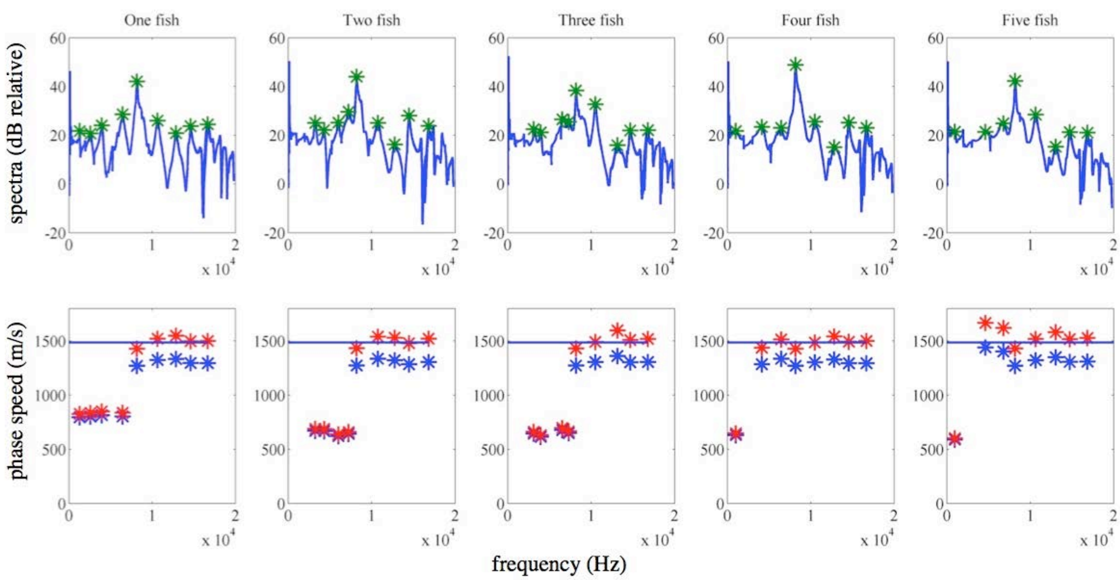

Fig. 6. Preliminary measured waveguide resonances (upper) and extracted fish school phase speeds (lower) are shown. Red stars in the lower curves have been corrected for elastic waveguide effects. The blue stars were the original uncorrected data. Comparison of these measurements to models is forthcoming.

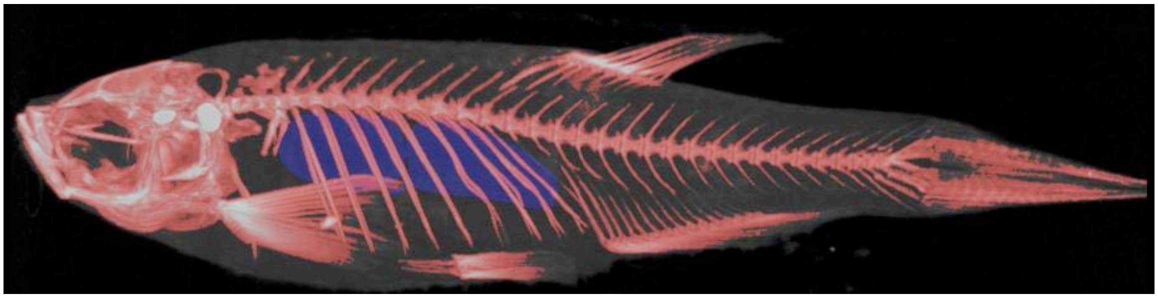

Fig. 7. A μ-CT scan of one of the zebra fish used in the resonator measurements is shown. This data was processed to show bones in reddish/pink/white colors and the swim bladder is shown in dark blue. Volume and density measurements will be extracted from this type of data.

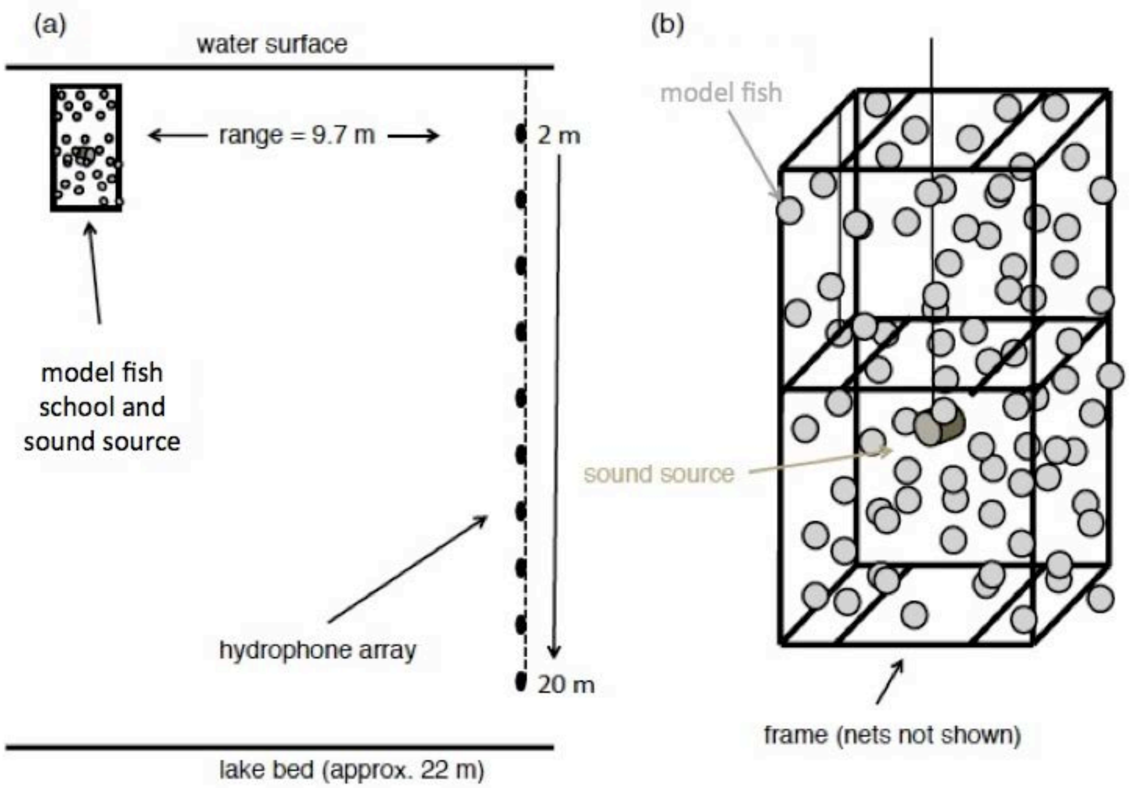

Fig. 8. The apparatus used to measure the free field sound speed and attenuation in a model fish school at LTTS is shown. The model fish were rubber-shelled air-filled balloons. The school was held together with a metal frame and netting. A source (Navy J-13) was placed in the middle of the model school. A five-element hydrophone array was used to receive the wideband signals from the source.

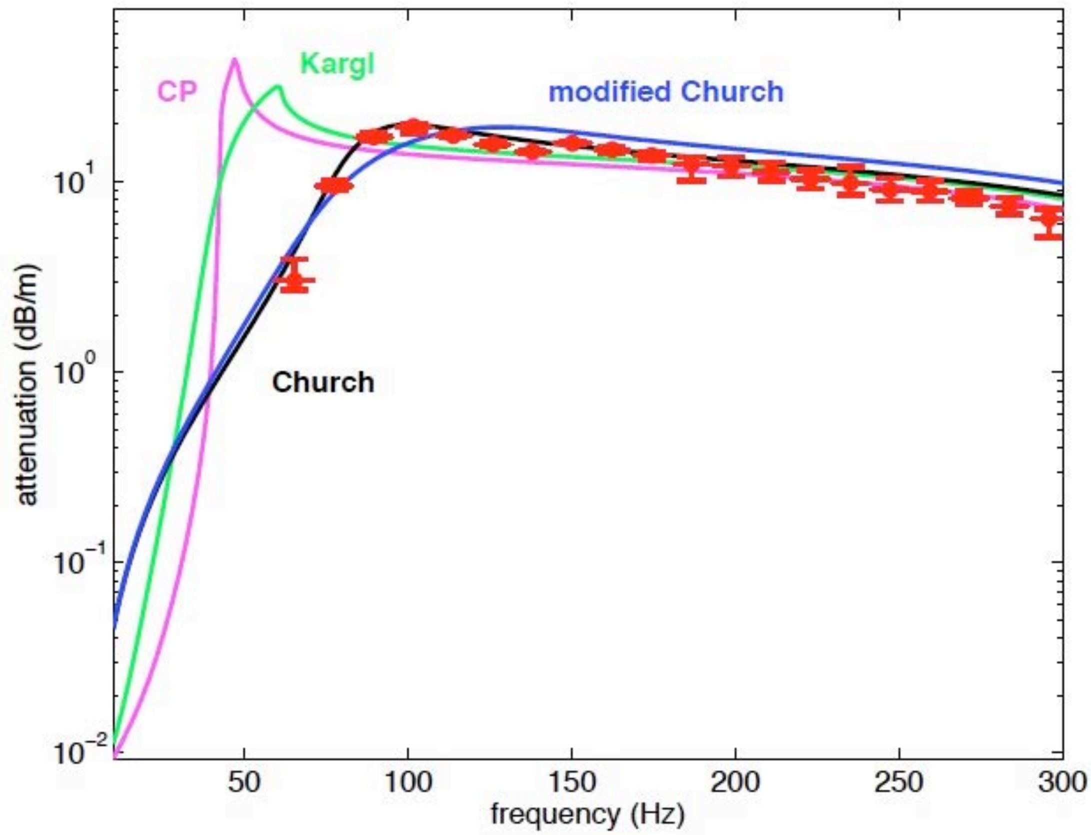

Fig. 9. Measurements of attenuation in a model fish school are shown. The measurements were obtained using the apparatus shown in Fig. 8. Three models are also shown. CP is the Commander and Prosperetti model [12], Kargl [11] and Church [10] are also shown. Finally, a modified Church model (still under development) is shown. The CP model does not account for shells or multiple scattering. The Kargl model accounts for multiple scattering but no shell. The Church model accounts for shells but no scattering. The modified Church model accounts for the shell, and uses the Kargl approach to account for multiple scattering. It is clear that the shell must be accounted for, but in this data, it is not clear that the multiple scattering is even encountered, as the Church model does a good job describing the data.

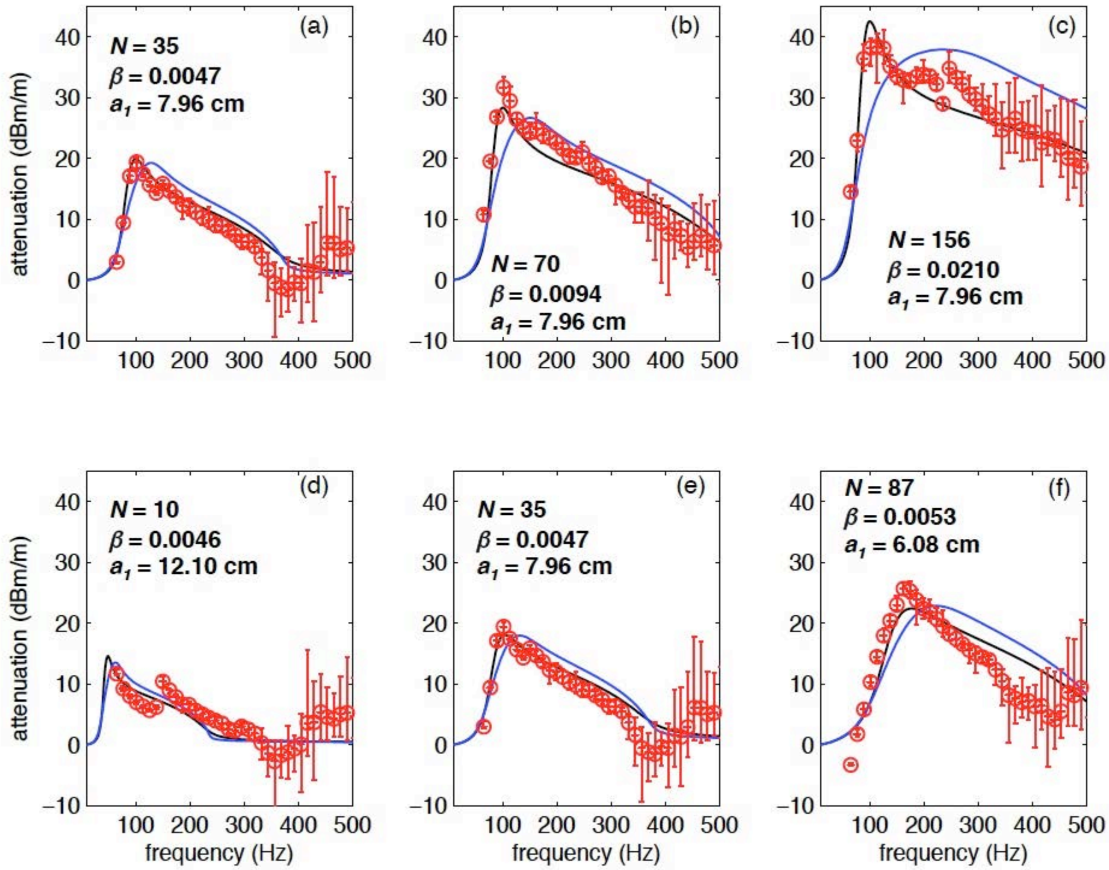

Fig. 10. Measurements of attenuation in model fish schools are shown. The measurements were obtained using the apparatus shown in Fig. 8. Only the Church [10] (black curves) and modified Church models (blue curves) are shown. N represents the number of model fish in the school, β is the void fraction, and a_1 is the mean radius of the swim bladder. Changes in swim bladder volume with depth are ignored. As expected, attenuation increases with fish school density (increasing N), and frequency shifts with swim bladder size, as expected. In most cases, it appears that ignoring multiple scattering effects (the Church model) does a better job of describing the data.

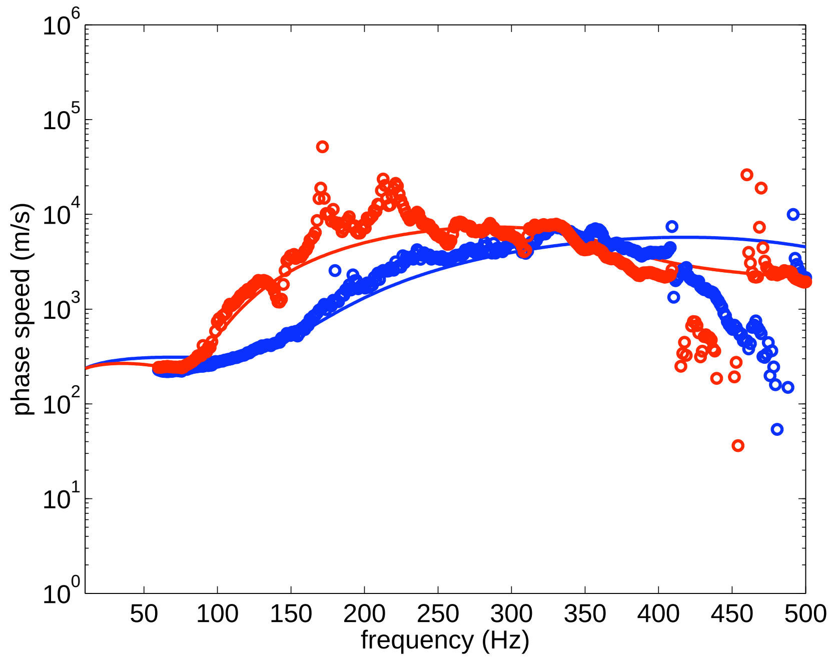

Fig. 11. Phase speeds associated with two of the cases shown in Fig. 10 are shown here. Data (circles) and the Church model (lines) for the 7.96 cm (red) and 6.08 cm (blue) model swim bladders are shown. These correspond with the attenuation data from Fig. 10(e), VF = 0.0047, and (f), VF = 0.0053, respectively. We are using a new technique to extract this phase speed data, and we consider these results to be preliminary. The technique did not work as well on the other cases from Fig. 10.

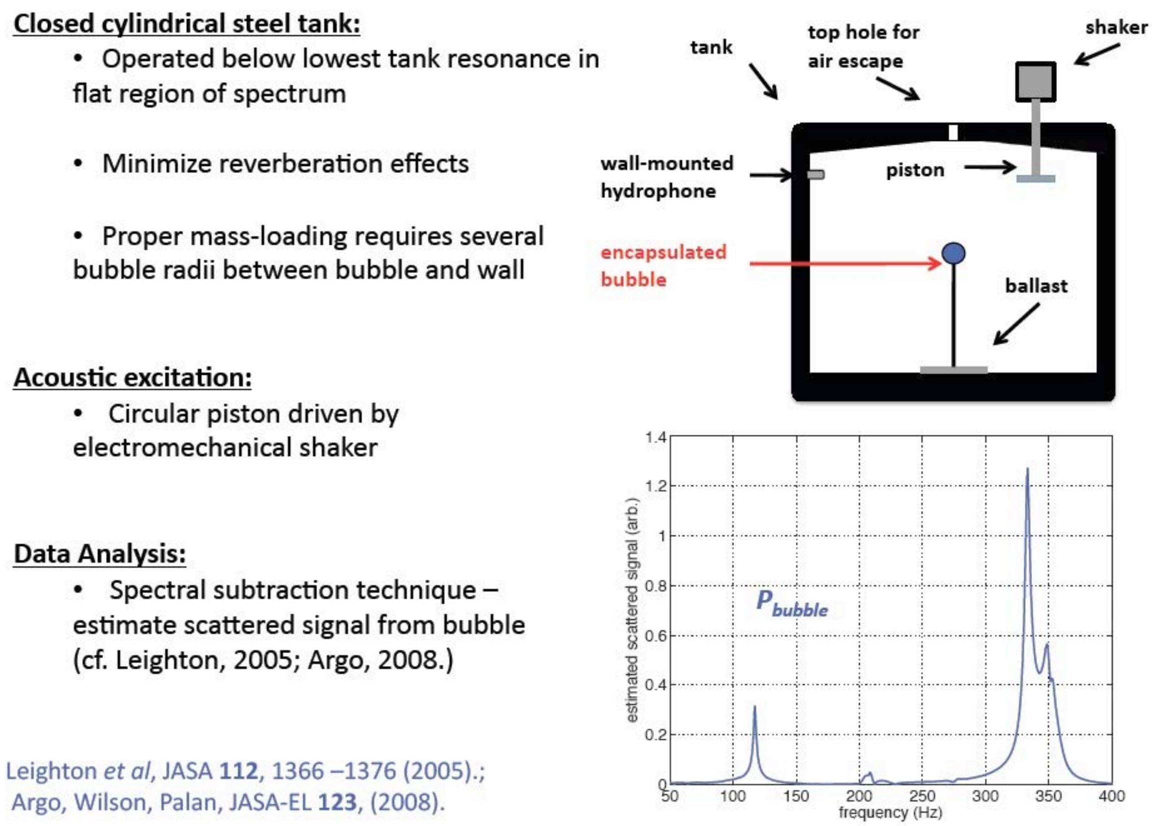

Fig. 12. Apparatus and method for measuring the resonance response from a single fish, or in the current reporting year, a single artificial swim bladder.

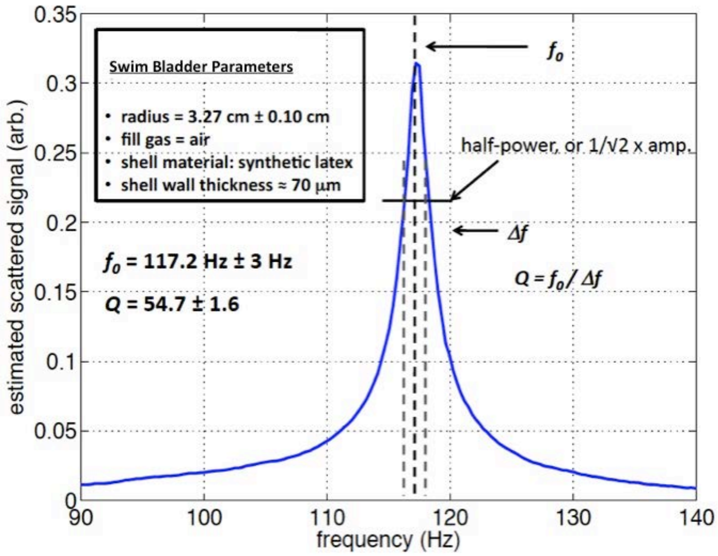

Fig. 13. Measurement of the scattering from a single artificial swim bladder is shown. Physical parameters are shown within the figure. Resonance frequencies and quality factors can be extracted.

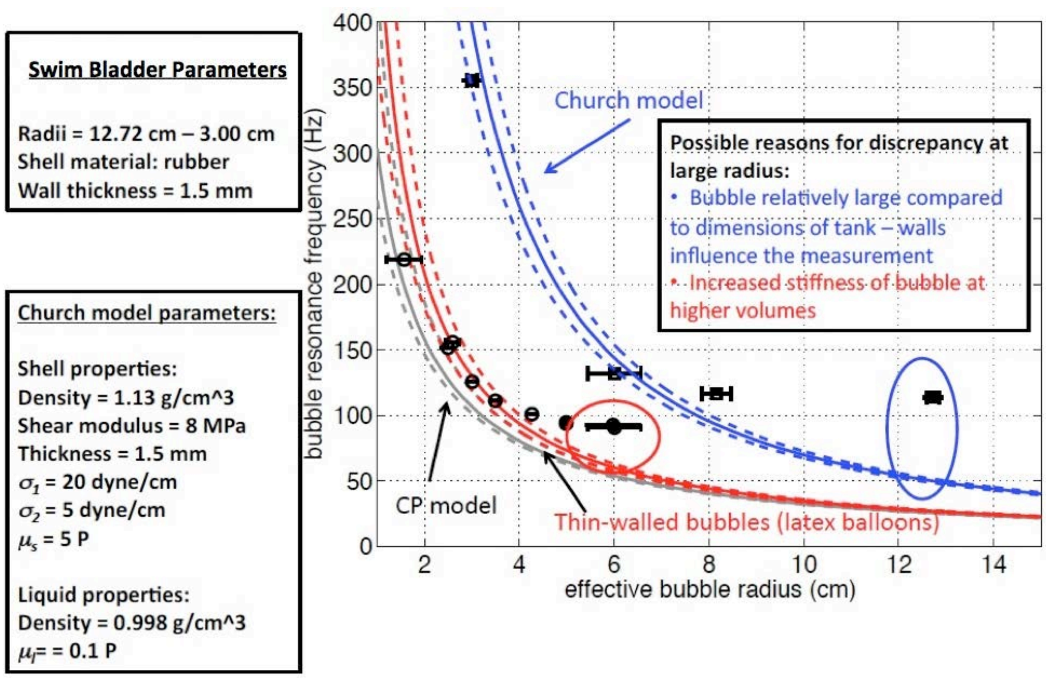

Fig. 14. Measurements of the resonance frequency of artificial swim bladders composed of rubber-shelled, air-filled bubbles are shown. These measurements were extracted from the peak of scattering curves like those shown in Fig. 13. Blue and red curves are the Church model for resonance frequency. As the shell gets thicker (data around blue curves) the effect of the shell is large, and CP model (gray curves) greatly under-predicts the resonance frequency. For thin shells, the Church model (red curves) still does a better job than the CP model, but the effect of the shell is not as large. Circled data points indicated likely experimental bias, as described in the text box within the figure.