MEASUREMENTS OF ACOUSTIC BACKSCATTERING FROM SYNTACTIC-FOAM SPHERES

Lian Sheng Wang and Stephen P. Robinson

National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK

Lian.wang@npl.co.uk

Abstract: *Spherical targets were fabricated by machining syntactic foam samples from three products, HYTAC-W, HYTAC-WF, and HYTAC-XTL manufactured by CMT Materials, Inc. The compressional and shear wave speeds in the materials were determined by measurements. The nominal diameter of the spheres was 60 mm. Each sphere was held within its own minimum-knot bag woven of monofilament nylon and suspended in a laboratory tank during measurements in order to minimise the additional scattering effects.*

Acoustic backscattering was measured by ensonifying each sphere with a short-duration broadband signal generated with a monostatic transducer, spanning the respective frequency range 80-200 kHz. Measurements of backscattering by the syntactic foam spheres were accompanied by similar measurements made with a sphere made of tungsten carbide with 6% cobalt binder, with a diameter of 75 mm which has a known response in order to verify the measurements. Measured form functions are compared with model prediction using the acoustic properties measured previously in a separate study.

keywords: *syntactic foam; acoustic backscattering; standard calibration target*

1. INTRODUCTION

The standard-target method [1-5] is the most accurate, operationally convenient, rapid, and cost-effective method for calibrating active sonars, whether used for measurement or used for quantitative imaging.

Standard targets have been fabricated from diverse materials. For solid homogeneous elastic spheres, these materials have included, among others, electrolytic-grade copper [6], tungsten carbide with 6% cobalt binder [7], alternatively with nickel binder, steels [8], and an aluminum alloy [9]. For hollow elastic spheres, the shell materials have included aluminum [10-12] and alumina [13]. For fluid-filled focusing spheres, the shell materials have included steels [14-16]. Solid-layered spheres have also been fabricated for calibration purposes, witness those manufactured by Subsea Asset Location Technologies (SALT) Ltd., Portland, Dorset, UK. Other, non-spherical targets have also been fabricated.

The exemplified diversity of material types and sizes just for the spherical targets witnesses to needs. These include considerations of sonar transmit frequency and frequency band, constraints on target strength, transducer nearfield-farfield transition, ordinary operating conditions at sea, and environmental conditions at the calibration site relative to those at the application site [17]. In every case, fabrication is a more or less complicated process that adds considerable value to the standard target, usually far in excess of the nominal cost of the material.

This study intends to determine the suitability of syntactic foam (SF) materials for use as a standard target as they are easy to machine and slightly buoyant. Three solid spheres were made of three syntactic foam materials with different mechanical and thermal properties. Three critical physical properties of each of three samples of syntactic foam were measured previously [18]. These were the mass density, compressional wave sound speed, and shear wave sound speed, assuming sample isotropy.

The goals of the present study are to measure the acoustic backscattering properties of three syntactic-foam spheres, and to compare the experimental results with the modelled results. Measurements in Acoustic Pressure Vessel with one of syntactic sphere will be reported in [19].

2. MEASUREMENT

Three product samples were provided by Engineered Syntactic Systems, CMT Materials, Inc., Attleboro, Massachusetts, USA. Each of these materials has other distinctive properties, for example, as quantified by thermal conductivity, thermal expansion coefficient, compressive strength, and flexural toughness, among other things.

They are HYTAC-W, HYTAC-WF and HYTAC-XTL, and referred to as W, WF and XTL hereafter. Their main physical characteristics are listed together with these measured physical properties: mass density, compressional wave speed, and shear wave speed, compressive strength Table 1. The wave speeds were measured at room temperature 20.5ºC. This assumes isotropy, which is plausible given the weakness of the observed anisotropy, less than 0.1% in two of the syntactic foams and perhaps as much as 2% in the third [18].

Three solid syntactic spheres with nominal diameters of 60 mm were fabricated from the bulk samples by machining. A precision sphere of tungsten carbide (WC) with 6% cobalt binder, with diameter 75 mm, was procured for comparative measurements. It is referred to as the WC sphere or WC75. Each sphere was bound in its own minimum-knot bag woven of monofilament nylon fishing line [4] to enable suspension.

The measurements of backscattering reported here were carried out in NPL's small open water tank (SOWT). The SOWT is 2.5 m x 1.5 m on the surface and 1.5 m deep. The measurements in SOWT were at a room temperature of 18.5°C.

Material	Density [kg/m^3]	Compressional wave speed [m/s]		Shear wave speed [m/s]		Attenuation [dB/λ]	
		measured	model	measured	model	compr-essional wave	shear wave
WC	14,900		6,853		4,171	0	0
W	716	2,110	2,118	1,121	1,100	0.2	0.9
WF	913	2,708	2,702	1,389	1,356	0.01	1.0
XTL	712	2,762	2,641	1,361	1,300	0.5	1.2

Table 1: *Physical properties of test spheres*

The experimental set-up to measure backscattering from the spherical targets is shown in Fig. 1. Short-pulse signals were used for the measurements in order to cover a large range in frequency. The transducer used provided good signal to noise ratio for the frequency band 80-200 kHz. All measurements were monostatic, with a single transducer used for both transmission and reception. The transmit signal consisted of a single cycle of a sinusoidal signal at 125 kHz generated by an Agilent 33220A signal generator coupled to a PA 400 (Precision Acoustics) power amplifier, thence a broadband transducer, the Reson TC-2130. This transducer is a piston type with a diameter of 50 mm.

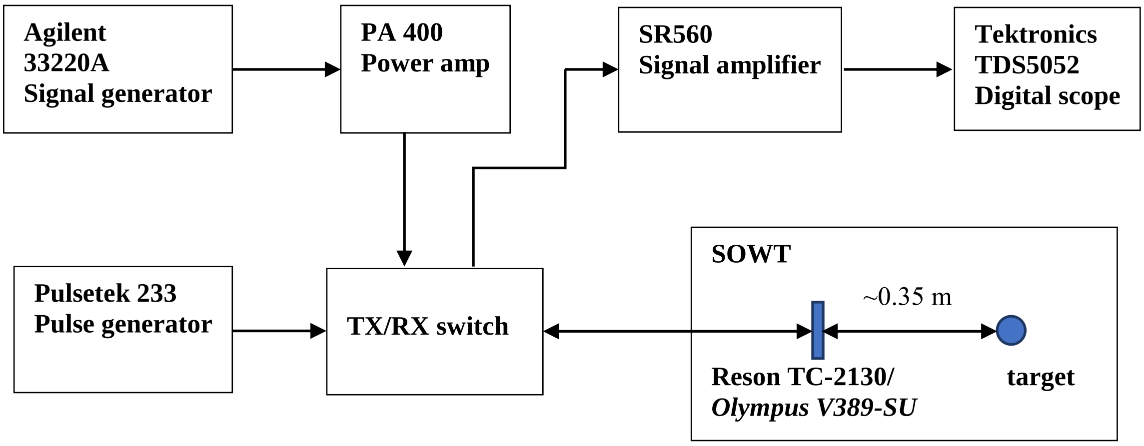

Fig. 2. Experimental set-up, where SOWT denotes the Small-Open-Water Tank

Because of the monostatic configuration with the transducer as both transmitter and receiver, a Pulsetek 233 pulse generator was used to control a TX/RX switch that short-circuited the input to the SR560 signal amplifier when the power amplifier was transmitting, and then connected it to the received signal from the transducer after a fixed time delay from the time of transmission. The received signals were filtered and amplified with the signal amplifier before being sent to the Tektronic TDS5052 digital scope to store the time waveforms of the measured signal for further processing. The signal waveforms were averaged typically 100 times in order to improve the signal-to-noise ratio.

Acoustic measurements were performed in SOWT on all three syntactic foam spheres. The water temperature was nearly constant at 18.5°C. Similar measurements were made with the 75-mm-diameter WC sphere, which has a known theoretical form function, for comparison purposes.

The acoustic results are expressed through a generalized form function, as in [5].

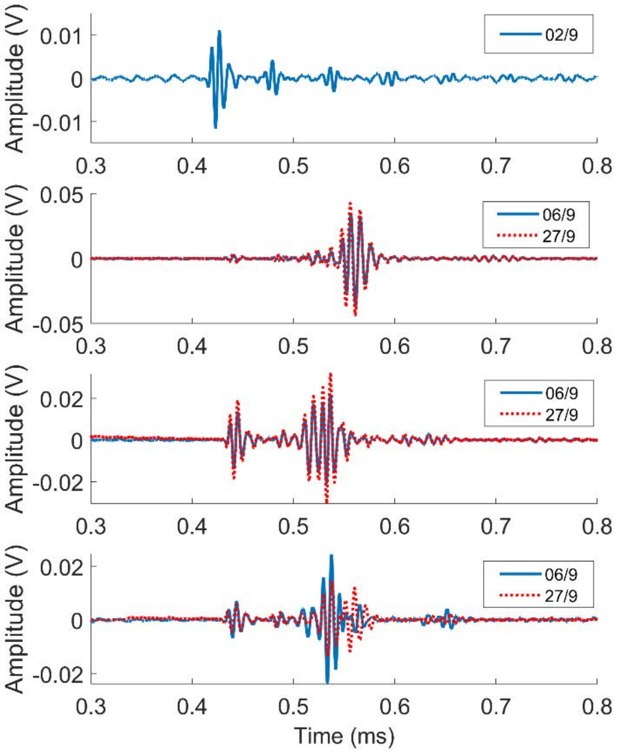

Fig. 1. Backscattering signal from target: WC, W, WF and XTL spheres from top to bottom plots

3. RESULTS AND DISCUSSION

Four spheres were ensonified in the frequency band 80-200 kHz using the TC2130 transducer in the SOWT. Echo waveforms are shown in Fig. 2 for WC75 and each of the three syntactic-foam spheres. These are duplicated for measurements repeated on the SF spheres after 21-day immersion.

The expected periodical wave train of circumferential waves due to scattering by a sphere is observed with the WC75 sphere. The first echo in the wave train represents reflection from the front interface of the sphere. This echo is separated reasonably well from the second echo in the wave train. This first echo can be used as the incident wave at the target in the calculation of the form function [20]. There was only a single distinct and dominant echo from the W sphere. The width of the echo was greater than that of the first echo from the WC sphere, indicating a narrower frequency response for the W sphere. There were two echoes from the WF sphere, and the second one is higher than the first one. The first echo was almost a replica of the first echo by the WC75, while the second echo had a longer duration. There were three separate echoes from the XTL sphere, with much smaller first and third echoes in comparison with the second echo.

Measured form functions of the WC75 and the three SF spheres are shown in Fig. 3. The form function was also calculated by a model that is applicable to an elastic sphere with absorption [21] for comparison. The density and sound speeds of all the spheres are listed in Table 1 for the model. The agreement between the modelled and measured form functions is very good over most of the frequency band for the WC sphere. The modelled results are also in good agreement with measured results of W and WF spheres. However, there is much greater difference between the predicted and measured form functions for the XTL sphere, especially for the second measurement.

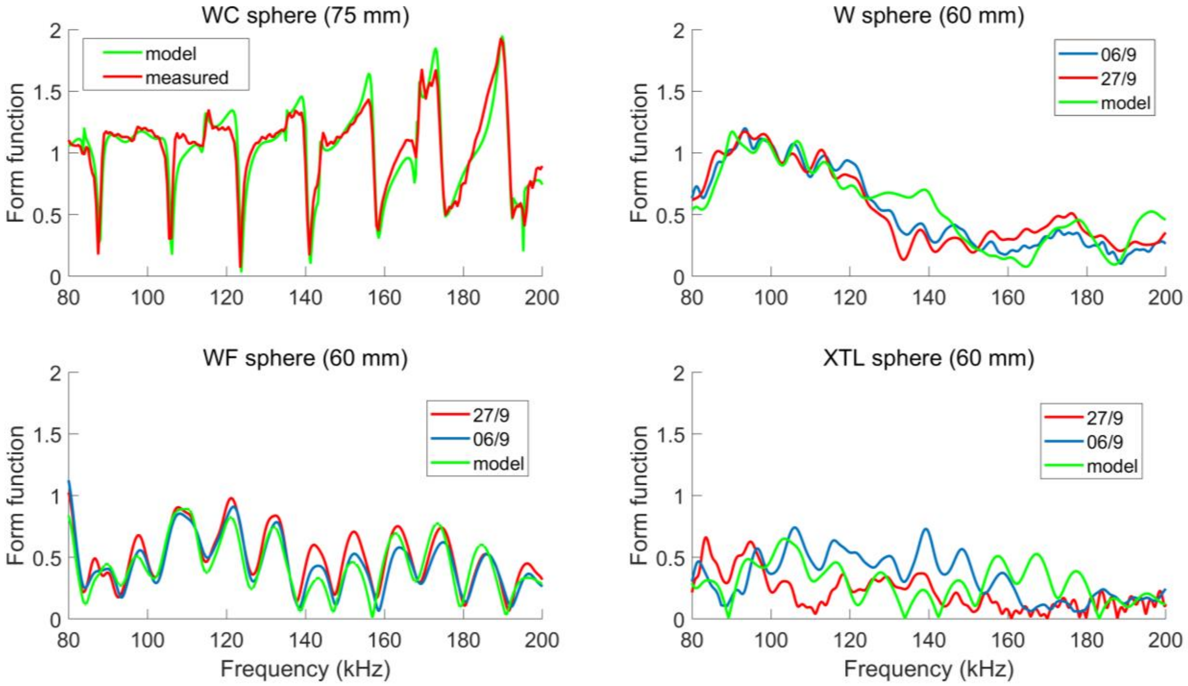

Fig. 3. Generalized backscattering form function of WC and three SF spheres

It was not unexpected that the backscattering from the three syntactic spheres was very different, because of the differences in their acoustic properties [18]. It is noticed that the W sphere shows a higher and relatively constant level of return over the frequency band 90-120 kHz than that at frequencies higher than 130 kHz. The relatively smaller bandwidth in the form function of the W sphere results in a longer pulse duration in the backscattered signal, as shown in Fig. 2. There are two dominant pulses in the reflected signal from the WF sphere in time domain, producing a periodical oscillation in its form function in the frequency domain as shown in bottom left plot of Fig. 3. The frequency span of the oscillation is about 10 kHz. The target echo is weakest from the XTL sphere in comparison with the echoes from the W and WF spheres.

Unlike metallic materials, the SF materials may be subject to water ingression while submerged. To examine the effects of water ingression into the materials, two measurements were carried out with a time span of 21 days, during which all three syntactic spheres remained submerged in water. There are reasonably good agreements among the measured data of the W and WF spheres over the time period. However, there are substantial changes between the two measurements of the XTL sphere both in time domain and in the frequency domain as shown in Fig. 3.

The acoustic scattering from an isotropic and homogenous spherical solid object depends only on its size, mass density, and sound speeds compared to the respective quantities of the immersion medium, namely water. This means that the bulk property of the XTL material changes with time of soaking as confirmed by the other tests [18]. It is likely that the sphere is still isotropic in its properties, but not homogenous, with presumed radial dependence. A surface layer with higher concentration of water was formed during the soaking, and the thickness of the layer should be a function of the soaking time. It can be seen that the form function from early measurement is closer to the predicted result as the effect of water ingression was less due to a short immersion time at the time of measurement, but there is little correlation between the second measurement and prediction because the prediction was only sensible with the initial acoustic properties before exposed to water. There was no or very little of water ingression into the W and WF spheres so that their backscattering responses remained reasonably constant.

4. SUMMARY

Experimental studies were performed to measure acoustic backscattering from three 60-mm-diameter spheres made of syntactic foams. Generalized form functions were determined over the frequency band 80-200 kHz.

The form functions from the three 60-mm-diameter syntactic-foam spheres are very different. The W and WF spheres are stronger targets than the XTL sphere. The W sphere showed little front interface echo, and it displayed a relatively flat response over the frequency band 90-120 kHz, while the WF sphere response was quasi-periodic, with period of order 10 kHz.

Both the W sphere and WF sphere showed stable backscattering strengths after long periods of immersion, while there were large changes with immersion time from the XTL sphere.

ACKNOWLEDGEMENTS

The authors are grateful to Kenneth G. Foote of WHOI who proposed the study. The following are thanked for sharing basic information on syntactic foams: Jim Teague of J. Teague Enterprises, LLC; Peter J. Fitzgerald and William J. Douglas, Global Dynamix; and Thomas J. Murray, Engineered Syntactic Systems, CMT Materials, Inc., who also generously provided the product samples that were measured in this study.

References

[1] K. G. Foote, H. P. Knudsen, G. Vestnes, D. N. MacLennan, and E. J. Simmonds, “Calibration of acoustic instruments for fish density estimation: a practical guide*,” ICES Coop. Res. Rep.,* no. 144 (1987), 69 pp.

[2] K. G. Foote, D. Chu, T. R. Hammar, K. C. Baldwin, L. A. Mayer, L. C. Hufnagle, Jr., and J. M. Jech, “Protocols for calibrating multibeam sonar,” *J. Acoust. Soc. Am.*, 117, 2013-2027 (2005)

[3] ANSI/ASA S1.20-2012, *American National Standard: Procedures for Calibration of Underwater Electroacoustic Transducers* (Acoustical Society of America, Melville, NY, 2012)

[4] D. A. Demer, L. Berger, M. Bernasconi, E. Bethke, K. Boswell, D. Chu, R. Domokos, A. Dunford, S. Fässler, S. Gauthier, L. T. Hufnagle, J. M. Jech, N. Bouffant, A. Lebourges-

Dhaussy, X. Lurton, G. J. Macaulay, Y. Perrot, T. Ryan S. Parker-Stetter, S. Stienessen, T. Weber, and N. Williamson, "Calibration of acoustic instruments," *ICES Coop. Res. Rep.*, no. 326 (2015), 133 pp.

[5] K. G. Foote, "Standard-target calibration of active sonars used to measure scattering: Principles and illustrative protocols," IEEE J. Oceanic Eng., 43, 749-763 (2018); doi 10.1109/JOE.2017.2713538 [Date of Publication: 14 July 2017]

[6] K. G. Foote, "Optimizing copper spheres for precision calibration of hydroacoustic equipment," *J. Acoust. Soc. Am.*, 71, 742–747 (1982)

[7] K. G. Foote and D. N. MacLennan, "Comparison of copper and tungsten carbide calibration spheres," *J. Acoust. Soc. Am.*, 75, 612-616 (1984)

[8] Y. Miyanohana, K. Ishii, and M. Furusawa, "Spheres to calibrate echo sounders at any frequency," *Nippon Suisan Gakkaishi,* 59, 933-942 (1993)

[9] K. G. Foote, D. T. I. Francis, and P. R. Atkins, "Calibration sphere for low-frequency parametric sonars," *J. Acoust. Soc. Am.*, 121, 1482-1490 (2007)

[10] K. J. Diercks and R. Hickling, "Echoes from hollow aluminum spheres in water," *J. Acoust. Soc. Am.*, 41, 380-393 (1967)

[11] T. K. Stanton, D. Chu, J. M. Jech, and J. D. Irish, "A broadband echosounder for resonance classification of swimbladder-bearing fish," In: *Oceans 2007 MTS/IEEE Conference Proceedings*, 3 pp.; doi: 10.1109/OCEANSE.2007.4302346

[12] T. K. Stanton and D. Chu, "Calibration of broadband active acoustic systems using a single standard spherical target," *J. Acoust. Soc. Am.*, 124, 128-136 (2008)

[13] P. R. Atkins, D. T. I. Francis, and K. G. Foote, "Broadband ultrasonic target strengths of hollow ceramic flotation spheres," In: *Oceans 2007 IEEE Conference Proceedings*, 4 pp.; doi: 10.1109/OCEANSE.2007.4302487

[14] D. L. Folds and C. D. Loggins, "Target strength of liquid-filled spheres," *J. Acoust. Soc. Am.*, 73, 1147-1151 (1983)

[15] D. M. Deveau and A. P. Lyons, "Fluid-filled passive sonar calibration spheres: design, modelling, and measurement," *IEEE J. Ocean. Eng.*, 34, 93-100 (2009)

[16] D. M. Deveau and A. P. Lyons, "Corrections to 'Fluid-filled passive sonar calibration spheres: design, modelling, and measurement'," *IEEE J. Ocean. Eng.*, 34, 202 (2009)

[17] K. G. Foote, "Using a sonar in a different environment from that of its calibration: effects of changes in salinity and temperature," In: *Oceans 2018 MTS/IEEE Conference Proceedings*, 5 pp.; doi: 10.1109/OCEANS.2018.8604573

[18] L. Wang, K. G. Foote, P. D. Theobald, and S. P. Robinson, "Material properties of three syntactic foams," In: *Oceans 2017 MTS/IEEE Conference Proceedings*, 6 pp.; doi: 10.1109/OCEANSE.2017.8084739

[19] L. Wang, K. G. Foote and S. P. Robinson, "Acoustic backscattering spectra of three syntactic-foam spheres", IEEE Oceans 2019

[20] L. R. Dragonette, S. K. Numrich, and L. J. Frank, "Calibration technique for acoustic scattering measurements," J. Acoust. Soc. Am., 69, 1186–1189 (1981)

[21] Takahi Hasegawa, Yoshiko Kitagawa, and Yumiko Watanabe, "Sound reflection from an absorbing sphere," The Journal of the Acoustical Society of America 62, 1298 (1977); https://doi.org/10.1121/1.381629