Ultrasonic focusing through a steel layer for acoustic imaging

Andreas Sørbrøden Talberg, Tonni Franke Johansen, Svein-Erik Måsøy, Tarjei Rommetveit, Svein Brekke, and Hefeng Dong

Citation:
Andreas Sørbrøden Talberg, Tonni Franke Johansen, Svein-Erik Måsøy, Tarjei Rommetveit, Svein Brekke, and Hefeng Dong , Ultrasonic focusing through a steel layer for acoustic imaging (2018) . In: Proceedings - IEEE Ultrasonics Symposium 2018.
DOI:10.1109/ULTSYM.2018.8580052

Ultrasonic focusing through a steel layer for acoustic imaging

Andreas Sørbrøden Talberg*,†, Tonni Franke Johansen*,†,‡, Svein-Erik Måsøy*,†,
Tarjei Rommetveit§, Svein Brekke§, and Hefeng Dong*,†
*Centre for Innovative Ultrasound Solutions (CIUS)
†Norwegian University of Science and Technology (NTNU), Trondheim, Norway
‡SINTEF Digital, Trondheim, Norway
§Archer BTC, Bergen, Norway
Email: andreas.talberg@ntnu.no

***Abstract*—Ultrasonic tools are being used for imaging in a large variety of fields, spanning from medical applications in a hospital to applications deep down in oil and gas wells. When applying ultrasonic imaging techniques to image through elastic materials, such as steel, one of the main challenges these tools have to overcome is the high impedance differences between the steel and the surrounding media, making it a barrier for the acoustic wave. Putting effort into focusing through steel, maximizing the energy propagating to a point on the outside of the elastic layer, we aim to use back scattered pulses from this point to conduct imaging of the volume outside a steel layer as well as for flow monitoring using Doppler techniques.**

To investigate the focusing of an ultrasonic pulse through an elastic layer, a numerical study was conducted using the 2D finite-difference time-domain (FDTD) simulation tool SimSonic. Applying the time delays corresponding to focusing in a water layer to a linear phased array, shows poor focusing through an elastic layer. By implementing beamforming to the ultrasonic array, calculated using techniques related to time reversal (TR) and by a beamforming tool based on ray-tracing, focusing was achieved. At the desired focus depth it is shown that for small angles, utilizing pressure waves in the elastic layer, we can get a focused pulse propagating through the desired focus position with 3dB beamwidths of 4.2mm and 3.7mm, depending on whether the TR technique or the beamforming code was being used respectively. Increasing the angle of incidence to focus via conversion to shear waves in the elastic steel layer, the focused pulse's maxima misses the desired focus position with 0.9mm, while the 3dB beamwidth is 5.1mm. It is shown that implementing techniques related to TR for focusing at small angles, and the beamforming code for both smaller and larger angles, makes it possible to focus the energy of the transmitted pulse through the steel layer.

***Keywords* - Ultrasound, Pulse-Echo, Steel, Focusing, Beamforming**

I. Introduction

At an oil or gas well, the operators have to be in total control of all the aspects of the operation to ensure that all the safety and environmental requirements during the production are met. Due to the huge consequences an uncontrolled event at an oil or gas well can cause, there are several requirements a well has to fulfill. Placing a cement sheath outside the casing in a borehole with the main purpose of preventing uncontrolled hydrocarbon flow is one of the operations which are conducted for the well to meet these requirements. If hydrocarbons were to leak to the surroundings, this could be disastrous for both the environment and the responsible companies [1], [2]. The operation of placing the cement sheath is difficult and can leave areas without cement if not conducted properly. Even if the cement is initially satisfying the requirements regarding isolation, temperature changes, chemical processes in the well, and changes in downhole conditions that can induce stresses, can and may destroy the integrity of the cement sheath over time [3], [4]. Some of these defects that can occur in a cement sheath are illustrated in Fig. 1. To inspect the properties of the cement sheath, both sonic and ultrasonic logging tools are in use, *e.g.* for observing the cement-to-casing bond or to detect flow channels within the cement layer [5]. As the pulse-echo technique has some limitations when trying to detect defects occurring within the cement sheath, *e.g.* due to little energy penetrating through the material of the casing [6], [7], efforts have been put into improving this technique. The following work will present numerical work conducted using the 2D finite-difference time-domain software SimSonic [8], [9] with the aim to improve transmit focusing, increasing the energy

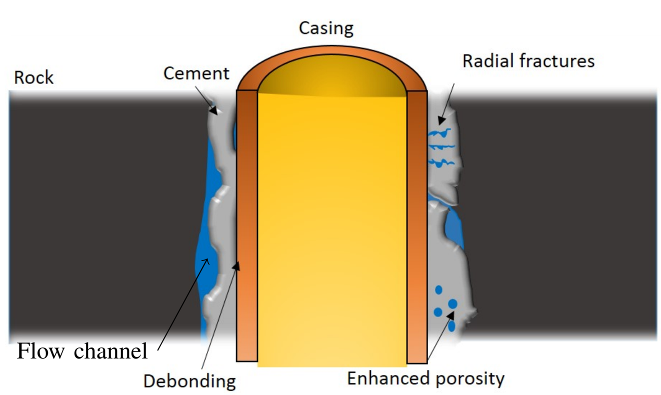

Fig. 1. Cement slurry displacement problems and defects that may occur within the cement sheath. Reprinted with permission from A. S. Talberg et al. "Laboratory experiments on ultrasonic logging through casing for barrier integrity validation", 2017 [13]

reaching the desired target point outside a casing. Due to much of the pulse energy being reflected back at the first water-steel interface, an oblique incidence angle was chosen. First, some simulations utilizing the pressure waves (*p*-waves) in steel will be presented, before a simulation utilizing the conversion to shear waves (*s*-waves) in the steel will be presented. The latter is inspected due to the transmission coefficient at a water-steel interface being higher for *s*-waves at incidence angles above the critical angle for *p*-waves than the transmission coefficient for *p*-waves [10], [11].

II. Methods

To improve the focusing through the elastic steel layer, a numerical study in the 2D FDTD simulation tool SimSonic was conducted.

The geometry of the simulation model consisted of an upper water layer of 50mm thickness, a steel layer of 8mm thickness, and a lower water layer of 40mm thickness. According to the chosen transducer center frequency, f_0 = 1.5MHz and the sound velocity in water, the element size in the model was set to dx = 0.03mm. With a width of 120mm, the whole simulation geometry was of size 4000×3267 elements ($N_x \times N_y$). With a Courant number of 0.9 and a maximum velocity in the model set to 6500m/s, the time step taken by the solver was dt = 2.9ns. At a height 30mm above the upper steel layer and 20mm from the geometry edge, a 64-element transducer (0.6mm pitch, 0.51mm element width) was inserted by defining the pressure at each transducer element position as a function of time. A sketch illustrating the simulation geometry is shown in Fig. 2 and the material parameters are listed in Table I. The signal emitted from the transducer elements was a short Gaussian pulse with a center frequency of 1.5MHz and a 3dB bandwidth of 0.75MHz. The time delay at each element was calculated using different techniques, explained in the following section. The first set of time delays used for transmitting the ultrasonic pulse was calculated as if the pulse was to focus in a pure water layer. To improve this crude attempt on focusing, a method based on time reversal was implemented. This was conducted by inserting a point source in the desired focus position (*x*=20mm, *y*=58mm) and logging the detected pressure at the intended position of the transducer elements. The time of arrival of the first pressure pulse arriving at these positions was logged and then used to calculate the time delays for transmit.

TABLE I
MATERIAL PROPERTIES USED IN SIMSONIC AND THE BEAMFORMING TOOL

Material	Parameter	Value	Unit
Water	ρ_w	1000	kg/m^3
	$c_{p,w}$	1500	m/s
	$c_{s,w}$	0	m/s
Steel	ρ_s	8000	kg/m^3
	$c_{p,s}$	5780	m/s
	$c_{s,s}$	3130	m/s

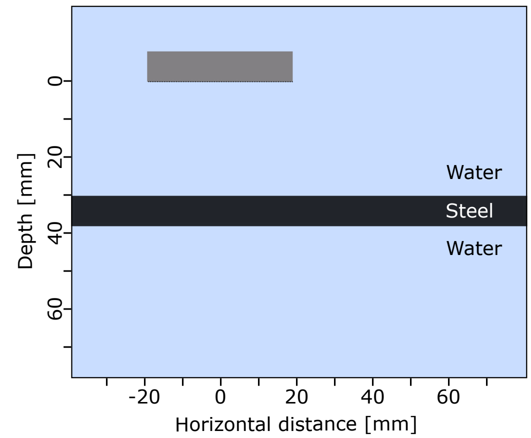

Fig. 2. Sketch of the simulation setup. The depth and horizontal distance is defined from the center of the transducer face.

The effect of transmitting pulses with a larger incidence angle was then to be investigated. This was conducted to ensure that less of the reflected energy at the upper water-steel interface propagates back to the transducer. An aim was also to utilize the increase in transmission coefficients for *s*-waves for incidence angles above 15degrees relative to the one for *p*-waves.

Examining this, a beamforming code calculating the time delays of each array element based on ray tracing was used. By inserting geometry parameters, the speed of sound in each material, and the desired focus point, time delays from the code can be read out and used in the SimSonic model. While the first iteration of the code was used to prove proper focusing in (*x*=20mm, *y*=58mm) through *p*-waves propagating in the steel layer, a second iteration was conducted with a focusing position further to the side of the array (*x*=40mm, *y*=58mm) and the time delays calculated via *s*-waves in the plate.

III. Results

The simulation using time delays calculated as if the transducer was to focus in the position (*x*=20mm, *y*=58 mm) in a pure water layer gave poor focusing through the elastic layer. To illustrate the effect of focusing, the maximum pressure in each grid of the geometry was found through all the time steps. These matrices with maximas were normalized against the maximum pressure detected in the water layers and displayed logarithmically in dB. In Fig. 3a) the pulse maxima is tracked through time, appearing as a beam being transmitted through the plate. A red circle indicates the desired focus position. At the desired focus depth (*y*=58mm) the pulse maxima can be observed at *x*=26.6mm with a 3dB beamwidth of 6.18mm. By implementing the time delays calculated using TR techniques, an improved focusing was achieved. Fig. 3b) shows a narrower beam (3dB beamwidth of 4.2mm) propagating through the desired focus point (maxima at *x*=20mm). The peak amplitude of the pulse in the focus point was decreased by 20.1dB relative to the maxima above the plate. A snapshot from the

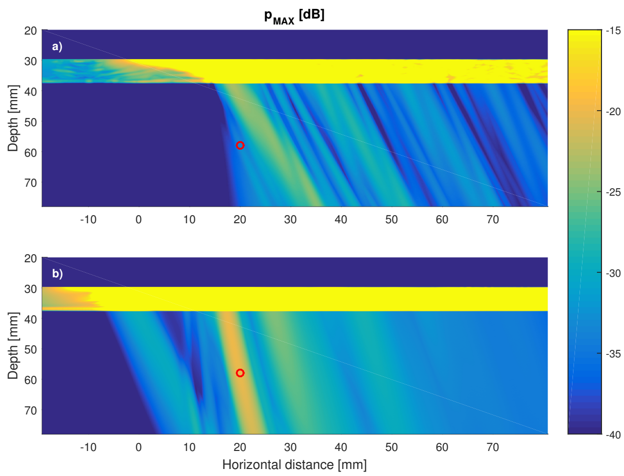

Fig. 3. The absolute value of the pressure plotted in dB scale for a) focusing as in water and b) focusing by using techniques related to TR. The red points indicate the desired focus point.

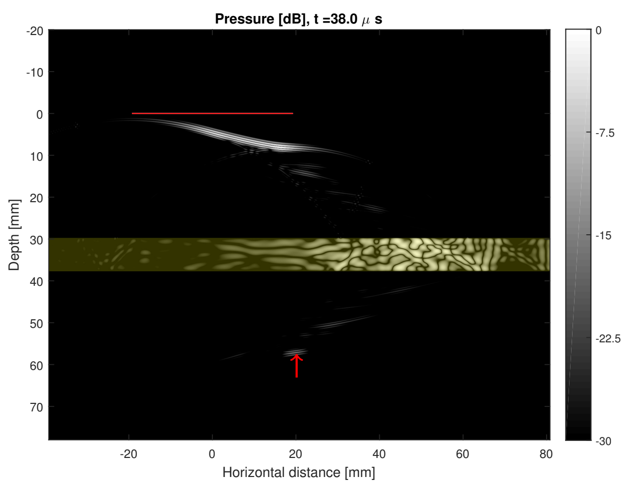

Fig. 4. Snapshot from SimSonic showing the absolute value of the pressure in dB. Time delays calculated using techniques related to TR. The red line shows position of the transducer and the arrow the desired focus.

SimSonic model, 38μs into the simulation run, is shown in Fig. 4.

To focus at larger angles, the beamforming code was implemented. Utilizing p-waves in the steel-layer, still focusing towards the desired position in (x=20mm, y=58mm), new time delays to be implemented in SimSonic was calculated. The result of this simulation is shown in Fig. 5a). The maxima of the pulse transmitted through the plate at the focusing depth was found at x=20mm and the 3dB beamwidth was 3.7mm. The amplitude in the focus was now decreased by 20.3dB relative to the pulse in the upper fluid layer. Using the beamforming to calculate the time delays for focusing at larger angles, the ability to focus via s-wave propagation in the steel plate was used. The desired focus point of (x=40mm, y=58mm) was chosen to have incidence angles larger than the critical angle of the p-wave in the simulation model, and the result of this simulation can be seen in Fig. 5b). For this

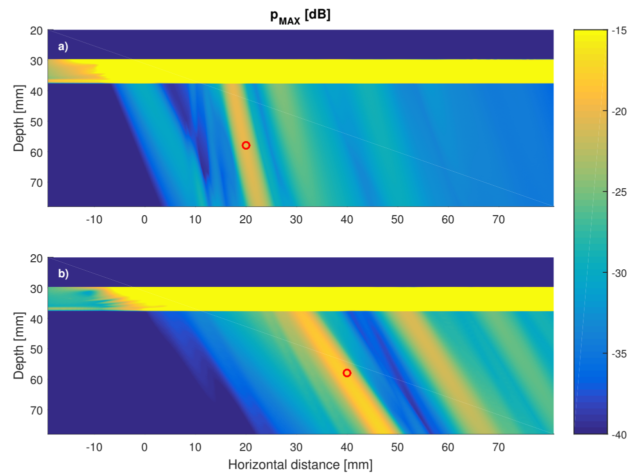

Fig. 5. The absolute value of the pressure plotted in dB scale for a) focusing towards x=20mm, y=58mm via p-waves in steel and b) focusing towards x=40mm, y=58mm via s-waves in steel, both using the beamforming code. The red points indicate the desired focus point.

simulation, the maxima at the focusing depth was obeserved at x=39.1mm while the 3dB beamwidth was 5.1mm and the amplitude reduction was 17.7dB.

IV. Discussion

The crude first attempt on focusing, using time delays calculated for focusing in water, show that no proper focusing towards the desired focus point was achieved. Using the point source simulation to log the time of arrival of the pressure pulse at the transducer position, the difference in propagation time for waves from each of the 64 elements to desired focus position was found. By applying these time differences as time delays on transmit, improved focusing was achieved. Calculating new time delays using the beamforming tool show that this tool works properly for p-waves in steel. To get more energy through to the focus point and to scatter more of the reflected energy from the upper water-steel layer away from the transducer, a higher incidence angle was inspected. By conversion from p-waves in the water layer to s-waves in the steel layer and back to p-waves in the lower water layer, focusing for incidence angles above the critical angle for p-waves in steel was achieved. From the amplitudes in the focus, an increase of 2.4dB was observed when utilizing s-waves in the steel instead of p-waves. The pulse maxima misses the desired focus point with 0.9mm, which is a topic for further investigation.

V. Conclusions

By applying new time delays to the linear phased array in the numerical model, calculated using a technique related to TR or a beamforming tool, focusing of the ultrasonic pulse was achieved. For the focusing at smaller incidence angles, the pulse propagating through the plate hits the desired focus point with 3dB beamwidths of 4.2mm and 3.7mm, depending on whether the TR technique or the beamforming code was being used respectively. The respective peak amplitudes of the pressure in the focus are in the two cases reduced by 20.1dB and 20.3dB relative to the peak amplitude above the steel layer. By increasing the incidence angle, focusing via shear wave propagation in the steel layer was achieved. The peak amplitude was reduced by 17.7dB while the 3dB beamwidth was 5.1mm. The reason for the maxima not to hit the desired focus point exactly (misses by 0.9mm), is a topic for further work.

In the future, the goal is to implement the time delays calculated using the beamforming tools in a laboratory setup at NTNU to experimentally verify the numerical work. A study on receiving the back-scattered signal from a defect behind a steel layer has also been initiated and a goal is to combine these two studies.

Acknowledgment

This work has been funded by The Centre for Innovative Ultrasound Solutions.

References

[1] I. Frigaard, S. Pelipenko, et al., "Effective and ineffective strategies for mud removal and cement slurry design", In SPE Latin American and Caribbean Petroleum Engineering Conference, Society of Petroleum Engineers, 2003.

[2] D. Calvert,Well cementing. Schlumberger, ch. preface, 2005.

[3] M. Allouche, D. Guillot, A. J. Hayman, , R. J. Butsch, and C. W. Morris, Well cementing. Schlumberger, ch. 5, 2005.

[4] L. Roy-Delage, C. Baumgarte, M. Thiercelin, B. Vidick, et al., "New cement systems for durable zonal isolation". In IADC/SPE Drilling Conference, Society of Petroleum Engineers, 2000.

[5] M. Bellabarba, et al., "Ensuring zonal isolation beyond the life of the well". Oilfield Review, 20(1), pp. 18–31, 2008.

[6] R. Hayden, et al., "Case studies in evaluation of cement with wireline logs in a deep water environment". In SPWLA 52nd Annual Logging Symposium, Society of Petrophysicists and Well-Log Analysts, 2011.

[7] R. van Kuijk, et al., "A novel ultrasonic cased-hole imager for enhanced cement evaluation". In International Petroleum Technology Conference, International Petroleum Technology Conference, 2005.

[8] E. Bossy, M. Talmant, and P. Laugier. "Three-dimensional simulations of ultrasonic axial transmission velocity measurement on cortical bone models." The Journal of the Acoustical Society of America 115.5 (2004): 2314-2324.

[9] www.simsonic.fr

[10] J.L. Rose, Ultrasonic Guided Waves in Solid Media, Cambridge University Press, 2014.

[11] J. D. N. Cheeke, Fundamentals and applications of ultrasonic waves. CRC Press, 2002.

[12] A. S. Talberg, "Experimental evaluation of broadband wave propagation in plates". Master's thesis, Norwegian University of Science and Technology, 2016.

[13] A. S. Talberg, T. F. Johansen, and I. Larsen, "Laboratory experiments on ultrasonic logging through casing for barrier integrity validation", ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering - Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology, Trondheim, Norway, June 25–30, 2017