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Tommiska, Oskari Mikael

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FEM-based time-reversal technique for an ultrasonic cleaning application

Oskari Tommiska [a,*], Joonas Mustonen [a], Petro Moilanen [b], Timo Rauhala [b], Maria Gritsevich [a,c,d], Ari Salmi [a,*], Edward Hæggström [a]

[a] Electronics Research Laboratory, Department of Physics, University of Helsinki, Finland
[b] Altum Technologies, Finland
[c] Finnish Geospatial Research Institute, Geodeetinrinne 2, 02430 Masala, Finland
[d] Institute of Physics and Technology, Ural Federal University, Ekaterinburg, Russia

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ABSTRACT

Ultrasound provides a way to clean fouled pipes in industrial settings without interrupting the production. Ultrasonic clamp-on cleaners are used to clean pipes, but they typically cannot focus the cleaning power. This leads to insufficient cleaning results in cases where the fouling is localized to certain parts of the pipe.

To solve this issue, we propose a finite-element method -based time-reversal (FEM-TR) technique for controlling the acoustic field produced by an ultrasonic clamp-on cleaner. We demonstrate by simulations and experimental validation that FEM-TR can be used to control the acoustic field in clamp-on cleaners featuring relatively few narrow-band and high-power transducers. The proposed method allows us to focus sound to arbitrary pre-selected locations inside the structure.

1. Introduction

Ultrasonic cleaning can remove and prevent fouling in industrial structures. It can increase the speed of chemical cleaning and it can mechanically remove fouling through inertial cavitation or acoustic streaming [1,2]. The removal of fouling from contaminated surfaces is mainly attributed to the inertial cavitation effect created in the fluid inside the structure being cleaned, whereas acoustic streaming prevents fouling from (re)attaching to surfaces [1]. The strength of both phenomena depends on the acoustic pressure [3,4], so to maximize the cleaning power, the local pressure near the fouling should be maximized.

Commercial ultrasonic cleaners are typically either bath or clamp-on type systems. Ultrasonic baths are used especially in cleaning of small equipment [5] but they can also be quite large [6]. However, when cleaning pipelines, ultrasonic baths may not be employed, since the whole pipeline would need to be disassembled prior to the cleaning, implying that clamp-on type systems are considered preferable. With clamp-on systems the cleaning can be continuous without any need to halt the industrial process or to disassemble the pipeline [7].

Clamp-on cleaners effectively remove fouling from the outer shell of pipes [8] but they may struggle to properly clean complicated structures located deep inside e.g., large heat exchangers. Cleaning the structure may be problematic, especially if the fouling mainly resides on internal parts. In such cases, the cleaner needs to be able to focus acoustic power to the fouled region.

This issue can be addressed by using a time-reversal (TR) technique to control the acoustic field generated by the clamp-on ultrasonic cleaner. TR is a method that can focus ultrasonic fields [9]. It relies on the reciprocity principle of the wave equation, in which initial conditions of a known field solution can be reached when the time is reversed [10]. By employing the TR technique for ultrasonic cleaning, the acoustic power can be focused to the desired area, enabling localized cleaning.

In practice, the TR technique is typically realized by recording a forward propagated signal. The recorded signal is reversed in time and transmitted back with the same equipment that was used to record it. Following from the acoustic reciprocity, backpropagated signals converge at the target location [11].

To use the TR technique, one needs to generate the forward propagated signals. In many practical use cases actuation of the forward propagated signals may not be possible, e.g. if the target area is located so that it cannot be reached without disassembly.

* Corresponding authors.

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This limitation can be solved by performing the forward actuation phase using finite-element method (FEM) simulation.

In the literature, FEM has been employed to study the cleaning action of typical non-focusing clamp-on systems [12,13]. FEM together with TR has been used for guided wave inspection of defects in pipelines [14]. To our knowledge, no other research group has previously applied FEM to employ TR in ultrasonic cleaning.

In our earlier contribution [15], we modelled a digital twin of a realistic industrial setup, consisting of an industrial size pipe and four high-power, narrowband transducers. In the FEM model the forward propagated signal was actuated by introducing a pressure source at or near the fouled area, and the propagated signal was recorded with simulated cleaning transducers. The simulated forward propagated signals can then be used to control the acoustic field in the corresponding experimental setup [16], and consequently to increase the cleaning efficiency in the desired area [17]. The introduced method is noted as FEM-TR.

Typically, experimental TR setups employ an array of broadband, low-power transducers, to avoid losses in frequency content of the initial direct impulse actuation [18]. In contrast, typical ultrasonic cleaning systems use narrowband, high-power transducers to maximize the mechanical output. Here, FEM-TR is implemented using narrowband cleaning transducers, to mimic a realistic ultrasonic cleaning system, even though the configuration is not ideal for time-reversal focusing.

In this paper we extend the work of [15], by studying the capabilities of the FEM-TR method with respect to acoustic nonlinearity, limited spatial access, and the effect that the number of transducers has on the focusing ability. These results provide insight into the FEM-TR method and its applicability in real-world use. Furthermore, we experimentally validated the simulation model, directly supporting the results shown in [17].

2. Methods

FEM modelling was done using the simulation software COMSOL Multiphysics (5.6). Two different simulation models were created (A) 3D model, to study the propagation of waves and to produce signals for the experiment, and (B) a simplified 2D model, to study the impact of nonlinear acoustic effects on the focusing efficiency and on the system's ability to focus on different areas inside the container.

The 3D model featured an acrylic water tank and four Langevin piezoelectric transducers. To reduce the computational demand, only a portion of the water tank was included in the model (Fig. 1A). The simplified 2D model featured a cross section of the water tank, with transducers replaced by 'Boundary Load' boundary conditions (Fig. 1B).

In both models, the propagation of acoustic waves was simulated using the"Pressure acoustics, Transient" interface of Acoustics module, the elastic waves were simulated using the"Solid Mechanics" interface, and the piezoelectric effects were taken into account by including the"Electrostatics" interface. Coupling between the different physics interfaces were done using COMSOL's built-in Multiphysics couplings. Fluids were simulated using the"Linear elastic" fluid model. A linear elastic approximation was shown to be valid, see section *3. Simulation results.*

The 3D simulation model featured a slice (80 mm) of the water container, to reduce the size of the simulation domain and thus the computational cost. The top and bottom surfaces of the simulation domain had the following boundary conditions: low reflecting boundary for solid domains and plane wave radiation for the fluid domain. This approach was chosen, since the reflections from the top and bottom surfaces of the container should contribute insignificantly to the results. Previously we showed this approximation to be valid [15].

Forward actuation in the 3D model was performed by introducing a spherical pressure source at the desired focus point. Actuation was done with a short 20 kHz sine pulse, with a Gaussian envelope. The forward propagated signal was recorded with the simulated transducers, by measuring the mean electric potential across the piezoelectric components.

The total simulated time during forward propagation was 2 ms, with the actuation occurring at the 0.1 ms mark at the pre-selected actuation point. During the simulation of the backward propagation phase the pressure source was disabled and the four transducers were driven with the previously recorded signals in reverse for 2 ms, therefore focusing takes place at 1.9 ms.

In the 2D model the forward and backward phases were similar to the ones described before, but instead of modelling the transducers, the recording and transmitting were performed using boundary conditions. In the forward actuation phase all transducer boundaries were set as 'free', with a coupling that recorded the average pressure on them. In the backward propagation phase, a 'boundary load' condition was set to each transducer boundary. During the backward propagation phase the time-reversed drive

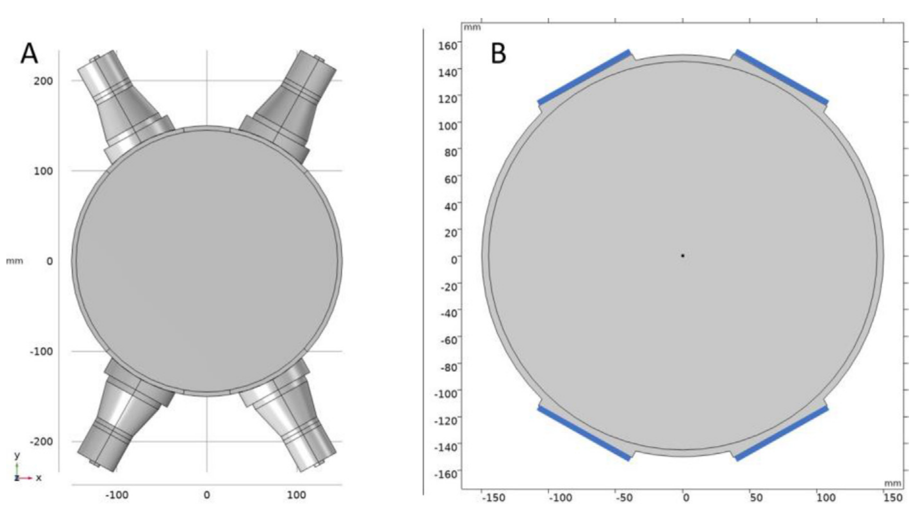

Fig. 1. (left): 3D Simulation model geometry; (right): 2D Simulation model geometry, with boundaries having the boundary load condition marked with blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

signal was modulated with a smooth step function, to reduce the contributions from the higher order reflections that are absent in the signals produced by the 3D model (Appendix A).

The simulation results were validated by comparing the measured frequency response of the transducers to the response predicted by the simulation, whereas the simulated backward propagated pressure field was compared to an experimental pressure scan. The transducers used in all experiments were f_c = 20 kHz, PZT-8, 100 W, Beijing Ultrasonics.

The frequency response of a free, uncoupled transducer was measured using a Digilent WaveForms Impedance Analyzer connected to an Analog Discovery 2. Results were imported into COMSOL and then compared with the simulation predictions.

The pressure field in water was scanned point-by-point using a custom-built, computer-controlled scan stage. The recording was conducted with an omnidirectional hydrophone (Bruël & Kjær Type 8103). The water-filled Plexiglas container used in the experiment was 303 mm tall, and had a diameter of 300 mm. The transducers were glued to the container with epoxy and positioned around it as shown in Fig. 1A.

3. Simulation results

3.1. Focus steering with FEM-TR

The 3D simulation model was used to determine whether the FEM-TR method can steer the acoustic field in a desired manner. The study was conducted by recording in the simulation domain the forward propagated signals from two different points, then reversing and transmitting them back. Fig. 2 shows the simulated backward propagation, at the moment of focusing. As the system features only four transducers, the observed side-lobes are significant compared to the focal pressure peak. However, the strongest pressure peak was observed at the expected spatial location in all targeted locations.

3.2. The number of transducers

The relative strength of the side-lobes may be decreased by increasing the number of transducers around the container. This was studied by modifying the 3D model to include different numbers of transducers, each located at equal distance from their neighboring transducers. Focusing in these cases was studied by performing TR focusing to four different target points in the same plane as the transducers. The locations of the focal points were chosen in a semi-random fashion, to avoid that all points would be simultaneously located directly in front of a transducer. The target point locations and example geometries for different numbers of transducers are shown if Fig. 3.

The results of simulated backward propagation were analyzed by evaluating the absolute value of the peak negative pressure (p_{focus}) at the desired focus point and the average of the absolute pressure in the whole water volume (p_{bg}), at the time of focusing. The peak negative pressure was selected as an indicator, being the most important factor to produce inertial cavitation. The ability to focus to each focus point was determined by calculating the 'focusing ability'.

$$focusing\ ability = \frac{|p_{focus}|}{\langle |p_{bg}| \rangle} \tag{1}$$

The mean focusing ability was calculated by taking the mean of individual focusing abilities to different pre-selected focus points. The mean focusing ability as a function of number of transducers is shown in Fig. 4. As expected, by increasing the number of transducers, the relative strength of side-lobes decreased. This result agrees with the literature [19].

3.3. Spatial limitation of focusing ability

To determine the efficiency of the acoustic field steering, the peak focus pressure in different locations was mapped in the simulation. As the mapping would require an excessive number of consecutive simulation runs, the lighter 2D model was preferred to the 3D model.

The mapping was realized by performing a series of simulations, with the forward actuation done at different points in the simulation domain (Fig. 5A). Symmetries in the simulation geometry were taken advantage of, to reduce the total number of actuation points to 1/4 of that required to cover the full geometry. The forward–backward propagation cycle was performed at all the pre-selected points and the results were mirrored along symmetry axes. The 'focusing ability' of each point was calculated with eq (1).

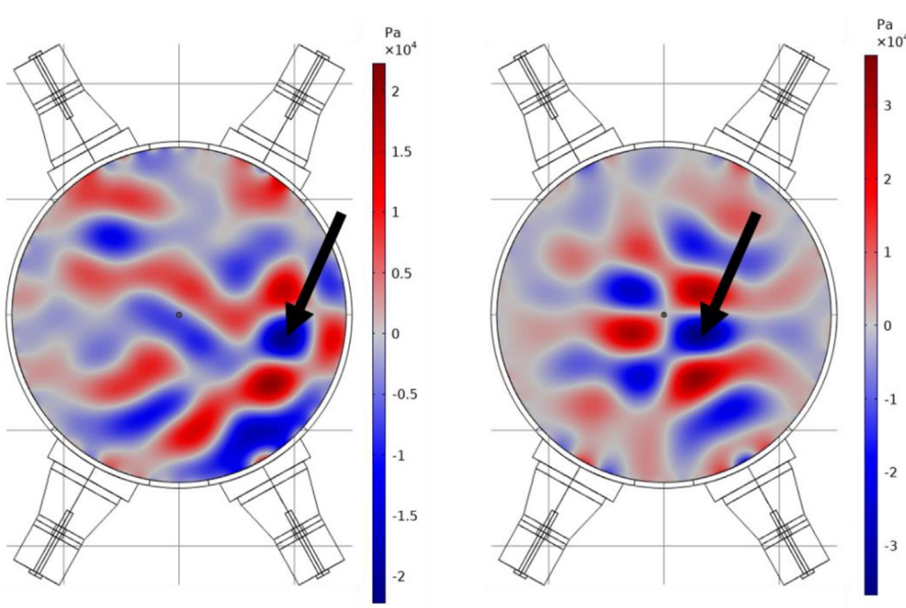

Fig. 2. Simulated backward propagation at the temporal moment of focusing. Black arrows indicate the location from where the forward actuation was originally performed.

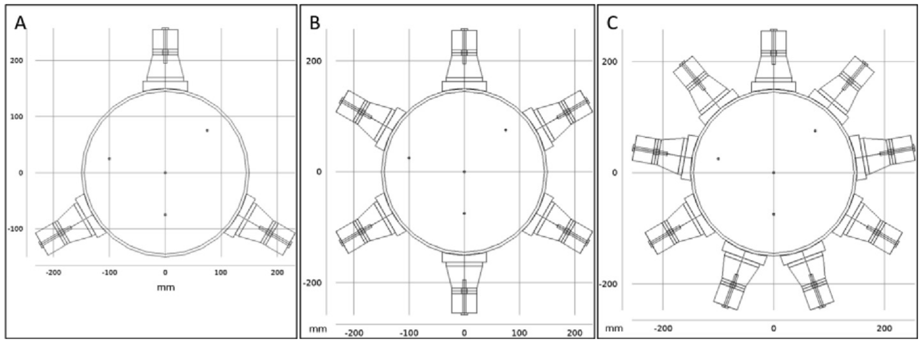

Fig. 3. Simulation geometries with three (A), six (B), and nine (C) transducers. Pre-selected focus points are marked as black dots inside the container.

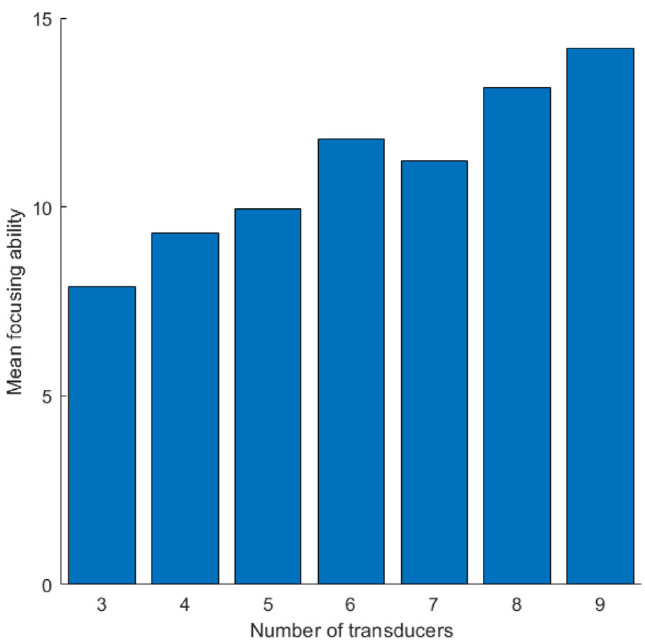

Fig. 4. Simulated focusing ability as a function of number of transducers employed. The relatively speaking poorer focusing ability for the case with 7 transducers is explained by multiple focus points being at disadvantageous positions related to the transducers.

Results of the mapping are visualized in Fig. 5B. This figure shows the focusing ability at each pre-selected focal point. As expected, the focusing ability is high around the center of the container, whereas close to the container walls the focusing ability declines. Low focusing ability at the point (x = 0, y = 0) is explained by the strong side lobes (Appendix B).

3.4. Contribution of nonlinear effects

In our simulation models, we assume that the ultrasonic field can be modelled using a linear elastic fluid model. To assess the validity of this assumption, a simulation study was done where we compared TR-focusing in fluids having either a linear or a non-linear material model.

Nonlinear acoustic effects were taken into account by including"Nonlinear Acoustics (Westervelt) Contributions" node to the"Pressure acoustics, Transient" interface in COMSOL and by changing the fluid model to viscous. The nonlinearity of water was defined by the parameter of non-linearity, B/A = 5.0 [20].

The simulation study was conducted by performing the forward–backward propagation cycle with two variations of the same 2D model. In the first variation, the reference model, the fluid was modelled as linear elastic, whereas in the second model the non-linear material model was used.

In the second, non-linear model, the transmit amplitude was increased by an arbitrary scaling factor, to increase the pressure in the fluid above the cavitation limit. With a scaling factor of 100, the peak negative pressure observed in the nonlinear model was p_{peak} = -2.39 MPa, which exceeds the cavitation limits reported for low-frequency ultrasound in water (0.1 to 1 MPa) [3,21]. Continuing to increase the scaling factor above 100, we see a drop in the relative pressure at the focus.

Results are shown in Figs. 6 and 7. When comparing the pressure fields, one may notice that in case of the non-linear model (Fig. 6B) there are minor distortions visible. Further, the overall

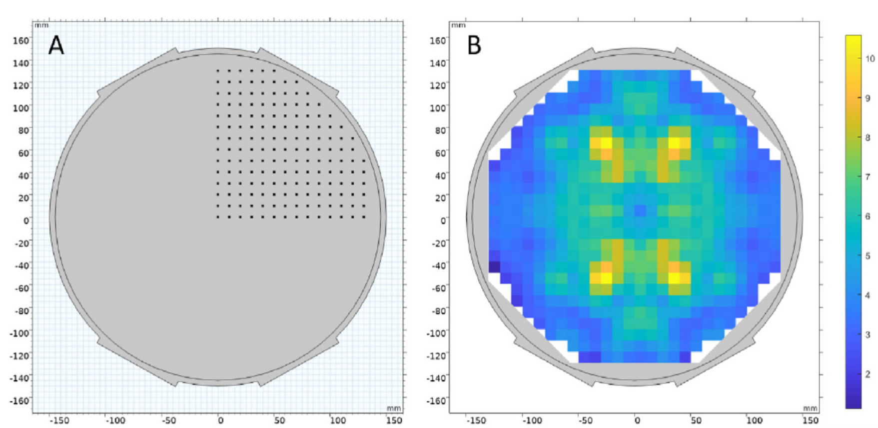

Fig. 5. Focusing ability depending on the target location. The relatively poor focusing ability to the center is a simulation artefact and it is discussed further in the Appendix B.

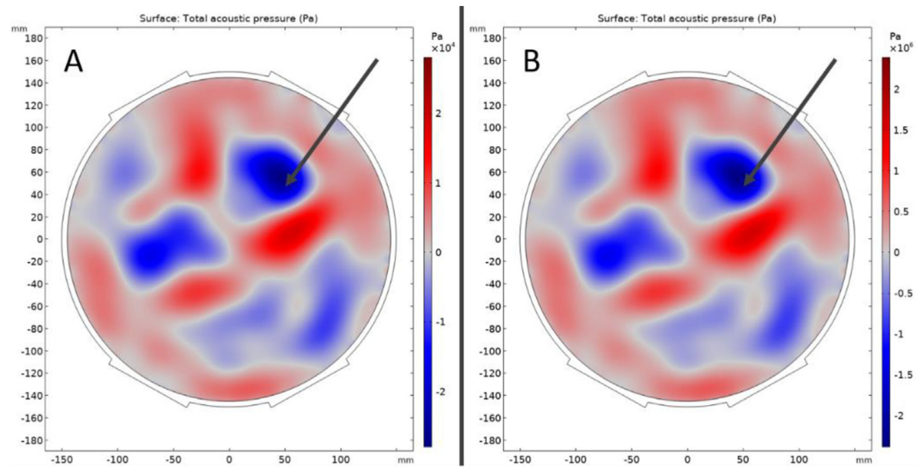

Fig. 6. Results of the non-linearity study. Figures show the pressure field at *t* = 1.9 ms. Arrows indicate the focus point. A: Focusing with fluid described by a linear elastic material model. B: Focusing with fluid described by a non-linear acoustic model and transmit amplitude scaled up by 100 times.

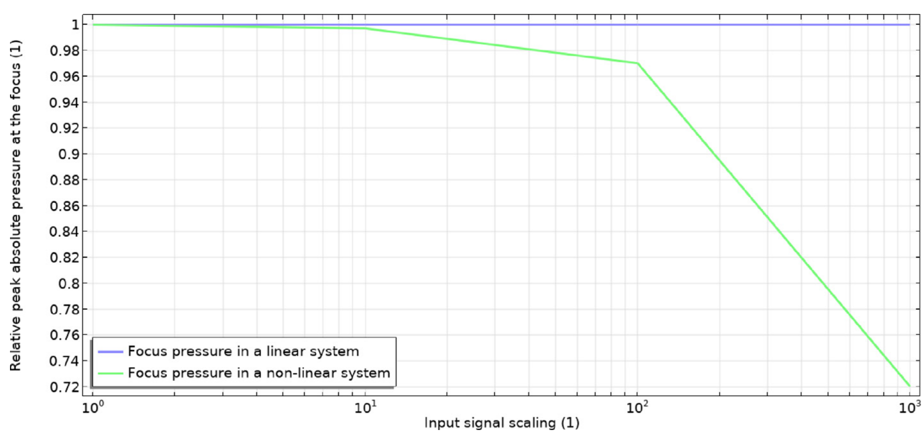

Fig. 7. Relative absolute pressure at the focus as function of the scaling factor. Pressure normalized to the peak pressure of the model using linear material model for water.

field shape is largely unchanged and the pressure maximum forms at the desired point, as was also predicted by the linear elastic model. Sweeping across the amplitude scaling factor (Fig. 7) reveals that the non-linear losses remain modest at the desired pressure level. Consequently, the results validate that FEM-TR can be used to focus high-power ultrasound and that within the desired pressure range the linear elastic fluid model is a fair approximation that can be used for FEM-TR.

4. Experimental validation

The experimental validation shown here consists of two parts: (1) the validation of the transducer model, and (2) the scan of the backward propagation.

The validity of the simulated transducer model was assessed by comparing its frequency behavior to that of the real transducer. Matching the impedance curves in the FEM-model and in the experiment is necessary to ensure that the simulated signals are properly translated to acoustic waves in the experimental setup.

Fig. 8 shows the comparison between the simulated and the measured impedance magnitude and phase of the transducer. Whereas discrepancies were observed, the modelled transducer's resonance frequency matched closely that of the real transducer. As cleaning transducers are intended to be run close to their natural resonance frequency, the developed transducer model was deemed to be appropriate.

To validate that the FEM-TR steers the acoustic power to the desired area, the simulated backward propagated pressure field was compared to the field recorded in an experimental scan. The experimental scan procedure is explained in detail in the section *2. Methods*.

The simulated and the measured pressure fields were compared at the time of focusing (t = 1.9 ms). Qualitative comparison of the simulated pressure field and the scan shows a close match (Fig. 9). Both, the phases and the amplitudes of the simulated backward propagation, matched closely those observed in the experimental scan. Therefore, it can be concluded that the simulation model represents its real-world counterpart and can be used for producing forward propagated signals for TR focusing. This claim is also supported by the earlier validation shown in [15] and the experimental results shown in [16] and [17].

5. Discussion

Our results show that the TR focusing technique can be used with clamp-on ultrasonic cleaners featuring a small number of high power and narrow-band transducers. Furthermore, we showed that to perform TR focusing, simulated forward propagated signals may be used.

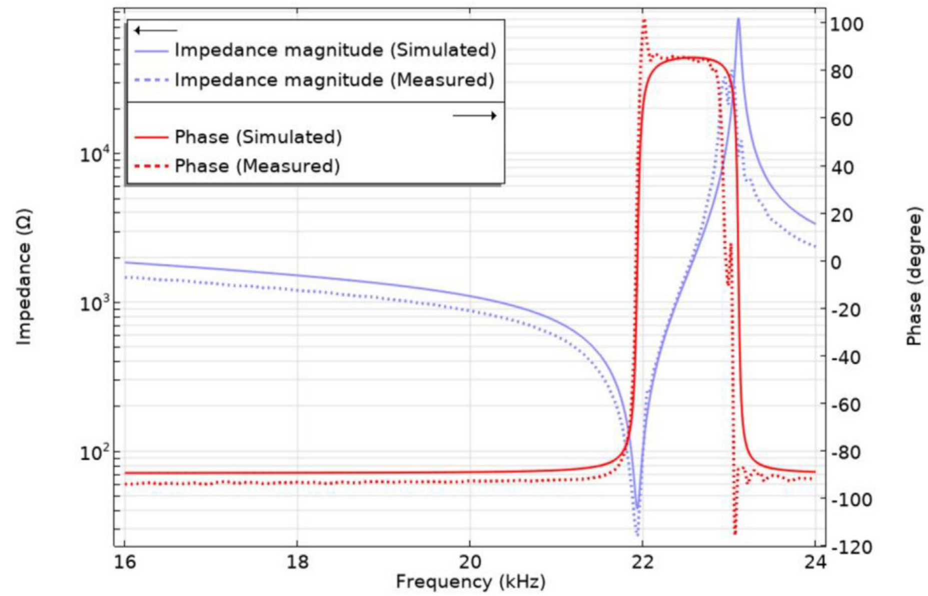

Fig. 8. Impedance and phase of a transducer simulated and measured (low power). The drive frequency in the experiments was 20 kHz.

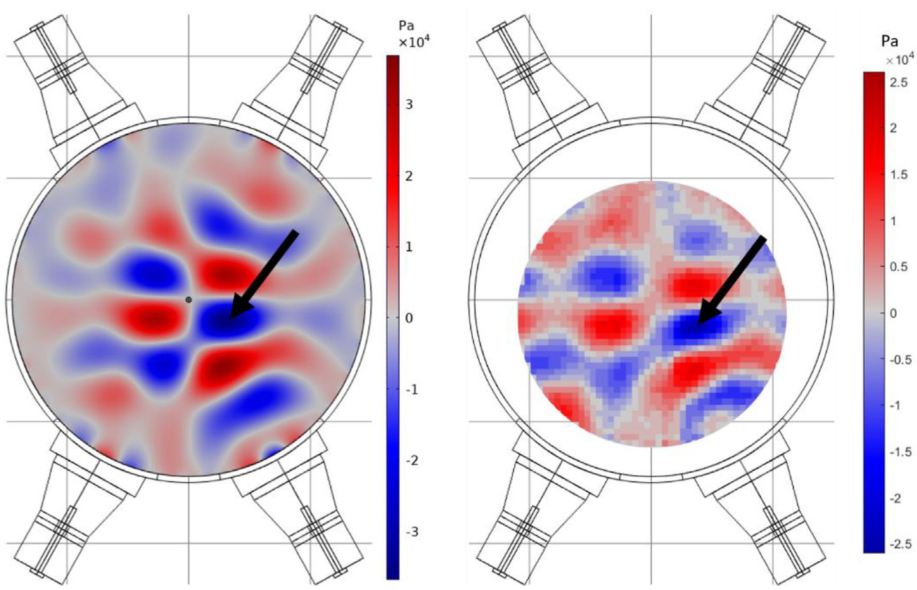

Fig. 9. Comparison of simulation (left) and experimental scan (right). Both show the pressure field at the moment of focusing. Due to the physical size of the hydrophone holder, the scan could not be performed near the container walls.

Having only a few transducers comes at the cost to focusing ability and strong side lobes, but for most cleaning applications side lobes are not considered to be a problem. In typical cleaners maintaining a single strong focus is not always even desired, but instead the cleaning should happen efficiently within the whole structure.

An advantage of FEM-TR method is evident in structures where fouling is localized to certain distinct areas. With prior knowledge of these problematic areas, one can use FEM-TR to steer cleaning power and thus improve the overall cleaning result. Alternatively, one can save energy by only focusing cleaning power to spots that need cleaning. Similarly, the FEM-TR method could be employed to maintain cleanliness of complicated structures, by sequentially focusing onto different targets, to ensure that all areas are cleaned equally.

The effect of cavitation on TR focusing was not studied as a part of this work. It is noted that the main cleaning effect of an ultrasonic cleaning system is due to inertial cavitation, but with the proposed FEM-TR technique and with careful selection of input power, inertial cavitation could be restricted to the area near the focus point.

We studied focusing in the plane where the transducers resided. Ability to focus along pipe-like structures could potentially improve the efficiency of ultrasonic clamp-on cleaning systems, by removing the need to install multiple cleaning systems along a long pipeline.

Implementing FEM-TR on large real-world structures, such as heat exchangers, would require a large and detailed simulation model with the internal structures modelled accurately. The computational load in such cases may be reduced by approximations and by truncating the model by using symmetries. However, e.g. removing small details and using boundary conditions to reduce the size of the simulation domain, may degrade the focusing ability of FEM-TR.

6. Conclusions

We introduced the FEM-TR method for an ultrasonic clamp-on cleaner. Simulations and experimental measurements were presented, and they supported our claim that the FEM-TR method can be used to control the ultrasonic pressure field in order to steer acoustic power to a desired area.

Limitations of performing TR using merely a few narrow-band ultrasonic cleaning transducers were studied with simulations. With a low number of transducers, FEM-TR was able to steer the cleaning power to a pre-selected location. However, focusing with only a few transducers causes significant side lobes, which reduces the cleaner's focusing ability. We showed that by increasing the number of transducers around the container, the relative strength of the side lobes could be decreased. Spatial focusing efficiency to different areas inside the container was investigated, revealing that the focusing ability decreases near the container walls. We also validated in simulation that a linear elastic fluid model may be used for FEM-TR.

Validity of the transducer model was confirmed through an experimental impedance analysis. An experimental scan of the focused pressure field was conducted, further validating the FEM-TR method's ability to steer acoustic power to desired area.

CRediT authorship contribution statement

Oskari Tommiska: Methodology, Validation, Formal analysis, Investigation, Visualization, Writing – original draft. **Joonas Mustonen:** Methodology, Investigation, Writing – review & editing. **Petro Moilanen:** Conceptualization, Writing – review & editing. **Timo Rauhala:** Software, Conceptualization, Resources, Writing – review & editing. **Maria Gritsevich:** Conceptualization, Writing – review & editing. **Ari Salmi:** Conceptualization, Resources, Supervision, Project administration, Writing – review & editing. **Edward Hæggström:** Conceptualization, Resources, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2022.108763.

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