Simulation of the Influence of Hydrophones used for the Characterization of Pressure Field Distribution in Low frequency, High Power Ultrasonic Reactor Vessels

G. Harvey, A. Gachagan & R.L. O'Leary
Centre for Ultrasonic Engineering, Dept. of Electronic and Electrical Engineering,
University of Strathclyde, 204 George Street, Glasgow G1 1XW, Scotland

Abstract— **This paper describes the use of a finite element (FE) modeling approach to investigate the influence of different hydrophone designs in laboratory scale reactor vessels. In addition to conventional PVDF membrane and piezoceramic hydrophone, the performance of a conceptual array hydrophone, comprising a 2D matrix of PVDF array elements, will be simulated. The FE modeling concentrates on two issues: the disturbance to the field through the introduction of each hydrophone configuration; and their suitability and response to measuring non-linear effects. To simplify the model the ultrasonic transducer is not directly represented. Here, a pressure loading function is used as the excitation technique, with a sawtooth waveform applied for the simulation of the non-linear detection capability of each hydrophone configuration. The results from the simulation programme demonstrate that the dynamics of the reactor vessel are critical to optimize the performance of the ultrasonic system. In addition, the introduction of a hydrophone alters the wave propagation, and hence the field distribution beyond a given probe location. Nevertheless, the spatial pressure distribution at the active area remains reasonably accurate if within the useable bandwidth of the device. Accordingly, the broadband nature of the membrane device is suited to operation in both the linear and non-linear regimes, with the PVDF array membrane device offering a fast, convenient measurement of the pressure field distribution for industrial applications.**

I. INTRODUCTION

The use of high power ultrasonic techniques for enhancement of industrial processes is of interest across a wide range of engineering applications [1,2]. Characterization of the pressure field generated within reactor vessels by low frequency, high power ultrasonic transducers is vital to ensure that the ultrasonic operation is correctly designed for many bespoke applications [3-7]. Moreover, calibration of the ultrasonic pressure generated in the load medium against the transducer excitation level can often provide critical information on the cavitation threshold, frequently a crucial metric in the active control of a reaction [8]. Hydrophone insertion offers a convenient measurement technique for this purpose. However, the probe require to be scanned in 3D to fully measure the pressure field for many applications. Importantly, the insertion of a hydrophone can disturb the field and may distort the measured pressure profile [5,6]. To alleviate this problem, a non-invasive approach has been developed which utilises the acousto-optic effect and tomographic processing techniques to map pressure fields within cylindrical test cells [7]. The principal drawback of this approach is that the light diffraction effects at the boundaries of the cell wall results in a reduction in the effective scanning area (or volume for 3D scans) within the transmission load, and the cell material must be transparent

Conventionally, the mapping of internal pressure fields within test vessels is achieved through the insertion of a measurement probe directly into the transmission load. Hence, this paper will investigate the measurement performance associated with two common types of probe, a piezoceramic probe and PVDF membrane hydrophone, on the harmonic field generation within a cylindrical cavity. A finite element (FE) modeling approach has been used to investigate the influence of these hydrophone designs in laboratory scale reactor vessels. In addition, the concept of extending the PVDF membrane hydrophone configuration to comprise a 2D matrix of PVDF array elements is simulated [9]. To simplify the model the ultrasonic transducer is not directly modeled. Here, a pressure loading function is used as the excitation technique and this offers the ability to directly input a sawtooth waveform into the model to analyse the non-linear detection capability of each hydrophone configuration. The simulation programme clearly demonstrates that the dynamics of the reactor vessel heavily influences the performance of the ultrasonic system; both hydrophone configurations are appropriate for pressure field measurement in the linear domain; the bandwidth of the piezoceramic probe is the limiting factor for the detection of non-linear effects; and the PVDF array membrane device offers the potential for fast, convenient measurement/calibration in industrial applications.

II. METHODOLOGY

A. System Overview

The simulation programme used industry standard vessel reactor materials, e.g. glass, aluminium and steel, to ensure the predicted results were relevant to practical applications. All the work presented in this paper has used aluminium as the vessel wall for consistency when comparing the relative performance of the hydrophone configurations. In addition,

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the vessel reactor dimensions were selected to ensure an aspect ratio (vessel length-to-width) of at least 2. Hence, the dimensions of the vessel were determined from the acoustic wavelength in the transmission load medium.

Two standard hydrophone configurations have been incorporated into this simulation programme. A piezoelectric polyvinylidene fluoride (PVDF) membrane structure [10] has been modelled as a 330µm thick layer, comprising a sandwich of three 110µm thick PVDF layers. The centre layer has the electrode pattern defined, with the inactive outer layers providing protection from the load medium. In all the PVDF simulations the active element width is 2mm: this is located in the centre of the membrane for the single element case; and a 6 x 6 regular matrix with a 4mm pitch has been utilized for the 2D array case. An omni-directional hydrophone probe configuration [11] is modelled as a 0.4mm thick piezoceramic disc encapsulated in a rubber outer protective layer. The diameter of the probe is 10mm and is supported using an aluminium rod of diameter 2mm.

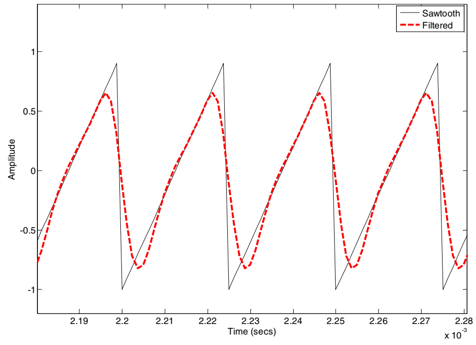
B. Finite Element Modelling

The PZFlex code [12] has been used to develop finite element models comprising a high power ultrasonic transducer, the reactor vessel construction, the load transmission medium and both hydrophone configurations. To simplify the modelling for this work, the transducer has been replaced by a pressure loading function which results in a smaller piezoelectric window in the model, and hence, a reduction in the computational processing time. In addition, this approach provides a greater control of the excitation waveforms used in the simulation programme as the constraints associated with the transducer sensitivity and bandwidth have been removed. In each of these modes the pressure function is applied in the centre of the aluminium face along the bottom of the reactor, with an effective transducer aperture of 62mm. An illustration of the PVDF membrane hydrophone in the reactor vessel is illustrated in Figure 1. The aluminium support ring is evident between the thin membrane stretched through the plane of the vessel, and the reactor wall.

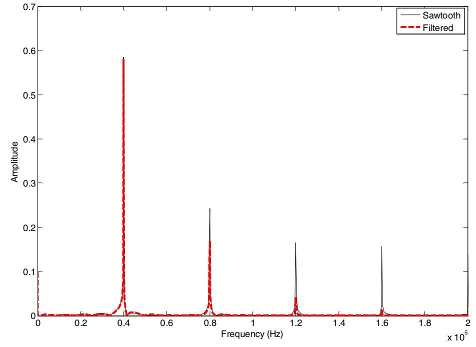
Fig. 1. *Example of FE vessel reactor model incorporating a PVDF membrane hydrophone*

C. Model Excitation Functions

Continuous wave excitation, at an operating frequency of 40kHz, has been used in all the linear simulations. In the non-linear case, a sawtooth waveform was generated using MATLAB [13], which was low pass filtered to reduce the magnitude of the higher harmonic components. This has resulted in a practical non-linear excitation signal and importantly, minimises the meshing demands of the FE model (note- the FE mesh should be calculated using the highest frequency of interest). In addition, the temporal waveform (Fig 2(a)) was inverted to accommodate the way in which PZFlex interprets non-linear behaviour [12].



***(a)** time domain representation*



***(b)** spectral characteristics*

Fig. 2. **S***awtooth waveform utilised an excitation function for non-linear simulations*

D. 2D Array Configuration

In order to improve the efficiency of hydrophone pressure measurements within a small vessel reactor, a 2D array concept has been simulated. This enables the hydrophone to simultaneously map the pressure field in the lateral dimension, with only a mechanical scan through the vessel thickness required to fully map the entire pressure field characteristic. In order to fully model this arrangement a 3D FE model has been used in which quarter symmetry has been adopted to reduce the model size. Thus only a 3 x 3 element portion of the 2D array has been modelled, as illustrated in Figure 3. Due to the computational demands of 3D FE modelling, the vessel reactor dimensions have been reduced to 2λ by 1λ. Thus the aspect ratio of the cell has been maintained, but the modelled volume significantly reduced to accommodate the 3D modelling approach.

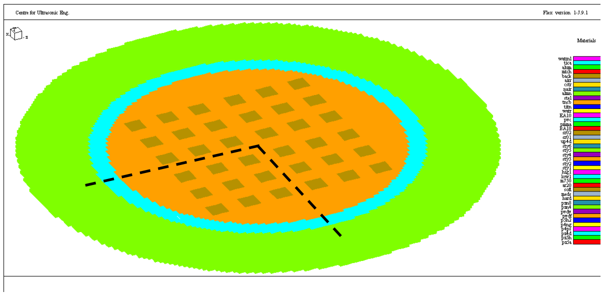


Fig. 3. *3D model used to simulate the performance of a 2D PVDF membrane array, with quarter symmetry indicated using dotted line*

III. RESULTS

A. Vessel Considerations

It is important to ensure that the vessel reactor will operate in a desired manner to facilitate high power intensification of an industrial process. Thus the pressure field characteristic must be determined and pressure maxima and minima, i.e. intensity 'hot spots', identified as areas where a cavitational field is most likely to be generated. Figure 4 illustrates the significant variation in pressure field characteristic as a consequence of small variations in vessel dimensions. Here, the cell width is constant at 3λ and the cell length varied between 6λ and 6.75λ. For the remained of this work, the cell dimensions will be constant at 6λ by 3λ (Fig 4(a)).

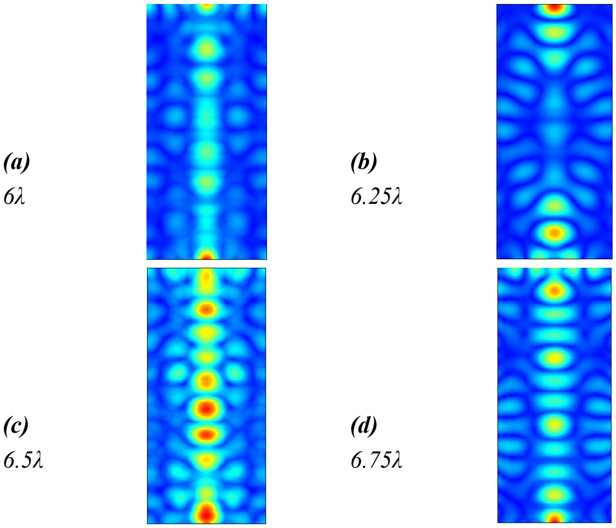

(a) *6λ*
(b) *6.25λ*
(c) *6.5λ*
(d) *6.75λ*

Fig. 4. *Influence of vessel dimensions (for constant width of 3λ) on the pressure field characteristic*

B. Hydrophone Performance – Linear Excitation

In order to assess the capability of each hydrophone to measure the pressure field within a vessel reactor, the voltage response from both hydrophones have been simulated at a number of axial positions. This voltage response has been converted into pressure using calculated calibration factors. Figure 5 illustrates this predicted axial pressure profile, under linear excitation conditions, from both hydrophones and compares this to the simulated response with no hydrophone present. It is apparent from this Figure that the membrane hydrophone has a reasonable correlation with the predicted free-field pressure field. Whereas the probe device has correctly predicted the basic trends associated with the axial pressure distribution, i.e. a reduction in pressure followed by an increase to a maximum value at the end of the vessel.

C. Hydrophone Performance –Non- Linear Excitation

The simulation was then extended to investigate the hydrophone performance under non-linear excitation conditions. Again, the axial pressure profile has been predicted using the voltage response from both hydrophones at a number of axial positions. It is apparent from Figure 6 that the non-linear axial pressure characteristic has distorted the regular standing wave configuration produced by linear excitation and illustrated in Fig 5. Again, the PVDF membrane hydrophone has accurately represented the pressure field characteristics and therefore could be utilised to provide pressure field measurements in an industrial vessel reactor system.

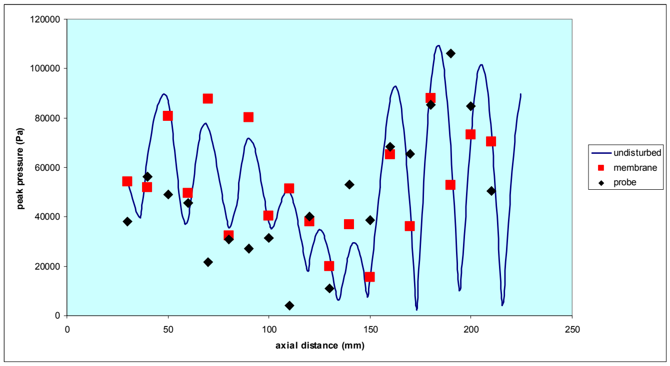


Fig. 5. *Axial profile showing undisturbed, membrane and probe pressure characteristics for linear excitation*

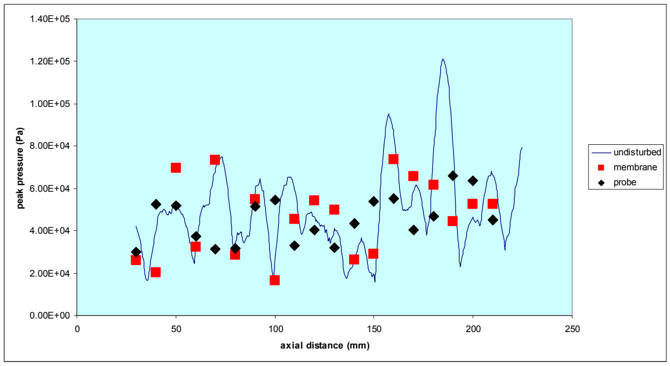


Fig. 6. *Axial profile showing undisturbed, membrane and probe pressure characteristics for non-linear excitation*

D. 2-D Array Hydrophone Performance

The 3D FE simulation was performed with the 2D hydrophone array at five discrete axial positions in the vessel. The predicted received signal on each array element has been acquired and translated to pressure using the membrane hydrophone calibration factor. The predicted pressure field has then been visualised using Matlab and compared to the undisturbed pressure distribution from a full 3D simulation without the hydrophone present. The undisturbed and hydrophone pressure field results at a distance 30mm from the excitation source are presented in Figure 7. Here the free-field pressure distribution, Fig 7(a), has been represented as the average pressure over the same field position and active area as the array hydrophone for ease of comparison. Good correspondence between these figures illustrates that the hydrophone array has the potential to accurately profile the pressure field in small vessel reactors, although the actual relative pressure values have not been accurately predicted. Interestingly, the resolution could be improved by increasing the number of elements and reducing the array element size, but this is not considered necessary as the acoustic wavelength at the low ultrasonic frequencies used in intensification processes will typically be at least one order of magnitude greater than the 2mm element dimensions used in this study.

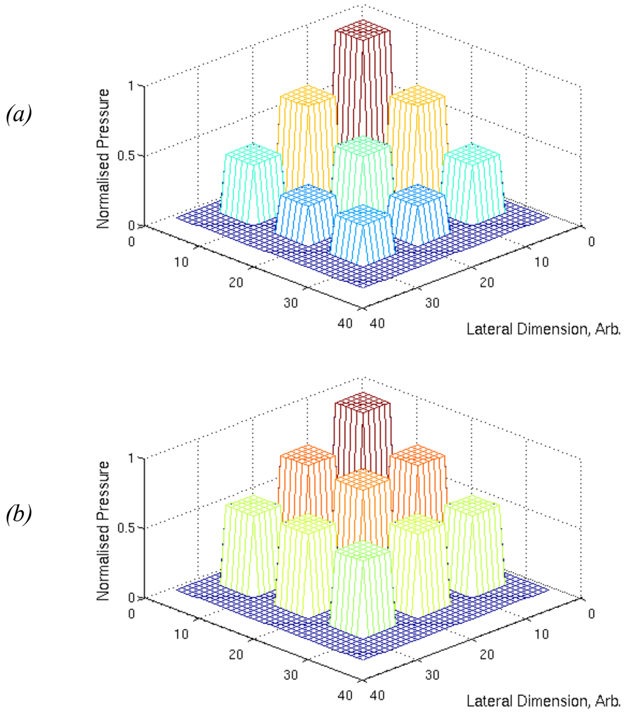


Fig. 7. *Comparison of pressure field slices at different locations through the thickness of the vessel (a) no PVDF membrane (b) with PVDF membrane.*

IV. DISCUSSION

The variation in pressure field characteristic illustrated in Figure 4 clearly demonstrates the importance of in-situ measurement of the pressure field characteristic in vessel reactors. Minor variations in cell dimensions or material properties will modify the vessel reactor dynamics and alter the pressure field profile, which may have an adverse effect on the efficiency of an intensification process. Thus, the potential of utilising a 2D membrane hydrophone to quickly provide a calibration of a vessel reactor for an industrial application would be of great benefit.

The majority of vessel reactors for process intensification applications will operate under high power field conditions. Hence, the ability to measure non-linear effects may be advantageous. Figure 8 illustrates the influence the additional spectral components through spatial spreading of the pressure peaks. It is apparent that the field characteristics from the linear and non-linear excitation FE simulations have the same general features, although the higher harmonic components in the non-linear domain have distorted the clear recognizable standing wave configuration present when only considering operation in the linear domain.

V. CONCLUSIONS

This paper has demonstrated the need to accurately measure the commonly complex pressure field distribution in vessel reactors used for process intensification applications. Small variation in any of system parameters can modify the characteristic of the pressure field and hence influence the systems performance. A PVDF membrane hydrophone device has been shown to offer a potential solution to the measurement of these fields in situ. Importantly, this hydrophone can measure over a wide frequency range and can be configured as an array of receive elements. This provides an ability to measure both non-linear aspects of the pressure field from a simple axial scan through the vessel length. Moreover, it may be possible to extend the 2D array concept to produce a multi-layered hydrophone comprising several individual layers each with a 2D array capability and separated by a finite distance, for example this could be one quarter wavelength. Thus a single measurement would be able to fully reconstruct the full pressure field characteristic.

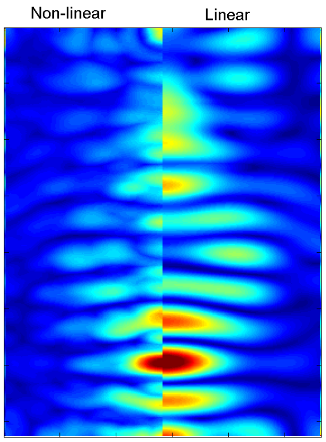


Fig. 8. *Modification of pressure field characteristic by non-linear wave propagation*

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