SIGNAL MODELLING USING THE FLOSIM SYSTEM MODEL IN ULTRASONIC INSTRUMENTATION FOR INDUSTRIAL APPLICATIONS

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ABSTRACT
A development of the FLOSIM system model for description of signal transmission in ultrasonic transmit-receive measurement systems incorporating finite-element modelling (FEM) of the piezoelectric transducers and the fluid medium, is described. An example from high-precision custody transfer flow metering of natural gas is used to illustrate the capabilities and possibilities of a system model of this type, in relation to system design, signal properties and signal processing. Challenges related to use of FE modelling in FLOSIM type of descriptions are addressed and discussed.

1. INTRODUCTION
Ultrasonics is today used within a broad spectrum of industrial applications, such as medical ultrasound, military and civil marine acoustics, fishery acoustics, oil and gas flow metering, process metering, subsea instrumentation, downhole instrumentation, non-destructive testing, meteorology and atmospheric research, etc. The role of ultrasound technology is becoming increasingly important. Although the various ultrasonic instruments and applications are subject to different challenges, and different signal processing strategies may be used, there are common factors for many of these instruments which need to be taken into account in the signal processing strategy.

An ultrasonic measurement system is normally based on one (or several) transmitting transducer(s) with dedicated electronics, a medium in which the ultrasound propagates (and which normally is to be measured or characterised in some way), one (or several) receiving transducer(s) with its dedicated electronics, signal filtering and signal detection / processing. Such components of the ultrasonic measurement system (transducers, electronics, filters, etc.) have their specific frequency characteristics, which in practice strongly influences on the ultrasonic signal, and thus on the signal processing strategies and solutions being chosen. For several reasons, such as e.g. to optimise the physical hardware components of the system and the signal processing methods, there may be significant advantages in being able to describe the ultrasonic transmit-receive system as a unit, with such components working together.

An extensive effort has been done internationally particularly during the recent decennia on developing powerful signal simulation models for such ultrasonic transmit-receive measurement systems. Some of this work is discussed in the references cited here [1-23] and in the further works referred to there.

The present paper describes a development of the FLOSIM numerical simulation model to improve the description of such measurement systems.

2. THE FLOSIM SYSTEM MODEL

2.1. Simplified approach using 1D acoustic modelling
A first version of the FLOSIM system model for description of an ultrasonic transmit-receive measurement system was described in [1,2]. FLOSIM consists of models for the signal generator, the transmitting electronics, the transmitting piezoelectric transducer, the propagation medium, the receiving piezoelectric transducer, the receiving electronics, filters, and the electrical termination (e.g. analog-to-digital conversion, ADC), cf. Fig. 1.
Fig. 1. Schematic overview of the module-based FLOSIM numerical simulation model for time and frequency domain modelling of an acoustic measurement system.

Interactive modelling in time and frequency domain is possible, including modelling and analysis of the signal and its frequency spectrum as it propagates from one node to another in the component network, as well as the transfer function and its impulse response between any two nodes in the network.

For example, in the configuration shown in Fig. 1, the output voltage frequency spectrum at node no. 8 is calculated as

\[ V_8 = V_0 \frac{V_1 V_2 V_3 u_4 p_5}{V_0 V_1 V_2 V_3 u_4} \frac{p_6}{V_7} \frac{1}{V_8}, \]

where \( V \) denotes voltage, \( p \) sound pressure in the fluid propagation medium, and \( u \) volume velocity. Subscripts represent node numbers in the model, at which the time signals, frequency spectra, transfer functions and impulse responses can be calculated. Note that node nos. 5 and 6 represent the sound pressure in the fluid at an axial distances of \( 1 \) m and at the receiver, respectively, the latter averaged over the receiver front (denoted by \( \{ \} \)).

The main calculations are performed in the frequency domain. Time domain responses (signal traces and impulse responses) are obtained through inverse Fast Fourier Transform (FFT) techniques [1].

The FLOSIM model has been further developed and used in industrial development work at CMR for more than a decade, for applications within e.g. custody transfer metering of natural gas and oil, wet gas metering, separator monitoring, high-temperature ultrasonics, flare gas metering, etc. (cf. e.g. [3-9]).

To overcome such simplifications and limitations, work has been started on using data resulting from finite element modelling (FEM) of piezoelectric transducers and sound radiation in the fluid medium, in the FLOSIM model. FEM is used for numerical calculation of the transfer functions related to the transmitting transducer, fluid medium and receiving transducer modules, cf. Fig. 1. That is, the transfer functions

\[ \frac{u_4}{V_3}, \frac{p_5}{p_6}, \frac{p_6}{V_7} \]

may be calculated using FEM, as an additional functionality to the Mason and plane piston type of models which have been available earlier, cf. Section 2.1.

The FE model used is based on the FEMP 3.0 model previously developed in a cooperation between CMR and UoB [17-19]. This model can describe effects of different parts in the transducer structure as well as the effects of the resulting vibrations on the radiated sound field, under the assumption of axial symmetry. In addition to being used and tested versus measurement results and numerical accuracy in connection with transducer design and construction, FEMP has been further developed such as to describe also the receiving transducer (voltage and current reception), animation of transducer vibration and sound propagation, inclusion of fluid medium losses, adaptation to FLOSIM time domain type of modelling, etc. The present code is denoted FEMP 3.4.
3. RESULTS AND DISCUSSION

3.1. Application to custody transfer flow metering of natural gas and oil

To illustrate the possibilities, capabilities and potentials of a system model of this type, examples from high-precision custody transfer flow metering of natural gas and oil [11-16] are used, cf. Fig. 2.

![Image](image1.png)

Fig. 3. (a) Illustration (largely simplified) of type of mesh used in FE modelling of transducers and sound fields (finite and infinite elements), and (a) example of a metal encapsulated ultrasonic transducer used in high-precision ultrasonic flow metering of oil.

In Fig. 3b a metal encapsulated ultrasonic transducer is shown as an example of related applications in ultrasonic precision flow meters (USM) for fiscal measurement of natural gas and oil (sales metering), which has been designed using FEMP as one design tool. Fig. 3a illustrates the geometry and finite element mesh used for the modelling of a more simplified transducer structure example, consisting of a piezoelectric element with a front matching layer and a backing layer. A 12 x 3 mm Pz27 type of piezoelectric element [20]) was used here.

The 12 x 4 mm front layer (quarter wavelength thick at 150 kHz) was modelled using a density of 1100 kg/m³, compressional velocity of 2500 m/s, Poisson’s ratio of 0.31, and compressional and shear Q factors of 20. The 12 x 18 mm tungsten/araldite backing layer was modelled using a density of 10000 kg/m³, compressional velocity of 1600 m/s, Poisson’s ratio of 0.2, and compressional and shear Q factors of 5. The propagation medium (surrounding the transducer) was natural gas at 25 bar, with density and sound velocity taken as 20 kg/m³ and 400 m/s, respectively.
Examples of FE modelling results (thick lines) for the transducer shown in Fig. 3a, and the radiated sound field (in natural gas): (a) input electrical conductance and impedance, (b) source sensitivity (magnitude and slow phase), (c) transducer vibration (exaggerated) and radiated sound field (nearfield) at 150 kHz, and (d) directivity (farfield, at 1 m dist.) at 150 kHz. Corresponding Mason type 1D/planar piston modelling results are shown in (a) and (b) using thin lines, for comparison.

As an example, a single path in a USM, with source-receiver distance 25 cm is considered here. Infinite elements are used for the outermost radiated field, beyond 2.5 cm, cf. Fig. 3a. For clarity, only a reduced mesh consisting of 292 elements is shown in Fig. 3a. (The results shown in Figs. 4 and 5 have been calculated using a mesh of 16736 8-node isoparametric finite elements.)

In Fig. 4a the input electrical conductance and the impedance magnitude of the transducer structure in Fig. 3a are shown over a frequency range up to 350 kHz, as examples of FE calculations using the FEMP model (thick lines). Fig. 4b shows the calculated magnitude and phase of the voltage source sensitivity (i.e. \( p_s/V_s \), cf. Fig. 1) for the same transducer and frequency range (thick lines). The calculated transducer vibration and sound radiation from this transducer (only the nearfield shown here) and the corresponding directivity pattern (farfield) are shown in Figs. 4c and d, respectively, both at 150 kHz (i.e. close to the fundamental radial mode of the piezoelectric element).

Frequency response functions such as those demonstrated in Figs. 4a and b are needed in the FLOSIM model, cf. Section 2.1. In order to obtain accurate results in the time domain, the frequency domain response functions (magnitude and phase) need to be calculated with sufficient accuracy and resolution, over a sufficiently wide frequency range.

For the present calculations, the excitation voltage signal \( V_d(t) \) is given as a 10 cycle constant amplitude (2 Vp-p) tone burst, starting positive. The internal impedance of the signal generator is \( Z_i = 50 \Omega \) (real). The carrier frequency of the excitation signal is 150 kHz, as a representative example of gas USMs. 6 MHz sampling frequency and 8192 sampling points were used. FE calculations were made to 1 MHz, above which the system response was set to zero (implying a rectangular lowpass filter). To avoid effects of (a) numerical inaccuracies of the FE calculations in the 400 - 1000 kHz band, and (b) effects of the truncation at 1 MHz, a Butterworth lowpass filter (LPF) was used, with -3dB cutoff at 300 kHz, and 40 dB/oct decay rate. To make the system as simple as possible, and still with sufficient realism to illustrate the main items, no specific electronics was used in these simulations.

The numerical inaccuracies of the FE calculations in the 400 - 1000 kHz band (not shown in Fig. 4) are related to insufficient number of finite elements per wavelength used in this high frequency band for the calculations shown here. High accuracy in this band is not critical for the results shown in the present work.

Fig. 5a shows an example of a signal trace calculated at node 6 in the network of Fig. 1 (the sound pressure in the gas at the receiving transducer front, averaged over the front surface, \( <p_r> \).)

3.2. Comparison with simplified Mason 1D and plane piston type modelling

For comparison, corresponding calculations have been made using the Mason type 1D model for the transducers, combined with the plane-piston-in-ininitely-hard-baffle model for the sound propagation in the gas between the transducers. Note that since today there is no useful analytical model available for the piezoelectric element’s radial modes describing the effects of front layer, backing and radiation load, a Mason type thickness-extensional (TE) mode model was used to model the transducer vibration in the frequency range of the fundamental radial mode (150 kHz). That is, in these 1D simulations the thickness of the piezoelectric element was set to 13 mm (instead of 3 mm). Otherwise the transducer and the medium were the same as in the FE simulations (except that shear waves are not accounted for in the Mason model). Use of the TE mode to “describe” the radial mode is of course an incorrect simplification, but still perhaps the only approach available today in terms of 1D modelling.

In Figs. 4a and b these simplified modelling results are shown using thin lines. Although many of the same response features are indeed present in these simplified simulation results as in the FE results, it appears that both the electrical and acoustical responses are signifi-
There are definitely challenges related to use of models for improved USM system design. These challenges include factors such as the accuracy of material data, control of model accuracy and numerical accuracy (especially at high frequencies), lack of reciprocity, and incorrect description of details. All of these properties contribute to the shape and properties of the acoustic signal, e.g., the pressure at the receiver.

By comparison with Fig. 5a, the difference in signal form and level is apparent. In USMs, the signal form (e.g., the signal rise time and possible “overshoot”) may be important in relation to achieving reliable and high precision transit time detection. Normally a rapid rise (wide bandwidth) is desired, and the 1D / plane piston modelling approach is obviously not capable of describing the signal and its shape sufficiently accurate.

This new capability to use FEM modelling as an integrated part of the system modelling opens up highly interesting perspectives for improved design of ultrasonic measurement systems, including signal generation, electronics, transducers and signal processing. For optimum design, these parts need to be treated as a unit.

For example, in relation to USM flow metering of oil and gas, essential factors in relation to signal processing are e.g., requirements to achieve reciprocity, optimum signal shape, high-precision transit time detection (order of ns for gas meters, and tens of ps for oil meters), correction of transit times (e.g., transducer delay, diffraction effects, possible lack of reciprocity), etc. For all of these factors, the capability to accurately model the electroacoustic system for the transducer vibration mode and system frequency response in question provides perspectives for improved USM system design.

3.3. Challenges

There are definitely challenges related to use of models such as FLOSIM and FEMP for applications as discussed above. Some of the ongoing work is concentrated on: (a) ensuring sufficiently reliable and accurate results for the FE calculated functions to be used in FLOSIM, with respect to magnitude and phase responses, (b) ensuring correct physical interpretations and uses of the FEM results, (c) obtaining FEM based integrated diffraction effects (diffraction corrections) on the receiving transducer, and (d) performing comparisons with simulations using the more traditional models for the transducers and sound field which are already available in FLOSIM, and with experimental results.

In the comparisons with experimental results, the available data for the material constants become crucial. For piezoelectric materials, for example, only typical data with a low accuracy (5-20%) may be available from the manufacturer, at best. Such data are obtained using standardized measurement methods (cf. e.g. [21]). However, the standardized methods have been shown to be physically incorrect because only one-dimensional models are used in the analysis of the measurements, resulting in systematic errors which can be up to several percent [22]. Practical work shows that adjusted values of the material constants may have to be used in the simulations. That has been done in the simulations shown in Figs. 4 and 5.

Also for non-piezoelectric materials the availability of reliable material data may be a challenge. The importance of this topic may be illustrated by an example: by changing the Poisson’s ratio of the transducer’s front layer to 0.4, the frequency response and signal form is considerably changed. This may also illustrate the importance of using FE modelling, such change would not be described using the Mason type of model.

As FEM accuracy is closely connected to number of elements per wavelength, gas media are normally - for a given frequency, due to the longer wavelength - numerically more demanding than liquid media, with respect to computer time, memory, accuracy etc.

4. CONCLUSIONS

Since in order to correctly process your signal you need to know your signal, better knowledge of the measurement signal will lead to improved processing and detection capabilities, with a more accurate, powerful and economic measurement system as a result.

By implementing FE based modelling (of the transmitting and receiving transducers, and their interactions with and propagation in the sound field) in an ultrasonic system models such as FLOSIM, a significantly more powerful and versatile simulation tool for design of ultrasonic instruments is obtained. A considerably more extensive and relevant range of problems can be run much more physically correctly and accurately than earlier. This results in the capability for use in more extensive simulations and studies of the signal propagation and signal processing in ultrasonic measurement systems than has been available before. Challenges are definitely faced in this approach, such as with respect to availability and correctness of material data, control of model accuracy and numerical accuracy (especially at high frequencies), etc. Developments are being addressed to overcome such challenges.

5. ACKNOWLEDGEMENTS

The present work has been supported by The Research Council of Norway (NFR), under a 4-year strategic institute programme “Ultrasonic technology for improved exploitation of petroleum resources” (2003-06). In addition, the work has evolved from project cooperation over time related to USM fiscal metering of gas and oil (custody transfer, sales and allocation metering), involving
several partners: The Norwegian Society of Oil and Gas Measurement (NFOGM), the Norwegian Petroleum Directorate (NPD), GERG (Groupe Européen de Recherches Gazières), FMC Kongsberg Metering, FMC Smith Meter (USA), Roxar Flow Measurement, Statoil, Norsk Hydro and ConocoPhillips.

6. REFERENCES


