Simulation of ultrasound signals for the study of velocity estimation techniques

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In this work we demonstrate the use of simulation of ultrasound signals in the study of velocity estimation techniques. To simulate the ultrasound signals the software Field II running under the Matlab environment was used. A flat piston shaped transducer was defined to emit and receive the echoes from the reflectors. Three types of flow were simulated: turbulent, laminar and uniform velocity profile. The accuracy and limitation of the velocity profile simulated are discussed. The velocity estimation techniques used to verify the simulation were the autocorrelation and time shift methods. Effects of transducer apodization in the accuracy of the velocity profile were also evaluated.

Keywords: Simulation of ultrasound signals, ultrasound velocity estimation, velocity profile, ultrasound Doppler method

1. Introduction

Simulation of physical processes is a fundamental tool in all engineering fields. In fluid engineering, ultrasonic Doppler method for velocity profile measurement, UVP, has proved to be a valuable tool for flow study [1]. However, there are still plenty of signal processing techniques that can be studied to improve velocity estimation. Using experimental approach to test a new signal processing methodology is a complex task, because of noise and the various uncertainties related to the experimental apparatus. In this context, simulation of ultrasound flow signals can be a valuable tool because it is possible to realize an ideal experiment without noise, stationary echoes from pipe walls, transducer angle uncertainty, non-uniform particles distribution, etc. After testing a new technique in an idealized environment, it is possible to add one or more of these undesirable effects in the simulation and thus study its individual effects in the velocity profile measured. Field II is an ultrasound simulation program that has been used for several years in the medical area. Although developed for medical field, it has the potential to be also applied to fluid engineering. However, there are no reports of application of Field II in fluid mechanics. This work aims to analyze the feasibility of application of the Field II ultrasound simulation software for the study of fluid engineering. Accuracy of simulated velocity profile is analyzed through the use of an autocorrelation and a time shift estimator. Three types of flow were simulated: uniform, laminar and turbulent. The simulation of transducer apodization is also studied to show its effects in the velocity profile.

2. Ultrasound Simulation using Field II

Field II is a fast ultrasound simulation program that is based on the concept of spatial impulse response [2-4]. It uses the Huygen´s principle to evaluate the impulse response as [5]:

$$h(\vec{r_1},t) = \int_S \frac{\delta\left(t - \frac{|\vec{r_1}-\vec{r_2}|}{c}\right)}{2\pi|\vec{r_1}-\vec{r_2}|}\mathrm{dS} \tag{1}$$

where $|\vec{r_1}-\vec{r_2}|$ is the distance from the transducer at position $\vec{r_2}$ to the field point at $\vec{r_1}$, $\delta(t)$ is the Dirac delta function, and c is the speed of sound. A large variety of transducers can be simulated, ranging from single element transducer to an array of transducers elements. This is acomplished by dividing the transducer aperture in smaller mathematical elements. In a real aperture, edges might vibrate less than the center (apodization, [6]), and this is simulated by specifying different weights for each mathematical element. Considering a pulse-echo technique, a medium with uniform density and uniform sound velocity, the voltage signal received will be [5]

$$v_r(\vec{r_1},t) = v_{pe}(t) * f_m(\vec{r_1}) * h_{pe}(\vec{r_1},t) \tag{1}$$

$$f_m(\vec{r_1}) = \frac{\Delta_\rho(\vec{r_1})}{\rho_0} - \frac{2\Delta_c(\vec{r_1})}{c},$$

where $v_{pe}(t)$ is the transducer excitation voltage convolved with both transducer electro-mechanical impulse response in transmit and receive, $f_m(\vec{r_1})$ is due to scatterers that cause spatial variations in density $\Delta_\rho(\vec{r_1})$ and speed of sound $\Delta_c(\vec{r_1})$ and $h_{pe}(\vec{r_1},t)$ is the convolution between the impulse response of the transmit and receiving aperture. The final signal for an ensemble of scatterers can be obtained as a linear sum of Eq.1 for each scatterer. Therefore, by defining the ultrasound velocity, transducer excitation voltage, transducer geometry and the position of a set of scatterers the voltage trace for each ultrasound emission can be evaluated. Field II comprises of a set of C files that are called by Matlab m-functions. This structure makes it very flexible and easy to use.

3. Methodology

3.1 Transducer

Ultrasound transducers in Field II are treated as an aperture, i.e., only the active element should be defined. For this work, Field II was configured to use the same aperture to transmit and receive ultrasound pulses. Therefore it will simulate a pulse-echo technique. Transducer geometry used was a piston shaped aperture with 10 mm of active diameter. Aperture geometry was divided into 1.2 mm x 1.2 mm square mathematical elements (Fig. 1). With this size for the mathematical elements, Field will evaluate acoustic pressure accurately for points located 1 mm apart from the aperture. More about the rules for defining the size of the square elements can be found in [6]. Ultrasound central frequency (f_c) was configured to 4 MHz. Transducer excitation was performed by a 4-cycle sinusoidal burst. Field II also allows to simulate the effect of apodization. This effect occurs because, in real transducers, the edges might vibrate less than the center. In Field, apodization is defined by establishing coefficients for each square element. For this work a 2D hanning matrix was used to define the apodization coefficients as show in Fig. 1 (color pallete). For simulations were apodization is not considered the coefficients were all set to “1”.

3.2 Pipe section

For this work, a pipe section with 30 mm of internal diameter was defined. Transducer aperture center coordinates was setup for the origin of 3-D coordinate system (Fig. 2). Pipe axis was positioned at an angle of 45 degrees with respect of z axis (Fig. 2). The number of reflectors was roughly 10 scatterers per measurement volume. Work fluid is water with sound speed defined as c =1480 m/s. A 2 mm thickness was used for the pipe wall. However, the amplitude of echoes from the moving reflectors was configured to be 100 times greater than the amplitude of the echoes from the stationary reflectors. The reason for that configuration is to avoid the use of stationary filters that may introduce an additional source of errors in velocity estimation.

3.3 Simulation parameters

The simulations were performed using Field II release 3.24. This software works under Matlab environment. Matlab version used was release R2013a. The sampling frequency utilized to generate the RF voltage signal was 100 MHz. Pulse repetition frequency (f_{prf}) was set to 2 kHz. Three types of flow were simulated: uniform velocity profile, laminar flow and turbulent flow. Flow direction simulated was towards the transducer, using negative signal convention for this condition. For laminar and turbulent velocity profile the models used were

$$v(r) = V_{max}\left(1-\left(\frac{r}{R}\right)^2\right), \tag{1}$$

$$v(r) = V_{max}\left(1-\frac{r}{R}\right)^{1/8}, \tag{2}$$

where R is the pipe internal radius and V_{max} the maximum flow velocity. To evaluate the spatial velocity profile, 1 second of data was acquired, or 2000 ultrasound pulses. Velocity estimation were carried by a 2D autocorrelation with subsampling algorithm [8-10] and by time shift estimator based in cross-correlation technique [11,12]. No post-processing filters were used. Matlab scripts written for this work can be found at http://dx.doi.org/10.13140/RG.2.1.1942.1046.

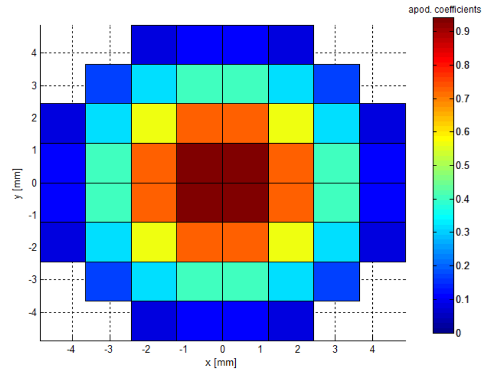

Figure 1: Transducer aperture geometry representation divided in 1.2 mm x 1.2 mm square mathematical elements. Apodization coefficients used for each element are also showed by color palette.

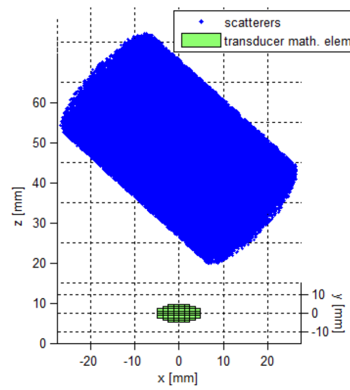

Figure 2: 3D representation of reflectors distribution with respect to the ultrasound transducer. Pipe walls were suppressed.

4. Results

4.1 Transducer apodization

To understand the effect in the spatial velocity profile measured when transducer apodization is simulated, two uniform velocity flows were simulated. In the first flow simulation, a non-apodized transducer was configured (i.e, all apodizations coefficients of Fig. 1 were set to 1). The second flow used same transducer but with the apodizations coefficients of Fig. 1. The velocity configured for the simulated flows was 0.8 v_a, where

$v_a = cf_{prf}/4f_c$, or the maximum velocity that can be measured by the 2D autocorrelation algorithm. Spatial velocity profiles were evaluated for each flow and are shown in Fig. 3. The difference in using apodization can be notice in the extent of the spatial velocity profile. Transducer apodization effect can be observed by the narrowing of the spatial velocity profile. Without apodization the velocity profile comprise of one extra velocity profile point (to the left in Fig. 3). The ultrasound beam diameter measured using the spatial profile obtained (without apodization) was 31.2 mm. Using apodization the beam diameter became 0.95 mm narrower. Such effect occurs because apodization reduces the effective ultrasound beam radius. With a narrow beam, the first reflector echo will appear at a far point relative to the wide beam from a non-apodized aperture.

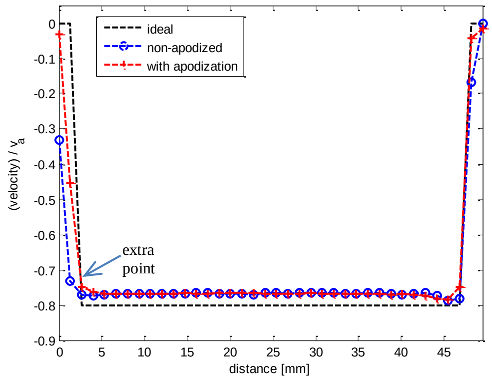

Figure 3: Comparison of velocity profile obtained from a non-apodized aperture with a velocity profile from an apodized aperture.

4.2 Accuracy assessment by Autocorrelation

Accuracy of the flow simulation was assessed by evaluating the mean flow velocity from the spatial profile measured for each type of flow simulated. For each flow, velocity profile was changed based in its maximum velocity, V_{max} (Eq. 1-2). Therefore, eight different velocity profiles were simulated where V_{max} ranged from 0.1 v_a to 0.8 v_a, where $v_a = cf_{prf}/4f_c$, or the maximum velocity that can be measured by the 2D autocorrelation algorithm. The number of emissions or pulses used to evaluate each velocity was N_{pulse}=50. A high SNR of 50 dB was established to avoid velocity estimation errors from noise. Since the transducer was excited by a 4-cycle sinusoidal burst, velocity spatial resolution was set to 4 wavelengths (1.5 mm). To generate 1 second of acquisition data, computer simulation time took roughly 49 minutes, using an Intel Core i7-2.6 Ghz computer.

Accuracy results are summarized in Fig. 4. A comparison between measured and simulated velocity profile is shown in Fig. 5 and 6, for turbulent and laminar flow ($V_{max} = 0.8\, v_a$), respectively. Mean flow spatial velocities measured were underestimated for all velocities and all flows (left axis, Fig. 4). For uniform flow, the relative mean spatial velocity error (right axis, Fig. 4) do not vary significantly, ranging between -3.92% to -3.95%. For turbulent flow, mean spatial velocity error also remains almost constant varying from -13.08% to -13.12%. However, turbulent flow relative error is roughly 3 times higher than the relative error from uniform flow. Such increase in error relatively to the uniform profile is due to the curvature of the turbulent velocity profile (Fig. 5). The mean velocity error is proportional to the intersection area between the measured and the simulated velocity profiles from Fig. 5. Since spatial velocity profile from turbulent flow has a large intersection area than uniform velocity profile, the mean velocity error of the former is expected to be higher than the last. For laminar flow, mean velocity error also maintains a stable behavior, ranging from -20.8% to -21.3% (Fig. 4, right axis). The mean velocity accuracy for this condition is worse than the turbulent velocity and the uniform velocity profile. Such error increase can be explained by the increase in the area between the two profile curves (Fig. 6). In laminar flow the profile curvature is greater than turbulent flow. Therefore is expected a greater mean flow velocity error for laminar flow.

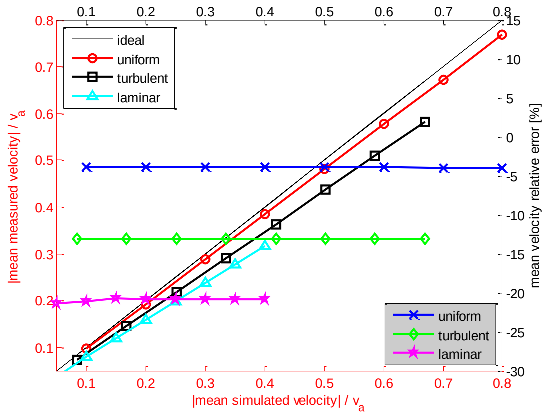

Figure 4: Left axis: Mean spatial measured velocity (autocorrelation) versus mean spatial simulated velocity, both normalized by the maximum velocity of the autocorrelation method, v_a. Legend at top left. Right axis: mean velocity relative error for each flow and each simulated velocity. Legend at bottom right.

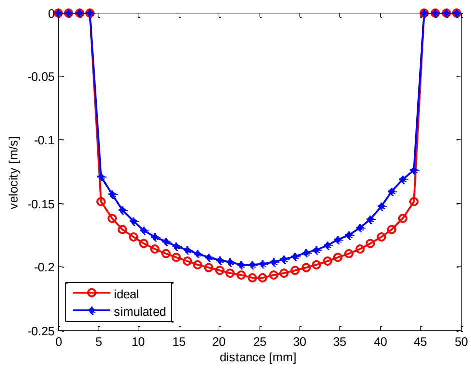

Figure 5: Spatial velocity profile measured versus spatial velocity profile simulated for turbulent flow where V_{max} =0.8 v_a , SNR=50 dB, N_{pulse}=50.

The mean velocity errors of Fig. 4 indicate a systematic behavior, where velocities estimated from the three flows are all underestimated. Since this error occurs systematically in every velocity tested, most of it can be suppressed by a simple calibration procedure.

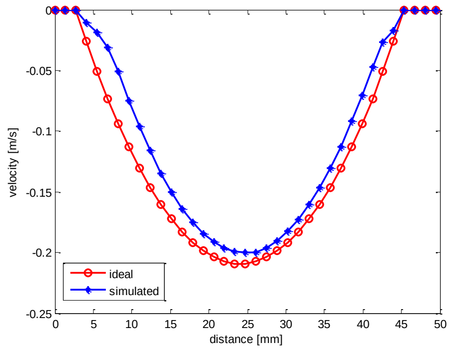

Figure 6: Spatial velocity profile measured versus spatial velocity profile simulated for laminar flow where V_{max} =0.8 v_a, SNR=50 dB, N_{pulse}=50.

4.3 Accuracy assessment by Cross-correlation

The underestimation observed in the measurement of the simulated data by the autocorrelation method motivates the use of another velocity technique to confirm the results obtained. The cross-correlation technique was chosen because most works published related to Field II only use this technique. The accuracy evaluation was performed using the same configuration described in section 4.2. Results obtained are summarized in Fig 7. Accuracy results of Fig. 7 also show that all velocities measured are underestimated for every flow tested (left axis). Turbulent and laminar mean velocity error presented larger error for low velocity values (Fig.7 right axis). However after these larger error values, the relative error remains roughly constant. Thus, the result obtained corroborates with the underestimation observed in the results obtained using the autocorrelation algorithm.

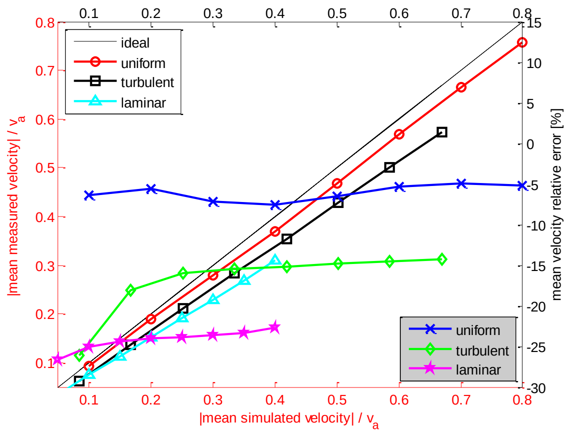

Figure 7: Left axis: Mean spatial measured velocity (cross-correlation) versus mean spatial simulated velocity, both normalized by the maximum velocity, v_a. Legend at top left. Right axis: mean velocity relative error for each flow and each simulated velocity. Legend at bottom right.

5. Conclusions

Some more work still need to be carried on in order to fully deploy Field II as an accurate simulation tool for fluid engineering study. At this stage, ultrasound flow signals simulation using Field II may only be used for the study of velocity estimation techniques if a prior calibration step is performed. The reason for the underestimation of velocities in the simulations results could lie in several factors. The discretization of the spatial impulse response, the division of the transducer in square mathematical elements, sampling frequency, can be responsible for the low velocities obtained. It is possible to change the simulation parameters mentioned to obtain an accurate result, however simulation time can increase considerably. Effects in velocity profile measured due to transducer apodization were also analyzed. Including transducer apodization in the simulation will incur in a narrow ultrasonic beam and thus will consequently generate a narrow velocity profile.

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