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Exploration of the Second Harmonic Signal for Vector Doppler Imaging: a Simulation Study

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***Abstract*— Ultrasound Vector Doppler methods are able to assess a full two dimensional velocity map of a moving reflector. Recent studies have shown great interest in Plane Wave imaging as a tool to increase the frame-rate. In the other hand, harmonic imaging has become a standard method in ultrasound imaging. This simulation study intends to explore the use of harmonic imaging with its benefits and Plane Wave imaging for high-frame-rate imaging to see the feasibility of Harmonic Vector Doppler Imaging.**

***Keywords*— Plane Wave, Harmonic imaging, Vector-Doppler, High-frame-rate**

I. INTRODUCTION

Ultrasound Doppler Imaging has become a well-established tool for measuring velocity field in both research and clinical investigation due to its non-invasive aspect, low cost and high temporal resolution. Among all Doppler techniques Color-Doppler-Imaging (CDI) technique is the most used. Classical CDI systems work by transmitting multiple periodic pulses into medium and by calculating the difference between the transmitted and the received frequency; the Doppler shift is based on:

$$f_d = \frac{2.f_0.\mathrm{v}.\cos(\theta)}{c} \qquad (1)$$

where f_d is the Doppler frequency shift, f_0 is the transmitted frequency, θ is the angle between ultrasound beam and motion axis, v is the velocity of the moving reflector and c is the velocity of sound in the medium [1].

CDI suffers from some drawbacks: limited frame-rate due to the line by line imaging and angle dependent velocity estimation. Recent studies have shown great interest in Plane Wave (PW) imaging as a solution to increase the frame rate [2]. Rather than multiple focused beam one single unfocused beam is used to insonify the medium, when coupled with a velocity estimator PW is able to measure the velocity from radio-frequency (RF) signal.

To solve the angle dependent velocity estimation of classical CDI, many method of in plane velocity estimation have been proposed. Among them, Vector-Doppler Imaging (VDI) has shown to be very promising. Vector Doppler is based on classical CDI, by capturing two steered Doppler images and recomposing their velocity components in a Cartesian coordinate we are able to construct a two dimension velocity map [3].

Besides, the use of harmonic imaging has proven to be very interesting in the meaning of improvement of lateral and axial resolution [4]. In this work, we use a steerable Plane Wave ultrasound beam in order to asses a quasi-full velocity vector map of a numerical spinning disc. First the use of steerable Plane wave allows the projection of velocity in two direction and also increase remarkably the frame-rate. The method of VDI is applied to the fundamental signal and then compared to results obtained with the second harmonic signal. Results are shown that emphasize the benefits of harmonic imaging when applied to Doppler methods.

II. THEORETICAL BACKGROUND

A. *Plane Wave imaging and Beam-Steering*

High-frame-rate imaging can be achieved by transmitting Plane Wave in place of focused line-by-line imaging technique. Once obtained the radio-frequency (RF) signal is beam-formed using a conventional Delay-and-Sum (DAS) method.

Compared to classical techniques which the maximal frame-rate is about 80 frames per second (fps), the Plane Wave imaging can easily reach the 500 fps which is better to characterize a fast moving target but this come with the cost of a poor spatial resolution.

In order to have an in plane velocity map, for each RF signal two beam-formed RF data are generated with steering in reception with an angle which is noted α . In this study we fixed the angle at 15 degree.

The main disadvantage of the beam-steering technique is the loss of information at the edge. In order to solve this issue Dort et al. (2013) [3] used several tilted compounded Plane Wave, but this decrease the frame-rate.

The present study doesn't use Plane Wave Compounding in order to keep the frame-rate as high as possible.

B. *Velocity Vector Imaging*

Once the two steered two dimensional RF signal are obtained, a velocity estimator is used on each one in order to have a one dimensional component of velocity.

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Tow widely used velocity estimator are used in ultrasound: the autocorrelation (ACM) [5] known also as the Kasai autocorrelation estimator and the cross-correlation (CCM) [6]. Since this study used the Kasai estimator, the basics of this method are discussed.

The ACM uses the phase shift also called Doppler shift from successive ultrasonic pulses from the complex demodulated signal [7]. Historically, the ACM method was the first to be proposed and still being implemented in many commercial ultrasound scanner. The phase shift is estimated by:

$$\phi_{autocorr} = \arctan(\frac{\mathrm{Im}\{\widehat{\mathrm{R}(1)}\}}{\mathrm{Re}\{\widehat{\mathrm{R}(1)}\}}) \qquad (2)$$

where $\widehat{R(1)}$ is the averaged autocorrelation function evaluated at the first lag, and Im{ }/Re{ } are the imaginary/real parts. Velocity is then calculated according to:

$$v_{autocorr} = -\frac{c.\mathrm{f}_{prf}}{4.\pi.f_0\cos(\theta)}\phi_{autocorr} \qquad (3)$$

where f_{prf} is the pulse repetition frequency.

The output of the velocity estimator is a 1-D component of the velocity vector with respect to the steering angle.

The 2-D velocity field reconstruction is performed using the two sets of oriented velocity and recomposing them into a common Cartesian coordinate system given by:

$$v_x = \frac{v_l - v_r}{2.\sin(\alpha)} \qquad (4)$$

$$v_z = \frac{v_l + v_r}{2.(1+\cos(\alpha))} \qquad (5)$$

where v_x and v_z are the axial and lateral velocity component, respectively, with v_l and v_r represent the 1-D velocity component parallel to the steered ultrasound beam at angle $\pm\alpha$, $+\alpha$ is left steered beamforming and $-\alpha$ is right steered beamforming.

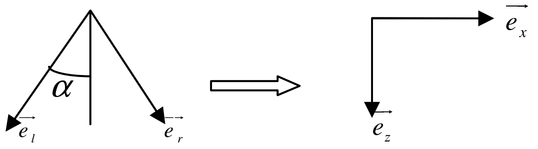


Fig. 1 Coplanar oriented basis resolved in Cartesian common basis.

Finally a discrete cosine transform based penalized least squares method of regularization was applied to the reconstruction in order to smooth the aberrant vector [8].

All the steps explained above intend to construct a full map of velocity vector of a moving target. In order to extract the second harmonic signal a 5th order Butterworth bandpass filter was applied to the generated signal and post-treated to assess also a velocity vector map.

To compare the performance and exactitude of measured velocity obtained from fundamental signal and second harmonic signal we calculated the root mean squared error (RMSE) for each point over the image:

$$RMSE = \sqrt{\sum\left|v_{true} - v_{est}\right|^2} \qquad (6)$$

where v_{true} is the theoretical velocity of the numerical spinning phantom and v_{est} is the estimated velocity obtained from the framework.

III. METHOD

A. Simulation set-up

To simulate the RF-signal the CREANUIS software has been used [9] [10]. CREANUIS has the ability to simulate the pre-beam-formed fundamental and second harmonic RF data with possibility to customise the transducer geometry.

Regarding the probe, the simulation was conducted with the geometry of the LA523 probe (Esaote, Florence, Italy). An 8-cycle 5 MHz sinusoidal pulse was transmitted with an initial pressure of 500 kPa used to emphasis the nonlinear character and strength of the second harmonic signal. The scatterers' density was 10 scatterers per resolution cells, a schematic of the spinning disc geometry is proposed in Fig. 2. All the simulation parameters are given in Table I.

B. Motion simulation

In order to simulate motion, 32 numerical 2-D map of a spinning disc and 32 pre-beam-formed RF-signal were generated for each theoretical velocity value. The typical B-mode images obtained are proposed in Fig. 3 with the corresponding spectrum in Fig. 4.

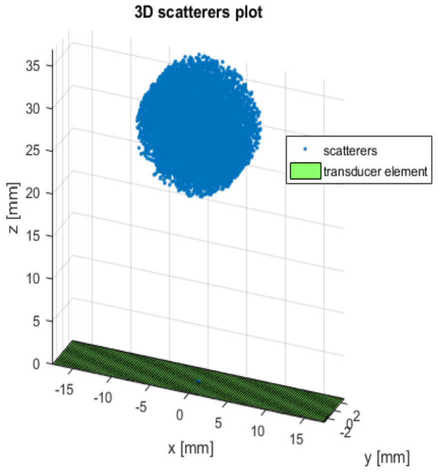
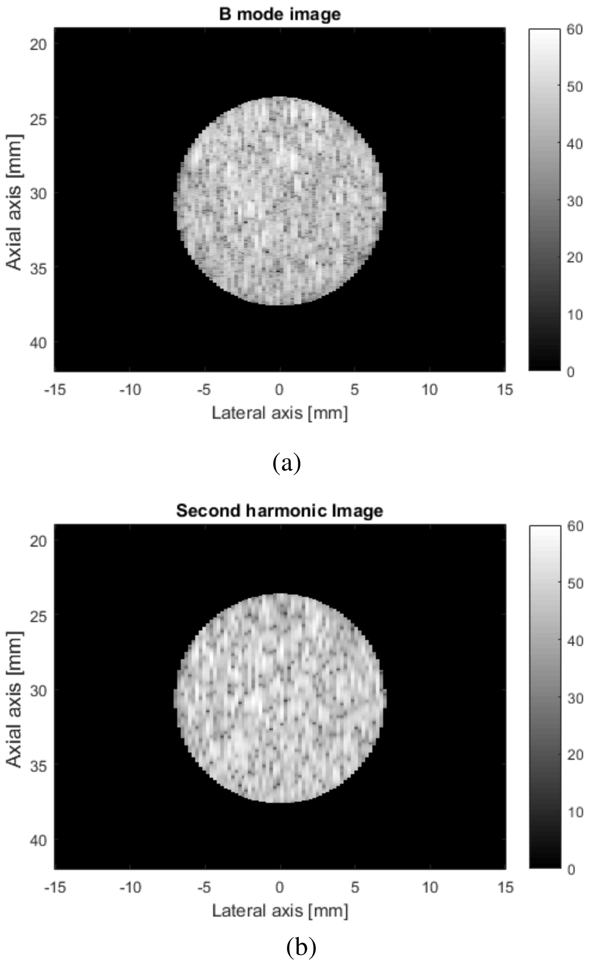


Fig. 2 3-D representation of reflector distribution with respect to the ultrasound transducer.

TABLE I
SIMULATION PARAMETERS

Probe geometry	
Probe central frequency	5 MHz
Pulse repetition frequency	[1000:10000] Hz
Number of active elements	128
Height	12.5 mm
Pitch	245 µm
Kerf	30 µm
Transmit focus	∞
Window	Hamming
Disc geometry	
Rayon	7 mm
Centre position in mm	[0 0 30] position [x y z]
Rotation velocity in cm/s	[3.08:30.8] with 3.08 step



(a)

(b)

Fig. 3 B-Mode image of the simulated disc based on the (a) fundamental or the (b) harmonic signals.

IV. RESULTS

As mentioned previously, with no use of Compounded Plane Wave there was a loss of signal at the edge of the spinning disc phantom but this was mainly observed in the method based on the fundamental signal.

Both methods, Vector Doppler with fundamental signal and harmonic Vector Doppler, showed good results for all velocity magnitude estimation and directional information.

The Doppler method based on the harmonic signal outperform the classic method for all simulated velocities and the difference increase with high velocity and this could be simply explained with the advantages of the harmonic imaging method which increases the lateral and transverse resolution and also make the signal better for autocorrelation estimation .

Figures 5 show an estimated velocity field on the rotating disc respectively for the fundamental and second harmonic signal. The RMSE, reported in figure 6 for the axial and lateral velocities, demonstrate the improvement of the harmonic VDI compared to the fundamental one.

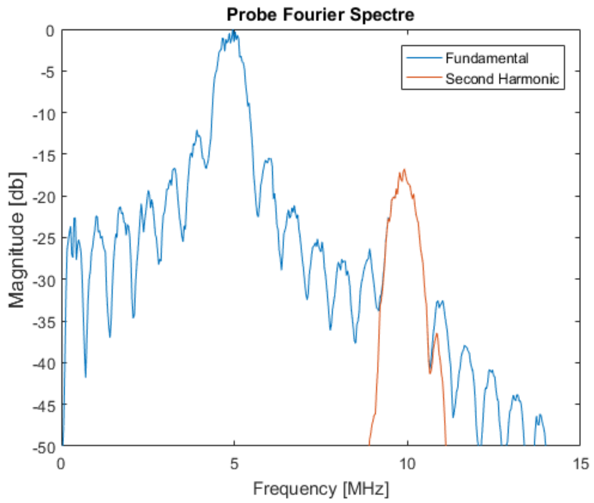
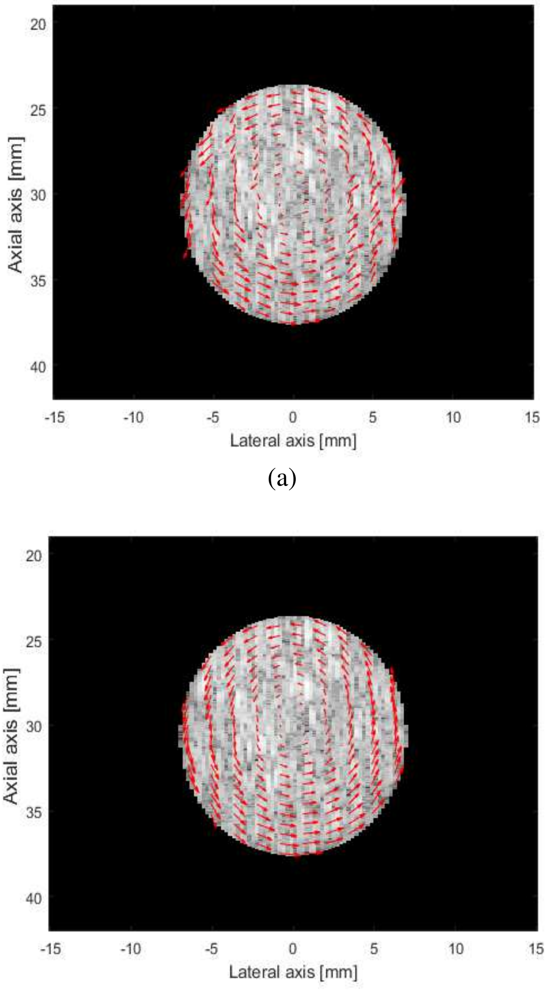


Fig. 4 B-mode image based on the second harmonic signal

V. CONCLUSIONS

In this study we proposed a motion simulation which explores the second harmonic signal using Plane Wave and Vector Doppler method. A nonlinear ultrasound simulator was used to have access to the ultrasound second harmonic signal which is CREANUIS. Both first harmonic and second harmonic contain exploitable Doppler information which can be used to assess a 2-D velocity map of the numerical spinning disc. The proposed method based on the second harmonic signal open a very promising perspective in Doppler velocity estimation. There was many initiative in the literature that intend to use the second harmonic signal for motion estimation but as far all this method are not Doppler based method.

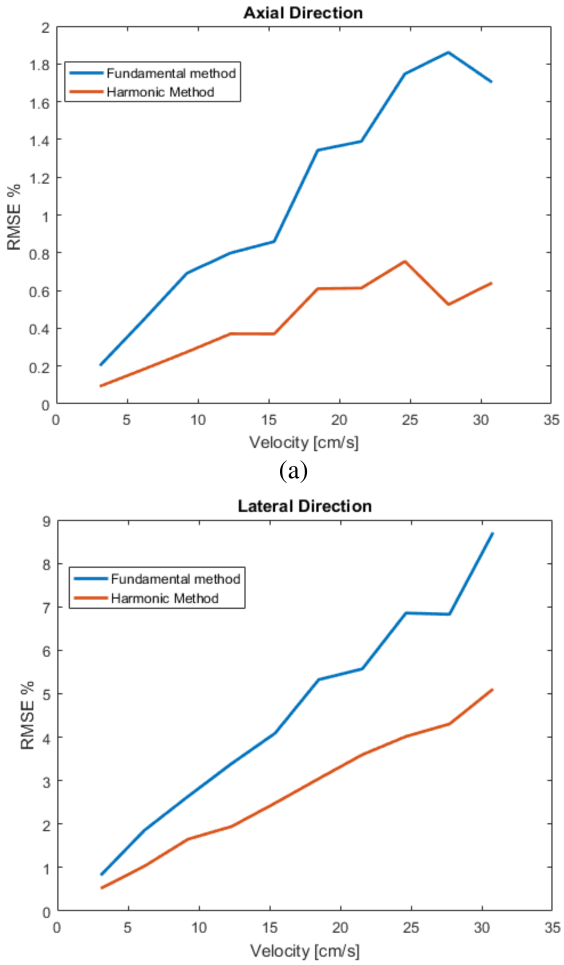
It remains to be noted that this study is only a simulation study and need to be validated with an in vitro evaluation which will be addresses in future work.



(a)

(b)

Fig. 5 Example of estimated velocity vector based on (a) the fundamental signal and (b) the second- harmonic signal. The velocity of the spinning disc was set at 15.4 cm/s



(a)

(b)

Fig. 6 RMSE obtained in (a) axial and (b) lateral direction for different spinning disc velocity.

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