Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

High velocity investigation with Multi Line Vector Doppler

Valentino Meacci
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
valentino.meacci@unifi.it

Stefano Ricci
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
stefano.ricci@unifi.it

Claudio Giangrossi
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
claudio.giangrossi@unifi.it

Riccardo Matera
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
riccardo.matera@unifi.it

Alessandro Dallai
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
alessandro.dallai@unifi.it

Enrico Boni
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
enrico.boni@unifi.it

Piero Tortoli
Dept. of Information Engineering
University of Florence
50139 Florence, Italy
piero.tortoli@unifi.it

***Abstract*— Vector methods based on the transmission of Plane Waves (PWs) produce impressive 2D maps of blood velocity. They are based on complex algorithms that process intensively huge amount of data. Producing 2D vector maps in real-time stresses the system hardware, limiting the achievable Pulse Repetition Frequency (PRF) which is frequently insufficient to measure, e.g., the blood velocities in stenoses, which may be higher than 2m/s. This work shows how the Multi Line Vector Doppler (MLVD) method, implemented on ULA-OP 256, overcomes part of the difficulties by using the new 'Virtual Real-Time' (VRT) processing architecture. In real-time, channel data are saved in the system memory, while in VRT data are re-processed from the memory as if they were coming from the probe. The ULA-OP 256 calculation power is used in real-time to achieve maximum PRF at the expenses of image quality, while in VRT the maximum image quality is restored as well. Experiments are reported where MLVD is shown capable of investigating flow jets up to 3 m/s with PRF of 16 kHz.**

Keywords—Blood velocity measurement, High PRF, Vector Doppler, Real-time, ULA-OP.

I. Introduction

Recent ultrasound systems use pulsed plane waves to generate detailed blood flow velocity maps [1][2][3]. The investigation of flow patterns in the carotid artery bifurcation, in particular, is widely used in clinical practice. The presence of stenotic plaques, which is one of the most common carotid pathology, produces flow jets whose velocity can be higher than 2-3 m/s [4]. This velocity range requires a correspondingly high Pulse Repetition Frequency (PRF) to be investigated by avoiding aliasing errors [5]. Unfortunately, ultrasound systems feature a calculation power that is often not sufficient to produce detailed 2D velocity maps at such high PRF in real-time. Techniques like staggered PRF [6][7] contribute to solve the problem. Using alternate sequences at different PRFs, it is possible to get velocity data beyond the Nyquist limit. However, this happens at the expenses of further data elaboration that should occur in the system in real-time. Multi Line Vector Doppler (MLVD) [8] is a method implemented in real-time in the ULA-OP 256 research scanner, which was designed at the Department of Information Engineering (DINFO) of the Florence University [9]. It is based on plane wave transmission and produces 2D velocity maps with vectors distributed in 8 parallel vector Doppler lines to cover a region of 1 cm lateral extension. It requires calculation efforts that the ULA-OP 256 hardware supports up to a PRF of about 7 kHz. In this work we propose a different approach based on the new Virtual Real-Time (VRT) [10] processing architecture implemented in the FPGAs of the ULA-OP 256. The acquisition session is divided in 2 steps: real-time and VRT. In real-time the MLVD runs with a 'light' set of configuration parameters designed to reduce the calculation effort so that the desired high PRF is achieved. At the same time channel data are saved in the system memory. In VRT the data saved are routed in the same hardware path normally used by the probe data so that the system processes the saved data as they sourced from the probe. In VRT the data flow can be artificially slowed down to make the processing of the full 8 vector Doppler lines feasible. Furthermore, all the parameters can be adjusted like in real-time, except those related to transmission and analog conditioning that was applied to the received data. The potentiality of the method is shown by investigating a flow jet produced by ejecting a blood mimicking fluid in water with a syringe positioned below the probe. Jet velocity of 3m/s was detected at PRF = 16 kHz.

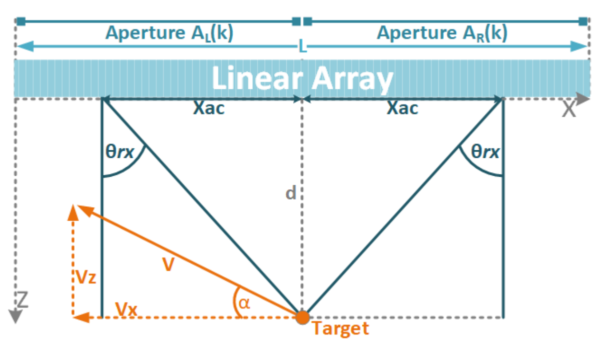

Fig. 1. Ultrasound probe apertures and geometry used for Multi Line Vector Doppler.

II. Materials and Method

A. Multi Line Vector Doppler

This section reports the basics of MLVD method, which is an extension of [11]. A more detailed description is available in [8]. In the MLVD, a linear array probe transmits no-steered plane waves at PRF rate. The Region of Interest (ROI) is given by 8 vector Doppler lines ($1 \le k \le 8$), perpendicular to the probe surface. These are the lines where the velocity vectors will be calculated. The vector Doppler lines are spaced by 0.125 mm, so that they cover a ROI of about 1 cm of lateral extension. In reception a couple of sub-apertures $A_R(k)$ and $A_L(k)$ is symmetrically located on the right and left of each vector Doppler line k (see Fig. 1). Thus, the probe is divided into 8 pairs of sub-apertures (16 sub-apertures). The echoes received by the sub-aperture pairs are simultaneously beamformed along the corresponding Doppler line. A scatterer, positioned at depth d and moving with velocity *V*, produces an echo that is received by the two coupled apertures. The echoes acquired by the left and right apertures are processed through coherent demodulation [12], wall filtering, and spectral analysis. The mean Doppler shifts, f_{dl} and f_{dr}, are computed by calculating the centroid of each Doppler spectrum. The lateral (V_x) and axial (V_z) components of the velocity vector are calculated by the trigonometric triangulation [13] [14]:

$$V_x = \frac{c}{2f_{tx}} \frac{f_{dr} - f_{dl}}{\sin\theta_{rx}}, V_z = \frac{c}{2f_{tx}} \frac{f_{dr} + f_{dl}}{1 + \cos\theta_{rx}} \quad (1)$$

where c and f_{tx} are the sound velocity and transmission frequency, and θ_{rx} is the receiving angle, which depends on the depth d. The velocity vector is finally obtained as:

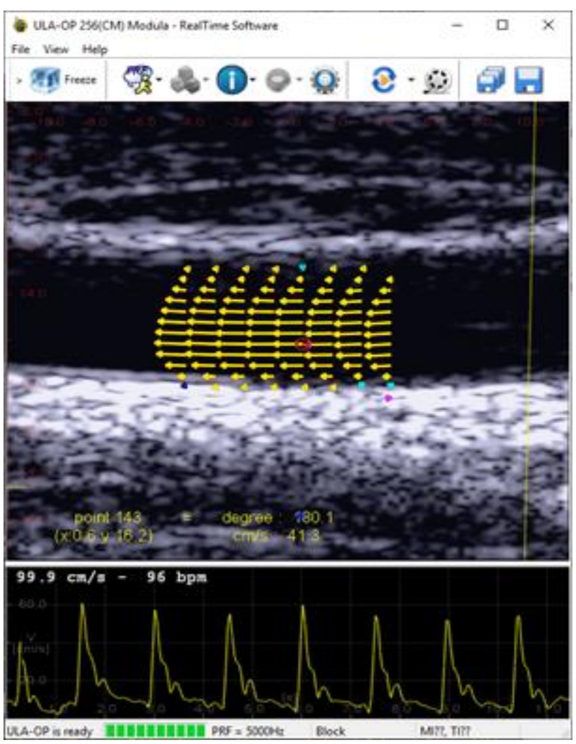

Fig. 2. ULA-OP 256 screenshot. Real-time MLVD while investigating a carotid artery of a volunteer at PRF = 5.0 kHz. The top panel shows the velocity vectors distributed in 8 lines. The bottom panel shows the angle corrected velocity at the cursor position (red circle).

$$V = \sqrt{V_x^2 + V_z^2}; \quad \alpha = \angle(V_x, V_z), \quad (2)$$

where V is the vector amplitude and α the angle. Fig. 3 shows a sample screenshot obtained from the real-time display of the ULA-OP 256 when investigating the common carotid artery of a healthy volunteer. On top, the 8 vector Doppler lines highlight the roughly parabolic profile of the artery blood. In the bottom section of the display the angle-corrected velocity taken in the cursor position is shown. A peak velocity of about 100 cm/s was detected by using PRF=5.0 kHz.

B. Virtual Real-Time

The Virtual Real-Time (VRT) modality expands the functionality of the ULA-OP 256 research ultrasound system. ULA-OP 256 manages up to 256 channels by using 8 Front End (FE) boards. Each FE embeds an FPGA (ARRIA V GX family from Altera-Intel, San Jose, CA, USA) and 2 DSPs (320C6678 from Texas Instruments Inc., Austin, TX, USA), and it is suitable to acquire and process data coming from 32 channels. The implementation of the VRT modality required to modify data flow and data management in the FPGA architecture of the FEs [15]. Fig. 2 shows a flow diagram of the ultrasound system front-end. During real-time operations the echoes collected from the probe are amplified and digitalized by the Analog Front End (AFE) and buffered in the Raw Data Buffer (RDB). Channel data are immediately read from the RDB and simultaneously sent to the beamformer (BF) and to a DDR Memory capable of storing 64MB of raw data for each channel. For the VRT mode a New Communication Channel (NCC) was added, to enable the data flowing from memory to RDB. During the VRT, the data flow from AFE to RDB is stopped and the raw data saving is disabled. Whereas, raw channel, data previously saved in the memory during the real-time, are transferred to the RDB through the NCC and processed exactly as the system worked in real-time. More details are given in [10]. The system uses the same hardware and algorithms for processing data in real-time and in VRT to such an extent that the system back-end ignores the data origin. However, the data management can be programmed to

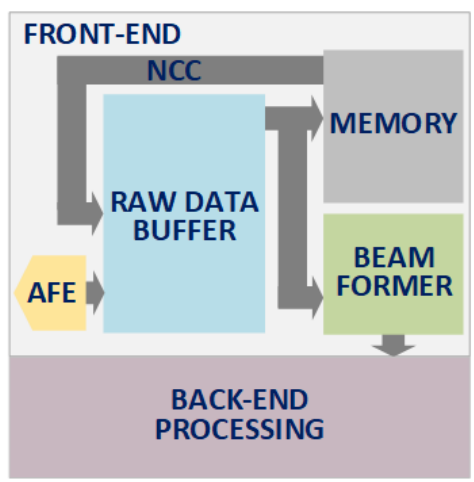

Fig. 3. ULA-OP 256 Data flow. In real-time data from probe (AFE) transit in the Raw Data Buffer and are immediately distributed to memory and the beamformer. In VRT, data are loaded from memory reaching the beamformer through the raw data buffer. The back-end processes data unaware of their origin.

slow-down the extraction of channel data from the memory to let the hardware have enough time to complete calculations that in real-time would not have been possible. On the ULA-OP 256 GUI a drop-down menu was added to select the rate at which raw data are accessed during the VRT mode and a button to switch the modality between real-time and VRT. Some parameters are changeable on the fly by means of sliders in real-time and/or VRT mode to optimize the image quality. For example, filters, thresholds, dynamics etc. can be adjusted through GUI controls.

C. MLVD with Virtual Real-Time implementation

MLVD is implemented by using a transmission sequence composed by 64 plane waves (i.e. packet size=64 for blood vectors detection) followed by 96 focused lines (for concurrent B-mode). Thus, every second, PRF/(64+96) MLVD+B-mode frames are produced. The vector Doppler lines are composed by 256 depths, which are filtered and decimated 4-fold before being displayed. Thus, the system calculates the following number of vectors per second:

$$\mathrm{Vec/s} = \frac{PRF}{160} \cdot 256 \cdot 8 \approx 13 \cdot PRF \qquad (2)$$

In real-time, ULA-OP 256 can implement this modality for PRF not exceeding about 7 kHz. The VRT architecture was used to extend the PRF range achievable with MLVD. During real-time, the MLVD was configured with a lighter set of processing parameters, by limiting to one, in particular, the number of calculated vector lines. This way the calculation burden of the system was reduced 8-fold. The operator can thus tune the PRF to the needed high value (e.g. PRF = 16 kHz). The displayed B-mode and single-line vector Doppler is used to locate the ROI, and, if necessary, optimize the TX/RX parameters. In this phase the echograph calculates B-mode and a single vector line, but still saves all the channel data required for full MLVD in its memory. When the display looks sufficiently good, the user switches to VRT. Now the system reloads the raw data from memory but calculates and displays all the 8 vector lines. Data are reproduced at a slower rate, which can be tuned by the user on-the-fly. The user can apply all the echograph commands as if it worked in real-time, except the commands that act on transmission and the analog front-end, i.e. before the channel data are acquired.

TABLE I. *TX / RX MLVD PARAMETERS USED IN EXPERIMENT*

Parameter	Symbol	Value
	PROBE	
Type		Linear
Elements		192
Element Pitch		0.245 mm
6 dB Band		3.25 – 12.75 MHz
	MLVD TX	
Frequency	f_{Tx}	8 MHz
Transmission cycles	N	5
Apodization window		Tukey
Pulse Repetition Freq.	PRF	16 kHz
TX Aperture		31.36 mm (128 el.)
Mode		Plane Wave
	MLVD RX	
Lines	k	1-8
Line-Spacing		1.225 mm
Total RX Aperture	A_{RX}	18.8 mm
RX Sub-Apertures	$A_L(k)$, $A_R(k)$	7.8 mm (32 el.)
Relative Aperture Pos.	Xac	5.48 mm
Steering angle	θ_{rx}	14° @ 22mm
Focalization		Dynamic
Aperture ratio	F#	5
Sampling Freq.	F_S	39.0625 MHz
Packet size		64

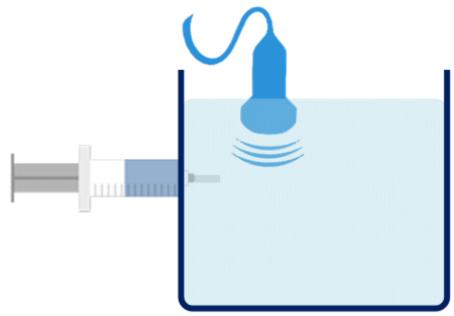

Fig. 4. Experimental setup: The ultrasound probe is immersed in a tank full of water where a syringe was installed. A high velocity jet of mimicking blood fluid was ejected by the syringe.

III. EXPERIMENTS

A. Experimental setup

MLVD with VRT was tested with ULA-OP 256 connected to the LA533 linear probe (Esaote spa), and with the operating parameters summarized in TABLE I. As a proof of concept, a tank was filled with water and a syringe was installed horizontally at a border, 15 mm below the water surface. (see Fig. 4). The syringe had a tip diameter of 4 mm. The probe was held longitudinally over the syringe output so that it could intercept the output flow. The syringe was filled with 150 ml of water mixed with corn starch. The syringe piston was manually pressed to eject the mixture in the tank. The velocity of the resulting jet was higher than 3m/s. According to the MLVD+VRT modality, during the flow jet, ULA-OP 256 acquired and processed in real-time the data to display a B-mode image of the jet superimposed to a single MLVD line, and at the same time it saved the raw data needed for the VRT mode. A PRF =16 kHz was used in real-time. Right after the jet flow, ULA-OP 256 was switched to VRT to reprocess the saved raw data by producing 8 Vector Doppler lines enabling a high details blood flow investigation. The rate at which the raw data are sent to the beamformers was slowed-down 5-fold (see TABLE II).

TABLE II. PARAMETERS SET FOR REAL-TIME AND VIRTUAL REAL-TIME MODE

Parameter	Real-Time	Virtual Real-Time
Depths	128	256
N° Lines	1	8
Vectors displayed per Line	32	32
Sampling Freq.	39.0625 MHz	39.0625 MHz
PRF	16 kHz	3.2 kHz

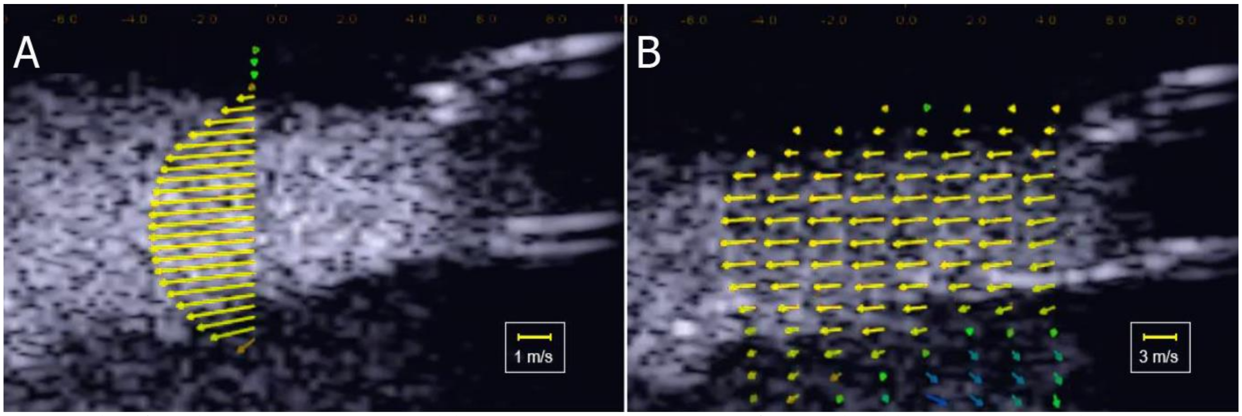

Fig. 5. Screenshots from the ULA-OP 256 scanner while investigating with MLVD a 3 m/s jet produced by a syringe. A: Real-time MLVD at 1 line is superimposed on B-mode at PRF=16 kHz; B: VRT MLVD at 8 vector Doppler lines is superimposed on the B-mode and slowed down 5-fold.

B. Results

Sample screenshots taken from the echograph during real-time and VRT are shown in Fig. 5. In particular, Fig. 5.A reports a frame obtained in real-time. On the right, the syringe's tip is clearly discernable. The jet intercepts the vector Doppler line at about 1 cm from the tip, where it develops a roughly parabolic profile. Fig. 5.B shows a screenshot taken during VRT reproduction. Here the flow trend is detected by the 8 vector Doppler lines for 1 cm lateral extension. A vortex is visible in the region below the jet. The velocity scale between real-time and VRT was changed to improve the display readability. In both the modalities the peak velocity of about 3m/s was detected.

IV. Conclusion

In this work an extension of the MLVD method for high velocity investigation was presented. The method is based on the Virtual-Real-Time strategy implemented in the FPGAs of the ULA-OP 256 scanner. This technique makes possible to investigate high speed flows in real-time through MLVD operating on a single line at high PRF, and then reprocessing the data saved during real-time with a different set of processing parameters that recover extended information. The test demonstrates that the MLVD using VRT is capable to measure velocity up to 3m/s with a PRF=16 kHz and to show the details of complex flows. Work is in progress to extend the use of the VRT modality to other processing techniques implemented on ULA-OP 256 like, for example [16].

References

[1] J.A. Jensen, S.I. Nikolov, A.C.H. Yu, D. Garcia, "Ultrasound Vector Flow Imaging—Part II: Parallel Systems", *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, 63(11): 1722 - 1732, 2016, DOI: 10.1109/TUFFC.2016.2598180

[2] I.K. Ekroll, A. Swillens, P. Segers, T. Dahl, H. Torp, L. Lovstakken, "Simultaneous quantification of flow and tissue velocities based on multi-angle plane wave imaging", *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*, 60(4): 727 - 738, 2013, DOI: 10.1109/TUFFC.2013.2621

[3] M. Lenge, A. Ramalli, E. Boni, H. Liebgott, C. Cachard, and P. Tortoli, "High-frame-rate 2-D vector blood flow imaging in the frequency domain," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 61, no. 9, pp. 1504–1514, 2014

[4] E. Grant, C. Benson, G. Moneta, et al, "Carotid artery stenosis: Gray-scale and Doppler US diagnosis—Society of Radiologists in Ultrasound Consensus Conference," *Radiology*, 2003, 229(2):340–346, DOI: 0.1148/radiol.2292030516.

[5] D. H. Evans, Doppler Ultrasound: Physics, Instrumentation, and Clinical Applications. New York: John Wiley & Sons, 2007.

[6] D. Posada, J. Poree, A. Pellissier, B. Chayer, F. Tournoux, G. Cloutier, D. Garcia, "Staggered Multiple-PRF Ultrafast Color Doppler", *IEEE Trans. Med. Imaging.*, 35(6):1510–1521, 2016, DOI;10.1109/TMI.2016.2518638

[7] S. Ricci, L. Bassi, A. Dallai, R. Matera, P. Tortoli, "Real-Time Staggered PRF for Vector Doppler Blood Velocity Assessment", 2017 *IEEE Ultrasonics Symposium Proceed.*, Washington, September 2017, DOI: 10.1109/ULTSYM.2017.8091797

[8] S. Ricci, A. Ramalli, L. Bassi, E. Boni, P. Tortoli, "Real-Time Blood Velocity Vector Measurement over a 2D Region", *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*, 65(2):201-209, 2018, DOI: 10.1109/TUFFC.2017.2781715

[9] E. Boni, L. Bassi, A. Dallai, F. Guidi, V. Meacci, A. Ramalli, S. Ricci, P. Tortoli "ULA-OP 256: A 256-Channel Open Scanner for Development and Real-Time Implementation of New Ultrasound Methods", *IEEE Trans. Ultrason*. Ferroelect. Freq. Contr., 63(10):1488–1495, 2016, DOI: 10.1109/TUFFC.2016.2566920

[10] C. Giangrossi, V. Meacci, E. Boni, A. Dallai, F. Guidi, S. Ricci, A. Yu, P. Tortoli "Virtual real-time: a new US operating modality", *in 2019 IEEE Ultrasonics Symposium (IUS), 2019, pp. 1-4*.

[11] S. Ricci, L. Bassi, P. Tortoli, "Real-time vector velocity assessment through multigate Doppler and plane waves", *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, 61(2):314–324, 2014, DOI:10.1109/TUFFC.2014.6722616

[12] S. Ricci, V. Meacci, "Data-Adaptive Coherent Demodulator for High Dynamics Pulse-Wave Ultrasound Applications", *Electronics*, 7(12), 434, 2018; DOI:10.3390/electronics7120434

[13] M. D. Fox, "Multiple crossed-beam ultrasound Doppler velocimetry," *IEEE Trans. Sonics Ultrason.*, 25(5):281–286, 1978, DOI: 10.1109/T-SU.1978.31028

[14] B. Dunmire, K. W. Beach, K.H. Labs, M. Plett, and D. E. Strandness, Jr., "Cross-beam vector Doppler ultrasound for angle-independent velocity measurements," *Ultrasound Med. Biol.*, 26(8):1213–1235, 2000, DOI: 10.1016/S0301-5629(00)00287-8

[15] E. Boni, L. Bassi, A. Dallai, V. Meacci, A. Ramalli, M. Scaringella, F. Guidi, S. Ricci, P. Tortoli, "Architecture of an Ultrasound System for Continuous Real-time High Frame Rate Imaging", *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*, 64(9):1276-1284, 2017, DOI: 10.1109/TUFFC.2017.2727980

[16] S. Ricci, D. Vilkomerson, R. Matera, P. Tortoli, "Accurate Blood Peak Velocity Estimation Using Spectral Models and Vector Doppler", *IEEE Trans. Ultrason., Ferroelect., Freq. Contr*, 62(4): 686-696, 2015, DOI: 10.1109/TUFFC.2015.006982