A New Perspective on the 4-point Balanced Velocity-encoding

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Target Audience: Researchers interested in improving the accuracy of multi-directional velocity encoded phase-contrast MRI (PC-MRI).

Purpose: 4-point balanced flow encoding is a practical way to measure three-directional velocity [1]. All three velocity directional components (v_x, v_y, v_z) can be reconstructed from every 4 consecutive measurements. Therefore, a sliding window width = 4 frames can be used to reconstruct velocities with high apparent temporal resolution. However, it has been reported that the sliding window reconstruction can introduce artifactual oscillations in the velocity curves [2]. This study provides a new perspective on the 4-point balanced velocity-encoding technique from the Fourier transform/frequency domain point of view. Velocity reconstruction is shown to be equivalent to a traditional filter design problem in the Fourier domain. A velocity reconstruction algorithm based on a simple Fourier domain filter is described and tested in a volunteer. The proposed method provides a clear physical description of velocity encoding in the temporal frequency domain, and an explanation and solution for the oscillation artifacts that can occur with a sliding window reconstruction.

Methods: Using the 4-point balanced encoding method, the phase measured in each frame includes contributions from all three velocity directions as well as the background phase. The velocities and background phase are encoded by multiplying either +1 or -1, alternating in the temporal direction, i.e., modulating the signal by four orthogonal modulation functions (Fig 1.). Interestingly, the four modulation functions are four basis frequency functions of the discrete FFT. Therefore, from a Fourier encoding point of view, each of the velocity directions is encoded into a sub-band centered on a different frequency by amplitude modulation. Decoding and reconstruction of all three velocity components in each frame can be formulated as a de-modulation and implemented as a filter design problem in the frequency domain. The sliding window reconstruction can be described using this formalism; it effectively represents a convolution with a width = 4 window in the time domain, and a sinc filter in the frequency domain (Fig 2.). Other filters can be prescribed to optimize the frequency response of the reconstruction process.

The proposed reconstruction method requires the following four steps: 1) Apply temporal FFT to the measured phase across all frames; 2) apply four band-pass filters in the frequency domain to separate the three velocity and one background phase signals; 3) demodulate each signal by shifting each pass band to the center of Fourier domain; 4) Inverse FFT to reconstruct each velocity waveform. We utilized a simple Tukey window with the width = ¼ of the frequency domain as the bandpass filter. In the temporal domain, each reconstructed velocity map is a linear combination of all temporal frames; the combination coefficients are the inverse Fourier transform of the frequency space Tukey window function. Note that the modulation functions associated with v_x *and* v_z have the same frequency, but different phase (Fig. 1). They can be separated by a simple linear transform.

Experimental data were collected from one healthy volunteer using a 1.5 T scanner (Avanto, Siemens, Germany) using a body phased-array coil. 4-point balanced velocity encoding was implemented using an EPI PC-MRI sequence with echo-train-length = 5. A segmented k-space acquisition was used to acquire a 68-frame dynamic series of 192x144 matrix images.

Results: Figure 3 shows (3a) the phase in each frame resulting from 4-point balanced velocity-encoding in an ROI in the descending aorta of the volunteer, and its frequency domain spectrum (3b). The four peaks corresponding to the four encoding frequencies, i.e., zero frequency, +/- half maximum frequency, and maximum frequency are clearly evident (Fig. 3b). The Tukey window centered on the background phase peak is also shown. Figure 4 shows the three-directional velocity curves from the same ROI reconstructed using the sliding window method (blue) and the proposed method (red). The oscillation is significant in v_x *and* v_y, but is not visible when the proposed reconstruction was used.

Discussion: It has been shown that the traditional 4-point balanced PC-MRI velocity reconstruction based on sliding window can cause oscillation artifacts in the reconstructed velocities. Our study reveals that the three velocity directions are encoded into different sub-bands in the frequency domain, and the reconstruction is equavelent to band-pass filtering. The sliding window based reconstruction utilizes a sub-optimal sinc function filter. The side lobes of the sinc function cause cross talk between the velocity signals and background phase, and components with slow velocities may be corrupted by oscillation artifacts. A simple way to reduce this oscillation artifact is to improve the filter design, and our study showed that a simple Tukey window filter effectively eliminated the oscillations.

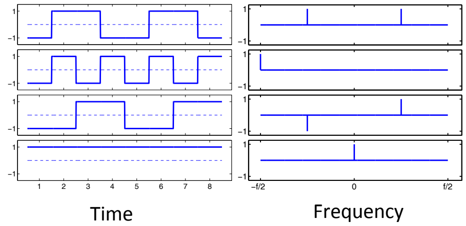


Figure 1: The modulation functions of 4-point balanced velocity encoding and their frequency domain spectra. From top to bottom: Vx, Vy, Vz, and background phase.

$$\hat{v}_x = \frac{-\phi_1 + \phi_2 + \phi_3 - \phi_4}{2\gamma\Delta M_1},$$

$$\hat{v}_y = \frac{-\phi_1 + \phi_2 - \phi_3 + \phi_4}{2\gamma\Delta M_1},$$

$$\hat{v}_z = \frac{-\phi_1 - \phi_2 + \phi_3 + \phi_4}{2\gamma\Delta M_1}.$$

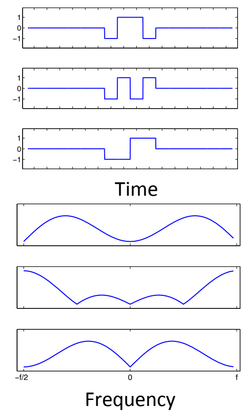


Figure 2: (Top left) the traditional reconstruction formula of 4-point balanced flow encoding using a sliding window; (top right) the corresponding temporal domain convolution function; (bottom right) the frequency response in the Fourier domain.

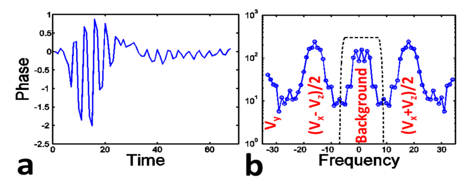


Figure 3: (3a) the phase vs time of the ROI; (3b) the frequency domain spectra. The four peaks in the frequency spectrum correspond to Vy, Vx and Vz, and background phase. The dashed line indicates one of the Tukey windows.

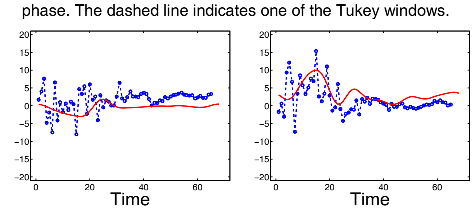
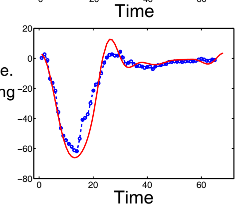


Figure 4: Vx (left), Vy (upper right) and Vz(lower right) vs time. The blue line indicates the sliding window reconstruction, and the red line is the proposed reconstruction.



Conclusions: We have presented and demonstrated a new method to reconstruct three-directional velocity components from 4-point balanced PC-MRI. It provides a clear physical picture of the encoding process in the frequency domain, and can improve the velocity reconstruction by filter design strategies. It is easy to understand and simple to implement, and may be applicable to other phase-based measurements of dynamic processes, such as DENSE and elastography.

References: [1] Pelc et al. JMRI **1** 405-413 (1991). [2] Ahmad et al. ISMRM 2013 p1336.