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

Dual Aperture Motion Compensation (DAMoCo)

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***Abstract*— One of the issues affecting motion compensation schemes in ultrasound imaging is sidelobe re-alignment, a cause of potentially significant image degradation. In this study, we propose a method to address this problem based on tracking the motion between frames that have been beamformed with different receive apodizations. As a result, the motion estimator is able to track the motion of only the mainlobe signal. Subsequently, the frames with the same receive apodization are motion compensated according to the Dual Aperture (DA) motion estimate (DAMoCo). Thus, only mainlobe signals are correctly rephased and coherently summed. This technique can be used in coherent compounding schemes where the point spread function's sidelobes tilt from subframe to subframe, as well as in adaptive coherent persistence modalities without sidelobe tilt, to further improve image quality by suppressing sidelobe signals. This technique was applied to diverging wave simulation data as well as in diverging wave and focused transmit *in vivo* cardiac data. In both cases, DAMoCo was found to be capable of suppressing sidelobes, thus improving contrast. However, its effects were milder for the *in vivo* datasets.**

Keywords—Motion Compensation, Motion Tracking, Ultrasound, Coherent Compounding, Dual Apodization

I. Introduction

Tissue motion is the most important factor contributing to phase misalignment when combining signals from different emissions (i.e. coherent compounding) or different frames (i.e. coherent persistence). Causes of motion include cardiac and/or vascular pulsation, respiratory as well as transducer motion. Thus, motion compensation is of paramount significance for image quality in both coherent compounding [1] and adaptive coherent persistence [2] schemes.

One of the issues affecting motion compensation schemes is sidelobe re-alignment, a cause of potentially significant image degradation. More specifically, motion estimation algorithms track sidelobe signals that exhibit motion in the form of rotation (due to tilt change of the diverging wave transmissions [1]) or in the form of motion in hypo- or anechoic regions, following the physiological motion patterns of nearby tissue [3]. Subsequently, MoCo schemes rephase the sidelobes, leading up to their coherent summation, which cancels the desired effect of coherent compounding and leaves high sidelobes visible in the compounded/persistence image.

Several methods have been proposed to address this issue. Most of them involve designing specialized transmit sequences and/or require specialized manipulation of the per-channel data (triangle sequence in [1], alternating sequence in [4] or repeated transmit sequence in [5]). In this study, we

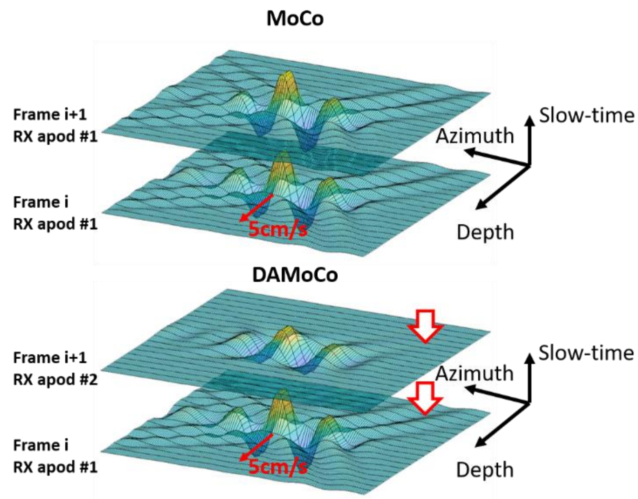

Figure 1: Simulated point scatterer moving at 5cm/s. Pre- and post-motion snapshots of the generated PSFs with the MoCo (same apodization: rectangular) and the DAMoCo framework (dual apodization: rectangular, hamming). Red arrows indicate different sidelobe patterns in each of the dually apodized frames.

propose a method based on dual aperture (DA) apodization, a concept that has been extensively studied within the framework of Dual Aperture with Cross-correlation (DAX) [6], [7].

II. Methods

The main idea of this method is based on tracking the motion between frames that have been beamformed with different receive (RX) apodizations. As a result, the motion estimator is able to track the motion of only the mainlobe signal (DA motion). In terms of multi-lag cross-correlation motion tracking, this outcome is expected, given that low sidelobe correlation coefficients are obtained even when applying cross-correlation to the dual apodizations of the same image [6]. To illustrate this dissimilarity of the sidelobe patterns of dually apodized frames, a PSF moving at 5cm/s away from the transducer was simulated and apodized with a rectangular and a hamming apodization. The result is shown in Fig. 1 and indicates that in the DA scheme mainlobe signals are similar while sidelobe signals differ (indicated by the red arrows).

Subsequently, the frames with the same RX apodization are motion compensated according to the DA motion estimate (DAMoCo). Thus, only mainlobe signals are correctly rephased and coherently summed. A schematic illustrating the principle of MoCo and DAMoCo is shown in Fig. 2.

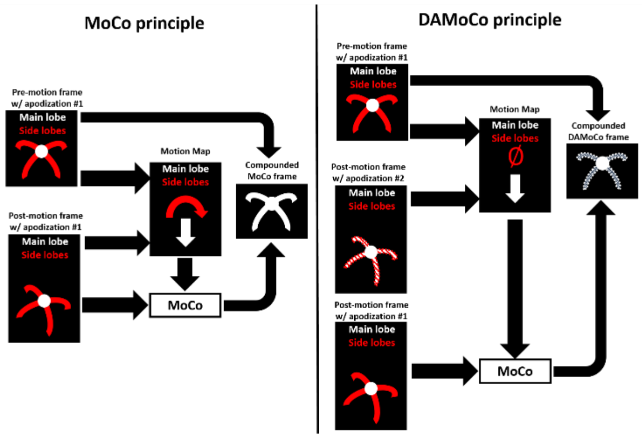

Figure 2: Schematic of the principles of MoCo and DAMoCo imaging an axially moving target with a rotating PSF. In MoCo, motion estimation between frames apodized with the same RX apodization function detects motion for both the mainlobe and sidelobe signals, resulting to both of them being motion compensated, coherently summed and thus being visible in the compounded image. In DAMoCo only the motion of mainlobe is estimated correctly as a result of performing motion estimation between frames apodized with different RX apertures and thus only mainlobe signals are being rephased and coherently summed. Compounding eliminates the sidelobes.

In this study, a rectangular apodization was used to generate the frames to be registered and a random selection apodization to generate the frames to be motion tracked. The random selection aperture entailed randomly activating a specific number of channels on receive (e.g. half of the receive elements in the Philips S5-1 phased array probe).

Motion estimation was performed between the frames beamformed with the random selection apertures using either a 1-D axial autocorrelation method or a 1-D axial cross-correlation method. Subsequently, motion compensation was performed on the rectangular aperture-apodized frames according to the estimated DA motion fields. Motion compensation was implemented as a phase shift in cases where a Doppler-based 1-D autocorrelation algorithm was used and as an axial time shift (image warping with linear interpolation) in cases where a 1-D axial cross-correlation algorithm was used. Subsequently, motion compensated frames were coherently summed producing the final images. The aforementioned methodology can be generalized for an ensemble of more than two frames by estimating the inter-frame motion between the frames apodized with the random selection apertures and then utilizing these displacement fields to register the ensemble frames to a single frame in the ensemble.

DAMoCo was tested in Field II simulation data as well as in cardiac sequences acquired using a Philips EPIQ scanner. In both simulations and acquisitions, a Philips S5-1 phased array probe was simulated/used.

III. Results

In Field II, a single moving scatterer and a moving resolution phantom were simulated with an axial wall velocity of 10cm/s (typical velocity in cardiac applications) away from the transducer (top to bottom). They were subsequently imaged with diverging waves (-30mm transmit focus) with an angular interval of 1° and total angular span of 9° (-4.5° to 4.5°) at a PRF of 2000Hz. 10 single diverging wave frames (1DW) were acquired and then combined with MoCo and DAMoCo (10x1DW). Velocity estimation was performed using a 1-D autocorrelation method. The resulting images were compared against a single static frame constructed with 10 diverging waves (10DW) coherently compounded. The resulting images as well as the estimated velocity maps are shown in Fig. 3.

DAMoCo suppressed the PSF's sidelobes yielding results comparable to the static 10DW case without distorting the mainlobe signal. In the case of the phantom, DAMoCo images showed improved contrast in the anechoic region of the phantom (CNR estimated at the top cyst: DAMoCo 5.4dB, MoCo 4.9dB and no MoCo 3.5 dB), with its main effect being sidelobe suppression. Inspection of the inter-frame frame velocity maps indicate that both MoCo and DAMoCo detected similar velocities in mainlobe signal areas, however, regular MoCo also tracked sidelobe motion whereas DAMoCo did not track sidelobe/clutter signals.

Additionally, DAMoCo was tested in cardiac sequences. In order to prove the feasibility of this method, it was used to motion compensate single DW frames before coherent compounding [3]. 5DW apical 4-chamber view images were obtained at an inter-frame frame rate of 60 Hz (much slower than a real DW acquisition would happen in practice – at 2-5 kHz rate). From each frame, a single DW was extracted, at a different transmission angle for each frame. The single DW frames were then motion compensated using the displacement fields generated with a 1-D axial multi-lag cross-correlation algorithm and subsequently coherently summed to produce an equivalent 5DW image. In Fig. 4 a single DW frame was compared with the MoCo 5DW and DAMoCo 5DW results as well as with an original 5DW frame (where all DW waves were taken from the same frame, therefore much less motion artifacts are expected). MoCo and DAMoCo significantly improved image quality compared to the single DW frame, however, compared to the ground truth 5DW image they were unable to sufficiently recover the echolucent endocardium. This can be attributed to the low SNR levels of the 1DW frames along with the relatively low motion estimation rate leading to signal decorrelation. As seen in the second row zoomed-in images DAMoCo further helped to alleviate some of the near-tissue sidelobes.

Finally, DAMoCo was tested as an adaptive coherent persistence modality in conventional focused transmit frame sequences. While the presence of sidelobes in this case was already minimal, DAMoCo provided marginal improvement in the form of extra de-cluttering and elimination of residual sidelobes (Fig. 5).

IV. Discussion

In this study, DAMoCo, a dual apodization-based motion compensation technique was introduced and its feasibility

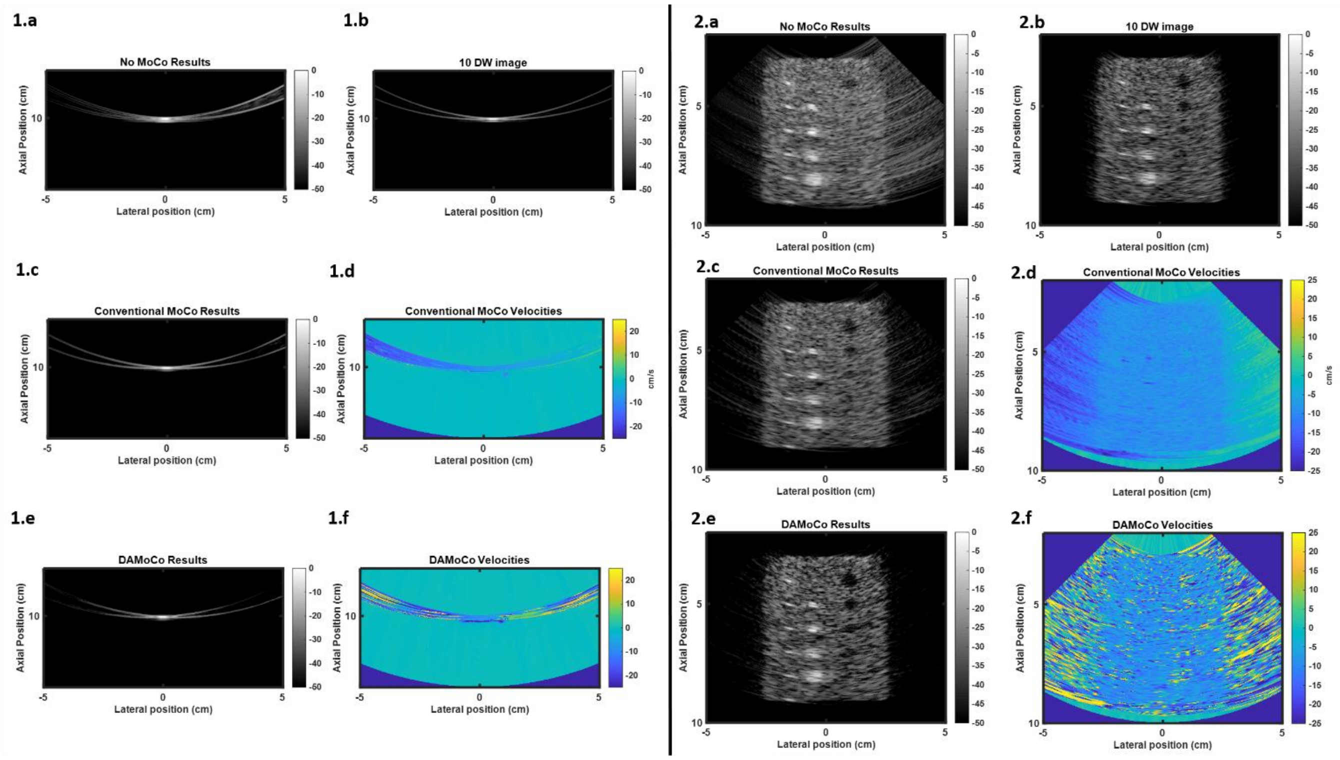

Figure 3: Field II simulations of a moving point scatterer and a resolution phantom. 1,2.a show the results of compounding ten 1DW frames with no motion compensation. 1,2.b show a 10DW static image (gold standard image). 1,2.c show the MoCo compounded ten 1DW frames (10x1DW) while 1,2d show the corresponding inter-frame velocities. Rotation of the sidelobes is detected, resulting to their rephrasing and thus making them visible in the MoCo compounded image. 1,2.e show the DAMoCo compounded ten 1DW frames (10x1DW) while 1,2d show the corresponding inter-frame velocities. It can be observed that rotation of the sidelobes is not correctly detected while the motion of the mainlobe signals is preserved. As a result, the sidelobes are not as visible in the DAMoCo compounded frames, thus making them more similar to the static 10DW images. Blue indicates motion towards transducer and yellow indicates motion away from transducer.

was shown in simulations and *in vivo* datasets. Its main utility compared to conventional MoCo was shown to be the suppression of sidelobe signals.

Its effects *in vivo* were found to be milder compared to the simulations. This can be attributed to the lower frame rate at which motion tracking was performed (2000 Hz simulated frame rate compared to 60 Hz *in vivo*) as well as to the larger increments between the transmission angles (1^o in the simulation datasets compared to 11.25^o *in vivo*). Lower frame rate leads to larger inter-frame displacements that may increase signal decorrelation. At the same time, out of plane motion also increases, further impacting the accuracy of displacement estimation [8]. Similarly, larger increments between the transmission angles lead to drastically rotated PSF patterns, increasing signal decorrelation and thus hindering motion estimation. Increasing the transmission angle increments in simulations led to sidelobe signal decrease in the MoCo image as well, at the cost, however, of image quality. Consequently, also given a lower SNR setting *in vivo*, rephasing sidelobe signals becomes challenging even for conventional MoCo thus rendering the effect of DAMoCo milder compared to MoCo.

One of the limitations of DAMoCo is the appearance of dark spots in the image, giving speckle regions a sparser appearance. This has also been observed in the case of DAX [6] and has been attributed to the random nature of speckle as well as to grating lobes and clutter comprising the most prominent portions of the signal in those regions.

The DAMoCo methodology could be potentially augmented with the implementation of a displacement filter that filters out low SNR motion estimates due to sidelobe signals. Ongoing work involves developing such a filter that could be based on the magnitude of the correlation coefficient, and would be very useful in denoising both DAMoCo motion fields and images. This would limit the appearance of artifacts and could also lead to the application of DA motion estimation in ultrafast Doppler where sidelobe rotation can be source of periodic noise [5].

Overall, DAMoCo showed promise in the suppression of sidelobe signals without the need for any specialized transmission schemes and could prove useful within the framework of motion compensated coherent compounding.

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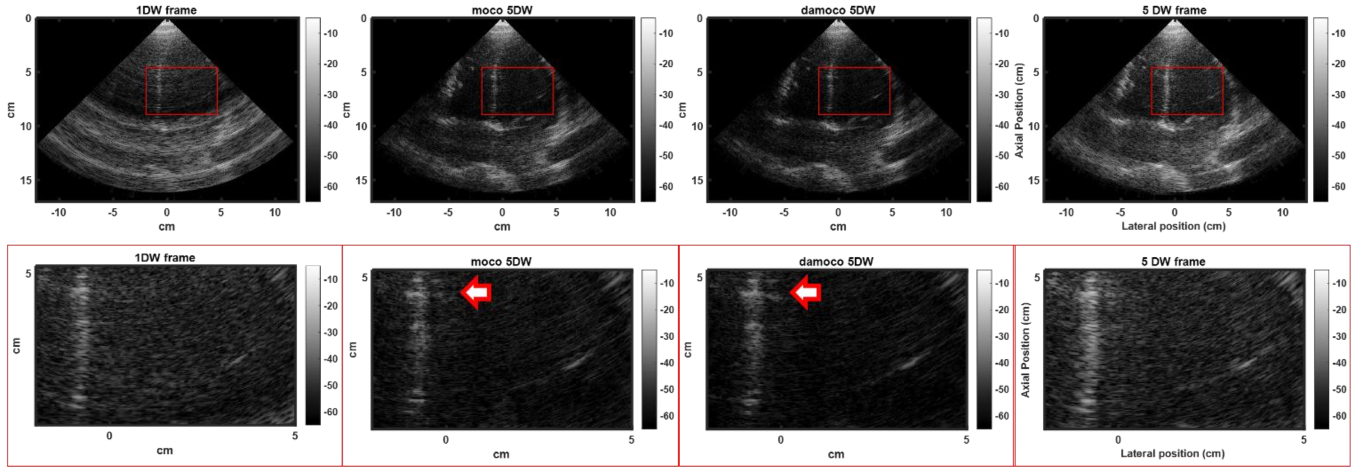

Figure 5: MoCo and DAMoCo in a cardiac dataset where five1DW frames are combined (5 different transmission angles for each DW frame) and compared with a ground truth 5DW image. Both MoCo and DAMoCo improve SNR in the compounded image while DAMoCo further helps in eliminating some sidelobes. In the second row, zoomed-in images of the region within the red rectangle are shown. The red arrows indicate sidelobe signals close to the septal wall that are preserved in MoCo but eliminated in DAMoCo.

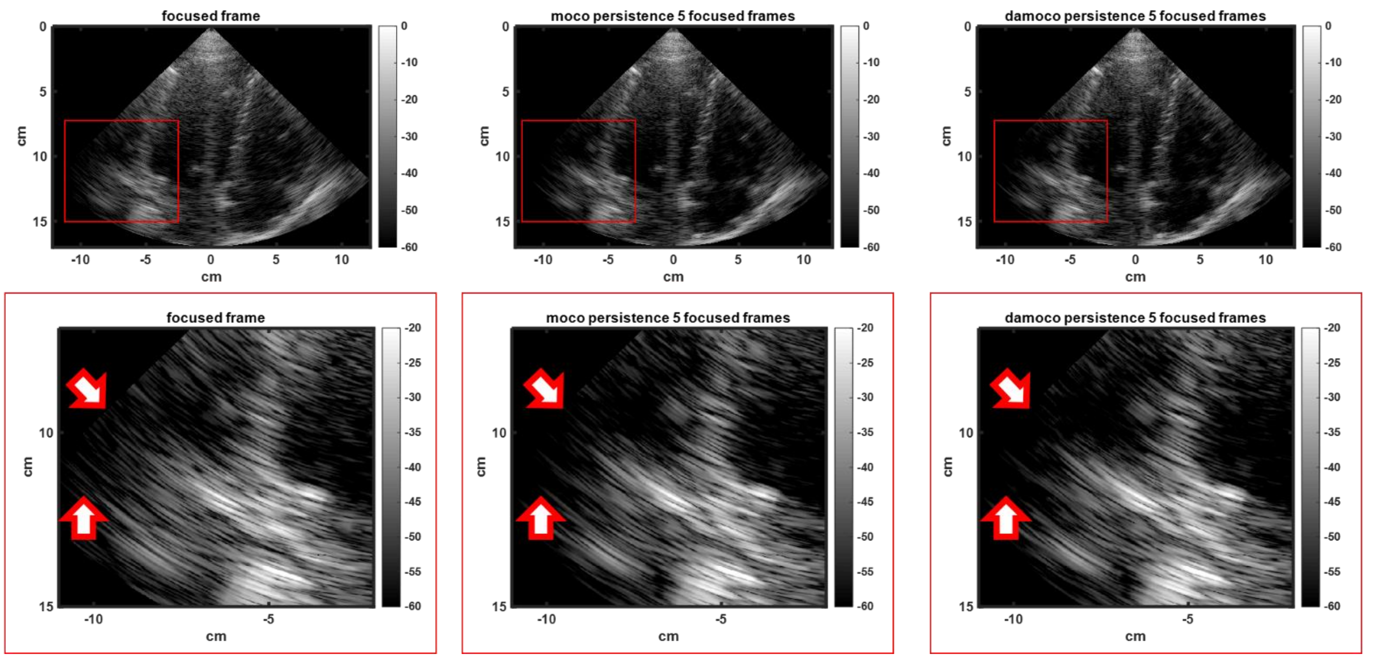

Figure 4: MoCo and DAMoCo used as persistence modalities in a conventional focused cardiac dataset (apical 4 chamber view). Both MoCo and DAMoCo improve SNR in the persistence image while DAMoCo further helps eliminate some sidelobes/clutter. In the second row, zoomed-in images of the regions within the red rectangle are shown. The red arrows indicate areas where DAMoCo eliminates some of the clutter.

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