REVIEW ARTICLE

Pulse Inversion Techniques in Ultrasonic Nonlinear Imaging

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Pulse inversion (PI) technique plays an important role in ultrasonic nonlinear imaging. For tissue imaging, PI technique provides suppression of spectral leakage and, thus, produces better image contrast. For contrast imaging, contrast between the agents and surrounding tissues are also enhanced with this technique by distinguishing nonlinear microbubbles from the background in either Doppler domain or radiofrequency domain. This paper reviews the theoretical backgrounds and relevant issues of the PI technique. Improvements in image contrast with the PI technique in both tissue harmonic imaging and contrast harmonic imaging are discussed in detail. In addition, potential motion artifacts and related contrast degradation are also included.

KEY WORDS — contrast detection, motion artifacts, nonlinear imaging, pulse inversion, ultrasonic contrast agents

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Introduction

Ultrasonic nonlinear imaging has demonstrated that it can provide superior image quality compared to conventional linear imaging, and it has become an important diagnostic tool in many clinical applications [1–5]. Nonlinear imaging differs from linear imaging in the mechanism of signal generation. In linear imaging, echoes linearly backscattered in the fundamental frequency band are used for imaging. In nonlinear imaging, however, generation of nonlinear echoes depends on the nonlinear properties of the imaged target and the propagation medium. In clinical applications, two sources contribute to nonlinear echoes: human tissues and ultrasound contrast agents (UCAs), which are usually introduced into the vascular beds via intravenous administration.

Nonlinear tissue signals are generated when the acoustic wave propagates in human tissues. Note that the acoustic velocity increases with the instantaneous pressure and the nonlinear characteristic of propagation tissue [6–10]. As a result of pressure-dependent velocity, the high-pressure crest propagates faster than the low-pressure trough when the original transmit signal is propagating in a nonlinear tissue. Over a distance of propagation, this leads to the progressive steepening of the ultrasound waveform. This process is referred to as *finite amplitude distortion*, which is characterized by the

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generation of harmonic signals whose frequencies are at multiples of the original transmit frequency. The acoustic waveforms before and after the distortion are demonstrated in Fig. 1A and Fig. 1B, respectively. The corresponding spectra are shown in Fig. 2. Since the tissue harmonic signal is generated gradually throughout the propagation path, the harmonic signal is usually weak in the near field. Though the weak intensity causes difficulties in imaging the superficial structures, the reverberations from the near-field anatomy are reduced in tissue harmonic imaging.

For UCAs, the mechanism of nonlinear signal generation is completely different. UCAs are mostly comprised of microbubbles encapsulated by protective shells. To improve the stability of microbubble contrast agents, gases with high molecular weights, such as sulfur hexafluoride and perfluoropropane, are usually used as the gas core. When UCAs are injected into the blood pool, the microbubbles produce strong backscattered signals due to the acoustic-impedance mismatch between blood and air [11,12]. Therefore, UCAs are capable of enhancing both grayscale images and Doppler signals.

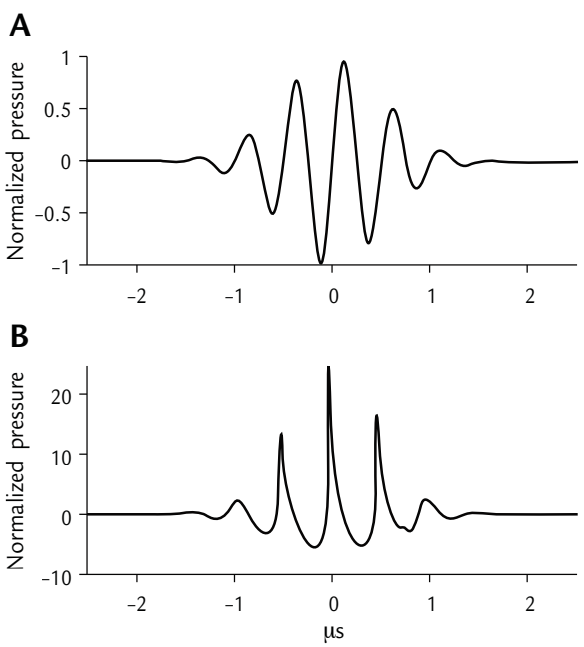

Fig. 1. *Simulated acoustic waveforms. (A) Waveform at the transducer's surface (i.e. before finite amplitude distortion). (B) Waveform at the focal point (i.e. after finite amplitude distortion).*

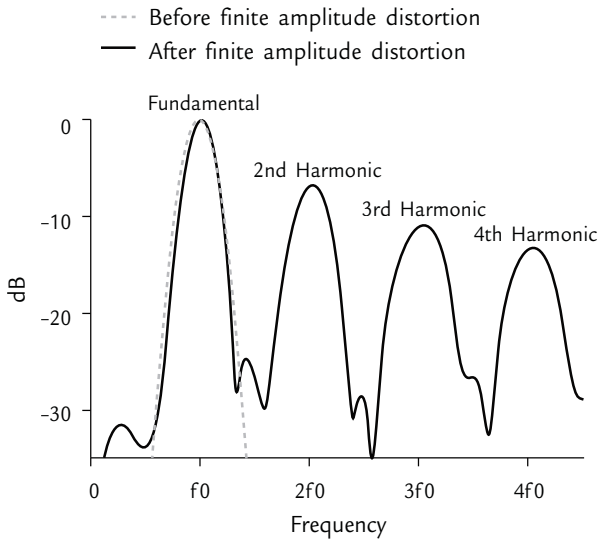

Fig. 2. *Simulated spectra of the waveforms before and after finite amplitude distortion. The dashed line represents the spectrum of the waveform in Fig. 1A and the solid line represents the spectrum of the waveform in Fig. 1B.*

One example of Doppler enhancement is demonstrated in Fig. 3. In addition, the microbubbles exhibit significant nonlinear oscillations when the impinging sound wave is near the resonance frequency of the bubbles [13]. Nonlinear responses from UCAs include harmonic and subharmonic generations [14,15]. An example of contrast harmonic imaging to evaluate a focal hepatic lesion is illustrated in Fig. 4. UCAs can be altered by exposure to intense insonification. The changes include reshaping, resizing and destruction of the bubbles [16]. UCAs may also be displaced by the acoustic radiation force [17]. Clinically, UCAs can be utilized to enhance the contrast between normal and diseased tissues, and may help to outline vessels and cardiac chambers. It can be seen in Fig. 5 that the border between the cardiac chamber and the myocardium is much better defined when intravenous administration of UCAs is applied.

Though the image contrast in nonlinear imaging is improved compared to its linear counterpart by using the nonlinear properties of either the native tissue or UCAs, the performance of nonlinear imaging is still limited. For example, the nonlinearity of the imaging system itself may degrade the image contrast [18]. It has also been shown that the