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Reducing Clutter Noise in Fast Ultrasound Imaging with Transverse High-Pass Filtering

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Abstract – **Clutter noise that appears as line strips in parallel with transducer surface is often seen in fast imaging with plane wave or waves of small divergences. In this paper, spatial high-pass filters of different cut-off frequencies are applied in the transverse direction in Fourier domain to reduce the clutter noise for the high-frame rate (HFR) imaging method developed previously. The noise reduction and contrast enhancement are significant when 11 transmissions (maximum frame rate of 413 frames/s at a speed of sound of 1500 m/s and 165-mm image depth) are used. However, with 91 transmissions (maximum frame rate of 50 frames/s), the method is less effective since the original image already has a low clutter noise and a high contrast.**

Keywords - ***Clutter noise, high-frame-rate imaging, fast Fourier transform, plane wave imaging, and diverging beams***

I. Introduction

Fast ultrasound imaging such as plane wave imaging [1]-[6] and imaging with waves of small divergences [7][8] is gaining a renewed interest in recent years due to the need of high image frame rate for elasticity imaging of moving objects [9]-[11], blood flow velocity vector imaging [12]-[15], and fast cardiac imaging [5][11][16]. However, due to a relatively flat wave front of the plane wave or waves that have small divergence angles [7][8], it is observed that there is clutter noise in images. The clutter noise appears as line strips that are generally in parallel with the surface of the transducer [1][2][4][5][7][17]. It is produced by imperfect receiver electronics [5][6][18], multiple reflections among parallel objects, and multiple reflections between the objects and the transducer surface. The clutter noise is most obvious in anechoic areas, at deeper depths where echo signals are weak and receiver gain is high, and the steering angle is small [4][5][7][17].

In this paper, the clutter noise is reduced with a spatial high-pass filter for the high-frame-rate (HFR) imaging method [1]-[8],[12][17]-[27] that was developed based on limited diffraction beams [13][14][28]-[35] and Fourier reconstruction. The filter is applied in the Fourier domain in a direction (transverse direction) that is in parallel with the transducer surface. Since the HFR imaging method is Fourier based, the application of the filter is straightforward [1][4][5].

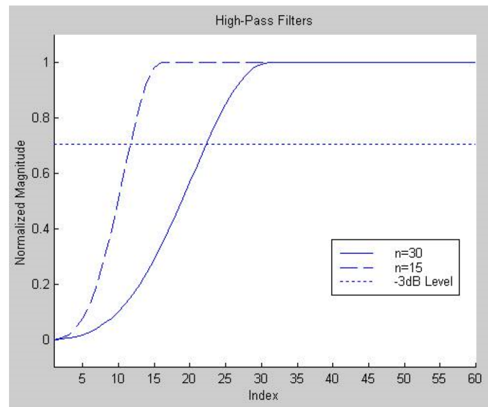

Figure 1. Transfer functions of the high-pass filters (they are an inverse of half of the Blackman window functions).

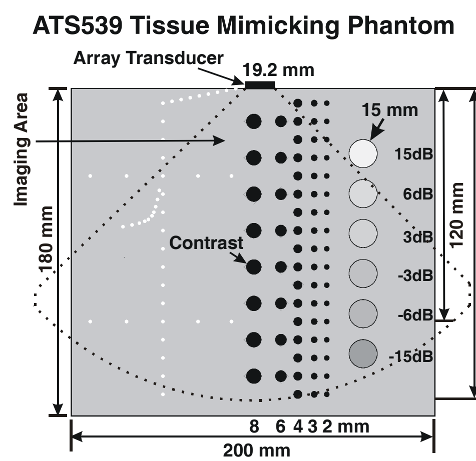

Figure 2. A cross-section of an ATS539 tissue-mimicking phantom showing the imaging areas of 120 mm and 165 mm depths with +/-45 degree field of view for the experiments. (Modified from Fig. 4 of [17].)

II. Method

In the study, two filters that have -3-dB cut-off frequencies of about 0.225 mm^{-1} and 0.45 mm^{-1} respectively were used ($\Delta k_x' = 0.02045$ mm^{-1} with a total number of points of 4096 and Δx =0.075 mm, where $\Delta k_x'$ and Δx are sampling intervals in the frequency and spatial domains of the image respectively). The transfer functions of the filters have a shape of an inverted Blackman window (see Fig. 1) and the half widths of the windows of the two filters are $n=15$ and $n=30$ points (or spatial frequencies of 0.307 mm^{-1} and 0.614 mm^{-1}) respectively [36]. The filters were applied to all sub-images in the Fourier domain before a coherent superposition to form the final image from the sub-images using the HFR imaging method [1][4][5].

III. EXPERIMENT

Images of an ATS 539 tissue mimicking phantom (Fig. 2) were produced experimentally with plane waves and waves of small divergence angles in transmissions using a home-made HFR imaging system [5][6][18], and were reconstructed with the HFR imaging method developed previously based on the Fourier transformation [1][2]. In the experiment, a 128-element, 19.2-mm aperture, and 2.5-MHz linear array transducer of about 58% -6-dB pulse-echo fractional bandwidth was used.

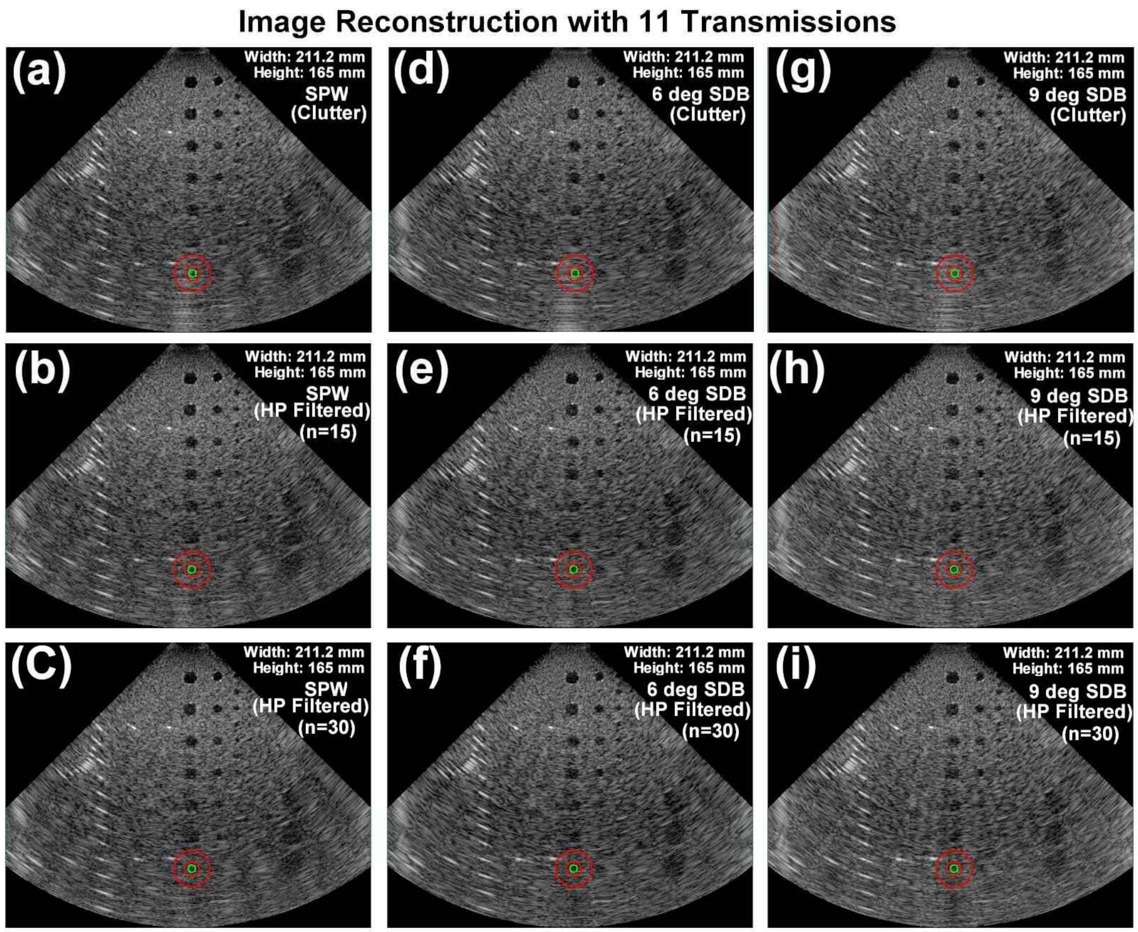

Figure 3. Effects of the high-pass filters on reduction of clutter noise (see areas around and below the red circles) for images reconstructed with the HFR imaging method with 11 transmissions and with echo signals acquired experimentally. 50 dB log compression has been applied.

IV. RESULTS

Fig. 3 and Fig. 4 show images reconstructed with the HFR imaging method with 11 (maximum frame rate of 413 frames/s at a speed of sound of 1500 m/s and 165-mm image depth) and 91 (maximum frame rate of 50 frames/s) transmissions respectively and with echo signals acquired experimentally. The images were obtained with steered plane wave (SPW) (first column), and steered diverging beams (SDB) of 6 (second column) and 9 (third column) degrees of divergence angles. Images reconstructed with the clutter noise reduction (second and third rows for the high-pass filter with $n=15$ and $n=30$ points respectively) (see areas around and below the red circles) are compared with those without the noise reduction (first row). From Fig. 3, it is clear that with the high-pass filters, the clutter noise at deeper depths where the signals are weak is reduced and the contrasts of the cyst are increased for images reconstructed with 11 transmissions (this is the case for both SPW and SDB transmissions) (Table 1). As for images reconstructed with 91 transmissions, their contrasts are slightly reduced after the clutter noise reduction (see Fig. 4 and Table 1). This means that the noise reduction method is more effective for fast image reconstruction where fewer transmissions are used and is less effective for slower imaging that already has a higher image quality before the noise reduction.

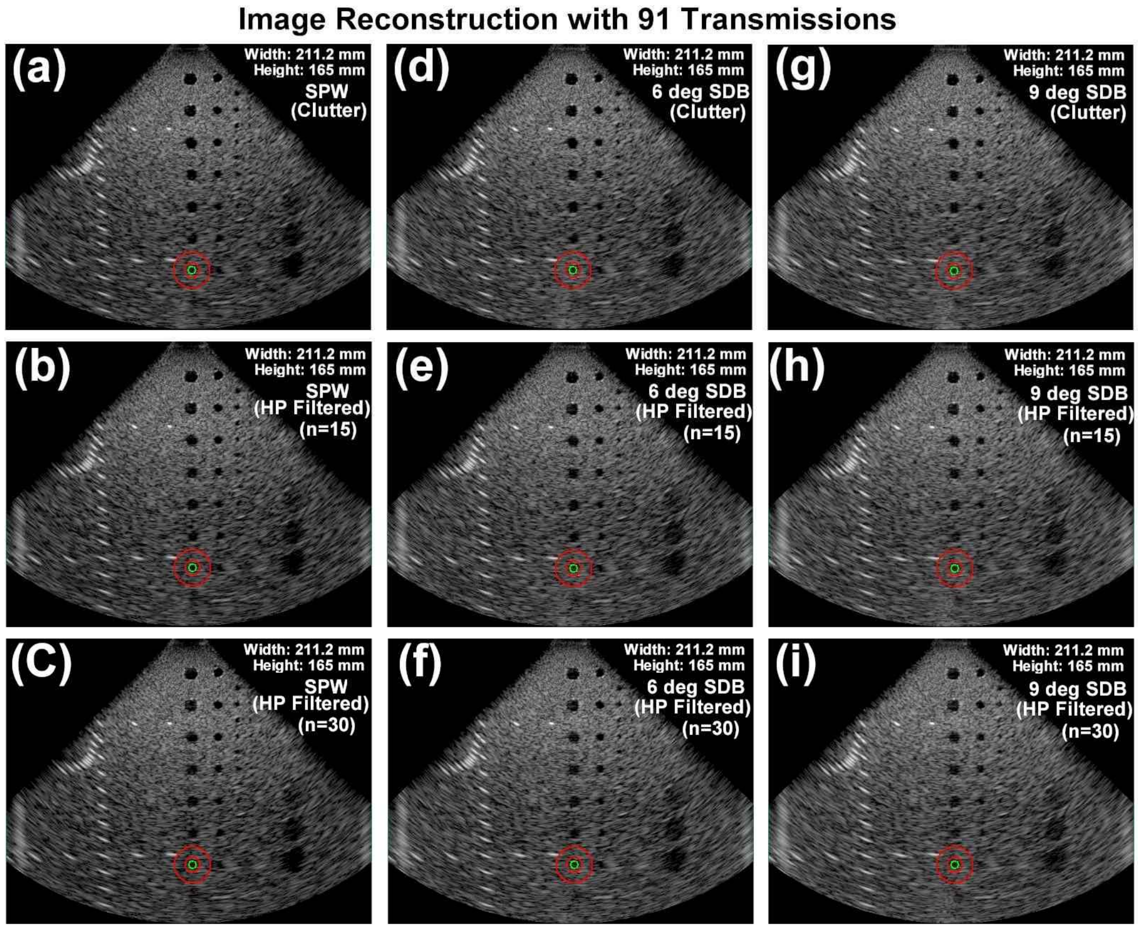

Figure 4. Effects of the high-pass filters on reduction of clutter noise (see areas around and below the red circles) for images reconstructed with the HFR imaging method with 91 transmissions and with echo signals acquired experimentally. 50 dB log compression has been applied.

Table 1. Contrasts (20 times the logarithm of the average pixel values inside the green circle over that between the two red rings) of the 7th large cyst (8 mm in diameter) from the top of the ATS539 tissue-mimicking phantom due to clutter noise reduction with high-pass filters (HPF) of different -3-dB cut-off spatial frequencies (0.225 mm^{-1} and 0.45 mm^{-1} for n =15 and n =30 respectively).

Cyst Contrast (dB)	11 Transmissions			91 Transmissions		
	SPW	SDB 6^o	SDB 9^o	SPW	SDB 6^o	SDB 9^o
No Filter	-2.32	-3.28	-3.16	-8.35	-7.29	-5.86
HPF (n=15)	-3.56	-5.64	-4.91	-7.93	-6.64	-5.73
HPF (n=30)	-3.30	-5.39	-4.35	-7.46	-6.64	-5.85

V. CONCLUSION

The clutter noise that appears as line strips in parallel with the surface of transducer is reduced significantly and image contrasts are increased greatly with high-pass filters for the HFR imaging of 11 transmissions. With a higher cut-off frequency, the clutter noise is further reduced but the image contrasts are also slightly reduced. With 91 transmissions, the effects of the filters are less effective since the original image already has a low clutter noise and high image contrast.

REFERENCES

[1] Jian-yu Lu, "2D and 3D high frame rate imaging with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 44, no. 4, pp. 839-856, July 1997.

[2] Jian-yu Lu, "Experimental study of high frame rate imaging with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Contro*l, vol. 45, no. 1, pp. 84-97, January 1998.

[3] Jian-yu Lu and Jiqi Cheng, "System for extended high frame rate imaging with limited diffraction beams," *United States Patent*, no. 7957609, Issued: June 7, 2011.

[4] Jiqi Cheng and Jian-yu Lu, "Extended high frame rate imaging method with limited diffraction beams," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 5, pp. 880-899, May 2006.

[5] Jian-yu Lu, Jiqi Cheng, and Jing Wang, "High frame rate imaging system for limited diffraction array beam imaging with square-wave aperture weightings," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 53, no. 10, pp. 1796-1812, October 2006.

[6] Jian-yu Lu, "High frame rate imaging system," *United States Patent* (claims were allowed in May 2013 and the patent is to be issued in 2013).

[7] Jian-yu Lu and Hong Chen, "High frame rate imaging with diverging beam transmission and Fourier reconstruction," in *2011 IEEE International Ultrasonics Symposium Proceedings*, pp. 2221-2224, 2011 (Digital Object Identifier: 10.1109/ULTSYM.2011.0551).

[8] Hu Peng and Jian-yu Lu, "High frame rate 2D and 3D imaging with a curved or cylindrical array," in *2002 IEEE Ultrasonics Symposium Proceedings*, 02CH37388, vol. 2, pp. 1725-1728, 2002.

[9] G. Montaldo, M. Tanter, J. Bercoff, N. Benech, and M. Fink. "Coherent plane-wave compounding for very high frame rate ultrasonography and transient elastography." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 56, no. 3, pp. 489-506, March 2009.

[10] J. Bercoff, M. Tanter, and M. Fink. "Supersonic shear imaging: a new technique for soft tissue elasticity mapping." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 51, no. 4, pp. 396-409, Aprio 2004.

[11] S. Wang, W. Lee, J. Provost, J. Luo, and E. E. Konofagou. "A composite high-frame-rate system for clinical cardiovascular imaging." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, no. 10, pp. 2221-2233, October 2008.

[12] Jian-yu Lu, Zhaohui Wang, and Sung-Jae Kwon, "Blood flow velocity vector imaging with high frame rate imaging methods," in *2006 IEEE Ultrasonics Symposium Proceedings*, 06CH37777, vol. 2, pp. 963-966, 2006 (ISSN: 1051-0117).

[13] Jian-yu Lu, "Improving accuracy of transverse velocity measurement with a new limited diffraction beam," in *1996 IEEE Ultrasonics Symposium Proceedings*, 96CH35993, vol. 2, pp. 1255-1260, 1996 (ISSN: 1051-0117).

[14] Jian-yu Lu, Xiao-Liang Xu, Hehong Zou, and J. F. Greenleaf, "Application of Bessel beam for Doppler velocity estimation," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 42, no. 4, pp. 649-662, July 1995.

[15] J. Udesen, F. Gran, K. Hansen, J. A. Jensen, C. Thomsen, and M. B. Nielsen. "High frame-rate blood vector velocity imaging using plane waves: simulations and preliminary experiments." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, no. 8, pp. 1729-1743, August 2008.

[16] Hasegawa, Hideyuki, and Hiroshi Kanai. "Simultaneous imaging of artery-wall strain and blood flow by high frame rate acquisition of RF signals." *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, no. 12, pp. 2626-2639, December 2008.

[17] Jian-yu Lu, "Effects of Masks on Reconstruction of High-Frame-Rate Images," in *2012 IEEE International Ultrasonics Symposium Proceedings*, CFP12ULT, pp. 2137-2140, 2012 (ISSN: 1948-5727) (Digital Object Identifier: 10.1109/ULTSYM.2012.0533).

[18] Jian-yu Lu and John L. Waugaman, "Development of a linear power amplifier for high frame rate imaging system," in *2004 IEEE Ultrasonics Symposium Proceedings*, 04CH37553C, vol. 2, pp. 1413-1416, 2004 (ISSN: 1051-0117).

[19] Jian-yu Lu, "Effects of data density of echo Fourier domain on quality of high frame rate imaging," in *2008 IEEE International Ultrasonics Symposium Proceedings*, CFP08ULT, vol. 1, pp. 974-977, 2008 (ISSN: 1051-0117) (Digital Object Identifier: 10.1109/ULTSYM.2008.0235).

[20] Jian-yu Lu and Sung-Jae Kwon, "Simplification of high frame rate imaging system with coordinate rotation," in *2007 IEEE Ultrasonics Symposium Proceedings*, 07CH37920, vol. 1, pp. 33-36, 2007 (ISSN: 1051-0117).

[21] Jian-yu Lu and Jing Wang, "Square-wave aperture weightings for reception beam forming in high frame rate imaging," in *2006 IEEE Ultrasonics Symposium Proceedings*, 06CH37777, vol. 1, pp. 124-127, 2006 (ISSN: 1051-0117).

[22] Jing Wang and Jian-yu Lu, "Motion artifacts of extended high frame rate imaging," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 54, no. 7, pp. 1303-1315, July 2007.

[23] Hong Chen and Jian-yu Lu, "Quantitative Assessment of Effects of Phase Aberration and Noise on High-frame-rate Imaging," *Ultrasonics*, vol. 53, no. 1, pp. 53-64, January 2013, DOI: 10.1016/j.ultras.2012.03.013.

[24] Jing Wang and Jian-yu Lu, "Effects of phase aberration and noise on extended high frame rate imaging," *Ultrasonic Imaging*, vol. 29, no. 2, pp. 105-121, April 2007.

[25] Jian-yu Lu and Shiping He, "Effects of phase aberration on high frame rate imaging," *Ultrasound in Medicine and Biology*, vol. 26, no. 1, pp. 143-152, 2000.

[26] Jian-yu Lu, "A study of signal-to-noise ratio of the Fourier method for construction of high frame rate images," in *Acoustical Imaging*, vol. 24, Hua Lee and G. Wade, Editors, pp. 401-406, 2000 (ISBN: 0-306-46518-3).

[27] Jian-yu Lu, Jing Wang, Hu Peng, and Jiqi Cheng, "Increasing frame rate of limited diffraction imaging system with code excitations," in *Acoustical Imaging*, vol. 26, Roman Gr. Maev, Editor, pp. 467-475, 2002 (ISBN: 0-306-47340-2).

[28] Jian-yu Lu, "Ultrasonic imaging with limited diffraction beams," in the book, *Localized Waves*, Editors: Hugo E. Hernandez-Figueroa, Michel Zamboni-Rached, and Erasmo Recami, Publisher: John Wiley & Sons, Inc., New Jersey, Chapter 4, pp. 97-128, February 4, 2008 (ISBN-10: 0470108851, ISBN-13: 978-0470108857, a sister book of *Non-Diffracting Waves* of 2013). (Invited book chapter that contains 190 X-wave related references to review the subject and to report previously unpublished results.)

[29] Jian-yu Lu, "Limited-Diffraction Beams for High-Frame-Rate Imaging," in the book, *Non-Diffracting Waves*, Editors: Hugo E. Hernandez-Figueroa, Michel Zamboni-Rached, and Erasmo Recami, Publisher: John Wiley & Sons, Inc., (Wiley-VCH), Chapter 5, November 11, 2013 (ISBN-10: 352741195X, ISBN-13: 978-3527411955, a sister book of *Localized Waves* of 2008) (Invited book chapter as a review with 88 references to the latest development of the high-frame-rate imaging) (to be published).

[30] Jian-yu Lu and Jiqi Cheng, "Field computation for two-dimensional array transducers with limited diffraction array beams," *Ultrasonic Imaging*, vol. 27, no. 4, pp. 237-255, October 2005).

[31] Jian-yu Lu, Jiqi Cheng, and Hu Peng, "Sidelobe reduction of images with coded limited diffraction beams," in *2001 IEEE Ultrasonics Symposium Proceedings*, 01CH37263, vol. 2, pp. 1565-1568, 2001 (ISSN: 1051-0117).

[32] Jian-yu Lu and Anjun Liu, "An X wave transform," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 47, no. 6, pp. 1472-1481, November 2000.

[33] Jian-yu Lu and J. F. Greenleaf, "Ultrasonic nondiffracting transducer for medical imaging," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 37, no. 5, pp. 438-447, September 1990.

[34] Jian-yu Lu and J. F. Greenleaf, "Nondiffracting X waves --- exact solutions to free-space scalar wave equation and their finite aperture realizations," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 1, pp. 19-31, January 1992.

[35] Jian-yu Lu and J. F. Greenleaf, "Experimental verification of nondiffracting X waves," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 39, no. 3, pp. 441-446, May 1992.

[36] A. V. Oppenheim and R. W. Schafer, *Digital Signal Processing*, Englewood Cliffs, NJ: Prentice-Hall, 1975, Ch. 1 and 5.