Second Harmonic Leakage Suppression by Notching

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Abstract — Harmonic imaging offers better contrast resolution than conventional B-mode image. However, in ultrasonic array imaging system, the transmitting source contributes not only the fundamental harmonic but also the other harmonics. It is shown theoretically and experimentally that the interference of the transmitting-leaked second harmonic signal to the object generated second harmonic signal can be reduced by array notching. To do this, the transmitting beamwidth is set to be wider than the second harmonic receiving beamwidth such that the receiving beam can be steered into the first notch of the leaked harmonic beam. Different degree of leakage suppression can be achieved by adjusting the ratio of the number of receiving elements to the number of transmitting elements and angle difference between transmitting and receiving beam.

INTRODUCTION

The finite amplitude field distribution in water from several kinds of ultrasonic source have been investigated [3][4]. It's easy to observe the strong nonlinear effect in water when it is insonified with high pressure up to several hundreds KPa or more. Nonlinear effect exists in soft tissues also.

Recent researches show that finite amplitude distortion-based second harmonic imaging offers better contrast resolution than conventional B-mode image due to its lower sidelobes [2]. However, using wideband array transducer for second harmonic imaging will raise transmitted harmonic leakage. Since there are two different harmonic signals over the same frequency band, co-channel interference occurs in harmonic imaging and image contrast will reduce. To protect the object generated second harmonic (OH) signal from the interference of transmitting-leaked harmonic (TH) signal, several approaches could be applied. Because temporal spectra of OH signal and TH signal overlap, it's difficult to separate the two kinds of signal in time domain. Recently, a two-pulse scheme suggested by T. Christopher is a solution [2]. In this scheme, nonlinear relation between fundamental frequency signal and second harmonic signal is utilized. Solving the leakage suppression problem in spatial domain is another approach. An example of spatial domain processing is the alternating phasing technique suggested by S. Krishnan and M. O'Donnell [1].

In this research, a different method to perform spatial domain filtering, namely notching, is proposed. The key point of notching is pointing the receiving harmonic (RH) beam to the first notch of transmitting harmonic beam. The principles and experimental results will be presented.

PRINCIPLES

To simplify the difficulty in introducing the concept of this work, the illustrations given in this section are based on the assumptions of narrow-band and far-field condition .

It's known that the OH beam (i.e., object generated harmonic distribution) is wider than the TH beam for fixed aperture size [2]. Let the beamwidth of transmitting beam of fundamental frequency be Θ_F, the beamwidth of TH beam be Θ_{TH} and the beamwidth of OH beam be Θ_{OH}. The relation among Θ_F, Θ_{TH} and Θ_{OH} is $\Theta_F > \Theta_{OH} > \Theta_{TH}$, as shown in Fig. 1. Since $\Theta_{OH} > \Theta_{TH}$, signal and interference do not overlap completely in spatial domain, therefore spatial domain filtering will work.

Because the magnitude difference between OH beam and TH beam is direction dependent, signal-to-interference ratio (SIR) depends on the direction of RH beam and SIR will be higher in the direction of notch.

By steering the direction of receiving beam to the first notch of TH beam, the echo due to TH signal could be suppressed. However, the effect of leakage cancellation depends strongly on the width and depth of notch. Let the beamwidth of RH beam be θ_{RH}. For fixed θ_{RH}, the larger is Θ_{TH}, the wider is the notch of TH beam. Therefore, the ratio of Θ_{TH} to θ_{RH} affects the degree of cancellation. In general, the degree of cancellation will increase as N_R / N_T increases, where N_R is the total number of

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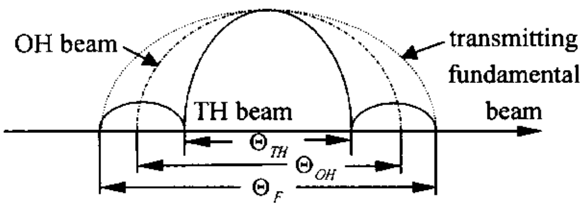


Fig. 1 Relation among Θ_F, Θ_{TH} and Θ_{OH}

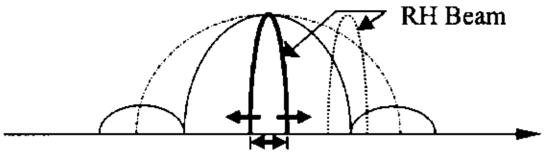


Fig. 2 RH beam could be steered to different directions.

receiving elements and N_T is the total number of transmitting elements. When θ_{RH} << Θ_{TH} and θ_{RH} << Θ_{OH}, the RH beam could be steered to the notch of TH beam and still inside the mainbeam of OH beam, as shown in Fig. 2. Under such condition, the echo due to OH signal will be left. However, the OH signal will be hurt partially as TH signal is suppressed. To evaluate the overall effect, one way is to check the improvement factor (IF). IF is defined as the ratio of SIR with notching to SIR without notching.

Let ψ_D denote the angular difference between the mainbeam directions of receiving and transmitting beams. When $\psi_D = 0$, the two-way beampattern is symmetric. But when $\psi_D \neq 0$ and $\theta_{RH} \neq \Theta_{OH}$, the beampattern will be skew as shown in Fig. 3. Fig. 3 shows the relation among OH beam, RH beam and two way beampattern. Note that when θ_{RH} << Θ_{TH} and θ_{RH} << Θ_{OH}, the direction and width of the mainbeam of two-way beampattern are determined mainly by the RH beam.

When ψ_D is set to be $\Theta_{TH}/2$, the right side of mainbeam of two-way beampattern will roll off faster than when $\psi_D = 0$, since there are two closed notches (one comes from transmitting and another comes from receiving) on this side. That is, the boundary on the right side of mainbeam will be sharper when the RH beam is pointed to the notch of TH beam.

An important property of the two-way beampattern is its skewness, which provides a possibility to distinguish two close-in targets while it causes image distortion. As shown in Fig. 3(c), the near sidelobes on the left side are higher than on the right side. Consider two targets put at focal distance. If the reflection from the left target is stronger than the right target, the boundary between the two targets would be more indistinct in the case of $\psi_D = \Theta_{TH}/2$ than in the case of $\psi_D = 0$. But if the reflection from left target is weaker than the right target, the result would reverse. The boundary could be more visible since sharper roll-off exists on the right side of mainbeam. Though there exists sharper roll-off, the far sidelobes on the right side will usually be higher in the case of $\psi_D = \Theta_{TH}/2$ than in the case of $\psi_D = 0$.

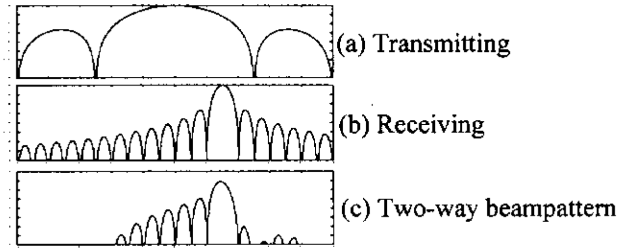


Fig. 3 Skew of two-way beampattern

EXPERIMENTS

Several experiments were performed. By transmitting pulses at fundamental frequency and second harmonic frequency separately, the effect of leakage suppression with notching was verified. Properties of two-way beampattern were demonstrated also.

An array imaging system was established with the following system parameters. The fundamental frequency is 2 MHz and second harmonic frequency is 4 MHz. All experiments were performed in a water tank. A 72-element convex array probe, made by ITRI (Industrial Technology Research Institute) in Taiwan, with 60 mm radius of curvature, 1 mm interelement spacing, 3.3 MHz center frequency and 70% 6dB fractional bandwidth was used. All elements could be fired under control. The focus was set to be 110 mm from the array center. The array beam can be scanned linearly with increment of 2.83 mm at focal point. The delay resolution is 1/(60 MHz).

There is only one receiver circuit. A multiplexer is used to switch the path between array elements and receiver. Received signals of different elements are sampled by a 10 bits analog-to-digital converter (ADC) with 30 MHz sampling rate and sent into the computer in turn. The gain of the pre-amplifier was 8.5 dB. The data length is 4K words.

Receiving beam was dynamic focused and beamformed in computer by baseband beamforming technique. While performing receiving beamforming, its center frequency was set at second harmonic frequency, which is twice the transmitting center frequency. All the data were filtered by a Gaussian window with 400 KHz 3dB bandwidth in demodulation.

SIR enhancement : single-wire target

In this part, the object was a wire put to be vertical to the scan plane and near the focus of central beam. The diameter of the wire is about 1.3 mm. For each transmitting beam, 4 consecutive elements were driven by signals with proper delay and all data received by each array elements were recorded. The beamwidth of TH beam is 21.21 mm at focal distance. Therefore, the receiving beam can be pointed to the notch of the TH beam when it was shifted by 3 or 4 elements, since the array beam was scanned with increment of 2.83 mm at focal point. Two experiments transmitting at fundamental and harmonic frequencies are given in the following.

Case 1: The array elements were driven by pulses of 7 cycles at fundamental frequency.

In this case, the received signals of array elements at second harmonic frequency should contain both the OH signal and TH signal.

Data received by 16 consecutive elements were taken to perform receiving beamforming. The beamwidth of RH beam at focal distance is 5.29 mm, one fourth of the beamwidth of TH beam, and could be treated as narrow enough to be put within the first notch of the TH beam. Define S as the angular difference between mainbeam directions of receiving beam and transmitting beam in the unit of elements shifting. For instance, let the set of transmitting elements be $\{10,11,12,13\}$, then $S=0$ if the set of receiving elements is $\{4,5,\cdots,19\}$ and $S=1$ if the set of receiving elements is $\{5,6,\cdots,20\}$. The angular response image of target varied as S's were changed. Another group of results were also obtained by using 8 elements for receiving.

Case 2: The array elements were driven by pulses of 14 cycles at second harmonic frequency

In this case, the received signals of array elements at second harmonic frequency should hardly contain the OH signal.

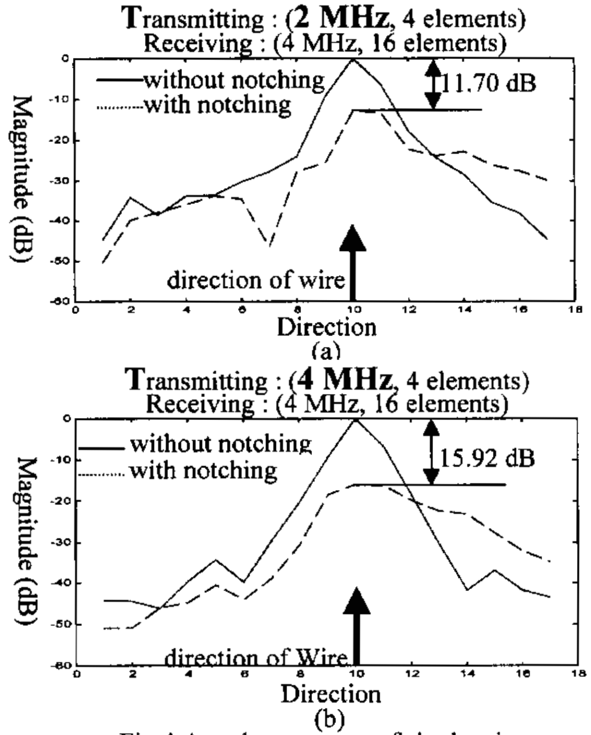
All the tasks here were the same as in case 1 except the transmitting frequency. Compare the results of case 1 and case 2, the effect of SIR enhancement by notching could be evaluated.

SIR Enhancement : two-wire target

There were two wires put to be vertical to the scan plane and near the focus of central beam. The diameters of the two wires are 1.6 mm and 0.5 mm, respectively. The two wires were at the same range and lateral distance between the two wires was about 6 mm. Same experiments as in the case 1 were performed.

RESULTS AND DISCUSSION

Fig. 4(a) and 4(b) display the angular responses of single wire at target range when transmitting frequencies were 2 MHz and 4 MHz, respectively. The receiving center frequencies were 4 MHz for both cases. N_T was 4 and N_R was 16. The curves plotted in dashed lines and in solid lines are the results with and without notching, respectively. In the two figures, the magnitudes responses were normalized individually with respect to the magnitude obtained in the direction of the wire when notching wasn't applied. In Fig. 4(a), the angular response is skew as notching is applied. Furthermore, the magnitudes are lower with notching than without notching . However, in Fig. 4(b), the angular response with notching is even lower than that in Fig. 4(a). It's due to different compositions of signal in two cases. In the case of Fig. 4(b), the received signal in harmonic band hardly contains the OH signal. Thus the harmonic signal would be canceled severely. In the case of Fig. 4(a), the received signal in harmonic band contains not only the TH signal but also the OH signal. Though the TH signal was canceled severely, partial OH signal would be left and the overall reduction of signal level will be lower.



(a)

(b)

Fig 4 Angular response of single wire

Improvement factor (IF) is a suitable parameter to evaluate the effect of leakage suppression since it can be defined as the ratio of SIR with notching to SIR without notching. Anyway, it cannot be achieved directly by present works since signal level reduction with notching is unknown. Another factor, approximated improvement factor (AIF), can be used to estimate the SIR enhancement. AIF is defined as the difference of magnitude reduction with notching between two cases of transmitting at fundamental frequency and second harmonic frequency. In the case of Fig. 4, magnitude reduction with notching is 15.92 dB when transmitting at 2 MHz and is 11.70 dB when transmitting at 4 MHz. Therefore, AIF = 15.92 dB - 11.70 dB = 4.22 dB. That is, a rough estimation of SIR enhancement is 4.22 dB.

When transmitting at 2 MHz, both of the echoes from the TH signal and OH signal were received. Therefore, one may expect that the magnitude reduction with notching will be lower if OH signal can be received independently and AIF is always less than IF.

The same experiments were performed twice. The averaged AIF was 4.04 dB (average of 4.22 and 3.85). When N_R was changed to be 8, the resultant AIF was 2.25 dB (average of 2.33 and 2.16). Thus AIF increases as N_R increases.

Due to the constraint of linear scan, the array beam can not be steered to any desired direction. The above results was obtained by setting $S = 4$ since shifting 4 elements can make the RH beam closest to the notch of TH beam and the condition 'with notching' can be satisfied approximately. For different S's, different AIF's was obtained and given in the following table.

AIF (dB)	$S = 3$	$S = 4$	$S = 5$
$N_R = 8$	-1.17	2.33	-5.54
$N_R = 16$	0.41	4.04	-5.44

When $S = 5$, the mainbeam of RH beam is outside the mainbeam of OH beam. By the table, it's obvious that AIF is a function of (N_R / N_T) and S.

Fig. 5 displays the angular responses of two wires at target range when $S = 4$. Without notching, the two targets aren't 'separable'. With notching, the boundary between two targets becomes obvious. It's due to the skew property of beampattern and unequal target strength as described in the section of principles.

So far, the notch is assumed to be deep enough for suppressing the TH signal. For narrow band signal, it is the case and good cancellation could be obtained. For wideband signal, it's difficult to produce deep notch because the position of notch will change as the frequency changes. Thus the cancellation effect will reduce. In wideband case, signal may be divided into several subbands and processed individually. However, reduction of axial resolution shouldn't be neglected. Besides, the effect of notching will reduce if the range is far from the focal distance, such as the case of near field. In fact, even if the notch aren't deep and the conditions of $\theta_H << \Theta_{TH}$ and $\theta_H << \Theta_{NH}$ aren't satisfied, pointing the RH beam to other directions but not outside the mainbeam of OH beam might still have gain in SIR. Anyway, this needs more studies. Array aperture processing is another way to improve the effect of leakage suppression. By changing the weighting and delay of array elements, higher SIR could be gained.

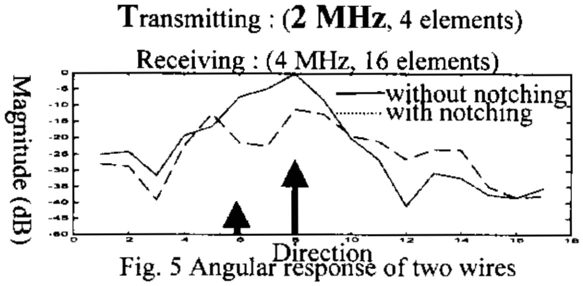


Fig. 5 Angular response of two wires

CONCLUSIONS

The results presented above demonstrate that steering the mainbeam of second harmonic receiving beam to the first notch of the transmitting-leaked second harmonic beam can suppress the transmitting leakage. Suppression of co-channel interference depends on the ratio of beamwidth of transmitting beam to beamwidth of receiving beam. The property of skew, faster roll-off on one side of the mainbeam of two-way beampattern was illustrated experimentally.

Future works include studies about notch and beampattern control, experiments for complicated target, better estimation of SIR improving factor and evaluation of geometric resolution reduction.

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