34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Source Effects in SWIPE: Shear-wave-assisted Ultrasound Imaging

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***Abstract*— SWIPE is a novel method for ultrasonic image reconstruction that uses echo phase modulation induced by traveling shear waves to decipher lateral k-space image data. Our prior experimental work has demonstrated lateral resolution with SWIPE at higher than expected sidelobe levels. Here we examine the effect of the location of the mechanical excitation source used in SWIPE. Surface and internal sources were simulated using finite element modeling. The interaction of shear and surface (Rayleigh) waves was found to degrade the SWIPE point spread function when surface excitation was employed. Internal excitation was not negatively affected and yielded near-ideal results. Regions of ideal performance, simulated point spread functions, and phase non-linearity measurements for the two methods are presented. The results indicate that internal sources, e.g. acoustic radiation force, can be expected to yield high-quality SWIPE images.**

I. Introduction

Ultrasound imaging of soft tissues is routinely performed with excellent results. Soft tissue imaging with ultrasound requires the presence of an acoustic window, a path from the target to the region of interest without significant obstructions, particularly gas or bone. Imaging of the brain with ultrasound is performed in infants with excellent results, as the fontanelles provide a viable acoustic window. In adults, brain imaging with ultrasound is hampered by the absence of a favorable acoustic window. However, the clinical use of transcranial Doppler ultrasound, performed at a frequency of approximately 2 MHz and using the relatively thin temple as the acoustic window, demonstrates that ultrasound echoes from weakly scattering targets can be detected successfully.

Challenges to adult ultrasound brain imaging stem from the high attenuation of the skull and the phase aberration induced by the significantly higher acoustic wave speed in bone (approx. 2300 m/s) vs soft tissue (1540 m/s). Ultrasound attenuation increases rapidly above 2 MHz, necessitating the use of relatively low frequency ultrasound to penetrate the skull and limiting B-scan lateral resolution. Sound speed variation over the face of the ultrasound aperture due to variations in skull thickness further limit the ability to achieve high lateral resolution with an extended aperture and delay-and-sum beamforming.

We have recently demonstrated a technique, Shear Wave Induced Phase Encoding (SWIPE), that allows B-scan-like images of tissue echogenicity to be formed without using a focused aperture [1]. Briefly, this method uses multifrequency (< 2 kHz) shear wave propagation perpendicular to the direction of ultrasound propagation to apply a variety of deformations to the target to be imaged. These deformations shift the phase of the received ultrasound echo. By proper demodulation of the phase shift of the ultrasound signal, the lateral position of the echo source may be determined. The axial (range) component of position is determined through time of flight as in conventional ultrasound. In SWIPE imaging, lateral resolution does not depend on the focal properties of the aperture, and only indirectly on the ultrasound frequency. Lateral resolution is determined by the range of shear wave frequencies used to interrogate the target. Any lateral focusing provided by an extended aperture serves to determine the illuminated region of the tissue.

SWIPE is potentially a good match to the challenges of transcranial imaging. The low frequency ultrasound needed for transcranial imaging only weakly influences the resolution of SWIPE. Phase aberrations in the receive aperture serve to distort the illumination profile but not the lateral resolution.

While our previous experimental results [1], [2] demonstrated the ability of SWIPE to achieve lateral resolution independent of aperture focusing, the point spread function (PSF) showed higher sidelobe levels than anticipated. The increased sidelobe levels were due to deviations from a linear dependence of target motion phase on shear wave frequency. Part of the deviation was traced to frequency dependent phase response of the electromagnetic shaker and amplifier used to generate shear waves [2].

In this work we investigate the effect of the interactions of shear and surface waves on the frequency dependence of the phase of target motion. Surface waves propagate at a slightly lower speed in incompressible media than do shear waves, and their depth of penetration of is likewise frequency dependent. We hypothesize that this results in the non-linear phase response noted in our previous work.

II. Theory

A. SWIPE method

The principle of SWIPE imaging is described in detail in [1]; here we give a brief synopsis. The echo $r(t)$ from a two dimensional collection of scatterers is given by [3]

$$r(t) = \iint_{-\infty}^{\infty} h(x,z,t)\gamma(x,z)\,dx\,dz \tag{1}$$

where $h(x,z,t)$ is the pulse-echo response to a point scatterer at (x,z), and $\gamma(x,z)$ is the scattering strength. The system can be treated as locally shift invarient, so that $h(x,z,t) = h(x,t-2z/c_l)$. A typical ultrasound imaging pulse is a bandpass signal with a center frequency ω_l. The effect of a small displacement of a point target in the

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direction of ultrasound propagation ($+z$) can therefore be modeled as a phase shift of the echo from the undisturbed target, that is,

$$h(x, z + \Delta_z, t) = h(x, t - 2z/c)e^{-2jk_l\Delta_z}. \quad (2)$$

where $k_l = w_l/c_l$. A shear wave induces a time-harmonic displacement Δ_z to the scattering sites within an elastic medium $\Delta_z = a\cos(\omega_s t - k_s x - \phi)$ where a is the displacement amplitude, k_s the wavenumber, and ϕ the phase of the shear wave. Using the approximation of Equation 2, Equation 1 can be written to include the effect of the shear wave as

$$r(t, k_s, \phi) = \int_{-\infty}^{\infty} \hat{\gamma}(x, t)e^{-j\beta\cos(\omega_s z/c_l - k_s x - \phi)}\,dx \quad (3)$$

where $\beta = 2ak_l$ and

$$\hat{\gamma}(x, t) = \int_{-\infty}^{\infty} h(x, t - 2z/c)\gamma(x, z)\,dz \quad (4)$$

$\hat{\gamma}$ is the object function convolved in the range direction with the time/axial component of the ultrasound pulse. $r(t, k_s, \phi)$ represents the complete echo as a function of time, modulated by the shear wave displacement of the scatterers. Equation 4 is a phase-modulated version of Equation 1. For small values of β, i.e. $|\beta| \ll \pi$, we can make the approximation $e^{-j\beta\cos(\omega_s z/c_l - k_s x - \phi)} \approx 1 - j\beta\cos(\omega_s z/c_l - k_s x - \phi)$. It can then be shown [1] that

$$r(t, k_s, \pi) - r(t, k_s, 0) + j\left[r(t, k_s, \frac{\pi}{2}) - r(t, k_s, -\frac{\pi}{2})\right] = 2j\beta e^{jc_s z k_s/c_l}\int_{-\infty}^{\infty} \hat{\gamma}(x, t)e^{-jk_s x}\,dx \quad (5)$$

that is, by collecting echos at ϕ equal to integer multiples of $\pi/2$, the Fourier Transform of $\hat{\gamma}(x, t)$ evaluated at spatial frequency k_s may be obtained. By interrogating the target at multiple shear wave frequencies, corresponding to multiple spatial frequencies, the lateral k-space data may be collected and inverse Fourier Transformed to recover $\hat{\gamma}(x)$, thus yielding an image of the object γ blurred by the axial (time) component of the impulse response h. The lateral resolution depends on the range of spatial frequencies interrogated, rather than on the ultrasound wavelength or aperture characteristics.

B. Shear and Rayleigh waves in incompressible media

The model developed above and in [1] assumes the presence of a plane, z-polarized, $+x$-going harmonic shear wave, which is conveniently described analytically. Unfortunately, waves generated by finite sources are more complex to describe, and do not lend themselves to compact analytical expressions. A further complication exists when the excitation is at the surface of the elastic body. As described in [4], surface or Rayleigh waves are generated in addition to shear waves. The propagation speed c_R of the Rayleigh wave is approximately 0.96 times that of the shear wave speed c_s. The amplitude of the Rayleigh wave is dominant near the surface, falling exponentially with depth into the medium in a frequency dependent manner. Because the Rayleigh wave is two-dimensional, it decays more slowly with distance from the excitation than does the shear wave. The interaction of Rayleigh and shear waves, and their varying relative amplitude at a given excitation frequency, can be anticipated to result in a non-linear dependence on the phase of the displacement in response to a harmonic excitation as a function of frequency. As this non-linear dependence violates the assumptions made in the previous section, it is reasonable to expect distortion of the image generated by SWIPE. The methods proposed next investigate the degree of this distortion for two excitation sources.

III. Methods

A. Simulation

Convenient closed-form expressions are not available for shear or surface waves resulting from a harmonic force. Therefore finite-element simulation (Comsol Multiphysics) was used to determine the total wave motion due to the application of surface and sub-surface forces. A two-dimensional axi-symmetric model was used to calculate the response to the applied loads. MKS units were used throughout. The model was cylindrical with a diameter of 0.20 m and a height of 0.10 m. Tissue was modeled as a homogeneous elastic solid with a density ρ of 1000 kg/m^3, a shear modulus G of 15 kPa, and a Poisson's ratio ν of 0.4999.

Two forcing methods were simulated — a "surface" load and an "internal" load. The surface load was a sinusoidal displacement of the form

$$D_z(t) = -A\sin(2\pi f_s t)$$

applied over a 5 mm diameter region centered at $r = 0$ atop the cylinder (z=10 cm). This simulated the displacement applied in our experimental apparatus by the electromagnetic shaker, described below. The internal load, designed to mimmick the forcing that would be applied by an acoustic radiation force source, was modeled as a body force with a Gaussian spatial distribution described by

$$F_z = -A\sin(2\pi f_s t)\exp\left(-\frac{r^2}{0.001^2} - \frac{(z - 0.05)^2}{0.01^2}\right)$$

The excitation frequency f_s ranged from 100 to 1000 Hz in steps of 20 Hz. A transient solver calculated the mechanical response to the harmonic load from $t = 0$ to 40 ms.

The phase of the z component of displacement in response to the two sources was calculated for each frequency. The deviation from linear phase was determined by a least-squares fit of the phase response of points on a 0.2 mm mesh in the medium to a line. The lateral component of the point spread function (PSF) was calculated from the measured phase response minus the linear component, which is responsible only for the lateral position and not the overall shape of the PSF. Thus the distortion of the PSF from the ideal may be observed. A Hamming window was applied to the simulated data to avoid sidelobes due to the otherwise abrupt truncation of the k-space data. The effect is similar to the apodization used in conventional ultrasound imaging.

The excess width of the PSF at the -6 dB and -30 dB levels was computed on the same mesh.

B. Experiment

Experimental data were collected with the system described in [2]. Gelatin cubes 12 cm on a side with a shear modulus G of 5 kPa were used, with embedded 0.13 mm diameter nylon monofilament used as a target. An electromagnetic shaker (Bruel&Kjaer4810) was used to generate harmonic displacements at the surface of the cube. Ultrasound echo data were collected as described in the Theory section.

IV. Results

Plots of displacement amplitude and phase at 500 Hz for both sources are depicted in Figure 1. Note that the phase fronts do not follow a constant radius curve from the surface source. The slightly slower propagation of the Rayleigh wave is visible in the wavefront distortion near the surface. The internal source does not show the presence of surface waves, and distortion of the phase fronts from Rayleigh/shear wave interaction is not evident.

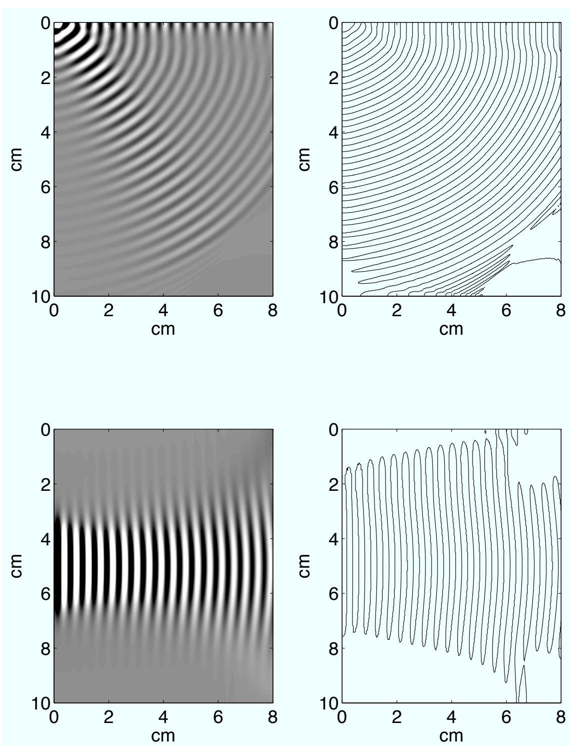

Fig. 1. z-component of displacement (left column) and zero-phase contours (right column) for the surface source (top) and internal source (bottom row) at 500 Hz

The deviation from a simple kr phase dependence is depict in Figure 2. The surface source shows a large deviation from linear phase at all points except the point of excitation. In contrast, the internal source shows a negligible variation, on the order of the simulation noise. Also presented in the figure is the phase error measured for the nylon monofilament target

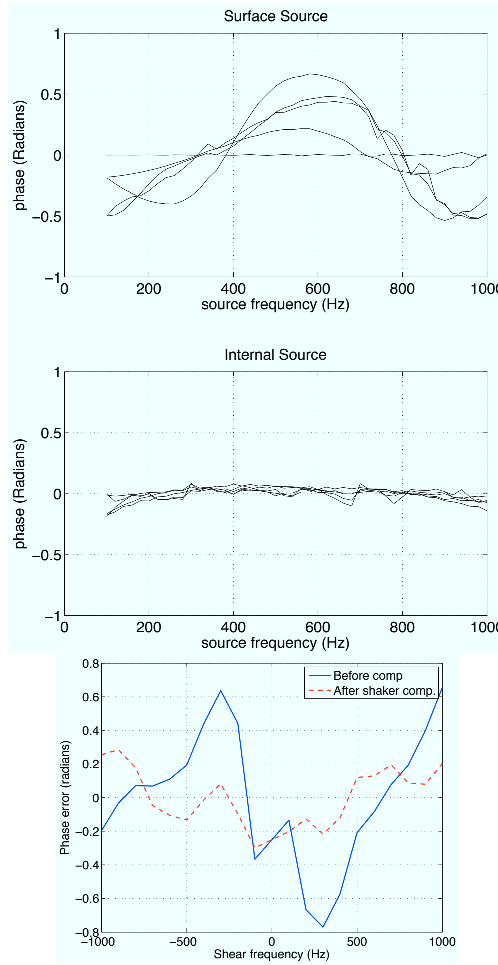

Fig. 2. Deviation from "ideal" linear phase dependence on frequency for simulated surface (top) and internal sources (center). Residual phase after a linear fit is plotted at ranges of 0, 2, 5, 10 and 20 mm from the source. For the surface source, the points lie on the line x=z, for the internal source the points lie on the line z=5 cm. The residual phase error of the electromagetic shaker used in the experiments is shown at the bottom.

in gelatin driven by the surface-applied electromagnetic shaker.

The resulting lateral PSF profiles are plotted in Figure 3. The effect of non-linear phase dependence is readily apparent. At all points except directly under the excitation source, the PSFs resulting from surface excitation are significantly wider than the ideal response. In contrast, the more nearly linear phase response associated with the internal source results in near-ideal PSFs.

Figure 4 illustrates the spatial dependence of the PSF width, with a grayscale indicating the increase in width relative to the ideal. At the full-width half-max (FWHM, -6 dB) level, the internal source achieves near-ideal performace over a 5x4 cm region centered at the source. The surface source achieves a FWHM on the order of 25% greater than ideal over the same sized region centered at the surface. At the -30 dB level , the surface source yields PSFs that are integer multiples worse than ideal, while the internal source achieves near-ideal performace over 2x2 cm region.

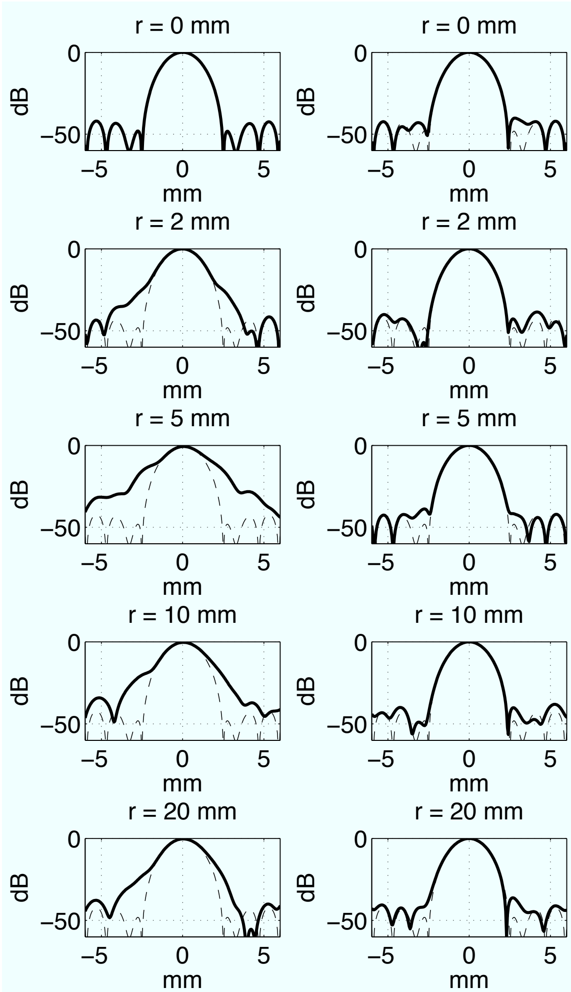

Fig. 3. Lateral point spread function profiles at the same locations used in Figure 2. The PSFs associated with the surface source are on the left, the internal source on the right. The dashed lines indicate the ideal PSF for the shear wave frequency range used.

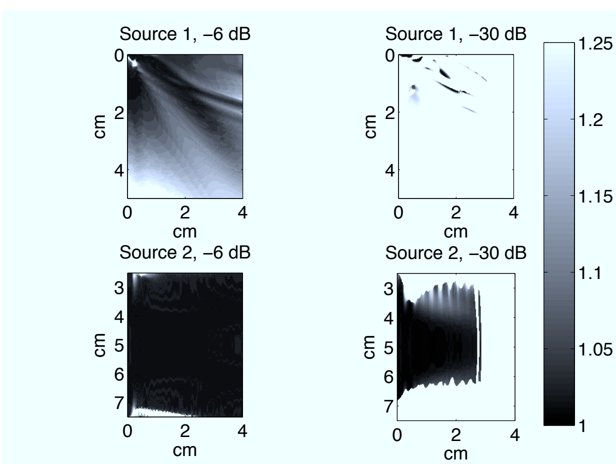

Fig. 4. Maps of the width of the simulated point-spread-function relative to the ideal as a function of position for the surface source (top row) and internal source (bottom row). The grayscale depicts the simulated width as a multiple of the ideal, with black indicating ideal response and white indicating a width 25% or more greater than the idea. The left hand column indicates the result at the -6 dB level; -30 dB is at right.

V. Discussion

The non-linear dependence of phase on frequency and the resulting distortion of the SWIPE PSFs associated with surface excitation of shear (and surface) waves seen in the finite element simulations displays a good qualitative matches to previous experimental observations [2]. Because the deviation from linear phase response is spatially dependent, elimination of this distortion is not straightforward.

The use of internal excitation, which allows shear waves to be generated while avoiding the creation of surface waves, yields a much more linear phase response and nearly ideal point spread function. The forcing function described is similar to what could be achieved with the acoustic radiation force of a weakly focused low-frequency ultrasound transducer.

Taken together these results suggest that further development of SWIPE is best suited to applications where acoustic radiation force or other means can be employed to generate shear waves sufficiently distant from any boundaries to avoid surface wave generation. The simulation results make clear that the previously observed distortion is due (in addition to any phase nonlinearities of the electromagnetic shaker) to the mechanical response of the elastic target itself, rather than any data acquisition issue.

VI. Conclusions

The effects of two contrasting shear wave sources on SWIPE imaging resolution was evaluated. The use of a surface source was found to present a strongly non-linear phase response. This was associated with the presence of both shear and surface waves, and resulted in significant distortion of the point-spread-function associated with SWIPE imaging. This result is consistent with prior experimental observations of PSF distortion not predicted by the simple plane shear wave model of SWIPE. The use of an internal source was found to very closely approximate the PSF quality expected for an ideal plane source. Future work will investigate the use of acoustic radiation force to realize this shear wave source.

Acknowledgement

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