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Shielding of Piezoelectric Ultrasonic Probes in Hall Effect Imaging

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Abstract

This paper addresses significant sources of electromagnetic noise in Hall effect imaging. Hall effect imaging employs large electrical pulses for signal generation and high sensitivity ultrasonic probes for signal reception. Coherent noise arises through various coupling mechanisms between the excitation pulse and the probe. In this paper, the coupling mechanisms are experimentally isolated and theoretically analyzed. Several methods of shielding the probe from electromagnetic interference are devised and tested. These methods are able to reduce the noise to levels below the random thermal noise, thereby improving the signal-to-noise ratio in HEI by two orders of magnitude.

Keywords

Hall effect; Hall effect imaging; piezoelectric; shielding; ultrasound probe

INTRODUCTION

Hall effect imaging (HEI) is an ultrasound-based method that provides information about the dielectric and conductivity distributions of the imaged sample. It relies on the interaction between a strong static magnetic field and externally applied radiofrequency currents in the sample medium.¹ Its unique characteristics are its conductivity-based image contrast and its suitability for 2D or 3D imaging with wide-angle signal reception, which may benefit biological applications. Piezoelectric ultrasound probes are desirable for HEI because they have high sensitivity and are commercially available in many designs, such as focused transducers and arrays. However, when using these probes for HEI, one encounters significant coherent noise. The purpose of this paper is to understand the mechanisms by which this noise arises, to experimentally isolate the noise sources, and to design shielding methods which remove the noise.

HEI evaluates an object's electrical and mechanical properties using a phenomenon called the Hall effect. The mechanism is as follows: The positive and negative charges in a conductive object tend to separate when the object moves in a magnetic field as a result of the opposing Lorentz forces on the charges. This leads to an externally-detectable voltage within the sample, the Hall voltage. A conductivity-based image of an object can be formed if the motion is induced with ultrasonic pulses. At any moment, the Hall voltage generated by such a pulse is a signature of the current position of the pulse. As the pulse sweeps through an object, the associated Hall voltage records its progression in time. In this fashion, the scanning ultrasonic pulse converts spatial information along its path to the time record of the Hall voltage. This relation between space and time is similar to conventional ultrasound imaging.

In HEI, coherent noise results from cross-coupling between the probe and the strong electrical impulse applied to the sample. Two cross-coupling mechanisms generally exist for piezoelectric (PE) probes. The first is electromagnetic (EM) crosstalk between the piezoelectric element and the EM field of the excitation pulse. The second mechanism we call Lorentz

vibration noise. It is a consequence of the strong static magnetic field in HEI. Direct EM crosstalk is independent of the static magnetic field, and therefore can be studied outside the magnet. The Lorentz vibration noise occurs only in the magnetic field. These noise mechanisms are detailed below, along with methods to defeat them. First, we provide a brief introduction to HEI and estimate the strength of the signal it produces.

HALL EFFECT IMAGING

The basic idea of Hall effect imaging is detailed in reference ¹. In practice, HEI can be carried out in two modes: the forward mode, in which one receives electrical signals produced by a strong ultrasonic pulse; and the reverse mode, in which one receives ultrasonic signals generated by an electrical excitation pulse. The reverse mode of HEI is advantageous in most situations, because it allows the use of receive-only array ultrasonic probes for fast image formation. The rest of the paper refers specifically to this mode.

The arrangement of a typical HEI experiment is shown in figure 1. The sample to be imaged (shown here as a polycarbonate block) is immersed in a tank of saline. The saline concentration is 0.5% to mimic biological conductivities. The tank is placed in a static magnetic field B_0 . A pulsed electric field $\mathbf{E}(\mathbf{r}, t)$ is applied to the saline via two electrodes. In reference ¹, it is shown that ultrasonic pulses are produced at conductivity discontinuities, such as the saline-block interfaces. The ultrasonic signal is detected with a piezoelectric probe.

To obtain a general estimate of the HEI signal level, we note that the quasistatic approximation is valid at medical ultrasonic frequencies (below 10 MHz), so that the electric field in the saline follows the same time course everywhere. $\mathbf{E}(\mathbf{r}, t)$ can then be expressed as $E_0(t)\mathbf{g}(\mathbf{r})$, where $\mathbf{g}(\mathbf{r})$ represents the spatial distribution. Following the derivation in reference ¹, assuming that the block is acoustically matched to saline so that there is no acoustic reflection at the interface, the HEI ultrasound signal in the vicinity of the saline-block interface is expressed in terms of the acoustic pressure:

$$p(t) = \frac{1}{2} B_0 \rho_s c \left[\Delta \left(\frac{\sigma}{\rho} \right) \right] g_x Q(t), \quad (1)$$

where ρ_s is the mass density of saline, c is the speed of sound in saline, g_x is the x component of $\mathbf{g}(\mathbf{r})$, $\Delta(\sigma/\rho)$ is the difference in the ratio of conductivity to mass density, σ/ρ , between saline and the polycarbonate block, and $Q(t)$ is the integral

$$Q(t) = \int_{-\infty}^t E_0(t') dt'. \quad (2)$$

This equation allows an estimate of the signal level. For example, in a 2.0 tesla magnetic field, an electrical pulse of 0.5 μ s duration and 1,600 V/m magnitude produces an ultrasonic pulse of 1.1 Pascal peak pressure.

It can be seen that the probes in HEI are required to detect signals on the order of 1 Pascal. For piezoelectric transducers, the corresponding output voltages are on the order of microvolts, commensurate with the coherent noise from EM coupling between the excitation pulse and the PE probes. In the following, the EM crosstalk noise and the Lorentz vibration noise are discussed separately.

MEASUREMENT AND SHIELDING OF EM CROSSTALK NOISE

The mechanism of electromagnetic crosstalk between the excitation pulse and the PE probe is as follows. When the excitation pulse is applied to the sample, it also produces an electromagnetic field in the vicinity of the PE probe. The PE element of the probe acts as an antenna and picks up the field, resulting in a voltage across it. This voltage induces strains in the element and results in acoustic emissions into the sample. The echoes of these acoustic emissions from within the sample are received later by the PE probe and appear as coherent noise, but at double the elapsed time of the corresponding HEI signals. The EM crosstalk is independent of the static magnetic field employed in HEI, and therefore can be studied outside the magnet, as described below.

To measure the level of the crosstalk noise, an experimental set-up shown in figure 2 is used. As stated above, the experiment is conducted outside the static magnetic field. Two brass electrodes are placed in a 0.5% saline tank of dimensions 23.5 cm $\times$ 13.5 cm $\times$ 5.8 cm (height). The electrodes are connected to a pulse generator (Panametrics), which produces an exponentially-decaying pulse of 400 volt peak voltage and 300 ns half-height width. The ultrasonic probe is a spherically-focused piezoelectric 2.25 MHz, 1.84 cm-diameter broad-band transducer (Krautkramer-Branson) with a focal length of 76 mm. A 1.0 cm layer of silicone oil is poured onto the saline to prevent direct electrical contact between the metal jacket of the probe and the saline.

Averaging over multiple data acquisitions is used to isolate coherent noise from random electronic and acoustic noises. Figure 3 is the signal from the probe after averaging over 1,000 acquisitions. Since no magnetic field is present, the peaks in figure 3 are not Hall effect signals. By their times of flight, they can be assigned to echoes of a pulse emitted by the PE probe due to EM crosstalk between the excitation pulse and the probe. Although the front surface of the PE element in the probe is sputtered with a nickel layer, the thickness of this layer is smaller than the rf penetration depth at 2.25 MHz (100 μ m). Thus, the PE element can still pick up a small voltage from the excitation pulse.

A direct approach to reducing the crosstalk noise in figure 3 would be to put shielding layers in front the probe that are much thicker than the rf penetration depth. However, it is difficult to find a material that does not disrupt the acoustic signal at those thicknesses. For this reason an electromagnetic waveguide shown in figure 4 is used. The waveguide is a thin copper cylinder coaxial to the probe, with one end connected to the metal jacket of the probe and the other end capped with a cellophane membrane. The diameter of the waveguide is 26 mm, and the distance between the probe surface and the cellophane membrane is 37 mm. The waveguide is filled with mineral oil as the acoustic coupling medium. The inner surface of the waveguide is lined with a foam layer for insulation against acoustic noise (as will be explained in detail later). In appendix A, it is shown that the electromagnetic field decreases roughly exponentially into the interior of the waveguide; thus with sufficient distance between the probe and the front end, the EM crosstalk noise should be greatly reduced.

The experimental test of this shielding scheme is slightly modified from the set-up in figure 2. The silicone oil layer is no longer needed, as the mineral oil in the waveguide acts as the electrical insulator. Figure 5 shows the result after averaging over 9,000 acquisitions. The EM crosstalk noise is suppressed by at least a factor of 200 (note the change in the vertical scale from figures 3 and 5), and cannot be seen above the random noise floor, which is reduced to 0.01 μ V by the extensive averaging.

With this reduction of the noise floor, two more coherent peaks of approximately 0.1 μ V amplitude are revealed. These peaks are not part of the crosstalk noise, since their times of flight are exactly half those of the expected crosstalk peaks from the waveguide-saline interface

and the bottom of the saline tank. This suggests that they are generated at these interfaces at the same instant the excitation pulse is applied, and are most likely due to thermoelastic expansions of the saline body caused by ohmic heating of the excitation pulse.² The significance of this phenomenon will be postponed to the Discussion section.

MEASUREMENT AND SHIELDING OF LORENTZ VIBRATION NOISE

The Lorentz vibration noise is the part of the coherent noise that only occurs in the static magnetic field. The mechanism for this noise is as follows. The excitation pulse applied to the sample also produces rf electric and magnetic fields in the vicinity of the PE probe. These rf fields induce eddy currents in the metallic components of the probe. Referring to figures 2 and 4, these components include the electrode platings of the PE element, the metallic acoustic backings, and also the metal walls of the waveguide if it is used for shielding. In the presence of the static magnetic field, the Lorentz forces on the eddy currents cause vibrations in these components. These vibrations either directly enter the piezoelectric element or propagate into the tank and create spurious echoes. Both result in coherent noise, which we call the Lorentz vibration noise.

To measure the Lorentz vibration noise, an HEI experiment is carried out with a piezoelectric probe shielded by the waveguide described above (Fig. 6). Because the waveguide removes the EM crosstalk noise, any additional noise will be related to the magnetic field. The experimental set-up is the standard one shown in figure 1. The excitation pulse is an exponentially decaying pulse of 400 volt peak voltage and 300 ns width. A polycarbonate target block of 6.2 cm (width) $\times$ 1.2 cm (thickness) is placed in a saline tank of 23.5 cm $\times$ 13.5 cm $\times$ 6.0 cm (height). A 2D cross-sectional image of the tank is acquired by moving the probe at 0.5 cm increments across the saline surface and collecting a scan line at each position. Figure 6 is the image from 26 line scans at 1,000 averages. Although the boundaries of the block are visible, the amplitude of the coherent noise is approximately 0.7 μ V, which is at least 50 times higher than the noise level outside the magnet (Fig. 5) and 40% that of the maximum HEI signal.

To reduce the Lorentz vibration noise from the waveguide shield, a foam layer is used to acoustically isolate it from the ultrasonic probe (Fig. 4). The rest of the noise comes from the metallic parts inside the probe, especially the ones in direct contact with the PE element, including the nickel electrode platings and the tungsten backing (Fig. 2).

Two methods are demonstrated to be effective in reducing the Lorentz vibration noise from inside the probe. The first is shown in figure 7. It is based on the idea that if the metallic platings on the PE element are made normal to the magnetic field, then the Lorentz forces on the platings will be tangential to the PE element and therefore will not emit acoustic noise into the element or the sample. With this probe orientation, an ultrasound prism is now needed to redirect the HEI signal into the probe. The prism is filled with silicone oil as the acoustic coupling medium. The acoustic reflection surface is a thin cellophane membrane. This prism adds an additional acoustic distance between the probe and the sample. To minimize this, the waveguide shield is replaced with a 15 μ m aluminum foil. This proves sufficient in shielding the EM crosstalk, which is already reduced by the added distance between the probe and the sample from the prism. The side of the probe is covered with a layer of copper tape lined with a foam layer, which prevents induced currents from developing in the metal jacket of the probe. Figure 8 shows an image of the saline tank acquired with this shielding method at 1,000 averages. The Lorentz vibration noise is reduced by at least a factor of 20, and cannot be detected above the noise floor of 0.03 μ V.

The above method is simple to implement, but it is limited to probes of planar piezoelectric elements and requires careful alignment of the probe with the magnetic field. These problems

are avoided in the second method, which employs active compensation. In this scheme, compensating electromagnetic fields are used to decrease the induced currents in the metal parts of the probe. Before describing the compensation, a better understanding of the mechanism by which the induced currents arise is in order.

In the waveguide shielding method shown in figure 4, the waveguide cylinder is acoustically insulated from the probe and the saline; thus, the Lorentz vibration noise comes from the metallic components inside the probe. Figure 9 shows the electric and magnetic fields around the probe of figure 4 produced by an excitation pulse. A conservative electric field E_0 results from the voltage difference between the electrodes, and a solenoidal rf magnetic field B is generated by the current flowing in the saline tank. A small portion of these fields reaches into the waveguide and induces currents in the probe. It is shown in appendix B that the current I_B induced by the magnetic field B is of the order 10^4 times the current I_E induced by the electric field E_0 . Thus, the rf magnetic field is the dominant source of the Lorentz vibration noise.

Based on this estimation, active cancellation of the rf magnetic field should greatly reduce the Lorentz vibration noise. This can be realized with a pair of coil windings that produces a compensating magnetic field near the probe. This field can be adjusted to cancel the field from the current in the saline (Fig. 10). The coils are supplied by the excitation pulse generator via an adjustable current divider circuit, which is manually adjusted to minimize the residual magnetic field. The rest of the experimental set-up is identical to that described in figure 2. The resulting image is shown in figure 11. The peak due to Lorentz vibration noise is just above the random noise floor of $0.03 \mu\text{V}$, roughly $1/10$ the noise level measured with-out active shielding (Fig. 6) and about 5% of the maximum HEI signal. This peak is the echo from the upper surface of the polycarbonate block, where there is a 46% acoustic impedance mismatch. In biological samples, the mismatch of soft tissue interfaces is below 5%,³ and the Lorentz vibration noise is expected to be lower still.

Compared to the ultrasound prism method, active shielding does not limit the orientation of the probe, and permits real-time compensation with feedback circuits. Orientation of the compensating field is not sensitive because the compensation current is actively set to null the undesirable peaks and because the current needed to null these peaks is a broad function of orientation angle. More sophisticated current control schemes may allow the compensation field to be both amplitude and phase-matched to the excitation field for precise field nulling at all relevant frequencies. For these reasons, active shielding may be more suitable for *in vivo* applications.

DISCUSSION

Once it is recognized that the rf magnetic field is the main source of the Lorentz vibration noise, the design of the piezoelectric probe can be modified to minimize the eddy currents. Nonmetallic materials should be used for acoustic backings. The thickness of the electrode plating on the PE element should be minimized to reduce the eddy currents in them. Other metallic components, including the outer casing and the connector, should be acoustically insulated from the PE element. These measures combined with the waveguide shield may reduce the Lorentz vibration noise to a level where the shielding methods described above will not be needed. It should be noted that because the forward and reverse mode of HEI are strictly reciprocal,⁴ the shielding methods described above are also applicable to the forward mode.

In incorporating these shielding principles into clinical imagers or piezoelectric arrays, two additional factors must be addressed. First, the waveguide, necessary for eliminating the EM crosstalk, will also modify the diffraction pattern of the piezoelectric transducer. For the designs tested here, the distortion was not significant, but it may become a problem for wide

acceptance angle array transducers. Modification of the waveguide shape from cylindrical to conical may reduce the distortion, although the overall waveguide length would need to be increased for the same degree of crosstalk noise isolation. Second, the waveguides act as acoustic standoffs and may cause reverberations,⁵ as seen in figure 3. To reduce these, care should be exercised to maintain good impedance matching and acoustic contact (e.g., no trapped air bubbles) between the sample and the end of the waveguide.

As shown in figure 5, after EM crosstalk noise is removed with the waveguide shield, there are residual peaks which are likely from the thermoelastic expansions of the saline tank, as suggested by their times of flight.² This thermoelastic signal is due to ohmic heating of the sample medium by the excitation pulse, and therefore it is expected to scale with the square of the current density in the sample. With the 400-volt, 300-ns excitation pulse, the amplitudes of these peaks are about 30 dB below the HEI signal at 2.5 tesla. In measurements with a larger pulser capable of producing a sine wave of 1 μ s period and 3 kV amplitude, the thermoelastic signal reached 1/4 of the HEI signal. These two signals cannot be distinguished by timing, since they both occur simultaneously with the excitation pulse, and both occur at conductivity discontinuities. They can, however, be separated by reversing the polarity of the electrodes relative to the static magnetic field. The HEI signal reverses sign under this condition, while the thermoelastic signal does not.

With high voltage pulsers, the thermoelastic effect may itself be a suitable mechanism for imaging. To have sufficient sensitivity, the peak excitation current density should be approximately 2 amperes/cm³ or higher, depending on the required spatial resolution. The mechanism of the thermoelastic effect involves not only the conductivity of the medium but also its heat capacity and thermal expansion coefficient, and possibly other parameters. Thus, the thermoelastic signal contains information that is different from both echo-based ultrasound and HEI.

Another source of coherent signal that also occurs concurrently with the HEI signal is the electroacoustic effect, or 'electrosound', in electrolytes.⁶ Although the details of this phenomenon are not completely understood, the general mechanism is that under an external electric field, the translational motion of charged molecules in an electrolytic sample pulls the surrounding medium with them and creates acoustic pressure waves. The electro-acoustic signal is generally emitted along the electric field, as opposed to the HEI signal, which generally propagates perpendicular to the electric field. However, there is mixing of the two to various degrees. In certain media, such as cooked egg white, where the charged molecules are large or extensively cross-linked, the electro-acoustic signal was observed to be as large as the HEI signal at 2.5 T. In more dilute media such as agarose, it decreased to 10 to 20 dB below the HEI signal. The electro-acoustic effect inherently occurs in electrolytic media, and it can be separated from the HEI signal by changing the direction of the static magnetic field relative to the sample.

An alternative to piezoelectric sensors that completely avoids the electromagnetic interference problem is optical ultrasonic sensors, such as laser-beam-based techniques⁷⁻¹⁰ and optical-fiber-based sensors.^{11,12} Currently, these technologies have not reached the sensitivity and robustness of piezoelectric transducers, but they hold the potential for ultrasonic imaging applications where EM interference is expected.

CONCLUSION

Hall effect imaging employs large electric excitation pulses, which induce coherent electromagnetic interference noise in piezoelectric probes used for signal reception. The two main noise mechanisms are direct crosstalk between the probe and the excitation pulse, and

the Lorentz vibration noise. A waveguide shield is shown to remove the crosstalk noise. The Lorentz vibration noise is mostly induced by the rf magnetic field produced by the excitation pulse. Two shielding methods are shown to be effective in removing the Lorentz vibration noise: one uses an ultrasound prism, the other employs an active compensating rf magnetic field.

Concurrent with the Hall effect signal, acoustic signals due to ohmic heating and thermal expansion are also observed. In addition, the electroacoustic effect in electrolytic media may also be present in the HEI signal. The signals from both effects are weaker than the HEI signal, but may be significantly increased with higher voltage excitation pulses or smaller samples. Methods for distinguishing these from HEI are discussed.

HEI technologies can benefit greatly from the existing tools of echo-based sonography, including sensor arrays, data acquisition and data processing. One critical issue is the adaptation of the piezoelectric array transducers. With a better understanding of the EMI issue and the shielding methods described here, it may soon be possible to test HEI with modified conventional echo scanners. The same EMI-related noise sources are also present in combined ultrasound-MRI applications, where these shielding methods may also be useful.

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APPENDIX A

A simplified model of the waveguide is a semi-infinite cylinder of radius a (Fig. 12). A uniform static electric field E_0 is applied perpendicular to the axis of the waveguide. Assuming that the waveguide is at ground potential, the potential function V in the interior of the waveguide satisfies the following equation,

$$\begin{aligned}\nabla^2 V &= 0, \quad r < a, \\ V &= 0, \quad r = a.\end{aligned}\tag{3}$$

Because of the azimuthal dependence imposed by the asymptotically uniform external field, the solution to Eq. (3) can be written as a summation of 1st order Bessel functions:

$$V = \sum_{i=1}^{\infty} C_i J_1(k_i r) e^{-k_i z} \cos(\phi),\tag{4}$$

where the k_i 's are the roots of the equation

$$J_1(k_i a) = 0.\tag{5}$$

This expression shows that the electric field generally follows a multiple exponential decay into the waveguide. The first term $\exp(-k_1 z)$ with the smallest root k_1 dominates at large z . For 1st order Bessel functions, $k_1 a = 3.832$; thus, the electric field at depth z into the waveguide decays as $\exp(-3.832 z/a)$. With the dimensions used in the experiment, this means the waveguide reduces the electric field by a factor of 3×10^4 .

Similar reasoning can be applied to the shielding of an rf magnetic field, assuming that the waveguide cylinder is perfectly conducting and thus prevents flux from running through its side wall. It can be shown that the dominant term in the magnet field is $\exp(-h_1 z)$, where h_1 is the first root of the equation $J_1'(h_1 a) = 0$. With the waveguide dimensions used in the experiment, the magnetic field is suppressed by approximately a factor of 2×10^2 .

These analyses do not give the exact solutions to the field distributions in the waveguide, which would involve solving multiple integral equations. However, they provide order-of-magnitude estimates of the shielding effect.

APPENDIX B

This appendix contains a rough estimate of the ratio between the eddy currents induced by the rf magnetic field and electric field, I_B/I_E . The electric field E_0 and the magnetic field B affect the probe differently and will be considered separately. As shown in appendix A, a residual of the E_0 field reaches into the waveguide and gives an electric field E' around the front nickel plating of the PE element of the probe. Electric currents arise in the plating such that the resulting charge distribution nulls the electric field in the plating. Denote α as the amount of electric field leakage into the waveguide:

$$E' \sim \alpha E_0, \quad (6)$$

and denote the radius of the waveguide as a . The current I_E in the plating provides the charge accumulation q to counter the field E' . Thus,

$$I_E \sim \frac{dq}{dt} \sim \omega q \sim \omega a^2 \epsilon_{\epsilon_0} E' \sim \alpha \omega a^2 \epsilon_{\epsilon_0} E_0. \quad (7)$$

where ϵ is the relative dielectric constant of the liquid in the waveguide.

Similarly, the rf magnetic field leakage into the waveguide B' can be described as

$$B' \sim \beta B, \quad (8)$$

and the induced currents I_B in the nickel platings and the metallic backing of the PE element counter this magnetic field:

$$B' \sim \frac{\mu_0 I_B}{a}. \quad (9)$$

Thus,

$$I_B \sim B' a / \mu_0 \sim \beta a B / \mu_0. \quad (10)$$

The magnetic field B is related to the current in the saline tank, and therefore the electric field E_0 . If the current in the tank is I_0 , the size of the tank is d , and the conductivity of the saline is σ , then

$$B \sim \frac{\mu_0 I_0}{d} \sim \frac{\mu_0 \sigma E_0 d^2}{d} = \mu_0 \sigma E_0 d. \quad (11)$$

Substituting Eq. (11) into Eq. (10) gives

$$I_B \sim \beta E_0 \sigma a d. \quad (12)$$

Comparing Eq. (12) and Eq. (7), the ratio I_B/I_E can be estimated:

$$I_B/I_E \sim \frac{\beta \sigma d}{\alpha \omega \epsilon_{\epsilon_0} a}. \quad (13)$$

Using the length dimensions of the experimental set-up, and assuming that electric and magnetic field leakage into the waveguide are comparable (α and β in Eq. (13) are similar), the ratio is approximately 8×10^3 at 1 MHz. According to appendix A, the electric field leakage is smaller than the magnetic field leakage by two orders of magnitude; thus the actual ratio of I_B/I_E can be even larger. This estimate shows that the rf magnetic field is the dominant source of induced currents in the probe.

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FIG. 1.
The set-up of a Hall effect imaging (HEI) experiment. The target sample is a polycarbonate block.

FIG. 2.

The configuration used to measure the EM crosstalk between the probe and the excitation pulse outside the static magnetic field.

FIG. 3.

The coherent noise due to EM crosstalk between the probe and the excitation pulse. The signal voltage is plotted against time, with zero time set at the instant of the excitation pulse. The peaks are echoes from the interfaces in the saline tank: (A) echo from the silicone oil-saline interface; (B) echo from the bottom of the saline tank; (C) multiple-reflection echo from the silicone-saline interface and the bottom of the tank.

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FIG. 5.

Result of the EM crosstalk measurement after the waveguide shield is installed, performed outside the static magnetic field. The remaining peaks are low in amplitude, and are due to thermal expansion of the saline body. (A) is the thermoelastic signal from the waveguide-saline interface; (B) is the thermoelastic signal from the bottom of the saline tank.

FIG. 6.
An HEI image of a polycarbonate block immersed in a saline tank, collected with the waveguide shielded probe. The level of the coherent noise is comparable to the HEI signal.

FIG. 7. Schematics of the ultrasound prism fitted to a probe, which allows the probe to align with the magnetic field for Lorentz vibration noise reduction.

FIG. 8.

A HEI image of a polycarbonate block immersed in a saline tank collected with the ultrasound prism. The Lorentz vibration noise is removed.

FIG. 9.

An illustration of the electric field and the magnetic field in the vicinity of the probe produced by the excitation pulse across the electrodes.

FIG. 10.

For active cancellation of the rf magnetic field, a pair of coil windings are placed across the saline tank to create a compensating field.

Wave-
guide

Saline

Block {

Saline

LV echo

FIG. 11.

A HEI image of a polycarbonate block in a saline tank collected with the active shielding in place. The light trace labeled 'LV echo' is the echo of the Lorentz vibration noise from the upper surface of the block, it is reduced by about 10 times compared to the noise level in figure 6.

FIG. 12.

In cylindrical coordinates, the waveguide shield can be modeled as a semi-infinite cylinder extending from $z = 0$ along the positive z axis. The material of the wall is assumed to be a perfect conductor.