An Inductive Method to Measure Mechanical Excitation Spectra for MRI Elastography

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ABSTRACT: Harmonic MR elastography (MRE) monitors the propagation of acoustic waves in tissues in the audio regime. Oscillatory motions with large amplitudes can induce nonlinear wave propagation effects resulting in harmonics that evolve over space. In order to understand these effects, knowledge of the motions of applied mechanical motion is needed to rule out the presence of harmonic motion arising from the mechanical source. We propose a simple technique to measure the spectral content of mechanical excitation based on the use of a set of detection coils mounted on the elastography excitation system. The motion of these coils causes a small signal to be induced from the applied static magnetic field of the MRI system. A detailed analysis shows that quantitative assessment of excitations is possible with correct geometrical arrangement of the detector coils. However, it shows that nonlinear effects can also occur depending on the alignment of the detection coils with respect to Bo. The system is easy to operate and allows for the time resolved observation of the actuator motion for each experimental setup. The system is intended to be used before and after MRE experiments to determine excitation spectral content and repeatability. We demonstrate its use in a one-dimensional elastography experiment and show that this information is an essential prerequisite for studying material nonlinear elastic properties using MRE.
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KEY WORDS: elastography; nonlinear acoustics; wave propagation; elastography instrumentation

INTRODUCTION

Harmonic MR elastography (MRE) requires the application of harmonic motion, which in turn interacts with the soft tissues under examination. Typically, the delivery of this motion is achieved with Helmholtz coils that are oriented perpendicular to the applied Bo field and then energized with alternating current (*1*, *2*). The Lorentz force arising from coil interaction with the applied field generates a torque on the coil that results in a time-dependent rotation that is coupled by various mechanical means to deliver either shear or longitudinal mechanical excitation to the patient's surface. The most elementary mechanisms uses a simple beam mounted on a bearing that directly couples coil motion parallel to the Bo field to the patient similar to that of Fig. 1. Such an arrangement results in a tiny angular oscillation of the beam with subsequent motions ranging from 1 to 1000 μm.

Imaging of the resulting tissue motions is achieved with a phase sensitive method that applies an oscillating gradient, which is phase-locked to the applied mechanical excitation (*3*). This generates a phase image of wave motion throughout the object that can be followed in its temporal evolution by adjusting the phase relation between the applied gradients and mechanical excitation. This experiment has been repeated by several investigators ranging in frequency

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from the audio range (50–1000 Hz) for soft tissue elastography (*4, 5*) up to 500,000 Hz to image the interaction of medical ultrasound in tissue equivalent media (*6, 7*).

Recently, there has been growing interest in the details of nonlinear wave propagation in tissues that can be assessed by monitoring the production of acoustical harmonics that arise from the nonlinear tissue interactions (*8, 9*). Thus by exciting the tissue at a given frequency and monitoring the presence of motions that occur at multiples of this frequency, one can probe the subtle details of the nonlinear properties of wave propagation through tissue. In order to quantify these effects, it is important to assess the frequency content of the mechanical excitation and normalize the motions observed with tissue to that applied with the spectral features of the mechanical excitation. Although one could consider using motion imaging with MRE itself for this means, this reflects the features of the motion as assessed over many repetitions of the mechanical excitation as one fills K-space of the MRE image. However, it would be useful to have an independent method of assessing the actuator motion that allows detection of individual mechanical excitations to determine the reproducibility of the excitation and provide some quantitative measure of what the actuator is delivering to the patient.

Various approaches for independent measurement have been proposed including piezoelectric accelerometers (*3*) and optical methods (*10*). In the case of an accelerometer, the linearity of these devices is less than ideal and the motions require integration of time-dependent acceleration data that can be subject to error accumulation. Alternatively, optical techniques have been proposed that monitor the moving reflections from a collimated laser beam reflected off a small mirror attached to the actuator assembly. With this system, the amplitude of the actuator motions can be easily measured; however, the harmonic content of the motions require more extensive tracking of the location of the laser spot throughout its motions. Such a system, based on optical methods to provide quantitative spectral assessment, would require substantial optical instrumentation installed in the bore of the MR system. Furthermore, it is difficult to reproduce the geometrical alignment of the optical unit with varying types of actuator devices as required for the special needs of an in vivo experiment. Therefore, expensive calibration experiments are necessary for tracking the transducers motion path of each individual experiment. For this reason it would be desirable to develop a motion probe, which i) gives rise to a signal that is linearly scaled to the actuator motion and ii) integrates easily onto the motion actuator for different experiments on patients.

In this article, we present a very simple electromagnetic technique that allows independent, real-time measurement of the spectral content of the motion of MRE actuators and illustrate its use in phantoms and nonlinear MRE studies.

A MOTION DETECTOR FOR ELASTOGRAPHY

In order to detect the tiny motions typical of elastography we mounted a pair of detection coils on the mechanical actuator that are oriented at an adjustable angle β relative to the applied field Bo (Fig. 1). Two coils are used to increase sensitivity and symmetry of the arrangement. As the beam oscillates, the oscillatory rotational motion of the coils in the Bo field induces an EMF that can be monitored with appropriate detection electronics. The temporal behavior of this signal reports the frequency and amplitude of this motion. Depending on the mutual inductance of the detection and excitation coils, the field arising from the excitation current can be coupled into the detection coils and produce a signal that will overwhelm the small signal arising from the motion of the apparatus (*11*). However, if we place the detection coils with their axes perpendicular to that of motion coil, this induced signal can be made arbitrarily small so that only signals arising from beam motion will occur. Regardless of the orientation of the coils, the system as described, cannot be used during an MRE experiment as time varying fields arising from the imaging gradients will induce large signals in the detection coils in addition to the signals arising from the actuator motion. As such, the system is best suited to measure motion actuation before and after the MRE experiments to determine the presence of harmonic motions and excitation reproducibility.

Nature of Induced Signal

In order to appreciate the characteristics of this system, assume that the beam is placed in an orientation perpendicular to the applied magnetic induction Bo as shown in Fig. 2. Furthermore, let the detection coils (total area A and carrying N turns) assume an angle β relative to the perpendicular of the applied field. Finally, assume the beam rotates about a bearing [Point A, in Figs. 1(b) and 2] through a moment arm (length L) resulting in a motion amplitude at point B of d units as shown in Fig. 2. If the beam oscillates with a

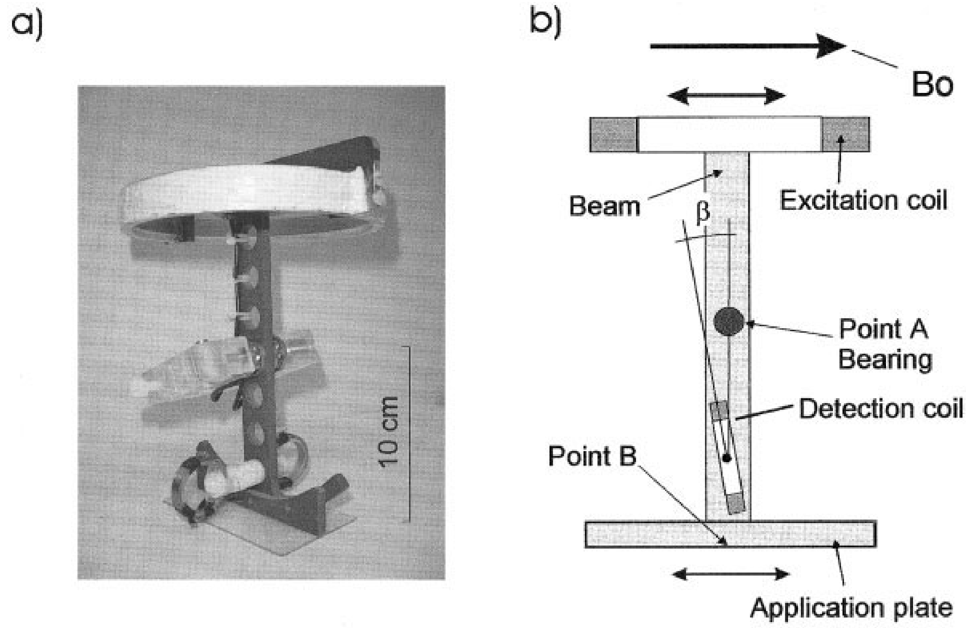

Figure 1 (a) Photograph of the actuator designed for nonlinear MR elastography measurements. (b) A schematic of the elastography actuator from saggital view.

frequency of ω, the angle of the coils relative to the Bo field is given by

$$\theta(t) = \beta + \frac{d}{L}\cos(\omega t), \qquad [1]$$

where β is the mean angle of the coils relative the perpendicular to Bo. Thus, the flux $\Phi(t)$ through the coils, arising from Bo is given by

$$\Phi(t) = ABo\cos(\theta(t)) = ABo\cos\left(\beta + \frac{d}{L}\cos(\omega t)\right). \qquad [2]$$

The induced signal V will be proportional to

$$V(t) = -N\frac{\partial\Phi(t)}{\partial t} \qquad [3]$$

to give

$$V(t) = -\frac{BoAdN\omega}{L}\sin(\omega t)\left\{\sin(\beta)\cos\left(\frac{d}{L}\cos(\omega t)\right) + \cos(\beta)\sin\left(\frac{d}{L}\cos(\omega t)\right)\right\}. \qquad [4]$$

This relation shows that the response of the coil is not necessarily linear depending on the geometry of the

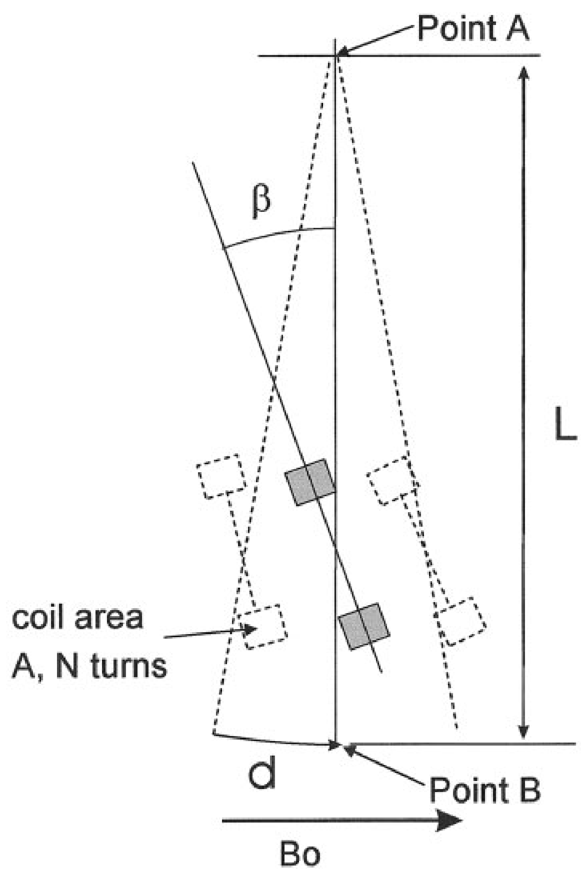

Figure 2 The geometry of the detector coil arrangement relative to the Bo field.

system. If we consider that the oscillatory motion to be very small compared to the beam moment arm ($d/L \ll 1$), then

$$V(t) \approx -\frac{BoAdN\omega}{L}\left\{\sin(\beta)\sin(\omega t) + \frac{d}{2L}\cos(\beta)\sin(2\omega t)\right\}. \quad [5]$$

Thus in general, we see that the signal contains components at frequencies of ω and 2ω together with their amplitudes dependent on the angle β. For example, if the angle β is set to 90°, the signal reflects the true frequency content of the actuator motion and reduces to

$$V(t) \approx -\frac{BoAdN\omega}{L}\sin(\omega t). \quad [6]$$

Although this signal correctly reports the motion of the coil, this orientation is not well suited to experimental use as this geometry maximizes the induced signal from the excitation coil. Alternatively, if we place the angle $\beta = 0$, which eliminates the mutual induction from the excitation coil, the induced signal V arising from motion appears at twice the frequency of applied oscillatory motion as

$$V(t) \approx -\frac{ABod^2N\omega}{2L^2}\sin(2\omega t). \quad [7]$$

We see that the signal in this case is reduced by $d/2L$ compared to the orientation with the coils at angle $\beta = 90°$. The ratio of the signal from the 2nd harmonic to that arising from the applied frequency is approximated by $d/(2L\ \tan(\beta))$. Thus assuming we want the contamination from the 2nd harmonic to be a factor of R less than that of the applied frequency requires that the coil angles be set at

$$\beta = \tan^{-1}\left\{\frac{d}{2LR}\right\}. \quad [8]$$

Taking a practical example and considering $d = 100\ \mu m$ with a beam length of 10 cm and assuming that we desire to have the contamination of the 2nd harmonic to be only 2% of the applied frequency requires that the angle $\beta \geq 2.8°$. Furthermore, assuming an applied magnetic induction of 1.5 Tesla, with the detector coil having a radius of 2 cm carrying 100 turns, a motion at 50 Hz with an amplitude of 100 μm will produce a signal of 2.5 mV.

Placing the coil at $\beta = 90$, gives much bigger signal and is free of corruption from 2nd harmonics, but the mutual inductance with the excitation coil would be larger.

METHODS

An elastography actuator was constructed for studying non-linear wave propagation (Fig. 1). The excitation coil is 16 cm in diameter with an impedance of 8 Ω to allow coupling to a 150 W audio amplifier (*12*). The bearing was constructed of glass ball bearings to ensure MR compatibility and smooth rotation of the beam in operation. The beam length (L) was 10 cm. Two detector coils of 3-cm diameter were composed of ~100 turns of 30-gauge magnet wire connected in series. They have been mounted so that their orientation relative to the beam axis could be adjusted. For our experiments, the coils where adjusted to eliminate any induced signal from the excitation coil. This entire structure was mounted in a birdcage coil for use with a gel phantom. The phantom was cubic with a volume of 1000 mL and composed of 1% agar gel and fitted into the coil assembly.

In order to test this concept without inductive coupling from the excitation coil, we placed the coils at an angle $\beta = 0°$. In order to eliminate 2nd harmonic generation, the entire beam with the attached actuator coil was tilted to an angle of ~80° from the Bo field, which is analogous to having an angle β of 10°. This had no substantial impact on the operation of the system and allowed a straightforward measurement of motion arising from oscillatory motion.

The actuator could be positioned in the bird-cage coils so that the contact pressure between the actuator and the phantom could be adjusted. This was used to probe for the introduction of nonlinear motion of the actuator based on the Fourier spectrum of the detected motion signal. In a similar manner, we adjusted the actuation amplitude to determine whether large amplitude motions would generate nonlinear motions.

Harmonic MR elastography experiments where conducted by using a two-dimensional radiofrequency (RF) pulse to excite a column of magnetization (*13*). This permitted the collection of motion in 1 spatial dimension in rapid succession. The RF pulse consisted of an 8-loop spiral lasting ~6 ms, and was used to excite a column of approximately 2.5 cm in diameter (full width at half maximum). This column was oriented at right angles to the plate used to mechanically excite the phantom. A sinusoidal gradient was applied immediately after RF excitation to make the sequence sensitive to oscillatory motion of a specific frequency. The motion-encoding gradient was oriented parallel to the shearing direction of the mechanical excitation and a gradient echo was used to achieve spatial-encoding. Each echo was collected at a bandwidth of approximately 16 kHz and was sampled for 256 points. The field of view of the one-dimensional projection of the excited column was 24 cm, with a spatial resolution of ~0.9 mm. Motion detection was based on the phase of each projection while correction for phase errors unrelated to motion was removed with two excitations with the phase of the motion encoding gradients inverted during the second excitation. The phase difference between the two acquisitions was then used in the motion calculations.

The sequence was implemented on a General Electric Signa LX 1.5 Tesla MR system (GE Medical Systems, Waukesha, WI). The sequence was externally triggered by the start of mechanical excitation every TR = 2 s. A variable delay of approximately 40 ms was inserted between the trigger and the start of the RF excitation to allow for steady-state motion to be achieved before the onset of motion encoding. This delay was then incremented with each successive acquisition, to introduce a phase delay between the motion-encoding gradient relative and the mechanical motion. A total of 32 increments were used to shift the gradient by one period.

Experimental Results

The transient response of our system is shown in Fig. 3, where we show the detected signal from 30 cycles of 200 Hz motion while in contact with a gel phantom. The signal is in the 10 mV range and shows a

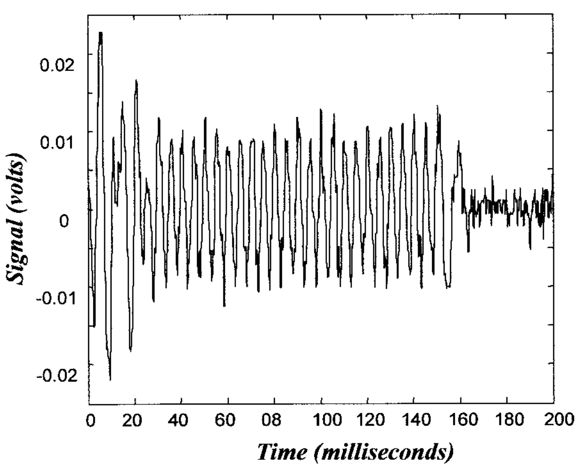

Figure 3 A typical detector coil output with 30 cycles of 200 Hz applied current to the actuator system.

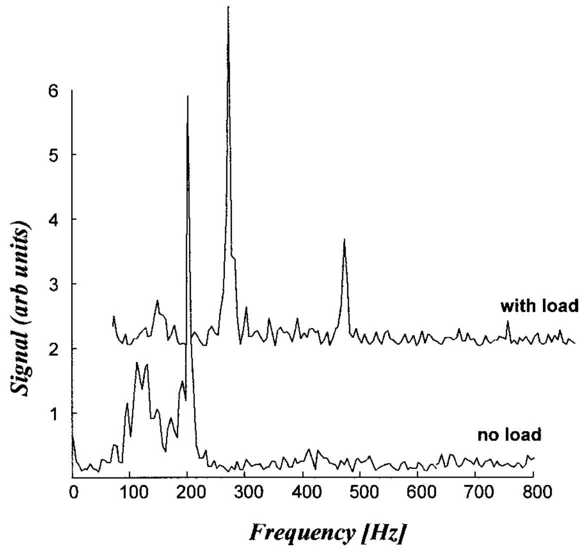

Figure 4 The spectrum of detected motion with the actuator in light contact with a gel phantom and then loaded with increasing contact pressure to generate higher order motions in the actuator. The frequency applied to the actuator was 200 Hz.

transient response at the beginning and end of the excitation characteristic of the differences in resonant frequencies between the gel phantom and that of the applied motion.

To probe for nonlinear motion induced by the actuator system itself, we increased the contact pressure of the actuator on the gel phantom. This effect is illustrated in Fig. 4 where we see the generation of 2nd harmonic effects with a load that is not seen when the actuator is in light contact with the gel phantom. Similarly, increasing the input voltage to the actuator amplifier results in a gradual increase in the presence of the second harmonic as shown in Fig. 5.

In the second set of elastography experiments, we used an actuation frequency of 150 Hz that resulted in the spectra of actuator motions as seen in Fig. 6. This shows modest nonlinear motions at 300 and 450 Hz but negligible motions at 600 and 750 Hz. To test for the generation of nonlinear wave motion arising from tissue nonlinear wave propagation in the agar, the MRE experiment was configured to monitor motion at 750 Hz. This frequency was chosen because there was no evidence of motions from the actuator at this frequency. The result of this experiment is shown in Fig. 7(a), where a temporal-spatial plot of the wave motions from the 32 phase offsets are shown. The motion actuation is at the top of these plots (i.e., at position 0). This clearly shows a wave at 750 Hz that is propagating toward the bottom of the phantom. More interestingly, the harmonic amplitude starts at

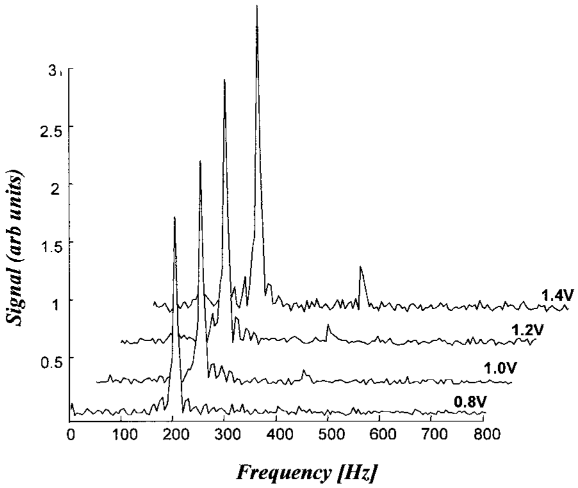

Figure 5 The spectrum of detected motion with increasing voltage applied the audio amplifier for the actuator system. The frequency applied to the actuator was 200 Hz.

essentially zero at the actuator surface and becomes apparent with ~3 μm maximum amplitude at the bottom of the phantom. To further illustrate this effect, we consider the temporal Fourier transform of the data of Fig. 7(a), which shows a clear harmonic at a frequency of 750 Hz, which becomes apparent at a location of approximately 40 mm [Fig. 7(b)]. The growth of this harmonic is consistent with the accumulation of a nonlinear propagation effects and the position of the onset of the nonlinear motion is a measure of the shock length of the nonlinear wave (*14*). The motion detection also serves to rule out the fact that nonlinear motions are delivered to the phantom as a result of the actuator itself and the motions at 750 Hz are entirely due to nonlinear wave phenomena.

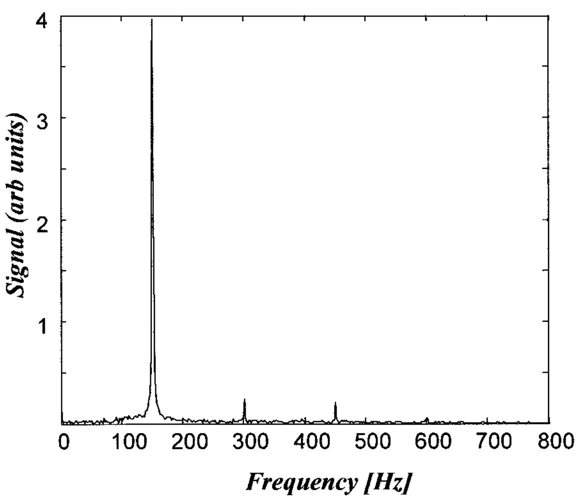

Figure 6 The spectrum of motions with a fundamental frequency of 150 Hz delivered to the actuator used in the data for Fig. 7.

DISCUSSION

In this article, we present a simple electromagnetic detector geometry that is capable of detecting micron scale motions for MRE. It is mounted directly on the elastography transducer and allows a direct tracking of the induced mechanical motions under the conditions of the MRE experiment. The system was used before the MRE experiment in order to avoid signal contamination from the imaging gradients. Thus we used the system to show the nature of the excitation motions expected to occur during the MRE experiment. In operation, the system was found to be very stable over multiple MRE experiments. It is clearly visible from typical vibration data (see Fig. 3) that the steady-state limit is reached within a certain time period after the start of excitation. The duration of such a transient vibration period is a parameter that depends on the individual actuator design as well as the load. Also if load is nonlinearly dependent on the actuators deflection due to the materials properties, the vibration amplitude becomes significant for the transient response of the system. Thus, careful assessment of the motion characteristics of the actuator is crucial for successfully performing nonlinear MRE experiments.

Depending on the orientation of the detector coils, a 2nd harmonic can be found that is not representative of the actuator motion when the coils axes are parallel to the Bo field. Alternatively, mounting the coils with their axes perpendicular to the Bo field eliminates this harmonic and substantially increases the motion-induced signal. In this configuration, inductive coupling from the excitation coil can overwhelm the motion-induced signal. One approach to overcome this issue would involve placing a second set of detection coils, which are stationary, but of a similar size and location as the moving detection coils. These coils would generate a signal due only to the mutual inductance from the excitation, which could be subtracted from the coils from the moving detection coils. This could be achieved through appropriate sampling of both signals followed by data subtraction, analog subtraction of the two signals with a differential amplifier or simply connecting a set of balanced coils in series but with the opposite phase. Alternatively, the two detection coils could be mounted in a common plane on the actuator plate parallel with Bo. Each coil would generate a signal from the excitation coil and the motion

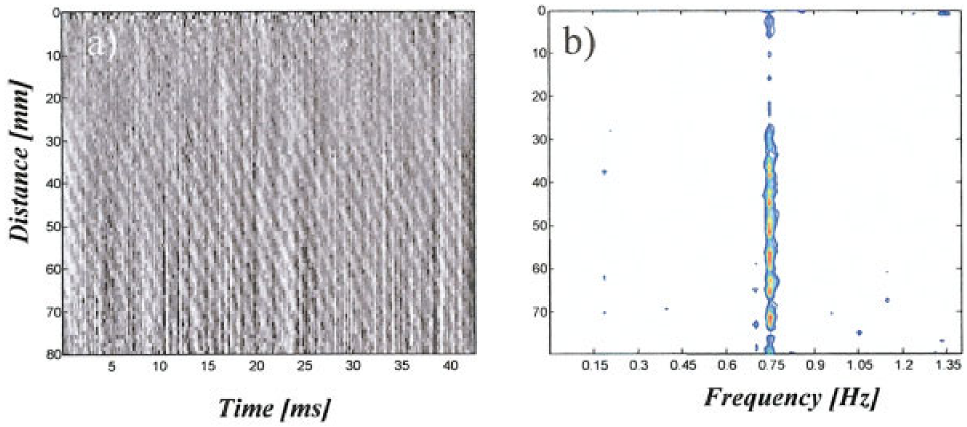

Figure 7 (a) The temporal-spatial plot of the one-dimensional elastography experiment with an applied motion of ~1 mm amplitude to the gel phantom. The applied frequency was 150 Hz and the gradient for the elastography experiments was set at 750 Hz for 20 cycles. The slope of the growing amplitude of the 750-Hz vibration with increasing distance from the actuator indicates the degree of the nonlinearity of the elasticity in the phantom. (b) The corresponding temporal Fourier transform of the same data. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

of the actuation plate. However, if the coils are placed symmetrically about the beam in a direction along Bo, the signal induced by the excitation coil would be in-phase, whereas the signal induced by the plate motion would be phase inverted. Subtracting these signals would null the induced component from the excitation coil.

The system we have described does not allow the measurement of motion during imaging as the imaging gradients would induce signals dependent on the exact location of each detector coil in the imaging volume and the details of the gradients used in the pulse sequence. For this reason, it is still necessary to measure the actuator motion prior to the elastography experiment. In our experience it is feasible to rely on the consistency of the actuator performance as long as the experimental setup (i.e., position and load) remains unchanged. Repeating measurements showed an identical motion path of the tracking coils over hours of elastography experiments.

Alternative approaches to detecting actuator motions exist, not the least of which would be using elastography methods directly. For example, one could observe these motions at the surface of the phantom by using tiny vials of gel as sources of moving magnetization mounted directly on the application plate. Using the same phase sensitive motion experiment done for the imaging of shear wave propagation, it would be possible to measure the actuator motion within the imaging field. Although this approach would be practical and could be used to detect the spectra of motion, it does not offer a means to conduct real-time and independent monitoring of the excitation motions. This can be of value to probe the stability of the motions throughout the acquisition of the elastography data with a spectral response for each K-space trajectory. Furthermore, by careful detector coil design the magnitude of the motions can be determined from simple constants and geometrical factors.

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