A LASER INTERFEROMETRIC MINIATURE SEISMOMETER

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ABSTRACT

This is the second year of a Phase II Small Business Innovation Research (SBIR) contract geared towards the development of a new seismic sensor. Ground-based seismic monitoring systems have proven to be very capable in identifying nuclear tests, and can provide somewhat precise information on the location and yield of the explosive device. Making these measurements, however, currently requires very expensive and bulky seismometers that are difficult to deploy in places where they are most needed. A high performance, compact device can enable rapid deployment of large scale arrays, which can in turn be used to provide higher quality data during times of critical need.

The use of a laser interferometer-based device has shown considerable promise, while also presenting significant challenges. The greatest strength of this optical readout technique is the ability to decouple the mechanical design from the transducer, thus enabling a miniaturized design that is not accessible with conventional sensing techniques. However, the nonlinearity in the optical response must be accounted for in the sensor output. Previously, we had proposed using a force-feedback approach to position the sensor at a point of maximum linearity. However, it can be shown that the combined nonlinearities of the optical response and the force-feedback curve necessarily results in a significant amount of unwanted noise at low frequencies.

Having realized this, we have developed a new approach that eliminates force feedback, allowing the proof mass to move freely at all times. This takes advantage of some advanced optical spatial filtering that was developed at Symphony Acoustics for other types of sensors, and was recently adapted to this work. After processing the signals in real time, the digital output of the device is intrinsically linear, and the sensor can operate at any orientation with the same level of resolution, while instantly adapting to significant changes in orientation. Ultimately, we expect the dynamic range to be up to 180 dB. Currently, we have observed the noise floor in a 0.1 Hz to 10 Hz bandwidth to be near -160 dB/Hz relative to 1 m^2/s^4. To meet the objectives of this program, we are finalizing the design of a 3 axis sensor for shallow borehole deployments, with a diameter of 40 mm and a length a 150 mm.

OBJECTIVES

The goal of this program, sponsored by the NNSA, is to advance the development of seismic sensors that are used for Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring. In particular, it is desirable to replace the existing 1 Hz geophones that are currently used at monitoring installations with devices that are much smaller and easier to deploy. Simpler deployment will necessarily lead to lower cost of deployment, and that can in turn lead to more monitoring stations, as well as more rapid and economical placement of temporary installations in hard to reach locales. Such devices will need to operate at or below the new low noise model (NLNM) over the frequency band of 0.2 to 40 Hz. It is also the stated goal of the DOE and NNSA to have these sensors produce digital outputs, thus further reducing the complexity of deployments. These miniaturized, three axis digital devices should consume less than 300 mW of power.

The objectives for this year of research were to greatly advance the technology readiness, to the point where we could begin field testing. In the process of our research, we uncovered many areas where substantially new advancements could be made in the signal processing as well as the hardware design.

RESEARCH ACCOMPLISHED

This paper describes the progress made to date in this final year of the Phase II SBIR project. We learned a great deal from our first two generations of prototypes. The optical interference displacement sensing that we have implemented has shown considerable promise, but only if certain factors are taken into account. Chief among these factors are the linearity of the transducer response, control of the thermal coefficients, and the proper implementation of (or lack thereof) force balancing. Our most recent designs implement techniques that overcome the issues associated with each of these factors. With the use of advanced micro-optics, we can use multiple beams of coherent light to sample the sensor position. This provides a means for self-normalization and linearization, while also allowing the proof mass to move freely across the full range of +/- 1g with a resolution near 1 nano-g at any static orientation. Feedback control is thus not required. We have also developed temperature control to enable stable operation down to very low frequencies, much lower than required for this particular application.

Addressing Nonlinearities

The small signal sensitivity of an optical interference transducer has long been known and understood. The periodic nature of this signal also means that the signal must be necessarily nonlinear as a function of position. While it is conceivable to take out this nonlinearity through the use of a force balance actuator, that approach actually undermines the benefits of the optical displacement sensor and introduces additional dynamic nonlinearities. Nonlinearities are very detrimental in low frequency sensor design if not properly accounted for. This effect can be examined by a simple non-parametric polynomial model for the local transducer response around a given operating point.

$$s(x) = \sum_{i=0}^{n} a_i x^i$$

Where s is the transducer response as function of the displacement from equilibrium, x. In this expression, the first coefficient would correspond to the bias and second would be the sensitivity. If all higher order terms were zero, then these two parameters would serve as a perfect representation of x. The effect of the higher order terms can be evaluated in the frequency domain. The Fourier transform of a product of time domain functions is the convolution of the respective Fourier transforms. Thus:

$$X_2(\omega) \equiv F\left\{x(t)^2\right\} = (X * X)(\omega) = \int_{-\infty}^{\infty} X(\omega')X(\omega - \omega')d\omega'$$

From this, we can easily see that the 2nd order nonlinearity rectifies all of the frequency components. In the limit of an uncorrelated white noise sequence, or in a pure sinusoid, rectification is the only real effect. A real signal, however, will typically be neither of these. Vibration signals can be represented in a number of ways. For example, an impulse filtered by a transfer function or a sinusoid with time varying phase/amplitude. In any case, such a signal will be strongly correlated in time, i.e., any peaks in the frequency spectrum will have a finite width. In such cases, the presence of nonlinearities will necessarily lead to high frequency ambient signal in the input being mixed down into low frequencies.

The optical response function has nonlinear terms that are quite large. If allowed to move freely, with a clipping range of 10% of the optical full scale, the nonlinearities will easily exceed 1%, about 30 dB above typical requirements for a seismic sensor. This can be compensated with digital post-processing, so long as the optical parameters are well calibrated.

Thermal Noise Design Considerations

The focus of this effort is upon the miniaturization of sensors. Existing geophones that are used within this bandwidth of 0.1 to 40 Hz are already optimized for size and noise performance for their given transducer design. They operate near the level of critical damping with a 1 Hz resonant frequency and a mass near 1 kg. The noise floor is limited by the thermal noise limit:

$$\eta_T = \sqrt{\frac{4K_B T\omega_0}{mQ}}\, f(\omega)\, \frac{m}{s^2 Hz^{1/2}}$$

Where K_B is Boltzmann's constant, T is the absolute temperature, ω_0 is the fundamental resonant frequency in rad/s, m is the mass in kg, and Q is the quality factor of the resonance. f is the frequency response function. In the case of high damping, the frequency response will be designed to reach its maximum within the bandwidth of interest, with a peak amplitude of Q. This is the typical design for geophones that utilize velocity transducers. Accelerometers will typically be somewhat underdamped, with a fundamental resonant frequency that is 2 to 3 times the maximum operating frequency. Within the operating bandwidth, f will be approximately unity. In either case, the quantity ω_0/mQ must be sufficiently small to be below the targeted noise floor. Using the NLNM as the target, this requires a noise floor of 5×10^{-9} $m/s^2/Hz^{1/2}$, which implies the design rule that $\omega_0/mQ < 1000$ (in cgs units, the right side becomes 1, which may be easier to remember).

Miniaturization implies primarily reducing the size of the mass. The resonant frequency will necessarily increase as well. For the desired bandwidth of 0.1 to 40 Hz, a resonant frequency near 100 Hz is about the lowest possible frequency. With a mass of a few grams and a Q near 100, we are in the right ballpark. A resonance of 100 Hz is also reasonably stiff and manageable, and would not require any special requirements for locking down the mass during shipping or handling.

Signal Extraction

If allowed to move freely, the proof mass will displace about 25 microns from its equilibrium point as it moves through 1 g of acceleration. If a single beam of light is used to detect this motion, then we will have interference fringes that repeat every half wavelength, approximately 400 to 800 nm depending upon the laser source that is used. The transducer design that is used must be able to accommodate this large range.

Maximum sensitivity is only achieved within a narrow band of each interference fringe. To realize the high sensitivity of the optical transducer, some means must be employed to guarantee that the sensor maintains its optimal sensitivity. One approach would be to implement a force feedback control that centers the mass on the nearest fringe. It is also possible to design an entirely passive device by probing the sensor with multiple beams at differing wavelengths or incident angles. We will consider both approaches.

The use of a force feedback actuator may at first seem like a reasonable solution. In one approach, it can be used in a static sense, wherein it is like a conventional mass centering actuator that only re-centers the mass periodically. The mass is then allowed to move freely. The dynamic range is limited by the fringe edge, or the linearity considerations described above, but it is still conceivable to achieve 130 dB in such an arrangement. The signal must be linearized based upon a model for the optical response. The drawback in this approach is that the actuator must have a sufficient dynamic range to move the sensor up to 1 full fringe. Since the sensitive part of the fringe is necessarily less than 1/4 of a fringe, this implies that the actuator must be stable to within -140 dB of its full scale range, over the signal bandwidth. Any fluctuations larger than this will increase the noise floor. This is not entirely outside the realm of possibilities, but it is a non-trivial problem to produce an actuator force that is stable to this degree.

Such an issue is not made any easier if the sensor is held in a tight closed loop, such that the proof mass remains stationary within the signal band, and the actuator signal becomes the sensor output. While this can serve to enhance the linearity and dynamic range, that is extremely difficult to realize in practice. As discussed above a miniature sensor relies on being highly underdamped in order to achieve the expected noise limits. The presents a challenging control problem, especially when the mass must be held accurately to better than 0.5 ppb of its full scale displacement. There is also a bit of irony associated with enhancing linearity by utilizing an electromagnetic actuator that depends quadratically on the actuator signal, and is cubic in the sensor displacement relative to the actuator.

The approach we have settled upon is the use of multiple optical beams to probe a purely passive sensor. This leverages all of the strengths of the optical sensing platform, while also providing ways for overcoming its weaknesses. The price is an increase in complexity in the optical and electronics design, but even still the design remains simpler than what you might find in a consumer blu-ray DVD read head.

The concept is illustrated in Figure 1 below. By simultaneously sampling the cavity at multiple phases, we gather much more information about the absolute position of the mass relative to the reference frame. Each beam also samples the optical response at a different point on the curve, as can be illustrated by the optical response curves in Figure 2.

This enables us to develop a model for discovering the underlying linear variable, which is the mass displacement, by using non-parametric modeling. This is done in real time digital signal processing at a high sampling rate (4 kHz per detector channel) as we must first linearize the signal prior to filtering and decimating it. From the multiple channels, a best estimate of the proof mass motion is derived at each unit of time. Time stamped digital data is then output on a serial line that is read in over USB into a data archive. A block diagram of the complete sensor system is shown in Figure 3.

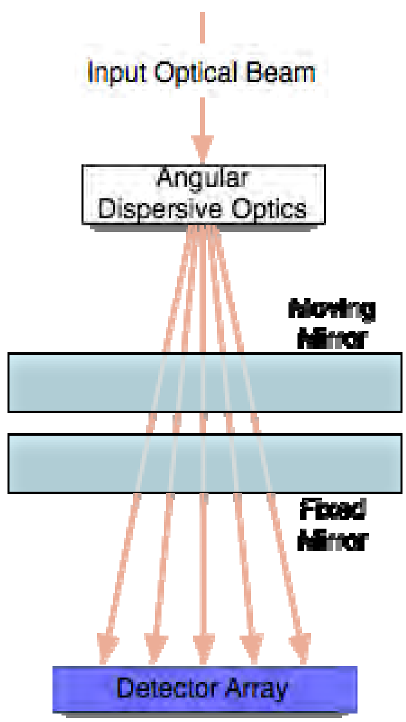

Figure 1. A schematic diagram of the new multi-beam optical sensor design that has been developed by Symphony.

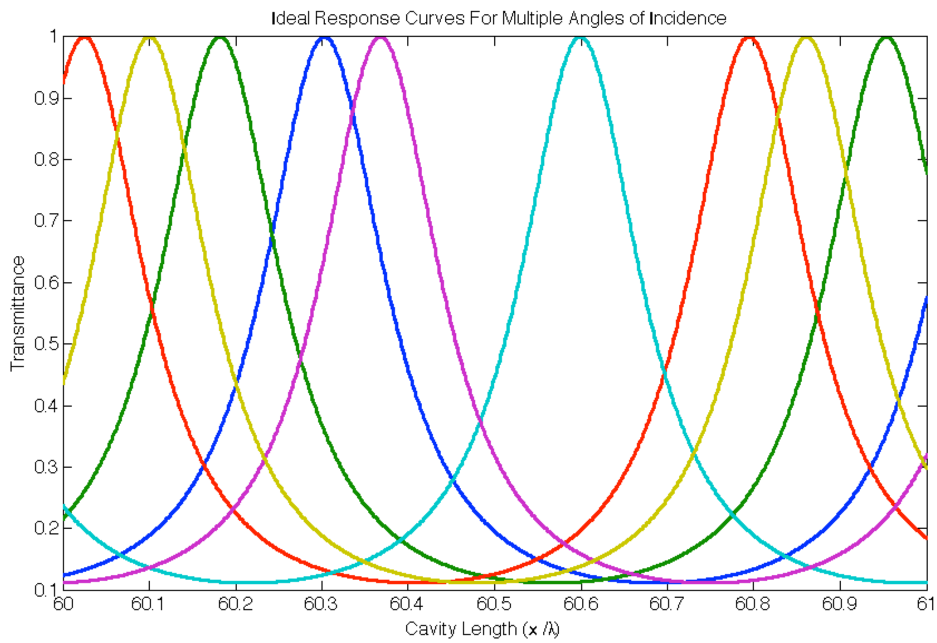

Figure 2. A set of optical response curves for a sensor illuminated at varying angles. The angles are linearly spaced between 4 and 11 degrees.

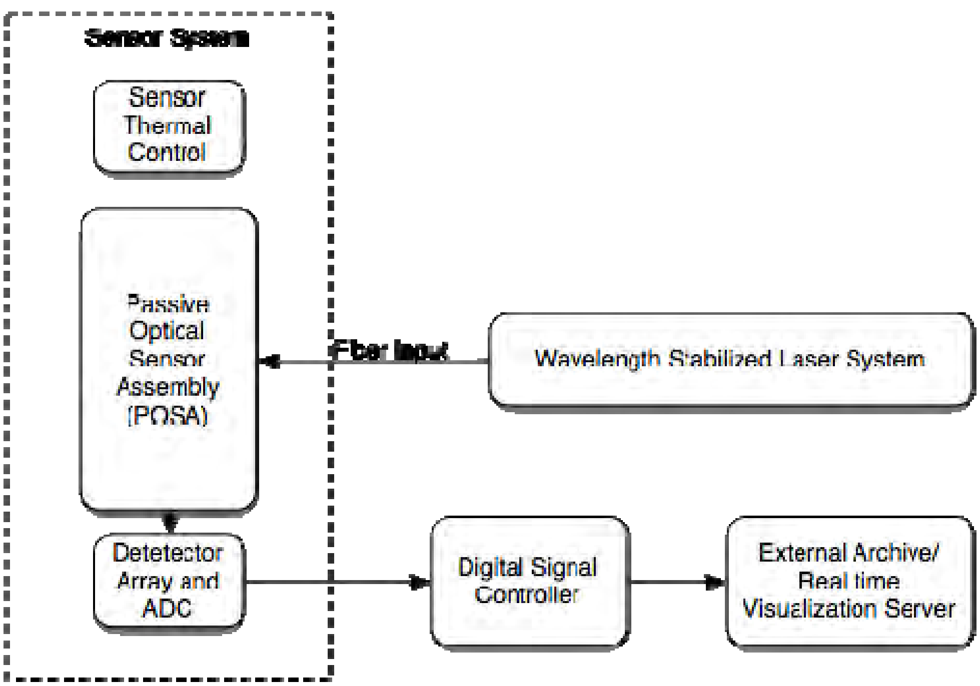

Figure 3. System block diagram for our seismic sensor system.

Figure 4. Complete sensor prototype built during this phase.

Figure 4 shows our latest sensor prototype. In this generation, we focused less on miniaturization, and more on the implementation of the new sensing modality. About 75% of the volume of the sensor is composed of the thermal insulation necessary for proper temperature control, as discussed below. Currently, the system is designed to operate in a static orientation, but the orientation is arbitrary. The same sensor can be operated in vertical or horizontal arrangement, and can rapidly switch between the two, and only a tare is required when changing orientations. Combining these into a 3 axis device is thus trivial. We are currently implementing a dynamic tracking algorithm that will extend operation to a full 160 dB, or more, of linear dynamic range.

Thermal stability also must be carefully considered in the system design. The relative change in cavity length due to thermal fluctuation must be below 0.1 ppb. With frequencies as low as 0.1 Hz, this is a non-trivial consideration. Even if the cavity could be designed with a thermal coefficient as small as 1 ppm/K, this implies a thermal stability of 0.1 mK. Undoubtedly, sensor noise at low frequency is limited primarily by this requirement, although it can be overcome with careful design. Our sensor is oven controlled using a flex heater design that maintains the temperature a few degrees above the ambient, and is stable to better than 0.1 mK within an environment with diurnal temperature variations of several degrees. Accomplishing this results in the heater being the dominant source of power dissipation in the sensor. In most deployments for these types of sensors, the environment will be static placement within a borehole, which has minimal diurnal temperature variation. In such an environment, passive isolation techniques could be sufficient for minimizing the thermal fluctuations at the sensor.

In our latest generation of prototypes, we choose to fiber couple the signal into the sensor from an external laser. This allows us to decouple the development of the wavelength stabilized source from that of the sensor system. This is not a permanent design decision, however, as we imagine incorporating the laser back into the system for our future multi-axis products. We are also now working at a wavelength of 1550 nm, due to the increased availability of quality optical components at this wavelength.

A sensor was deployed on an isolated pier in a suburban Texas laboratory for several weeks, while we refined real time embedded signal processing algorithms. Figures 5 and 6 below show some typical data. We did not have a reference seismometer in this lab, so the calibration is not absolute, and the noise floor out to 0.05 Hz appears to be below the ambient noise level during the quietest periods, but that is still 15 to 20 dB above the low noise model.

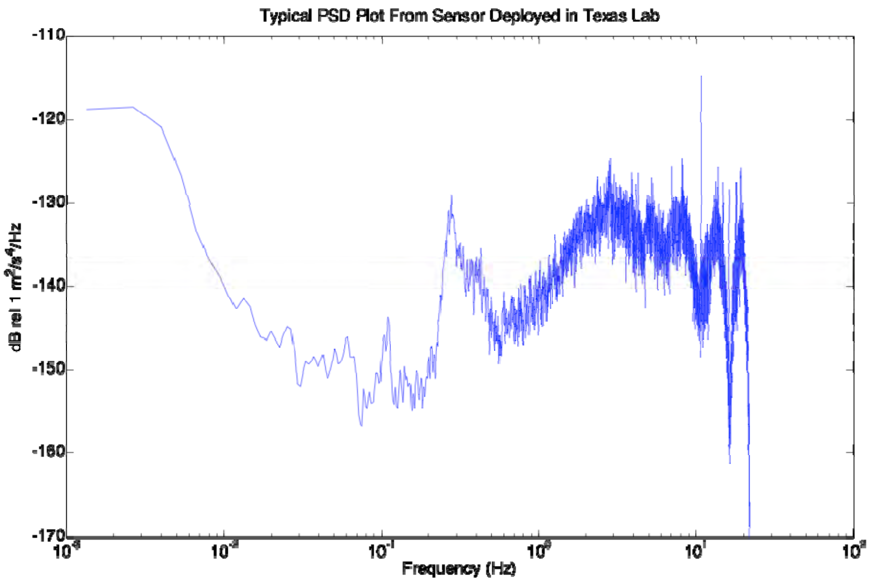

Figure 5. Typical power spectrum from sensor.

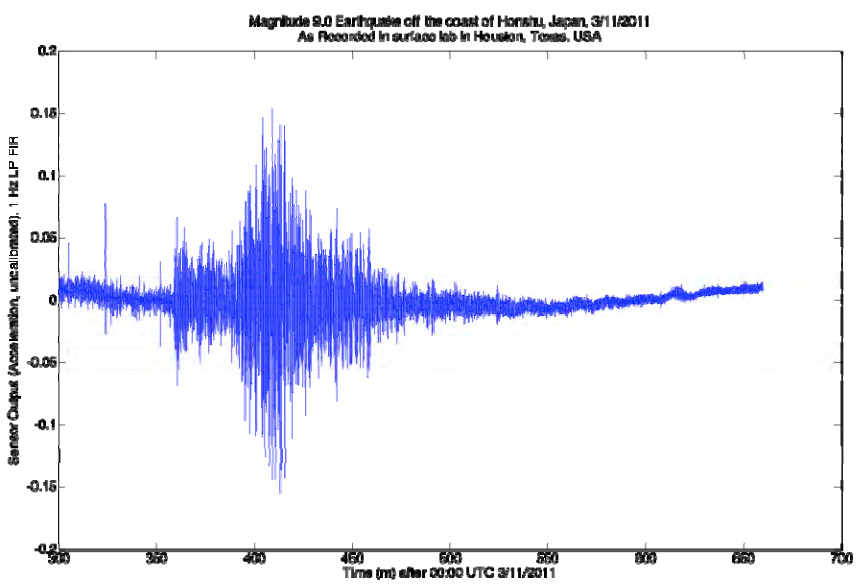

Figure 6. Seismogram of the March 11, 2011, earthquake off the coast of Honshu, Japan, as recorded by our sensor in Houston Texas.

CONCLUSIONS AND RECOMMENDATIONS

Effective implementation of an optical interferometric transducer requires a deep understanding of all aspects of sensor design. We have now developed a signal extraction modality that can realize the full potential of an optical sensor in a seismic device. The final set of prototypes built under this SBIR project will be tested later this year, and we anticipate that these will offer a compelling solution for test ban treaty monitoring going forward.

ACKNOWLEDGEMENTS

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