SEISMIC DETECTION USING MINI SEISMOMETER

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ABSTRACT

The goal of this Phase 1 SBIR project is to develop a very small, versatile, rugged, low power, low noise, one or three-axis short-period seismometer. The total sensor size should be less than 1 cubic inch; and low power consumption and low sensor self noise below the USGS Low Earth Noise Model, with dynamic range at least 120 dB over a frequency band of 0.2 to 40 Hz. All commercially available high performance seismometers using various technologies are large, heavy and consume high power. The user must often face a difficult choice: use instruments with significantly lower performance characteristics, or reduce the size of the network. Our company, eentec, proposes a solution for this problem of designing a seismometer using a new technology of liquid inertial masses and electrochemical transducers. This overall approach will miniaturize a medium period seismometer while maintaining low self noise with low power consumption.

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OBJECTIVES

This project, if followed to its successful completion, would lead to the implementation of a state-of-the-art miniature, affordable, rugged, reliable, easily-installed high quality instrument, well suited for mass production and commercialization for use in many areas of seismic, civil engineering, geotechnical investigations, and many other areas were highly sensitive motion detection is required.

The seismometer resulting from our investigation is intended to meet the following requirements:

- miniature size—about 1 cubic inch
- power consumption below 100 mW for a basic analog sensor
- dynamic range—at least 120 dB
- high resolution in the required passband of 0.2 to 40Hz
- low self noise below the USGS Low Earth Noise Model (e.g., approximately 0.5 ng/sqrt[Hz]) while not sacrificing the high sensitivity required to be useful in the applications intended
- capable of operation at any selected orientation of its axis of sensitivity rugged and suitable in harsh field conditions

Overview of eentec Seismometer Technology

The principle of operation is basically electrochemical in nature. The sensor element consists of a cylindrical channel with elastic membranes on the ends, and is filled with an electrolyte. A microporous ceramic plug containing platinum grid electrodes is within the channel. When translational motions are applied, a pressure differential occurs across the sensor cell, which causes the electrolyte to flow, and generates a current in the wire connected to the platinum grid.

Overview of the Actual Physical Process

The motion of the fluid caused by an external acceleration must be converted into an electrical signal to be useful. This is accomplished in the following manner.

When a small dc offset is applied between the anodes and cathodes, the flow of ions of each type is given by the following expression:

$$\mathbf{j}_a = -D \cdot \nabla c_a + q_a \cdot c_a \cdot \mu \cdot \mathbf{E} \qquad (1)$$

where D = diffusion coefficient, μ = mobility, c_a = concentration of active ions, E = the electrical field vector. Since the strong electrolyte is an excellent conductor, the electric potential drops rapidly in the vicinity of the electrodes, and there is no electric field, E, in the bulk of the fluid. The second term in Eq. 1 can therefore be ignored. Thus, the application of a bias voltage results *only* in a concentration gradient. This is in contrast both to conductors, in which the current is driven by the external electric field, and to semiconductors, in which both the field and the concentration gradient determine the currents.

An external acceleration, **a,** along the channel creates a pressure differential, **ΔP,** across the transducer, which forces the liquid in motion with a velocity, **v**. This flow of electrolyte entrains ions and causes an additional charge transfer between the electrodes:

$$\mathbf{j}'_\mathbf{a} = \mathbf{v} \cdot c_a \qquad (2)$$

The total current from active ions, in the presence of acceleration, will thus be:

$$\mathbf{j}_\mathbf{a} = -D \cdot \nabla c_a + \mathbf{v} \cdot c_a \qquad (3)$$

The transducer thus generates an electrical signal in response to an input motion. The symmetric geometry of the transducer cell ensures its linear behavior over a wide range of input signals.

With a highly concentrated specially formulated electrolyte, the electric field is non-zero only in a narrow boundary layer adjacent to the electrodes. In this case, the electric current is fully determined by the diffusion**.**

These transducers are characterized by a very high conversion coefficient of mechanical motion into electrical signal. That is why the electronics noise plays a noticeably smaller role in the total signal-to-noise ratio than in the traditional electromechanical seismic motion sensors. In addition, this technology results in low power consumption, typically several times smaller than in any other active seismometers.

The Current State of eentec's Technology

Over the years eentec has taken the basic technology described above and slowly but surely refined and continually improved it. A number of significant advancements were introduced such as;

- introduction of a force balancing feature to improve the linearity of the older open loop designs
- improved construction material used in the sensor elements which significantly increased the ruggedness and long term field operation.
- improved membrane designs and electrolyte solutions leading to lower sensor self noise, currently at 140dB.
- coupled with the above, electronic improvements which enable the sensors to be manufactured at periods of 120 seconds.
- external mechanical improvements in the leveling legs, level bubble, and handle to facilitate easy of transport and installation in filed conditions.

Some Benefits of eentec Technology Over Other Technologies

High performance seismometer technology is still based on its roots of the mass and magnet technology used for over 80 years. Although the introduction of active seismometers that included electronics to increase their performance characteristics, their basic technology is still the mass and magnet. There are other technologies used for motion sensors such as piezo electric, monolithic miniature micromachined sensors (MEMS), formed from a silicon substrate, and opto-electric. However these other technologies are not currently used in high performance seismometer applications. The benefits that eentec has over other technologies are;

- sensitivity and dynamic range in the range of the mass and magnet technology but much better than the other technologies
- no mass centering required resulting in a large operational installation tilt for the sensor. This leads to lower cost and less complicated borehole and OBS sensor applications.
- no mass locks required for transport. With the current improvements detailed above the sensors are more rugged, easily and safely transported and deployed.
- inherently low power
- operational in high magnetic fields. Not influenced by magnetic environments.
- very little operational sensitivity to temperature changes over the operational temperature range on the sensor

RESEARCH ACCOMPLISHED

This research funding allows eentec the opportunity to more rapidly advance its technology to the next level. Taking advantage of the current state of the technology and the years of field experience and data obtained, we have a solid footing to make the advancements necessary to accomplish this projects goal.

Evaluation of Pre-Phase I Preliminary Test Results

We will initiate Phase I research with the analysis of data that will have been collected in tests of our present production units and conceptual prototype electrochemical instruments to determine the best directions to be taken to achieve the Phase I development objectives of the new technology.

The historical data will be run through the following revised models because the operation of a molecular electronic transducer cell is based on the convective diffusion of charge carriers and may be described by the following, generally non-linear, system of partial differential equations:

$$\frac{\partial \mathbf{v}}{\partial t} = (\mathbf{v}\nabla)\mathbf{v} = -\frac{\nabla p(t)}{\rho} + \nu \cdot \Delta\mathbf{v} \qquad (4)$$

$$\operatorname{div} \mathbf{v}(t) = 0 \qquad (5)$$

$$\frac{\partial c}{\partial t} + \mathbf{v}(t) \cdot \nabla c = D \cdot \Delta c \qquad (6)$$

where: (4) Navier-Stokes equation; (5) liquid incompressibility condition; (6) convective diffusion equation; where v = velocity of the electrolytic solution; p = pressure distribution; ρ = electrolyte density; ν = electrolyte viscosity; c = concentration of charge carriers; D = diffusion coefficient; e = elementary charge; This system of equations can only be solved with the proper boundary conditions. The solution cannot be found analytically and will require various computer simulations depending on the packaging of the system.

Also our current math models will be analyzed differently. Earlier we found solutions only for standalone equations of diffusion and hydrodynamics and never considered the relationship between them. Since eentec has acquired access to more powerful computers in the last several years, this will allow us to calculate the total math model including all equations involved.

Development of the Improved Mathematical Model.

Since the behavior of a sensor cell is described by non-linear differential equations, the accuracy of the calculated values of their coefficients has a decisive effect on the properties of its physical implementation. For example, a computer-generated dependence, based on our initial mathematical model, of the electrochemical cell sensitivity vs. the electrode geometry of the cell shows that relatively small deviations of the electrode mesh size may cause significant changes in the sensitivity. Also cell geometry of the electrochemical transducer defines its hydraulic impedance, the major parameter that affects the self-noise of the sensor. Basic increasing the size of the electrode assembly to ½ inch would give us 2 times lower noise ~1.5 $ng/\sqrt{Hz}$ while maintaining the dynamic range at the same 120 dB range. Analysis of the test data will result in the refinement of the mathematical model, which, in turn, will prompt the desirable modifications in the cell geometry and other parameters.

Selection of Electrolytic Liquid for the Transducer Cell

The selected configurations will require the use of electrolytic working liquid with a specific set of properties: density, viscosity, boiling and freezing temperatures, conductivity and permittivity. The advance knowledge of these parameters narrows the search field and saves time by eliminating excessive laboratory testing.

It should be noted that sensor cell self-noise is determined by the damping factor (R_h), which depends on the viscosity of the electrolyte, and the density (ρ) of working liquid:

$$\left\langle a^2 \right\rangle_{\omega} = \frac{2R_h kT}{(\rho \cdot L)^2} \qquad (7)$$

where R_h= transducer's hydraulic impedance; ρ = electrolyte density; L = electrolyte dimension along the sensitivity axis.

Development and Optimization of the Membrane Design

Fitting the sensor in 1 cubic inch requires reducing membrane diameter from the current 37mm to no more than 25mm. While changing sensor mechanical design will be a routine engineering task simulated on the computer, shrinking the membranes presents a much more difficult problem. Indeed, several important requirements must be met.

- Membranes should be sufficiently soft in order to provide for the sensor's adequate response at the lower frequency cutoff and at the same time sufficiently firm to support the combined column of liquids regardless of the sensor spatial orientation.

- Membranes must be designed to ***minimize their response to a pressure gradient across their diameter,*** such as would result from an external acceleration action along a perpendicular axis.

To meet the desired requirements, the specific design of the membrane will require a significant number of computer simulations. The low cut-off frequency of the sensor depends on the volumetric rigidity, ***μ***, of the membrane:

$$\omega_l \propto \frac{Eh^2}{R_h S^3 \left(1-\mu^2\right)} \tag{5}$$

Where E = Young's modulus; h = thickness of the membrane and S = membrane effective area.

It should be noted that the geometry, elastomer, and mold that will work with both of these items respectively would be included in the simulations required to complete this task.

Electronic Circuit Design

The transducer cell requires properly designed infralow-current electronic circuitry. In addition to its ability to condition and measure sub-nanoampere currents, the circuitry designed will have to meet the other specifications of the described devices: noise level, operating temperature range, etc. The circuits should also consume very little power so that the total power consumption would be less than 30 mW. The experimental circuit will have to be versatile enough to allow shaping of the required frequency response.

Assembly and testing of prototype sensors

After completion of all the modeling and simulations noted above, we plan to build at least 6 prototype sensors. These will initially be tested at our facility and then tested further at an outside facility by one of our consultants in the project. These results will lead us to further modify and improve the computer models and simulations created during the first phase.

CONCLUSIONS AND RECOMMENDATIONS

The goal of the Phase I effort is to prove that the proposed technology can provide a sound foundation for producing and further enhancing the specifications and practical implementation of miniaturized, inexpensive, high performance short-period seismic sensors. In order to achieve this goal, the following technical objectives will be met (the corresponding Phase II target numbers are shown in parentheses):

1. Fabricate and test in the laboratory conceptual prototype of miniaturized electrochemical sensor with the following parameters;
2. Miniature size – about 1 cubic inch (1 cubic inch or less)
3. Dynamic range of 114 - 120 dB (≥132);
4. Passband of 0.2(0.07) to 40(50)Hz
5. Self-noise in the required passband: below 1 (0.5) ng/sqrt(Hz)
6. The sensor will be capable of operation at any selected orientation of its axis of sensitivity
7. Demonstrate that the cost of such sensor will be significantly less than that of traditional mechanical instruments;
8. Develop and test a miniature prototype rotational accelerometer with translational sensitivity <0.5% and a frequency band of 0.2 (0.07) to 40 (50) Hz.
9. Identify work to be performed in Phase II of this project.

There are several important improvements of the proposed sensors, which should be investigated during the Phase II project. They will result not only in the implementation of a more advanced sensor exceeding the proposed Phase I objectives but also in a more universal instrument such as, but not necessarily limited to the above mention strong/weak motion combination seismic sensor.