United States
Environmental Protection
Agency

Health Effects Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA/600/S1-85/021 Jan. 1986

EPA

Project Summary

A System for Measurement of Small Vibrations at Material Interfaces Induced by Electrostrictive Forces

Joseph S. Ali and William T. Joines

The mechanisms of interaction of ELF and ELF-modulated RF fields with biological systems is presently an active area of research. Some models propose that field-induced forces may influence certain observed biological effects such as RF hearing and calcium ion efflux. To investigate the validity of the field-induced force model for the calcium-ion efflux effect, a system is needed which is capable of exposing samples to ELF fields or to ELF-modulated RF fields. At the same time the induced vibration caused by the forces of electrostriction must be monitored preferably by a noncontacting method.

A microwave phase-sensitive receiver was designed to sense the small vibrations. Limitations on the receiver sensitivity imposed by phase noise is discussed. Phase noise measurement systems were designed and used to characterize the key receiver components. A limiting amplifier in the IF section of the receiver eliminates the need for knowledge of the reflection coefficient of the object of interest for quantitative vibration measurements.

A special exposure cell is described which is a section of X-band waveguide which has been modified by the addition of a center conductor to form a rectangular transmission line. The center conductor with a sample placed under the waveguide broad wall is excited by a low-frequency or low-frequency amplitude modulated signal. In addition an X-band signal is fed through the waveguide, scattered by the sample and detected by the phase-sensitive receiver.

The fields and the resulting forces on certain standard shaped samples are derived. With the measurement of the Young's modulus and Poisson's ratio of the samples, the resulting vibration amplitude of the field-induced vibration is estimated. Actual vibration measurements verified with a piezoelectric crystal indicate a vibration sensitivity of about 1 nanometer peak-to-peak. Vibrations in this range were predicted to occur in certain calcium-ion efflux studies. This system therefore promises to help unravel some of the uncertainties surrounding the interaction of RF fields with biological systems.

This Project Summary was developed by EPA's Health Effects Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Conclusions

The characteristics of an RF field scattered from a linearly vibrating object were derived. The scattered signal was shown to be phase modulated with, for sinusoidal vibration, the phase modulation index proportional to the amplitude of the vibration. The spectral characteristics of this signal were derived and it was shown that for a small modulation index, only one pair of sidebands is significant. When the ratio of one sideband to the carrier was formed, this suggested a method of extracting the vibration amplitude information without a knowledge of the reflection coefficient of the vibrating object. The sideband to carrier ratio was shown to be dependent only on the vibration amplitude and the wavelength of the incident field.

Several receivers were considered for the recovery of the vibration information from the received signal. The Doppler transceiver offered the advantages of simplicity and good sensitivity; however, the recovery of the vibration amplitude would require a knowledge of the reflection coefficient of the target. In addition, the receiver would have to be a certain distance from the target to establish phase quadrature between the transmitter reference signal and the received signal. The homodyne receiver incorporated a manual phase shifter which eliminates the special target-receiver spacing requirement; however, knowledge of the reflection coefficient is still required for quantitative vibration measurements.

The sideband heterodyne receiver with an IF limiting amplifier was selected for the final receiver design because this design permitted quantitative vibration measurements. It was initially thought that this receiver would also provide enhanced sensitivity over the Doppler and homodyne receivers because of the expected improvement in noise figure. However the sensitivity was not improved. Noise figure was not found to be a good measure of receiver sensitivity when the carrier to sideband ratio is large and when the sideband is close to the carrier. When the sensitivity is limited by flicker noise, as it is in this receiver, the actual sensitivity can be considerably less than predicted by the noise figure.

An analysis of the factors limiting sensitivity was performed. Phase noise theory was reviewed as well as modern techniques for its measurement. The quadrature phase detection method for high sensitivity phase noise measurements was described. A system for making quantitative phase noise measurements in terms of the single-sideband phase noise (L(f)) was assembled. The ultimate sensitivity of the quadrature phase detection method is limited by the flicker noise of the phase detector diodes. The sensitivity for the measuring systems used were presented graphically. Key receiver components such as an RF amplifier, the limiting amplifier, the low noise IF amplifier, the RF mixer and the phase detector were all characterized in terms of their residual single-sideband phase noise. The RF amplifier produced an excessive level of residual phase noise. The RF amplifier was therefore not used in the final receiver design because receiver sensitivity would have been degraded severely. The low noise IF amplifier had negligible residual phase noise compared to the limiting amplifier.

The phase detector RF drive level was found to be important for minimizing residual phase noise. For a fixed LO level the absolute level of the noise at the output at baseband frequencies increased with increasing RF drive level. However the phase detector constant increases with an increasing RF drive level. When the residual phase noise was measured, which is computed from the ratio of the absolute noise level to the phase detector constant, the lowest noise performance was obtained with an RF drive level between 0.6 and 5.0 mW for a 5.5 mW LO drive level.

All oscillators exhibit phase noise and furthermore the oscillators used in this receiver have greater SSB phase noise than most of the other active components. However, because of the correlation effect and the short transit time experienced by a signal travelling from the transmitter to the target and other reflecting objects in the waveguide and back to receiver, the apparent oscillator phase noise is reduced substantially below the level of the phase noise of the other active components in the receiver. Therefore, the oscillators do not limit the sensitivity of the receiver in this application. Examination of the single sideband phase noise data revealed that the microwave mixer (M2) and the limiting amplifier were the components that limited the sensitivity of the receiver.

A unique exposure cell was designed to simultaneously expose samples to an ELF or an ELF-modulated RF field while providing for the non-contact vibration monitoring of the sample with an X-band signal. The cell has a return loss of greater than 20 dB up to 1 GHz at the exposure field input port. Properties of the exposure cell however, do place limitations on the size of the sample that can be accommodated. If the sample is larger than about one-third of the center plate to wall spacing, charge redistribution increases the effective field to which the sample is exposed. The effective field then becomes a strong function of the sample size and the gap between the object and the center plate and this tends to add large uncertainties to the calculations. If the sample is too small, on the other hand, the return loss of the sample begins to approach the return loss of the empty exposure cell. When this happens, quantitative measurements become impossible because of an unknown amount of carrier cancellation or augmentation of the signal scattered from the vibrating sample.

Starting with the Lorentz force law, the force per unit area at a dielectric interface due to electrostrictive forces was derived for the cases of the electric fields normal and tangent to the dielectric interfaces. It was shown that for both the electric fields normal or tangent to the dielectric interface, the force at the interface is always directed from the region with the higher dielectric constant to the region with the lower dielectric constant and does not depend on the sign of the electric field. The electric field normal to the surface of a high dielectric constant or conducting prolate spheroid was calculated. From this expression the vertical force on a half-prolate spheroid with its base on a ground plane was derived. Agar gel was used as a mechanical model for tissue. The Young's modulus of agar gel was measured as a function of concentration and the modulus was found to increase linearly with the concentration of agar in deionized water. Poisson's ratio was also experimentally determined for a 0.6% c of agar gel. With these values, estimates of the expected vibration amplitude and the expected receiver signals were computed for three sizes of half-prolate spheroid samples exposed to an ELF electric field.

Measured values of vibration amplitude for the half-prolate spheroid samples in a sub-resonant ELF field agreed most closely with the calculated values for the 3.5 mm base sample size. Samples of other sizes differed from the calculated values for the reasons stated above. The measured vibration frequency was always at twice the frequency of the exposure field as predicted by the theory.

The major resonance frequency of both the half-prolate spheroid and cubical samples were measured. Simple models including the simple harmonic oscillator model and others derived for the transverse or longitudinal vibration of continuous systems of standard shapes were applied. The resonance frequencies observed for the cubical-shaped samples agreed most closely to the calculated resonance frequencies for the transverse vibration of a prismatic bar. For the half-prolate spheroid samples it was impossible to conclude with certainty from the simple models employed whether the vibration at the major resonance frequency was longitudinal or transverse.

A receiver with an exposure cell has been designed and characterized that is capable of vibration measurement in the nanometer range. Vibrations in this range were predicted to occur in certain calcium ion efflux studies which demonstrated a biological effect. This system therefore promises to help unravel some of the uncertainty surrounding the interaction of RF fields with biological systems.

The full report covers a period from October 1, 1982 to April 15, 1985 and work was completed as of April 15, 1985.

The EPA authors, **Joseph S. Ali** (also the EPA Project Officer, see below) and **William T. Joines**, are with Health Effects Research Laboratory, Research Triangle Park, NC 27711.

The complete report, entitled "A System for Measurement of Small Vibrations at Material Interfaces Induced by Electrostrictive Forces," (Order No. PB 86-116 530/AS; Cost: $16.95, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:
Health Effects Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use $300

EPA/600/S1-85/021