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**ELECTROACTIVE ELASTOMERIC
STRUCTURES (EAES) FOR
HYDROACOUSTIC APPLICATIONS**

R&D STATUS REPORT

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R&D Status Report

Smart Materials and Structures

Electroactive Elastomeric Structure (EAES) For Hydroacoustic Applications

ARPA Order No.:	BAA-94-17	Program Code No.	4V360
Contractor:	General Atomics	Contract Amount:	\$739,177.00
Contract No.:	N00014-94-C-0264		
Effective Date of Contract:	29 September 1994		
Expiration Date of Contract:	30 September 1996		
Principal Investigator:	Dr. Terry D. Gulden		
Telephone No.:	(619)455-2893		
Short Title of Work:	Electroactive Elastomeric Structure (EAES)		
Reporting Period:	1 October 1995 through 31 December 1995		

Description of Progress

The emphasis in this reporting period has been on test sample fabrication and on testing in the NUWC Water Tunnel and Acoustic tube facilities.

Water Tunnel Tests - During this quarter, high voltage experiments were performed in the New London Quiet Water Tunnel Facility. The test articles for each facility were of the two electrode type. Each of the test articles had been pre-tested at high voltage at GA prior to shipment. The tests consisted of short duration voltage applications to verify voltage stand-off and configuration integrity. The maximum voltage applied was approximately one half the anticipated stand-off capability. Each of the test articles passed the test at GA. When the test articles arrived at the New London facilities, they were again tested for voltage stand-off by New London personnel with a conventional power supply with a slow run-up to voltage. During these tests which lasted for several minutes each, the test articles demonstrated an unusually high and increasing current draw. The preliminary tests were terminated to avoid damaging the test article before data runs could be performed.

The EAES test article placed in the water tunnel was 7 inches long (streamwise), 2 inches wide (spanwise) and 0.26 inches thick. The first tests were conducted with a free stream velocity of 30 ft/sec, with the temperature held constant at 73 degrees F. A voltage of 500 volts was applied, which is equivalent to an electric field across the test article of 250 V/mm which is well

below the activation threshold of approximately 800 V/mm. The current draw was 0.062 milliamps. There was no measurable change in the measured autospectra from the pressure sensors with respect to the case with zero voltage applied as would be expected (The zero voltage autospectra were presented and discussed in the previous quarterly report). The voltage was then increased to 1000 volts yielding an electric field of 500 V/mm and a current draw of 0.37 milliamps. Again there was no measurable change in the autospectra with respect to the zero voltage case. The voltage was then increased to 1500 volts which produced a field of 750 V/mm which is very near the activation threshold. This voltage level was maintained for approximately 30 seconds until the current exceeded 15 milliamps and the power supply tripped. An autospectra was obtained and again showed no measurable change. With an applied voltage of 2000 volts, the power supply tripped after only 5 to 10 seconds and autospectra data could not be obtained. This series of tests was repeated and the same results were obtained.

The EAES sample was removed, and subsequent analysis at General Atomics showed that the gap between the conducting scrim electrodes had diminished to approximately 1.0 mm at several locations due to electrode warping. It was suspected that this close and irregular electrode spacing was leading to a thermal runaway condition when the voltage was applied. To evaluate this possibility a one dimensional thermal analysis was performed as described below.

The problem was formulated as a one dimensional thermal transport problem with the following equation:

$$K \frac{d^2 T}{dz^2} + Q = \rho C_p \frac{dT}{dt}$$

with the symbols defined as follows:

- K = thermal conductivity of the EAES material
- T = EAES temperature
- z = vertical coordinate
- Q = heat input
- ρ = density of the EAES
- C_p = specific heat of EAES

After factoring in the experimental results for the dependence of current density on temperature, the equation can be rewritten in the following form which allows for an approximate numerical evaluation:

$$\ln\left(\frac{j_m}{q_0 E^3}\right) = \frac{q_1}{T_0 + \frac{j_m E_m \Delta t_0}{\rho C_p} * \frac{1}{1 + \frac{K \Delta t_0}{\rho C_p \Delta z^2}}}$$

with the newly introduced symbols defined as:

- j_m = fraction of total current into the closely spaced grid regions
- q_0 and q_1 = fitting parameters for current density as a function of temperature
- E = electric field
- T_0 = initial temperature=(21°C)
- Δt_0 = time of current application
- Δz = EAES gap dimension at closest approach

Then specifying the observed experimental conditions and the properties of the EAES material, the equation can be solved for the thickness of the reduced EAES gap which would produce the observed current thermal runaway conditions for the two voltages which exhibited this behavior. The analytical results were 1.16 mm and 1.06 mm for the 1500 and 2000 volt data respectively. These gap values are very close to that which was measured at GA after the test article was returned, confirming the thermal runaway explanation for the large current draw.

Two approaches are being taken to solve the thermal runaway problem: (1) the use of insulating spacers to ensure a uniform standoff between the electrodes, and (2) formulation of lower electrical conductivity ER fluids. Insulating spacers being evaluated include reticulated polyester foams and large cell composite honeycomb core. Four new electrode sets have been fabricated with physical spacers separating the electrodes. In two of the electrode sets, a 20 ppi polyester foam has been inserted between the metal screen grids. In one of the sets, the foam was further modified by removing approximately one half of the foam with a pattern of circular holes evenly spaced over the entire surface. Metal screen grids were then glued to the foam surfaces. A third electrode set was fabricated with a thin honeycomb structure supporting the metal screen grids. In this electrode set, less than 5% of the surface area is occupied by the supporting structure. The fourth electrode set was assembled by suspending the metal screen grids on polyester threads which crossed the plexiglass picture frame in the spanwise direction. After the EASE is poured and set-up, the threads will be cut to allow the grids to be free floating. The four grid structures will be assembled into test articles as soon as the new acrylic base plates are returned from New London with the sensors installed.

The second approach to minimizing the thermal runaway is to reduce the electrical conductivity of the ER fluid. The maximum voltage applied to the previous test article was 2000 V which resulted in an electric field of approximately 2.0 kV/mm at the closest grid approach. Even with properly spaced electrodes a 2.0 kV/mm field is not sufficient to produce the magnitude of ER effect desired. This issue is being addressed by modifying the composition of the ER fluid. A new fluid has been obtained for the next set of experiments. The new fluid exhibits approximately half the electro-activity of the previous fluid, but draws approximately 1/8 of the current for a given voltage. This fluid should allow relatively high voltages to be applied without thermal runaway. The degree of electro-activity should be sufficient to produce observable changes in the autospectra in the water tunnel tests.

Acoustic Tube Tests - An attempt was made to measure the acoustic impedance (including damping properties) of the EAES air tube sample in the Air Tube Facility at NUWC. The EAES sample was mounted on the end of a 20 ft. PVC tube (7.5 in. inner diameter). A speaker mounted on the other end provided a broadband (5-500 Hz) excitation. Two-point microphone measurements were made at 5 points along the length of the tube to characterize the spatial and temporal resonances of the air column with the EAES sample in place. Due to the high mismatch of acoustic impedance between the air and the EAES sample, the microphone measurements looked identical to those obtained when a comparatively rigid surface (aluminum) was placed on the end of the tube. A significantly softer (lower impedance) EAES material (e.g., an ER material with entrapped air) will have to be developed in order to significantly alter the reflection of the acoustic waves and thereby act as a tunable reflection/absorption surface. The near-term focus of the program will be on the water tunnel tests.

Schedule Status

The program schedule is shown in Figure 1.

Technology Transition Plan

Transition Plan for Electroactive Elastomeric Structure (EAES)

The EAES concept is currently being developed and evaluated for adaptive control of acoustic and flow noise in undersea applications in a joint program between General Atomics and the Naval Undersea Warfare Center (NUWC) Detachment New London. The results of the on-going program will verify the feasibility of the EAES concept for active filtering and control of acoustic and turbulent flow noise using the quiet water tunnel and acoustic tube facilities at New London. Assuming success in this program, the next steps will be to address the engineering and design issues involved in the use of a soft material like EAES in real applications and to perform engineering tests and demonstrations of the concept under realistic conditions. We envision the initial transition of EAES technology being to active control of Wide Aperture Arrays (WAA) on submarines, or to Forward Facing Arrays (FFA) in torpedoes. However, additional transitions to non-undersea applications and even to commercial applications are being considered.

Once the technical feasibility of EAES has been demonstrated in the current program, a number of issues remain before it can be transitioned to a fielded system. These include:

1. Durability; eg, when used externally as active control coatings over hull arrays
2. Effect of hydrostatic pressure and high speed operation on EAES performance
3. Effect of the operating voltage on the EMI signature
4. Repairability, paintability.

Some of these issues require further work at the 6.1 and 6.2 level, while others can be resolved only through engineering demonstration tests.

Transition to Active Control for Submarine and Torpedo Sonar Arrays

Conventional submarine sonar hull array designs attempt to reduce turbulence-induced flow noise by shielding the array elements (hydrophones) from the turbulent flow through the use of an elastomeric outer decoupler layer. This approach permits the discrimination of low wavenumber acoustic information from high wavenumber wall pressure fluctuations for all frequencies, $f > U_c/h$, where U_c is the convection velocity of the wall pressure field and h is the thickness of the elastomeric layer. Consequently, if effective flow noise reduction at low frequencies is to be achieved, thick elastomeric layers or small convection velocities are required. Such requirements are undesirable from a mission and ship design perspective. Thick elastomeric layers increase array weight, hydrodynamic profile, and variable ballast; and attenuate acoustic signals. Small convective flow velocities imply slow ship speeds and reduced search rates. Hence EAES technology has the potential to reduce the outer decoupler thickness and reduce array weight, while providing effective flow noise reduction to low frequencies. The EAES concept also provides the capability to tune the response of the structure to compensate for changes in hull speed or in ambient conditions such as temperature.

Sonar arrays for torpedoes also use elastomeric (urethane) windows. Undesirable variability in sonar transparency of the arrays is observed from one lot to another. This apparently results from variability in the properties of the elastomeric material. Use of the EAES concept would provide the capability to tune the response of the window material, thus providing a greater tolerance to factory defects. The transmission loss resulting from the observed variability is in the range of 2 to 3 dB which results in as much as a factor of two in detection range.

Another possible application to torpedoes is in the terminal homing sonars (planar forward looking or side scan) that operate at very high frequencies (100 to 300 kHz). The acoustic windows that protect these arrays are very sensitive to material variability through the thickness of the window. The EAES concept could be used to tune materials properties and maintain them constant to eliminate diffraction effects.

For all of these applications the use of EAES in conjunction with the conventional urethane elastomeric materials (as the inner layer of a laminated structure) offers the benefits of adaptive control along with the proven serviceability and durability of the urethane material. In the remaining portion of the on-going program, design concepts for these applications will be further formulated, and if possible some limited testing of a sonar array window consisting of an integrated EAES/conventional urethane structure will be performed.

The next step in the transition of the EAES concept to deployment in a sonar array window material is envisioned to be in a "pop-up" test such as those performed at Lake Pend Oreille in Idaho. A plan for a "pop-up" test of the EAES concept will be developed over the next several months.

Transition to Applications Involving Control of Airborne Acoustic Energy

There are many potential applications for active control of airborne acoustic energy. The effectiveness of the EAES concept for this class of applications will depend on the ability to couple acoustic energy into the material. Ways of accomplishing this are being investigated in the current program. A plan for transition in this area will be developed based on the results of the acoustic tunnel testing at NUWC.

Other Transition Opportunities

Other potential transition opportunities that are envisioned for the EAES concept include dampers for machine tool vibrations, and control of structure-born vibrations, for example from airplane engines.

We are currently working with Professor Liang at San Diego State University on an IRAD effort to apply EAES to in conjunction with an active Terfinol damper for control of vibrations in machine tools. Preliminary results are encouraging. As more data are developed a transition plan will be considered for this application.

Control of structure-born vibration is a very important class of application in which the EAES concept could play an important role by providing active control to compensate for changes in conditions such as engine speed or ambient temperature. Potential opportunities for transition into this class of application will be sought.

Problems Encountered and/or Anticipated

As described previously in this report, higher than anticipated current flow necessitated premature termination of the recent water tunnel tests. Analysis showed that the problem was caused by uneven electrode spacing which occurred during processing. New samples are currently being fabricated utilizing positive techniques for insuring the maintenance of uniform electrode spacing. This along with the use of a new, higher resistance ER fluid is expected to solve the thermal runaway problem.

Action Required By The Government

No action required.

Fiscal Status

1. Current contract value	\$ 739,177
2. Expenditures and commitments to date (31 December 1995)	\$ 459,241
3. Funds required to complete work	\$ 279,936

Figure 1: Electroactive Elastomeric Structures (EAES) Program-Schedule and Milestones

