DEVELOPMENT AND TESTING OF AN ELECTRONICALLY CONTROLLED SHOCK AND VIBRATION DAMPER HAVING AN ELECTRORHEOLOGICAL FLUID MEDIUM

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Electrorheological (ER) materials are suspensions of micron sized particles in insulating, dielectric fluids. The mechanical properties of these materials can be controlled by regulating an electric field through them. Variable properties include stiffness, damping, and yielding behavior. At high electric fields, material property changes are rapid and immediately reversible.

ER technology has numerous applications in the structural control field, using ER devices to control the response of systems subjected to diverse shock and vibration excitations.

Results are presented on continuing research into ER damper design and fluid formulation, plus test output on a 1,000 lbs. force ER damping device.

INTRODUCTION

Active isolation elements have long been considered a cost effective solution to the problem of control-structure interaction, where attenuation of diverse inputs is a primary design requirement. These active elements can either produce driving forces to directly control a structure’s response, or can be used to alter or modify the output of controllable passive elements such as springs, dampers, or tunable masses. In the former case, the type of control element is often referred to as “fully active,” in the latter case, the active control of a passive element is referred to as “semi-active.”

Potential applications for active structural control exist today within several market sectors. For example, Naval equipment must contend with the relatively low level vibration inputs of MIL-STD-810, the high level vibration inputs of MIL-STD-167, and the high impact shock inputs of MIL-S-901D (Navy). In a similar fashion, within the structural engineering community, optimal control of building, bridge, tower, and antenna structures often requires attenuation of diverse vibration, wind and even seismic inputs.

Many critical Naval systems and equipment items are passively isolated, using combinations of spring and damping elements. For any specific system, the worst case input from the various shock and vibration requirements will usually drive the design of the passive isolation components. A very abbreviated summary of Naval shock and vibration requirements is as follows:

MIL-STD-810, Vibration

This is a general standard, with various categories of vibration environments, depending on end use of the equipment. For shipboard service, the basic test standard specifies a random vibration input, applied in each of 3 orthogonal equipment axes. The test has a duration of 2 hours per axis, over the range of 1-50 Hz, with a constant threshold power spectral density of $.001g^2/Hz$.

MIL-STD-167, Shipboard Vibration Tests

This standard calls for separate exploratory, variable frequency, and endurance vibration tests. All tests are performed three times, in each rectilinear axis the test item would encounter as installed on the ship . Initial testing consists of exploratory vibration, searching for resonances in the tested item over a specified range of 4-50 Hz. These resonances are recorded, and used later during endurance testing. The variable frequency test sweeps the 4-50 Hz range, dwelling at every 1 Hz interval for 5 minutes, while holding amplitude at specified levels. Input amplitude levels range from ±0.03 inches in the 4-15 Hz range to ±0.003 inches in the 41-50 Hz range. The endurance test consists of a 2 hour dwell at the worst case resonance found in the range of 4-33 Hz during the exploratory tests. Input amplitude can range from ±0.10 inches at 4-10 Hz, to ±0.01 inches at 26-33 Hz.

MIL-S-901D, High Impact Shock Tests

Testing consists of discrete application of shock pulse inputs, having varying levels of intensity, intended to simulate near-miss underwater weapons' effects. Depending on the size of the test item, the test input can be generated by the underwater detonation of explosives (UNDEX testing), or by the impact of a rigid mass from one of two different shock testing machines (the Light Weight Shock Machine or the Medium Weight Shock Machine). Design and operating parameters for test fixtures and test machines are rigidly defined. Due to interaction between the test machine, test fixture, and the tested item, exact input transients to equipment are highly variable. Input shock spectra for items in the 2,000-4,000 lbs. weight range typically encompass frequencies of 20 Hz to 3,000 Hz, with peak spectral accelerations in the 200 g to 400 g range. Larger equipment will often encounter somewhat lower input levels, smaller equipment may see higher inputs, due to interaction with the test machine and/or test fixture.

In the majority of cases, the high level of shock generated by MIL-S-901D will require relatively large amounts of damping and spring forces if the system is to be packaged with minimum rattlespace in the equipment mountings. However, these relatively stiff isolator parameters can result in excessive high frequency forces being transmitted to the isolated equipment during testing to MIL-STD-167 and MIL-STD-810. Conversely, the use of low frequency vibration mountings to provide high attenuation on vibration tests will result in dangerously large excursions during shock tests.

Previous experiments studying active control of large structures have utilized powered hydraulic servo-actuator cylinders or controlled passive dampers in an attempt to solve the problems associated with diverse inputs. Powered actuators have proven useful for vibration control, where power demands are relatively low. Conversely, it has proven difficult to attenuate high level shock with actuators, since extreme control power levels are required. By example, the San Bernardino County Medical Center in Southern California, is a 900,000 ft^2 facility, passively isolated on low frequency bearings, using 186 passive fluid dampers to absorb the energy of seismic inputs. Each damper is rated for 320,000 lbs. output force at 60 in/sec. ground shaking velocity, for a maximum credible earthquake lasting some 60 seconds. The power dissipation of the 186 dampers during this seismic event is 403 megawatts. This power level is typical of a modest size, land based nuclear power station at full capacity.

Controlled passive elements have been demonstrated to be more successful for attenuating high level shock, since power demands are low. Extensive research on controlled passive elements for seismic shock attenuation has taken place at the State University of New York at Buffalo, as reported by Symans and Constantinou (1995), Constantinou, Symans, Taylor, and Garnjost (1994) and Shinozuka, Constantinou, and Ghanem (1992). These experiments used electro-hydraulic control valves to vary the orifice area of a fluid damper. This previous research has demonstrated that the size and cost of the electro-hydraulic control valves becomes quite high when a controlled response to the high frequencies of a shock spectra is needed. This is due to the inertia of moving valve parts impeding the valve's ability to respond to the input of a high level shock. Indeed, it has become apparent that even at the small scale level, a realistic end to end response time from sensor detection to a resultant change in control force response is 10-20 milliseconds with conventional control valves. Even this relatively slow response assumes a simple set of control equations, a computer larger than current generation PC's, and direct acting valves using no pilot control circuitry. Approximately 80% of the response time is utilized by the control valve and its moving mechanical parts.

Figure 1 shows a typical fluid damper using an external control valve, as reported by Symans and Constantinou (1995). Basic parts arrangements and operation of this damper is similar to most fluid damper designs. The device is operated by the deflection of the attachment clevises, in either compression or extension directions. This input causes the piston head to move relative to the damping fluid. Since the fluid is relatively incompressible, it is swept through orifices contained both in the piston head, and in an external control loop, which in this case contains a flow control valve. As fluid is swept through these restrictive orifices, it generates a pressure, which is both viscous and inertial in form. The pressure generated results in a damping force being produced by the piston head, in a direction opposing motion of the damper. Viscous damping pressures are generated by the drag of the fluid on the surfaces of the orifices. Inertial damping pressures are generated by the acceleration of the fluid molecules to high speed as the fluid enters the restrictive orifice. In general, viscous damping pressures dominate the damper's response at very low fluid flow velocities (typically less than 100 ft/sec). Inertial damping pressures dominate the response at higher fluid flow velocities. Figure 1 also depicts an accumulator valve, with a very small bleed orifice, which controls flow into an internal accumulator. The accumulator accommodates the displaced volume of the piston rod as it enters the damper cylinder in compression, and exits the cylinder in extension. The accumulator itself consists of closed cell polyurethane foam, which is compressed by the volume of the piston rod displacement in compression, and which expands to replace the piston rod volume displacement when the damper extends.

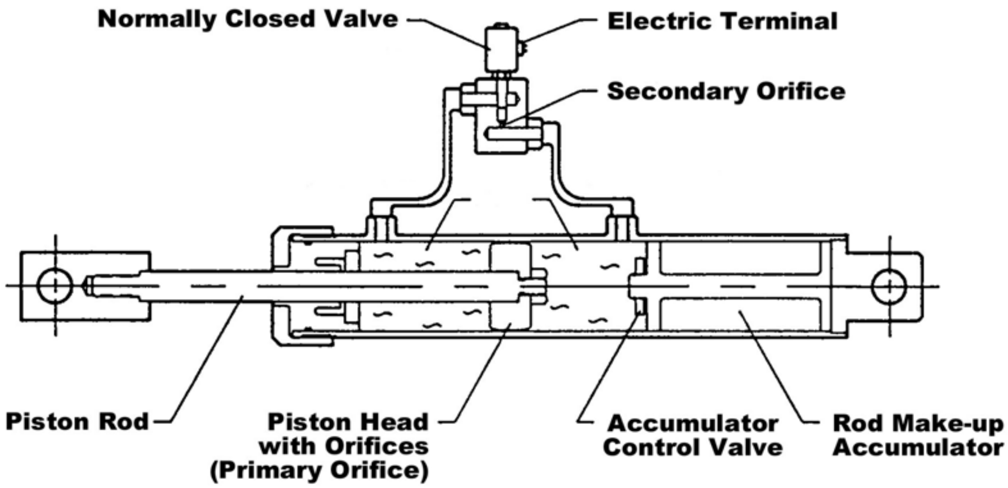

FIGURE 1
FLUID DAMPER WITH EXTERNAL CONTROL VALVE

ELECTRORHEOLOGICAL FLUIDS

Electrorheological (ER) fluids are suspensions of micron sized particles in non-conductive oils or similar fluids. ER materials exhibit a dramatic change in properties when stimulated by an electrical field. These fluids have been proposed by several researchers as an effective means of providing fast response from a structural control system. Gavin and Hanson (1994), and Makris et al. (1995) provide extensive historical and background data on ER devices. From the engineer's viewpoint, the most appealing changeable characteristic of ER materials is apparent fluid viscosity. With modern ER fluids, the application of an electrical stimulus changes the fluid viscosity from a relatively low, oil-like character to that of a viscous gel, exhibiting rubber-like viscoelastic properties. One obvious use of this material in structural control is to use the viscosity change to alter the output of a fluid damper. The damper includes orifices which bypass fluid with relatively low resistance when the ER fluid is not stimulated. When an electrical input is applied to the fluid, it reverts to its gel-like state within a very short time period, often approximating 1 millisecond. In order for the activated material to flow through orifices, it must be sheared, with resultant apparent shear stresses in the range of 40 lb/in^2 to 1000 lb/in^2, depending on fluid type. Thus, the activated fluid allows the damper to provide a high damping force under these conditions. Various styles of ER dampers have been evaluated by previous researchers. Most of these utilized essentially low speed viscous flows, either by design or from concern that high flow speeds would cause decomposition of the fluid, or erosion of orifices due to the abrasive quality of the ER particles. Figure 2 is a schematic cutaway of the ER damper constructed for this research project. This design utilizes a single control duct to produce two levels of selectable damping. Conceivably, this damper design can use multiple flow loops to provide different levels of damping, by sequential loop activation. Flow through the duct is forced by positive displacement of the piston head in either compression or extension. By design, this damper is intended to use relatively high speed inertial flows, producing high operating pressures. Damper orifices are constructed from high-strength steel to accommodate the potentially abrasive ER particles. Cylinder bore of the damper is 1.31 in, and the damper provides a minimum swept damping area of 1.19 in^2.

Basic operation of the ER damper is similar to the damper with external control valve, as shown previously in Fig. 1. Instead of a mechanical control valve, the ER control consists of an inner rod centered inside a small external cylinder, providing an annular orifice, shown as “h” in Fig. 2. For these experiments, the optimum value for “h” was found to be approximately 0.04 in. for the input voltages and fluid used. To operate the valve, it is necessary to provide a control voltage between the inner rod and external cylinder.

Due to the anticipated high viscosity and density of the ER material, a floating piston, pressurized by a sealed gas reservoir, is used as a rod make-up accumulator. This eliminates the need for the closed cell foam accumulator and accumulator control valve used in the damper with external control valve of Fig. 1.

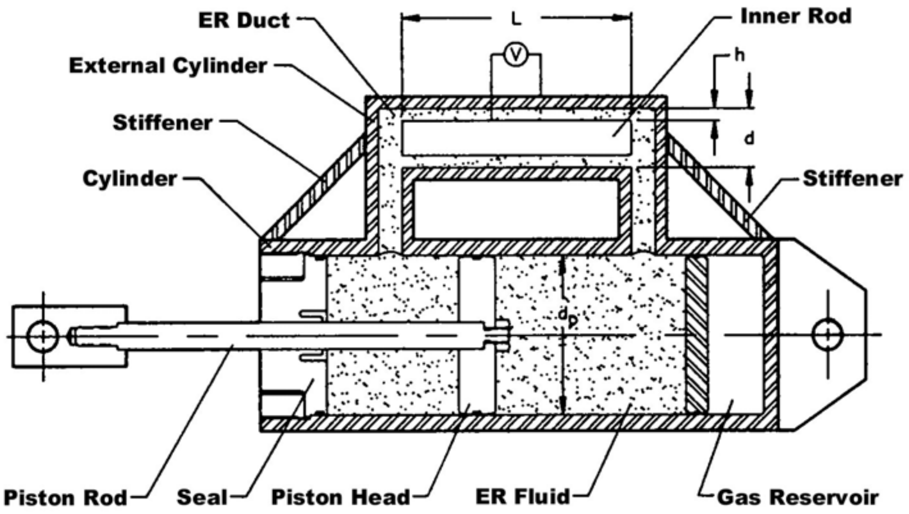

FIGURE 2
ER FLUID DAMPER WITH INERTIAL FLOW LOOP

DESIRED FLUID PROPERTIES

When an electric field is applied to an ER fluid, the fluid radically changes its properties, and begins to exhibit an apparent yield stress, similar to ductile polymers, such as Teflon®. Early experiments in ER material date to the late 1800’s, with the effect being largely a laboratory curiosity. In fact, an ER fluid suitable for elementary school science classes can be made by saturating corn starch in olive oil!

In the late 1980's a series of patents were filed on the use of zeolites and alumino-silicate particles in ER fluids. When an electric field is applied to this type of fluid, the particles are thought to become polarized, oriented in such a manner so as to exhibit plastic-like characteristics. Many papers have been presented, providing theoretical examples and experimental results on tiny sub-scale ER fluid dampers using various ER fluids. In general, these dampers use a series of precisely machined parallel plates, with alternating charges on adjacent plates. This type of device produces damping forces by applying a shear stress to the fluid, as the parallel plates move relative to one another. Unfortunately, for proper operation, the plates must be located very close to one another, and the allowable shear stress available is limited to relatively low pressure levels, otherwise, cavitation bubbles form and the operation of the damper becomes unstable. The only previous attempt known by the authors to build a large scale ER fluid damper was by Gavin and Hanson of the University of Michigan (1994). This damper was of the parallel plate type, using zeolite or alumino-silicate based fluid, and was roughly 10 inches in diameter, with a useable displacement of ±3 inches. Maximum output force obtained from this large device was approximately 1,300 lbs. In general, this device was large, intricate, very expensive to manufacture, and produced an apparent output force of only 26 lbs. for every square inch of cylinder bore cross section. In comparison, present day high performance passive fluid dampers operate with output levels in the 6,000 psi range, more than 200 times the output of the Hanson and Gavin (1994) device. Thus, the most important criteria for this research program was to develop an ER material that would function at pressures of at least 500 psi, and preferably higher. Additional criteria resulted from review of various problems noted by the previous researchers referenced. Also incorporated were requirements specific to Naval Systems use, as reported by Yagla and Kuchinski (1994). This complete list of criteria for fluid development in this research is as listed below:

1. Activated apparent shear stress in excess of 500 psi.

2. Anhydrous fluid components must be used to insure performance at temperatures below the freezing point of water.

3. Insensitivity to atmospheric moisture.

4. Environmentally safe chemistry, not comprising any polymers or solvents dangerous to man, or subject to deterioration into dangerous or unsafe byproducts.

5. The ER effect must not be compromised over time by the orificing of the fluid through restrictive orifices at high pressures.

6. The components of the ER material must not exhibit long term settling or layering when subjected to long-term storage or periods of non-use.

7. Fast response, with the ER fluid device having an end to end response time of less than 10 milliseconds (end to end response defined as time of sensor detection to time of application of control forces to the structure).

8. Relatively low voltage for the ER effect, to minimize potential hazards to personnel.

9. The ability to improve a system’s response to high level transient shock.

10. The ability to improve, or at least not degrade, military equipment response under conditions of normal vibration (to MIL-STD-810), high level vibration (to MIL-STD-167), and internally generated acoustic noise.

FLUID DEVELOPMENT

In light of the above criteria, extensive fluid testing indicated that an ER fluid consisting of a saturated mixture of finely ground zeolite particles suspended in a dimethyl silicone oil base would meet all of the desired criteria.

Zeolite is a mineral, usually found as a secondary mineral in lava deposits. It is essentially a silicate, analogous in composition to feldspar. Dimethyl silicone oil is odorless, cosmetically inert, non-flammable, and non-combustible, using present U.S. Food and Drug Administration and OSHA regulations. This type of silicone has been used in passive dampers on U.S. Navy warships since the 1950’s. Examples of Naval Systems’ use includes the Tomahawk Missile, MK29 Seasparrow Missile Launcher, the MK88, MK92, and SPS-49 Radars, and the MK26 gun mount for the .50 cal. Browning Machine Gun.

To manufacture the ER fluid, the zeolite is reduced to fine powder, then exposed to the atmosphere to stabilize it chemically against parameter drift over long term use. Note that atmospheric moisture is fully absorbed by the zeolite particles and that no free water exists in the powder after stabilization. The zeolite powder is then mixed with the dimethyl silicone fluid, which is roughly of the same viscosity as SAE 80W-90 viscosity automotive gear oil. Silicone fluids have very low film strength, such that each zeolite grain becomes thoroughly coated with the silicone.

The mixture is saturated with the zeolite, so that the result is essentially a slurry. Experiments have demonstrated that this saturated mixture or slurry provides optimal performance with minimum power and voltage required. Zeolite and silicone oils are inexpensive materials, making them ideal for large scale applications. No special process equipment is needed to manufacture this fluid, and no critical measurements of constituents is required.

After the zeolite has been mixed with the silicone oil, a small quantity of dispersant additives are mixed into the slurry. The additives have been proven effective in preventing caking of the zeolite mixture over extreme long term storage, and are similar to those used in commercial and household powder based fire extinguishers. These additives are commonly available from chemical manufacturers, and no attempt was made to analyze their exact constituents.

During the course of this research, numerous other types of ER materials were evaluated for performance. Water based (hydrous) ER fluids with zeolite or alumino-silicate particles were deemed as unacceptable due to freezing of the water at low temperatures, rending the ER material non-functional. Several proprietary anhydrous polymer based ER materials were obtained from a chemical manufacturer in Great Britain. These did not exhibit temperature problems, but encountered severe settling into multiple stratified layers during a 30 day storage test. The heaviest layer was found to exhibit hard caking, resulting in loss of ER properties plus an inability to flow through damper orifices. Fluids based on zeolite suspended in various and hydraulic fluids were found to exhibit similar caking problems. Evaluated fluids included automotive motor oil, automotive transmission and gear lubricants, mineral oil, aircraft hydraulic fluid, water soluble hydraulic fluid, and even olive oil.

The fluid development portion of this research resulted in a zeolite-silicone ER fluid that appeared to meet all criteria for this project. However, it was now required to demonstrate the fluid's ability to control the test damper.

TEST RESULTS

The extreme fast response available from an ER damper is largely due to the fact that the fluid is activated by a voltage potential only, with no current flow required through the fluid. In comparison, other controllable dampers require appreciable power flow, and it takes time to both generate the power flow, and to stop it.

Testing of the zeolite-silicone ER material in the test damper revealed that the material exhibited its fully plastic properties at a voltage potential of 3,000 V/mm, with a measurable current flow across the narrow ER duct of less than 0.5 mA. Total control power required was less than 1 watt for this 1,000 lbs. output device, with an equivalent damping pressure of 840 psi.

The damper was tested at various displacements and frequencies with the fluid both in the activated and de-activated states. The test input was obtained by applying sinusoidal wave forms to one end of the damper with a controlled hydraulic servo-actuator cylinder, the other end of the damper being connected to ground. Instrumentation consisted of an LVDT for displacement measurements, and a load cell to measure damper output force. Test results are presented in Fig. 3 through Fig. 7, all of which were performed at 70 degrees temperature. The results reveal the desired controllable behavior, with the differences between activated and de-activated states being more pronounced at lower flow velocities. Other tests exercised the damper at forces to 1,100 lbs., where response became fully passive. The results for Fig. 3 and Fig. 4 show a modest amount of force axis noise, traced to a combination of load cell amplifier noise and a poor ground connection. This was corrected in the results of Fig. 5 through Fig. 7.

Significant is the fact that the fluid seals within the damper were of a relatively high friction type, with measured dynamic drag at low speeds of 25-30 lbs. Thus, the actual ratio of activated to de-activated dynamic damper force is higher than apparent in the results, due to the seal drag present at all times. The results from Fig. 3 are at a very low velocity, primarily to evaluate seal response, this being 25-30 lbs. of the 50 lbs. peak force recorded. Results show no evidence of seal binding or stick-slip. This particular seal, manufactured from acetyl resin, was selected for compatibility with the zeolite particles, which were anticipated to be relatively abrasive to conventional elastomer seal materials. Post test tear down and inspection of the damper after 5,000 cycles of operation revealed no evidence of deterioration to seals or metallic parts of the damper. Future experiments will evaluate lower friction seals.

Overall, the test results show the effects of activating the ER material are much greater at lower damping pressures. This is as expected, since damping pressures of 1,000 psi and above are dominated by inertial flows of fluid, i.e., where damping force is a function purely of the mass rate of flow through the orifice. At lower pressures, the effect of viscous shear stress forces are much more pronounced. At this point in the research, no formal attempt has been made to generate an analytical model of the fluid and damper, due in part to the degree of difficulty in modeling the transient internal fluid flows involved.

CONCLUSIONS

An electrorheological (ER) fluid has been developed comprised of zeolite particles suspended in silicone oil. Testing of this fluid in a damper of 1,000 lbs. nominal output force rating has demonstrated the ability to control damper output with internal pressures above 500 psi, and control power requirements of less than 1 watt.

The damper control valve is a simple ER duct, with no moving parts, requiring only that a voltage potential exists across the duct’s cross section to activate the ER material, and thus cause the material to exhibit plastic behavior.

All tests were successful, with no degradation of the damper or ER material occurring over large numbers of activation cycles or with time. The next phase of this research will be to construct and test a large scale ER damper, having output levels in the 30,000 lbs. range, with multiple parallel ER ducts to provide multiple selective damping constant values.

ACKNOWLEDGMENT

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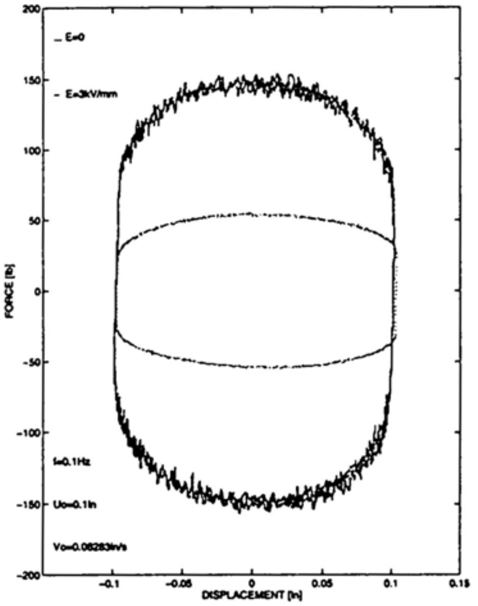


Figure 3
Test Results

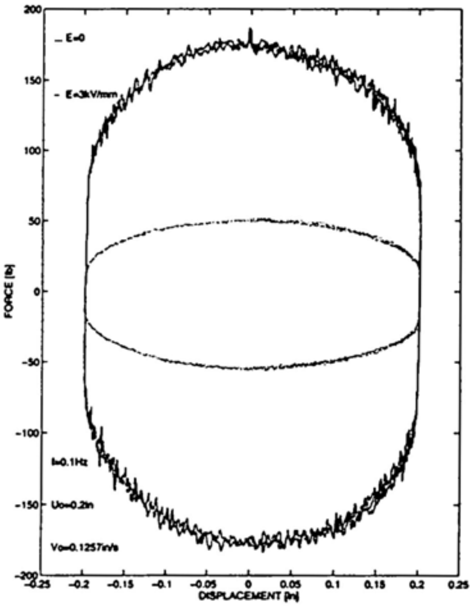
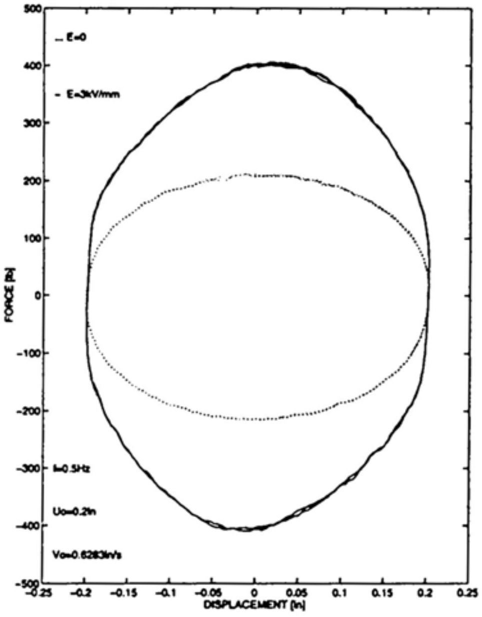


Figure 4
Test Results



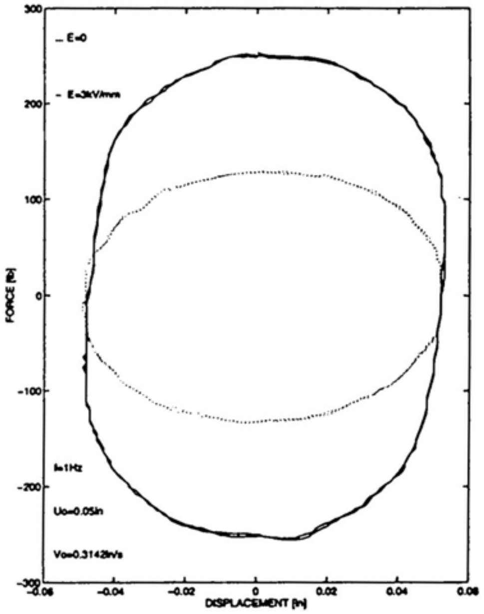


Figure 5
Test Results

Figure 6
Test Results

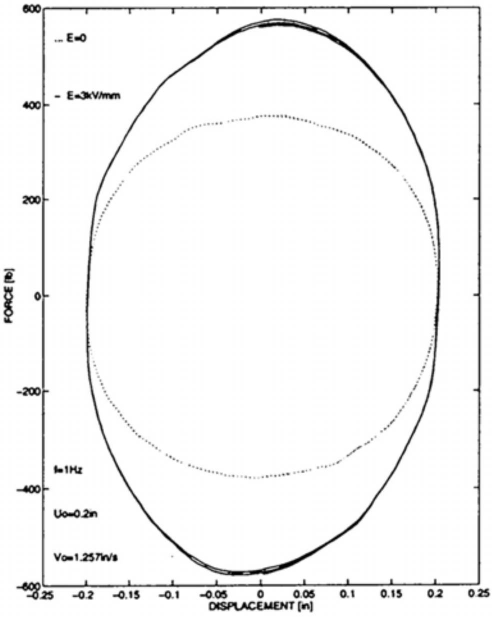


Figure 7
Test Results