3-1999

Electro-hydrodynamic Pumped Hydraulic Actuation with Application to Active Vibration Control

Ahmad Reza Kashani
University of Dayton, akashani1@udayton.edu

Sung Kang
University of Dayton

Kevin P. Hallinan
University of Dayton, khallinan1@udayton.edu

Electro-hydrodynamic Pumped Hydraulic Actuation with Application to Active Vibration Control

Kashani, R.[1], Kang. S., and Hallinan, K. P.

Mechanical and Aerospace Eng. Dept.
The University of Dayton

ABSTRACT

A new type of actuation device has been conceptualized that meets the needs of both large displacement, force and bandwidth within a package more compact than currently available magnetostrictive and stack-type piezoelectric actuators of similar rating. This concept relies on micro-scale electrohydrodynamic (EHD) pumping of a dielectric liquid within small channels. Configured as an actuator, the EHD pump(s) would be used to move fluid between two reservoirs—each having a compliant membrane that interfaces to the world to provide the means to achieve vibration cancellation or micro actuation.

Ordinarily limited to generating flow in macroscale applications, the EHD pump, when operating in a thermal induction mode, is shown to exhibit an exciting scaling law as its size is reduced. As the pump volume to surface area decreases, the energy going toward increasing pressure in the pump has an increasingly larger effect. Since the volume/surface area is proportional to *1/a*, where *a* is the characteristic width or diameter of the channels comprising the pump, the pressure head generated scales similarly. Analytical and numerical studies have shown the EHD-pumped actuator to be capable of delivering equal force and bandwidth to magnetostrictive and stack-type piezo actuators, but with considerably greater displacement and roughly $1/10^{th}$ of the size. Further, this type of actuator offers the possibility for deployment in active vibration control or micro actuation applications at significantly greater temperatures than for piezoelectric and magnetostrictive devices.

Keywords: Actuator; Hydraulic Actuation; Electro-hydrodynamic; Active Vibration Control; Ion Drag; EHD; Micro-electrohydrodynamic Pump

1. INTRODUCTION

Active response to vibration (through damping and/or cancellation) is very effective, adaptable, and sometimes the only solution to lowering the deleterious effects of vibration on a system. The success of active vibration control in most applications hinges on the capability of the actuator(s) used in those applications.

Much progress has been made in recent years using both piezoelectric and magnetostrictive, high–bandwidth actuators for active vibration control of structures and micro–positioning of mechanical systems. Shape memory alloys have also been used for actuation purposes but their use for applications such as vibration control has been limited due to their lack of agility, i.e., low bandwidth. Successful utilization of these actuators depends on their bandwidth, effectiveness—force/displacement generation— and high-temperature tolerance[2]. High displacement could be generated through proper levering, but at the expense of losing the force and increasing the size and weight. Moreover, these actuators can not be deployed in thermal environments exceeding 200 ° F.

This research in progress deals with a newly envisioned, highly effective, hydraulic actuator employing an array of electrohydrodynamically (EHD) driven pumps to pump liquid between two reservoirs and to generate pumping head that can be used to provide actuation. Generally noted for their inability to generate significant head, *a scaling analysis is presented which shows that when such pumps achieve micro sizes significant pressure head generation is possible.*

---

[1] The corresponding author: Mechanical and Aerospace Eng. Dept. /The University of Dayton/ 300 College Park/ Dayton, OH 45469-0210. Email: rkashani@engr.udayton.edu

[2] A piezoelectric or mangnetostrictive actuator with the diameter of 25 mm and length of 100 mm has the block force capability of around 400 N and the maximum displacement of about 40 to 50 micrometers. Increasing the cross-sectional area and length will increase the force and displacement, respectively but with the weight and cost penalty.

Part of the SPIE Conference on Smart Materials Technologies
Newport Beach, California • March 1999
SPIE Vol. 3675 • 0277-786X/99/$10.00

There have been two primary emphases in our research. First, we performed an analytical/computational assessment of the theoretical potential of the actuator. The predictions verified the potential of the actuator. Secondly, we developed working prototypes of the electro-hydrodynamically driven pumps that will ultimately 'drive' the actuator. An experimental evaluation and optimization followed the development. This evaluation has proven that sufficient force is achievable for the purposes of actuation. A pressure differential of 0.03atm has been generated for a single electrode EHD-pump. **Coupled with our observation that the pressure generation is linearly related to the number of electrode pairs in series, the potential for 10-100atm pressure generation now seems plausible**.

1.1 Electrohydrodynamic Pumping Background

EHD pumping is made possible by the generation of electrohydrodynamic forces within a dielectric fluid due to the application of electrostatic fields.

Traditionally, two types of EHD pumps have been modeled either by the ion drag model of Stuetzer or the induced charge model of Melcher. Stuetzer [i] studied the iron-drag pressure generation theoretically and experimentally. He presented an approximate theory for iron-drag pressure generation applicable to unipolar conduction in gases and insulating liquids. In his experiments, the free ions were created by corona discharges. The theory gave good agreement with the experiments but was limited to the static case, i.e., a nonmoving fluid. Later, Stuetzer [ii] presented a theoretical model with supporting measurements which described the dynamic behavior of an iron drag pumping arrangement for unipolar ion conduction. Pickard [iii,iv] re-examined the iron drag pumping theoretically and experimentally. He obtained new theoretical results for both the static and dynamic cases. Sharbaugh and Walker [v] investigated the pumping of transformer oil by an iron-drag pump experimentally. They were able to achieve a velocity close to 5 cm/s with a 6-cm diameter pipe. Melcher [vi] developed the basic theory for thermal induction pumping and demonstrated a small working model. He showed that an EHD traveling-wave induction interaction could pump slightly conducting liquids without electrical contact with the flow. Okapal [vii] examined the generation of a traveling wave by using a single-phase voltage excitation. He demonstrated EHD pumping with a single-phase voltage supply using discrete circuitry composed of resistor and capacitors only. Results were sporadic, but a peak flow velocity of 0.5 cm/s in macroscopically large tubes was achieved. Krein [viii] continued the work performed by Okapal and was able to achieve reproducible velocities on the order of 4 cm/s, also in macroscopically large tubes, using a single-phase voltage supply. Kervin [ix] carried out numerous measurements of pump velocity under different operating conditions. The traveling wave was produced by a three-phase power supply. He achieved maximum velocity of 10 cm/s within a 2.2-cm diameter pore. His work indicated that polyphase EHD pumping was more promising than single-phase. Kuo [x] performed a numerical study of an EHD pump in a horizontal configuration for underground electric cable systems with temperature dependent properties, particularly viscosity. He found that the temperature-dependent properties had only a minor effect on the axial velocity and on the friction factors.

Seyed-Yagoobi [xi] performed a theoretical, numerical, and experimental study of EHD pumping in a vertical configuration with steady-state flow and temperature dependent variables. He studied the controlling factors of an operating an EHD pump by varying thermal, electrical, and physical properties. His parametric study of EHD pump operation improved the understanding of thermal induction pumps. Crowley at el. [xii] theoretically studied the effects of various dielectric fluid properties on the efficiency and flow rates of an EHD pump. Their theoretical analysis of the physics of the EHD pump revealed insight into the conditions that could produce maximum flow rate and efficiency for given volumes.

At small scales, Bart et al. [xiii] and Richter et al.[xiv] were the first to demonstrate the feasibility of generating fluid motion in a microfabricated structure as a result of application of an electric field Fuhr et al. examined the feasibility of using travelling wave-driven microfabricated electrohydrodynamic pumps for liquids. They concluded that the best opportunity for achieving electrostatic pumping was to use the thermal induction pumping approach of Melcher. They suggested that the minimal required temperature gradients in the fluid could be easily tolerated by microscale devices [xv]. Recently, Choi et al. [xvi] designed, constructed, and tested a micro EHD pump (3 mm long, 40 microns wide, and 50 microns of channel depth). They were able to produce a pressure differential of nearly 100 Pa between inlet and outlet without any heat addition, using only a 120-Volt source. Finally, also at the microscale, Fracais et al. [xvii] and Bourouina et al. [xviii] have developed micropumps that are electrostatically actuated, but rely upon the use of an electric field to deform a membrane to displace fluid.

In summary there has been significant progress in the development of thermally induced EHD pumps. But outside of the work by Choi et al., the work has focused on macroscopically large sizes. They showed that generating head was possible for

a micro–sized EHD pump but were far from pushing the envelope of possibility for generating head with their micro EHD pump system.

2. EHD PUMPED HYDRAULIC ACTUATOR

This actuator relies upon the use of an electrohydrodynamically driven pump array to actively provide force, in a controlled manner. Electrohydrodynamic pumping results from the interaction between electric fields and charges in a dielectric fluid medium. The pumping is achieved by imposing travelling electric fields along the channel that attract or repel free charges that are present in the fluid. Free charges may be established in the fluid medium in two different ways. The first is by direct injection of free charges into a fluid, where an electric field is established between two electrodes (emitter and collector). This electric field pulls the ion molecules through the fluid thus setting the fluid in motion. This approach requires a constant source of free charges since the charges are neutralized when they come in proximity to an oppositely charged electrode. A second means is by corona discharge, where a locally high electric field is sufficient to strip electrons from or add electrons to a neutral molecule. A third means is via induction of a charge due to the presence of a permittivity gradient in the fluid. Most commonly this is achieved through a temperature gradient imposed normal to the flow direction within the pump.

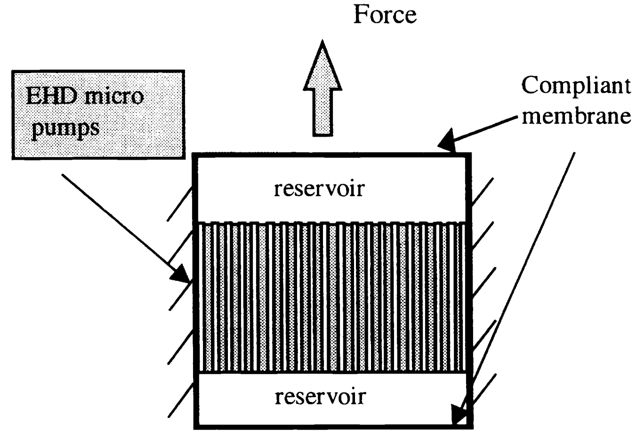

Figure 1. Schematic of the EHD pumped actuator

Figure 1 shows a schematic of one possible design for an EHD hydraulic actuator (with other variations possible). In this design, two liquid reservoirs are connected by an array of electrohydrodynamically driven micro pumps. Generally, the electrodes are configured so that at least three phases of electric waves can be made to march along the length of the channel, as is shown in Figure 2. The free charges in the fluid move with the travelling electric field.

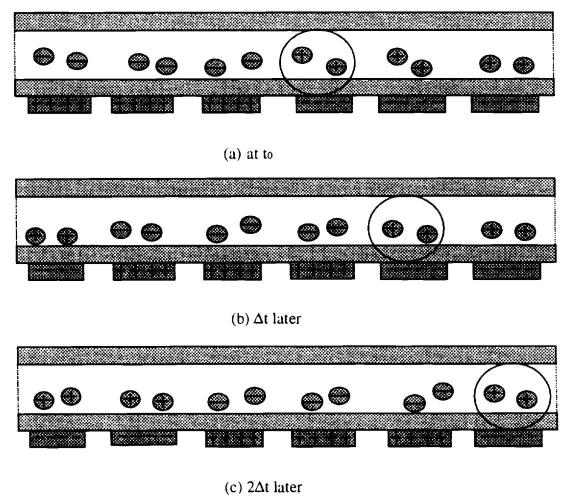

Figure 2. EHD Pump with Three Phases of Electric Waves

High force and high displacement can be achieved for different arrangements of the stacks in the EHD pump; see Figure 3. Stacks in series result in high pressure drop leading to high force and stacks in parallel result in high flow rate which in turn leads into high displacements. Depending on the application, a combination of series and parallel stacks can be used to achieve the desired actuation specifications.

2.1 Benefits of Miniaturization of EHD Pumps

The primary benefit of miniaturizing EHD pumps for use in an actuator device is a practical one. The requirement of a high voltage source in macroscopically larger channels to create the electric fields required to yield flow and pressure makes them impractical. High voltage sources are bulky and expensive compared to pumps. For this reason, EHD pumping has strictly been

mostly an academic exercise. In a scaled down system, however, with the advent of micro-machining and mesoscale manufacturing, the spacing between emitter and collector electrodes can be minimized. Electrode spacing can be as little as a few microns, eliminating the requirement for a high voltage source.

For ion drag pumping, there is the additional practical benefit of ease in manufacture. For macroscopically large pumps, it is difficult to manufacture electrode pairs that distribute a force over the full volume of the fluid. At small scales, this same problem does not exist.

For thermal induction pumping the scaling benefits are more tangible. The time-averaged electric field generates an electric shear stress that is most significant at the wall of the channel, i.e., where the emitter and collector electrodes are generally positioned, particularly for operation of the pump in a backward pumping mode. Thus the energy added to the fluid is primarily added at the fluid-wall interface. In steady state, the energy can be dissipated in three ways. First of all, it can overcome viscous work, which is a surface phenomenon. It can also contribute to Joule heating, which was shown by Seyed-Yagoobi to be small. Finally, it can increase the potential energy (pressure) of the fluid within the volume of the channel [xi].

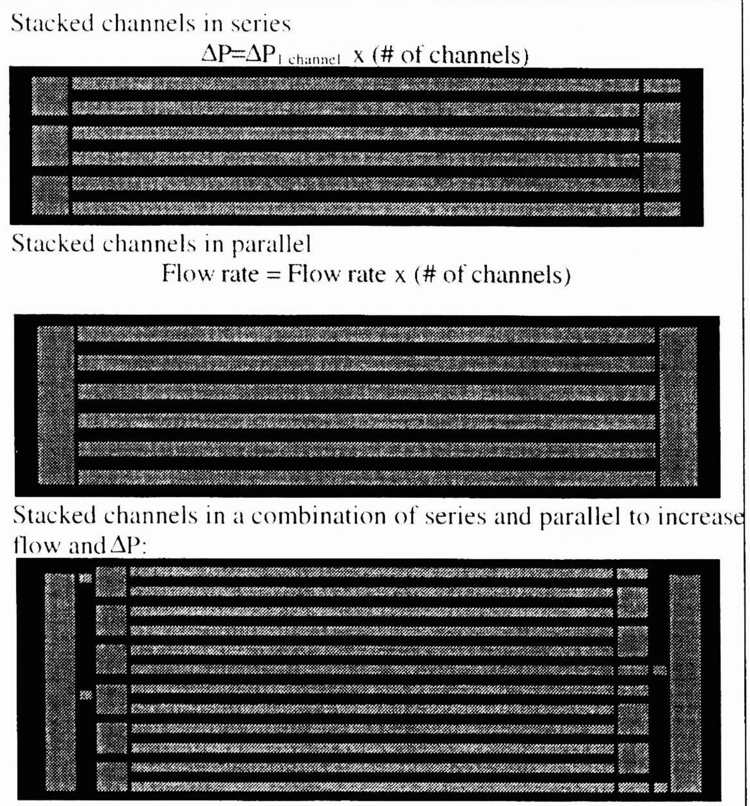

Figure 3: EHD pump seris and parrallel arrangements

In the new EHD pump actuator concept, the primary interest is in generating head (increasing pressure). If the volume of the fluid is large compared to the surface area, it will be intuitively difficult to generate significant pressure increase, because the energy added to the fluid capable of increasing its potential internal energy is spread out over a large region. If however, the surface/volume ratio is large, the possibility for generating head is increased. For a circular channel, the surface/volume ratio is proportional to the inverse of a radius, $1/a$. Thus, as the radius is decreased, this ratio increases rapidly. Heuristically, the EHD pump pressure head generation is expected to increase inversely with decreasing pore size. The following analysis seeks to develop a more quantitative confirmation of this intuitive argument.

Support for this heuristic reasoning comes from a closer examination of the forward and backward pumping mechanisms. Figure 4 depicts the backward pumping mode in a channel of depth a. Heat is added at the top and removed at the bottom. The emitter electrode induces a charge at the bottom electrode. The field itself is responsible for ionizing molecules in the fluid (frees some electrons in the fluid). Because the fluid conductivity increases dramatically with temperature increase, the freed electrons near the heated wall are able to conduct rapidly toward the hot wall. The positively charged ions remain and are repulsed by the emitter electrode. A backward flow results. Ultimately, it is the temperature difference that generates the free charges (ions) in the fluid. Without a conductivity gradient in the fluid, there would be no free charge build-up and no flow (or pressure head generation).

The real benefit in downsizing for backward pumping is that it is far easier to generate sizeable and controllable temperature gradients in the fluid for smaller channel depth than for larger ones (with equivalent heat addition and removal). Generally, the heat input/removal will be transient in nature within the actuator – since heat will be added only when an actuation force is required.

With a transient heat addition at a surface, the penetration depth δ_E for the heating at any time is $\delta_t \sim \sqrt{\alpha t}$

where α is the thermal diffusivity of the fluid. For t=10 μsec. and for Sun #4 oil, δ_E= 1.0 μm. Thus, the thermal penetration is relatively small. It is only over this distance that there will be a charge gradient.

As shown in Figure 5, the electric force is confined to the region of charge gradient. The driven region therefore drags the remainder of the fluid. If the channel is large, most of the electrical energy doing work on the fluid must overcome the viscous losses associated with the large "dragged" region. If it is small, i.e., a is such that the dragged region is negligible, the EHD forces are for more effective in generating both flow and pressure head. The same reasoning applies for forward pumping.

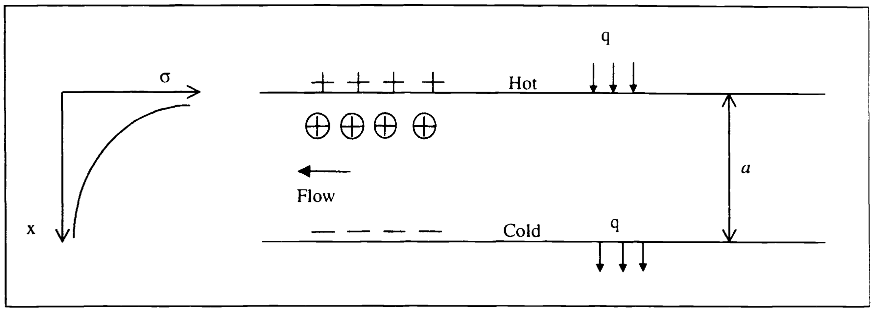

Figure 4 Thermal Induction Backward Pumping

A more thorough justification of these scaling arguments follows. The electric shear stress in radial coordinates is equal to [xi]:

$$\tau_{e,rz} = \frac{\varepsilon}{2}\mathrm{Re}\left(-jKC\frac{dC'}{dr}\right)$$

where ε is the dielectric constant of the medium, K is the inverse of the wavelength of the traveling waves (1/λ), C is the voltage potential, and C' is the complex voltage potential.

In order to establish the scaling analysis, the following scaling variables are defined: δ_e is the radial distance of a channel where the electric shear stress is present (is a fraction of the radius, a) and φ_o is the voltage applied. Accordingly, the electric shear stress scales as:

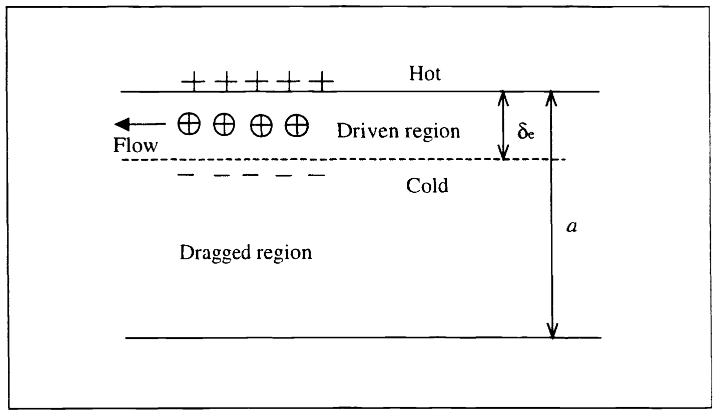

Figure 5: Driven and Dragged Region in the Thermal Induction Pump

$$\tau_{e,0} = \frac{\varepsilon}{2}K\frac{\phi_0^2}{\delta_e}$$

From an axial force balance on the control volume defined by the channel, the following relation is obtained when the acceleration term is negligible.

$$\Delta p \pi a^2 - \left[\int_{a-\delta_e}^{a} \tau_{e,0} 2\pi r dr - \tau_w 2\pi a\right] L \approx 0$$

where L is the length of the channel.

While the electric shear stress term and the viscous shear stress term are invariably on the same order of magnitude, from the results of Choi et al.[xvi] we know that substantial pressure head is achievable for micro sized EHD pumps, and therefore also expect it to be of the same order as the electric shear stress term.

$$\Delta p \approx \frac{2\tau_{e,0}\delta_e L}{a^2}$$

Accordingly, with λ ~ a the pressure scales as:

$$\Delta p \approx \frac{\varepsilon K \phi_0^2 L}{a^2} = \frac{\varepsilon \phi_0^2 L}{\lambda a^2} \approx \frac{\varepsilon E^2 L}{a}$$

The important features to note here are that the pressure head generated rapidly increases with decreasing channel diameter (1/*a*) and increases linearly with increasing channel length.

Computational simulations of the micro–scale EHD actuator concept have supported these predicted scaling laws. The model effectively solves the Navier-Stokes equations within the EHD pump, modified to include time-averaged electrohydrodynamic stresses induced in the fluid as a result of the marching electric fields imposed. The pressure rise is evaluated by integrating the electric shear stresses and viscous shear stresses over the entire solid/liquid boundary surface area, of a single channel. The conditions prescribed for the simulations are presented in Table 1. These inputs were considered to show the influence of the electric field on the pressure rise which can be generated. It should be noted that the maximum electric field which can be generated is approximately 2e8 V/m corresponding to the breakthrough voltage of the Sun Oil #5 fluid.

Table 1. Simulation conditions

Fluid	Sun Oil #5		
Channel Radius (R)	25 μm	100 μm	1000 μm
Channel Aspect Ratio (L/R)	50	100	200
Electric Field (V/m)	$1\text{x}10^6$	$1\text{x}10^7$	$1\text{x}10^8$
Heat input (W/m^2)	10	100	1,000

From the simulations, the following basic trends consistent with the scaling arguments were observed:

- The pressure rise produced increases by the square of the electric field constrained to the maximum electric field corresponding to the breakthrough voltage of the liquid.
- The pressure rise produced increases linearly with increasing channel or pore length.
- The pressure rise produced increases nearly linearly with increasing the amount of charged particles, e.g. thorough heat input to the dielectric liquid, constrained to remaining dielectric.
- *The pressure rise produced per unit length increases with the inverse of the square of the diameter.*

The 1/a scaling law derived offers exciting ramifications for producing an actuator capable of delivering large force in a compact housing, with better results evident as the pore size decreases. For example, for the simulation conditions of $E = 1\text{x}10^8$ V/m (slightly less than the breakthrough voltage of the oil considered), R = 100 microns, L= 5 mm, and q=100 W/m^2 (a relatively small heat input), a pressure rise of 1/10 of an atmosphere and a volume flow rate of 4 mm^3/s were predicted. In another simulation conducted to establish the upper-end potential of EHD pump actuator, the pressure rise for channel dimensions of R=25 microns and L=1.25 mm, exposed to the travelling field of 1e8 V/m with an electrode spacing of 50 microns was simulated. The results of this simulation revealed a pressure rise of 0.5e5 N/m^2 (1/2 atm.) with an associated flow rate of 0.2 mm^3/sec. Extending the length of the channel to 100 mm, typical of a magnetostrictive actuator with maximum displacement of about 50 microns, will increase the pressure rise by 80 fold to 40 atm. Stacking these channels in parallel, to yield an actuator cross-section of 1 cm^2, will result in the actuation force of 400 N which is equivalent to the maximum block force of a magnetostrictive actuator with the same length and a cross-sectional area of nearly 10 times larger (diameter of 34 mm*)*. ***Using the same cross-sectional area for the EHD pump actuator, the force will be an order of magnitude larger than the equivalent magnetostrictive actuator.*** The flow rate of the EHD pump with the dimensions described above will be around 8 cm^3/sec resulting in an actuator displacement of about 100 microns in 1 msec. Moreover, the maximum displacement is limited only by the compliance of the membrane.

2.2 Parametric Study

A parametric study of a thermal induction EHD pumped actuator has been conducted to determine the effects of: 1) electric field intensity; 2) aspect ratio; 3) pressure drop; and 4) radius on the performance (in terms of responsiveness) of EHD pumping:. In this study, a disturbance force acts on the actuator made of a single EHD pump. This in turn imposes a disturbance pressure on the fluid causing it to flow. After the flow becomes fully developed, the electric shear stress is applied on the surface of the channel of the pump to arrest the flow. The time it takes to stop the bulk flow near the entrance region is measured. This time is called "time to zero flow" and is an indication of the agility of actuator. The shorter the time to fully arreste the flow, the faster (higher bandwidth) the actuator.

The results of the parametric study are summarized below.

- The electric field intensity has a great effect on the performance of the EHD pumping. Higher responsiveness is achieved with increasing electric field.
- The responsiveness increases as the aspect ratio increases.

- The greater the disturbance pressure that is imposed on the fluid, the slower the response is.
- Reducing the pump radius greatly increases the agility of the pump thus increases the bandwidth; see Figure 6.

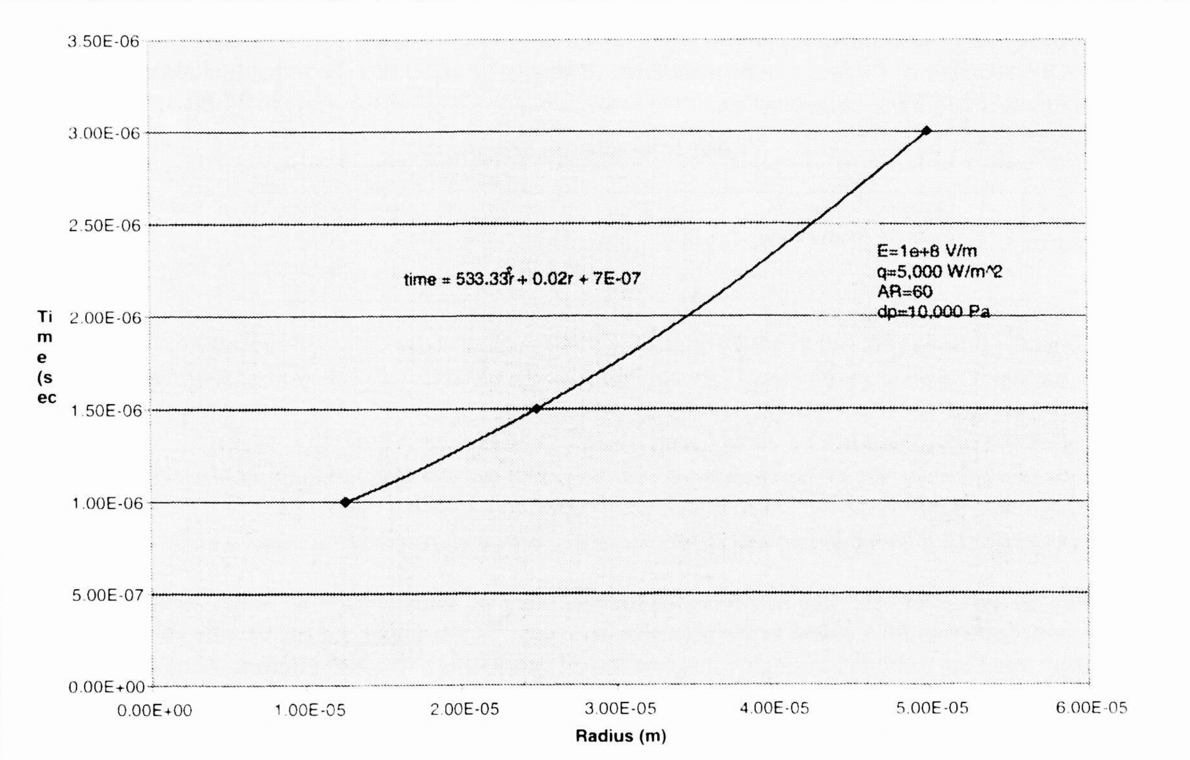

Figure 6 Time to zero as a function of radius

Note that the computational model has been benchmarked experimentally against the available experimental data of Sayed-Yagoobi and Choi et al [xix].

3. OTHER APPLICATIONS OF MICRO-EHD PUMPING

Micro-EHD pumping can also be used in another very important active vibration control area, i.e., isolating the engines and gearboxes from the chassis using active hydraulic engine mount; see [xx,xxi]. In this application, EHD pumping action could be used as a pump to actively displace liquid in the inertia track of these isolators.

Microfluidic pumping is another application of this concept. Currently, most research on the development of microfluidic pumping is based on miniaturizing mechanical pumps. This brings with it all the undesirable attributes associated with mechanical devices, e.g. friction, backlash in gearing, etc. EHD pumping contains no moving part is an alternative to the current practice.

4. EXPERIMENTAL DESCRIPTION

Our focus in the experimental phase has been oriented toward the development of EHD pumps that are capable of generating sufficient pressure head within a small volume. A number of EHD pump prototypes have therefore been designed, fabricated, and tested. These prototypes, shown schematically in Figure 7, have generally consisted of a channel plate and an electrode plate. The channel plate is manufactured from 1/2" thick lexan and was epoxied to the electrode plate. Channels of variable width and thickness were machined in the channel plates.

The electrode plates have generally consisted of a 2mm thick epoxy resin substrate on which electrodes were vapor deposited. Generally, we have considered a three phase electrode configuration, i.e., the emitter electrode (high voltage electrode) in every fourth electrode pair are common. Figure 8 shows a typical three phase electrode configuration.

Over 100 electrode configurations and a total of five channel configurations were evaluated. For each of these, phase frequencies from 0.2 - 100 Hz were considered. Tests with and without heat input and with and without the introduction of free charges into the fluid were conducted.

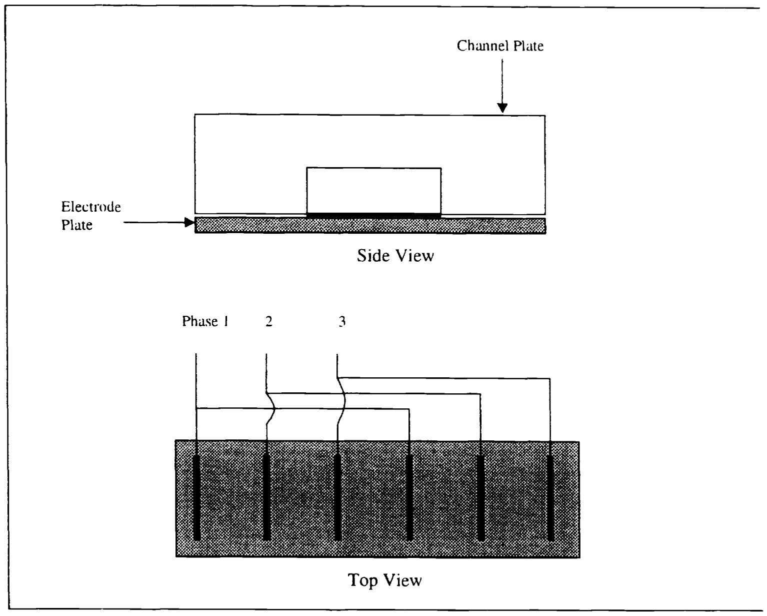

Figure 7 General EHD-pump configuration

4.1 Experimental Results And Observations

Several significant conclusions have been drawn from the breadth of the experiments that we have conducted thus far. These are summarized below:

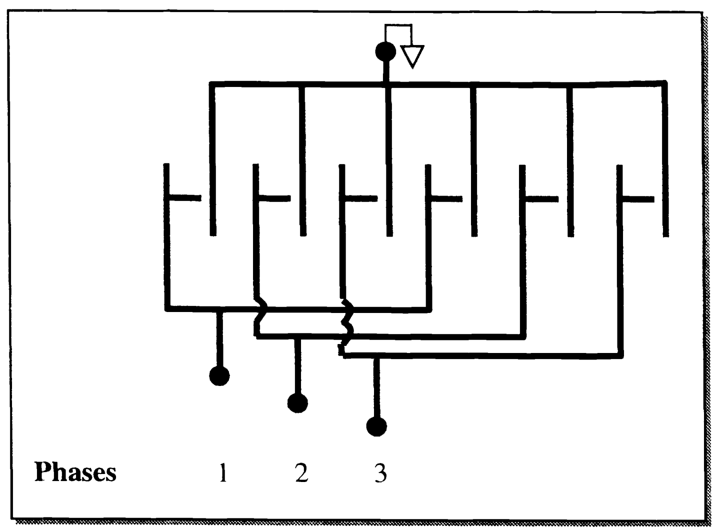

Figure 8 Three-phase electrode arrangement

- The application of heat in the thermal induction EHD-pump produces significant volumetric changes in all fluids considered. In an actuator application, unless the heat input could be exactly balanced by cooling at all times, actuator displacement would occur as a result of the thermal expansion. We concluded that the thermal induced EHD-pump driver is far from ideal. The thermal expansion of the pump/actuator fluid complicates the control of the EHD-pumped actuator. It turns out that this added complexity is unnecessary.
- An ion drag mechanism in an unheated pump is adequate for generating the pressure head needed to make the actuator practicable.
- It is essential to insure the continuous generation of ions in the fluid. In several tests, we attempted to add ions to the test fluid. The ions were neutralized very rapidly. When they moved into proximity with the ground electrodes, they took on an electron and as a result were no longer capable of being 'dragged' by the applied electric field.
- We determined that the best way to generate the ions was through the application of the electric field itself and that a 'uni-polar' fluid is optimal. In a uni-polar fluid, the electric field, if sufficiently high, can remove an electron or electrons from a molecule. The electrons freed are unable to re-attach themselves to other molecules and diffuse toward the ground electrode. The ions produced are drawn by the field toward the ground electrode.
- We determined that the electrode design was critical for producing an electric field sufficient to remove electrons from the molecule. Initially we considered parallel 'lines' on the electrode plate. The flow rates and pressure head generated were insignificant. Our next electrode design attempted to concentrate the electric field at the tip of the emitter electrode (i.e., the finger) as is shown in Figure 9. In fact, the electric field is maximum just outside the tip of

the finger. An even better electrode configuration from a field generation perspective is shown in Figure 9. In it, a sufficient electric field is induced for ionizing molecules without need of application of an excessive voltage potential.

- We have determined that the pressure head generated increases linearly with the number of electrodes configured in series. We have also shown that the flow rate is independent of the number of electrodes in series. The flow rate has been shown to increase linearly with an increase in the number of channels in parallel.

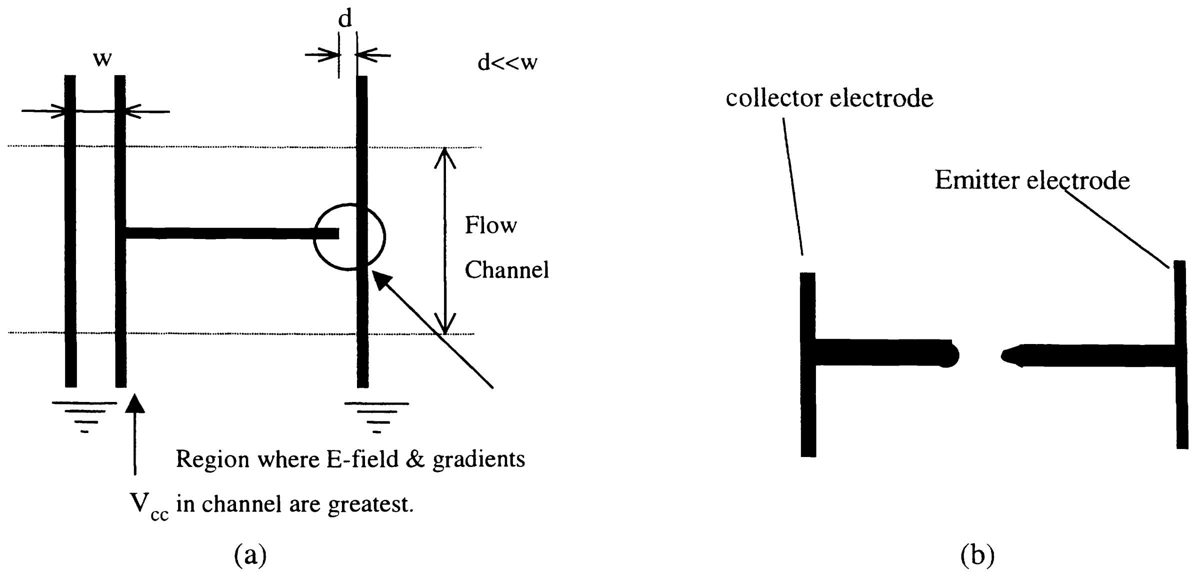

Figure 9 (a) Electrode design with a tip finger (b) Sharp emitter electrode configuration

Results for the best ion drag pump configuration employing a single electrode pair are shown in Figure 10, with pressure head being related to time. In this pump, the liquid was pumped up a tube. An electric field of 1×10^7 V/m was applied. The position of the liquid front was measured as a function of time. A total pressure head of nearly 0.03 atm was obtained. With 300 electrode pairs configured in series, a pressure head of 10 atm would be realized. With an increased electric field, even greater head generation would be feasible.

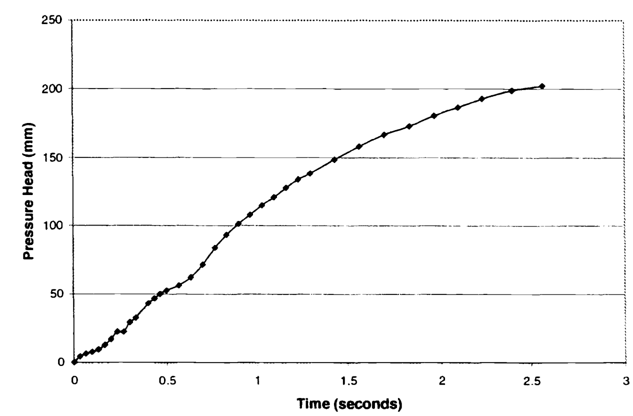

Figure 10: Pressure Head versus Time

5. SUMMARY

An innovative, high-performance, high-bandwidth, compact actuator capable of providing force/displacement well beyond what piezoelectric and magnetostrictive actuators can deliver which is also tolerant of higher temperatures is conceptualized. The actuation mechanism relies on the use of electro-hydrodynamic pumping in microscale. The intended use of such actuators is for active vibration control of structures, noise reduction, precision pointing, and vibration isolation.

Analytical, numerical, and experimental studies have shown the EHD-pumped actuator to be capable of delivering equal force and bandwidth to magnetostrictive and stack-type piezo actuators, but with considerably greater displacement and a smaller size. Moreover, due to its fluidic nature, this actuator offers more flexibility in the way it can be packaged in a structure than the traditional smart material actuators.

ACKNOWLEDGEMENT

This work is partially supported by the Propulsion Division at the Air Force Research Laboratory. The technical advice and suggestions of Mr. William Braisted and Mr. Michael Drake of the University of Dayton Research Institute are warmly acknowledged.

REFERENCES

i. Stuetzer, O. M., "Iron Drag Pressure Generation," J. of Applied Physics, Vol. 30, 1959

ii. Stuetzer, O. M. "Iron Drag Pumps," J. of Applied Physics, Vol. 31, 1960, pp. 136-146

iii. Pickard, W. F., "Iron Drag Pumping I Theory," J. of Applied Physics, Vol. 34, 1963

iv. Pickard, W. F., "Iron Drag Pumping II Experiment," J. of Applied Physics, Vol. 34, 1963

v. Sharbaugh, A. H., and Walker, G. W. , "The design and Evaluation of an Iron-Drag Dielectric Pump to Enhance Cooling in a Small Oil-Filled Transformer," IEEE-IAS Meeting, Mexico City, Oct. 19, 1983

vi. Melcher, J. R., "Traveling-Wave Induced Electroconvection," Phys. Fluids, Vol. 9, 1966, pp. 1548-1555

vii. Okapal, M. F., "Traveling-Wave Generation and Electrohydrodynamic Pumping with a Single-Phase Voltage Supply," MS thesis, University of Illinois, 1978

viii. Krein, P. T., "Analysis and Operation of an Electrohydrodynamic Pump Using a Single-Phase Voltage Supply," MS Thesis, University of Illinois, 1980

ix. Krevin, D. J., "Three-Phase Variable Parameter Electrohydrodynamic Pumping," MS Thesis, University of Illinois, 1981

x. Kuo, B. "Flow Characteristics and Heat Transfer for Pressure and Electric Field Driven Laminar Flow with Temperature-Dependent," Ph.D. Dissertation, University of Illinois, 1982

xi. Seyed-Yagoobi, "Theoretical, Numerical, and Experimental Study of Electrohydrodynamic Pumping in Vertical Configuration," Ph.D. Dissertation, University of Illinois, 1984

xii. Crowley, J. M., Wright, G., Chato, J. "Selecting a Working Fluid to Increase the Efficiency and Flow Rate of an EHD Pump," IEEE Transaction On Industry Application, Vol. 26, Jan. 1990

xiii Bart, S. F., Tavrom, L. S., Mehregany, M. and Lang, J. H., 1990, "Microfabricated electrohydrodynamic pumps, Sensors and Actuators, A: Physical v 21 n 1-3 1990 p.193-197

xiv Richter, A., and Sandmaier, H., "An Electrohydrodynamic Micropump," Proc. of IEEE MEMS, pp. 99-104, 1990.

xv Fuhr, Gunter, Schnelle, Thomas, and Wagner, Bernd, 1994, "Travelling wave-driven microfabricated electrohydrodynamic pumps for liquids, J. of Micromech. Microeng., Vol. 4, pp. 217-226.

xvi. Choi, J. and Kim, Y., "Microelectrohydrodynamic Pump Driven by Traveling Electric Fields," Proc. of IEEE IAS, 1995, pp. 1480-1484.

xiv Smith, Douglas R. Parekh, David E. Kibens, Valdis. Glezer, Ari. Thrust vectoring with hybrid synthetic jet actuators High Speed Jet Flows American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED. v 8 1997. ASME, New York, NY, USA

xv Bhagat, W. W., King, W. P., and Hallinan, K. P., 1997, " Electrohydrodynamic Enhancement of Heat Transport Capacity of a Micro Heat Pipe," presented at the 1997 International HeatTransfer Conference, Kanpur, India, Dec. 29-31.

xvi Hallinan, K. P., Bhagat, W. W., Kashaboina, B. and Kashani, R. "Electro-hydrodynamicAugmentation of Heat Transport in Micro Heat Pipe Arrays," 1998, to be presented at the 1998 ASME-ISE, Anaheim, California, November.

xviii Kashani, R. "High Power Actuators in Intelligent Rotor Application," Proceedings of *the 1993 SPIE North American Conference on Smart Structures and Materials*, Albuquerque, NM, Feb. 1993.

xvix Little, E., Kashani, R. Kohler, J., and Morrison, F., "Tuning of an Electro-rheological Fluid-Based Helmholtz Resonator as Applied to Hydraulic Engine Mounts," *Trasnportaion Systems,* Kashani, R. Editor, the ASME Book #G00898, DSC-Vol 54, 1994, pp 43-51

xvii Francais, O., Dufour, I., and Sarraute, E., 1997, "Analytical Static modelling and optimization of electrostatic micropumps," J. Micromech. Microeng., Vol. 7, pp. 183-185.

xviii Bourouina, T., Bosseboeuf, A., and Grandschamp, J-P, 1997, "Design and simulation of an electrostatic micropump for drug-delivery applications, J. Micromech. Microeng., Vol. 7, pp. 186-188.

xix Kang, Sung, "Feasibility Study of New Concept EHD-driven Micro-Pumped Actuator"., 1999, Ph.D. Dissertation, University of Dayton.

xx Flower, W. 'Understanding Hydraulic Mounts for Improved Vehicle Noise, Vibration, and Ride Qualities' SAE \#85079.

xxi Singh, R., 'Linear Analysis of Automotive Hydro-Mechanical Mounts' J. of Sound and Vibration, V.158, No.2, p.219