Electrokinetic Microactuator Arrays for Sublayer Control in Turbulent Boundary Layers

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Recent progress is summarized in the development of microactuator arrays that function on the electrokinetic principle to permit active control of streamwise sublayer vortical structures in turbulent boundary layers. Electrokinetic microactuator arrays induce volume displacements in the sublayer by electrokinetic pumping under an impulsively applied electric field. Individual microchannels are formed in a substrate and filled with a 1 μ m-scale doped porous polymer matrix material that provides the required -potential when wetted by the corresponding electrolyte. The resulting microactuator arrays have many characteristics that make them potentially suited for practical sublayer control on full-scale aeronautical and hydronautical vehicles. Several such micro electrokinetic actuator (MEKA) arrays have been fabricated from a three-layer design. Essentially loss-less frequency response has been demonstrated to 10 kHz; theoretical bandwidth is in the MHz range. Our current MEKA-5 is a full-scale hydronautical array with 25,600 individual electrokinetic microactuators on 350 μ m spacing in a 7 × 7 cm mylar tile with a unit-cell architecture. The array has a MEMS-fabricated top layer with leadouts to unit-cell processing. In addition to the electrokinetic microactuators themselves, the MEKA-5 design is based on several other innovations that can potentially provide dramatic reductions in both the sensor and processing requirements needed to achieve practical sublayer control on real vehicles.

1. Introduction

Active sublayer control for drag reduction in turbulent boundary layers is one of the highest-impact applications for "smart" control of turbulence. A reduction of just a few percent in the drag created by the turbulent boundary layeron a commercial airplane or ship can translate into large reductions in fuel consumption and corresponding reductions in both operating costs and environmental emissions. For these reasons, reducing the drag on a vehicle through proper manipulation of the viscous sublayer has been a focal point of fluid dynamics research since the discovery of organized vortical sublayer structure in the 1960's. While there are other areas where passive or active control of turbulence can provide substantial benefits for various applications, drag reduction via active sublayer control remains the "holy grail" of turbulence control.

The likelihood of achieving practical sublayer control in turbulent boundary layers under actual vehicle conditions may be far more realistic than it might at first seem. It is precisely in the realm of full-scale vehicle operation that the underlying physics of the problem at hand and the inherent characteristics of a microsystems-based approach are ideally matched. The thin viscous sublayer directly adjacent to the surface of any practical vehicle is one of the most powerful nonlinear systems found in nature, capable of amplifying the effect of small microactuator-induced perturbations into very large changes in the momentum transport between the inner and outer layers. Moreover, the exceedingly small length scale associated with flow structures in the sublayer is ideally matched to microscale actuators. The sublayer vortices typically are centered as little as 10 µm above the wall, spaced

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about 100 μ m apart and roughly 1 mm long, and advect past any fixed point at frequencies up to 100 kHz. Thus the inherent problem of matching the length and time scales between microactuators and the physical problem at hand makes the viscous sublayer of a turbulent boundary layer a natural choice for microsystems-based control.

Microsystem sensor technologies are capable of identifying these vortical structures in the viscous sublayer via their wall shear stress signature. Practical detection of high-speed sublayer streaks in turbulent boundary layers has been demonstrated with a variety of sensors, including micro hotwire anemometers, micro surface shear stress balances, and micro pressure sensors. A number of excellent reviews of these can be found in the literature (e.g., Bushnell & McGinley 1989; Fiedler & Fernholz 1990; Wilkinson 1990; Gad-el-Hak 1989, 1994, 1996; McMichael 1996; Ho & Tai 1996, 1998; Pollard 1998; Lumley & Blossey 1998; Löfdahl & Gad-el-Hak 1999). Moreover, by combining such sensors with remarkably simple control algorithms and associated processing electronics, a number of studies have successfully demonstrated drag reduction in laboratory-scale flows (e.g., Breuer et al 1989, Moin & Bewley 1994, Jacobsen & Reynolds 1998). Several papers at the 1st Symposium on Smart Control of Turbulence reviewed the current state of progress on active control of wall turbulence in the U.S. (Gad-el-Hak 1999), in Japan (Yoshida 1999), and in Europe (Choi 1999).

The principal area that remains lacking is the development of microactuators suitable for practical sublayer control under full-scale vehicle conditions. Although several types of microactuators based on a variety of different operating principles have been examined to date, none of these meets the requirements for practical sublayer control on real vehicles. The high performance required for sublayer control places rather stringent limits on the types of actuators that may be suitable for this task.

This paper describes progress in the development, fabrication, and testing of a new class of microactuators for sublayer

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control based on the electrokinetic principle, and presents a system architecture that integrates these electrokinetic microactuators into large, dense arrays capable of meeting the requirements for sublayer control in turbulent boundary layers on vehicles. Electrokinetic microactuator arrays are based on a three-layer design, with a center layer consisting of microchannels in which an electrolyte is electrokinetically pumped by an electric field, as indicated in Fig. 1. In addition to the electrokinetic microactuators themselves, the approach being pursued in this study involves several other innovations that can potentially provide dramatic reductions in both the sensor and processing requirements needed to achieve practical sublayer control on real vehicles.

2. Microactuator Performance Requirements

The bursting process associated with streamwise vortices at the outer edge of the viscous sublayer sets the rate of momentum transport from the wall to the fluid, and hence the drag that acts on the vehicle. The sublayer bursting process can be interrupted by acting on the streamwise vortices inany of a number of ways. For the present microactuator arrays, the individual actuators serve as point volume sources that displace (either positively or negatively) a fixed volume of fluid between the wall and the inner layer. Each actuator produces locally positive or negative volume displacements over a brief interval, corresponding to local suction or blowing at the wall, to displace the streamwise sublayer vortices along the spanwise direction. Key performance requirements include the actuator spacing, frequency, and flowrate needed to achieve adequate displacement of individual sublayer vortical structures.

Based on the sublayer vortex structure and dynamics, actuators must be separated by typically 100 wall units, and displace a volume of fluid with an equivalent hemispherical radius of the order of 10 wall units, with a step response that corresponds to a frequency in wall units of f^+ 10^{-2} . The size and performance requirements to which these conditions correspond depend on the fluid density and viscosity and on the vehicle length and speed. Figure 2 shows the resulting microactuator spacing, frequency response, and equivalent DC flowrate requirements at four downstream locations and for four different pressure gradients on various vehicle types. For a given fluid, vehicle speed is the principal factor that drives these requirements. For the UAV application these requirements are relatively benign, with actuator spacings of several millimeters and step response of 100 Hz sufficient to act on virtually every sublayer streak. At the other extreme, the fighter and transport aircraft require actuator spacings of 100 - 200 µm and step response of 10-90 kHz. The various hydronautical applications require microactuator spacings around 300 µm but frequencies of only about 1 kHz and equivalent DC flow rates in the range of 10 µl/min.

These frequency and flowrate requirements represent what is needed to act on essentially every streamwise vorticalsublayer structure in the turbulent boundary layer. While the actuator spacing requirements are inflexible, adequate control may be possible with somewhat lower frequency performance. This would involve acting on some, but not all, of the vortical structures, since it is only necessary to manipulate those structures that are at the point of incipient bursting.

The small actuator spacings required for sublayer control on real vehicles implies that large dense arrays of microactuators must be used to cover key parts of the vehicle surface. However, the inherently local nature of the sublayer vortex dynamics and bursting process suggest that large tiles of such arrays can be composed of much smaller independent unit cells, each with their own sensors, control processing, and actuators. Fundamental considerations suggest that these will typically consist of 6×6 arrays of microsensors and microactuators. This local nature of the problem greatly simplifies the sublayer control of turbulent boundary layers,



Figure 1. Three-layer design of electrokinetic microactuator arrays; center layer contains microchannels filled with porous polymer matrix in which electrokinetic pumping occurs.



Figure 2. Microactuator spacing, frequency, and equivalent DC flowrate requirements for various vehicle types. Aeronautical applications lead to a wide range of performance requirements due principally to vehicle speeds. Hydronautical applications span a narrower range of conditions and need lower flowrates; microactuators require 300 μ m spacing, 10 μ L/min flowrates, and frequency response up to 1 kHz.

as will be discussed in §4.

3. Electrokinetic Microactuator Principles

Electrokinetic microactuators function on the electrokinetic principle, first discovered in 1807 and now used in a wide variety of macroscale devices and processes. This study exploits its potential advantages as the basis for microscale actuators suitable for boundary layer control on vehicles.

Electrokinetics

Electrokinetic processes operate by means of a double-layer of ions that forms at an interface, in this case between a solid channel material and an electrolytic fluid. The double-layer thickness in the electrolyte is set by the Debye length, which is typically only 10 - 100 nm. The inner layer contains immobile ions attracted to the charge distribution on the wall, and is at most a few ionic radii thick. The outer layer ismuch thicker and contains the remainder of the ions, which are free to move. When a potential difference is applied along the channel, the electric field induces a drift in the mobile ions within the outer layer. This ion drift extracts energy from the applied field and transfers this kinetic energy to the bulk fluid through collisions in the thin outer layer. The bulk fluid then transfers momentum from the thin outer layer across the rest of the channel by viscous diffusion. In this manner, an applied voltage along the length of the channel produces motion of the bulk fluid within the channel.

Coulomb's law gives the electrostatic force $F = e_0 E$ acting on an ion of effective charge e_0 in an electric field of strength E. This accelerates the ions until the drag force D resulting from collisions with the surrounding solvent molecules matches the Coulomb force; the time to reach this steady state is typically $O(10^{-13} \text{ sec})$. Assuming that D can be approximated by the Stokes sphere-drag formula gives

$$D = 4 \quad r \mu U \quad , \tag{1}$$

where *r* is the equivalent spherical radius of the ion, μ is the solvent viscosity, and *U* is the speed at which the ion drifts, with the constant reduced to correct for the geometry. Equating gives U = E, where is the ionic mobility

$$\frac{e_0}{4 r\mu} \quad . \tag{2}$$

When the field is created by an applied voltage V across an actuator channel of length L and radius w, then the resulting flow speed is

$$U = -\frac{V}{L} \tag{3}$$

and the volume flowrate is

$$Q = w^2 \quad \frac{V}{L} \quad . \tag{4}$$

If the actuator becomes plugged, then the pressure gain along the electrokinetic channel is balanced by the pressure drop in the backflow along the actuator. The latter is obtained from the Poiseuille flow solution as

$$p = 8\mu \quad \frac{V}{w^2} \tag{5}$$

and hence the force achieved by the actuator channel is

$$F = 8 \mu \quad V . \tag{6}$$

It is popular to equivalently express the mobility in terms the potential achieved across the inner layer (the "zeta potential" or "wall potential") as

$$= \frac{0}{\mu} , \qquad (7)$$

where $_{0}$ is the permittivity constant and is the dielectric constant.

These scalings are for a single channel. For a channel of radius *R* consisting of $(R/w)^2$ individual pores each of radius *w*, the flow rate in (4) becomes

$$Q = R^2 - \frac{V}{L} \quad . \tag{8}$$

Benchtop tests with electrokinetic microactuators formedfrom capillaries packed with glass beads of size w and operated with steady applied fields verified that the pressure increased linearly with applied voltage V and varied with bead diameter (and hence effective channel radius) as w^{-2} , as suggested by (5). The volume displacement rate Q was observed to increase linearly with applied voltage and the ionic mobility as in (8).

The flow speed in (3) is independent of the pore radius w, but the pressure in (5) increases as the pores are made smaller. This suggests that by fabricating electrokinetic channels with sufficiently small pores, it may be possible to meet the flowrate requirements while achieving sufficiently high pressure for any plugged actuators to unplug themselves.

Frequency Response

The extremely short time scale on which the Coulomb force equilibrates with the ion drag suggests that, in the presence of a time-varying applied field, the frequency response of a microactuator based on the electrokinetic principle will be very high. The response limit in then set by inertial damping by the flow within the electrokinetic driver matrix. For electrokinetic channels with extremely fine pores, the resulting pore Reynolds number Uw/ will be very low, and thus the inertial limit on frequency response will be very high.

The theoretical frequency response and the key parameters that set the response limit can be obtained from the hydrodynamics of electrokinetically driven flow. Consider the flow in a typical pore of radius w within the porous matrix of the electrokinetic driver section. The response of the pore flow to an unsteady electrokinetic forcing can be approximated by simple hydrodynamic models. Two closely related limits are relevant. The first applies when the electrokinetic double layer thickness is much smaller than the pore radius w, as is typically the case. The motion induced in the double layer by either an impulsively applied electric field, or by a sinusoidally oscillating applied field, is then equivalent, respectively, to Stokes' first or second problem for the flow induced by viscous diffusion above a moving wall. The "wall" in this case is the oscillating thin double layer, and viscosity acts to diffuse the induced motion within it throughout the pore. The solutions are classical, and in both cases lead to the development of a "Stokes layer" of $(/2)^{1/2}$ adjacent to the wall within which the thickness motion is confined, with is the viscosity of the electrolytein the frequency of the applied field. The the pore and frequency at which the Stokes layer becomes smaller than the pore radius is then max ($/w^2$), beyond which diffusion has insufficient time to transfer momentum from the double layer to the rest of the pore. For an aqueous electrolyte with kinematic viscosity comparable to water (10^{-6} m²/s), this gives a maximum frequency of the order of 1 MHz for 1 μm pores, and 10 kHz for 10 μ m pores, but drops to 400 Hz for 50 μ m pores. The porous polymer matrix used to fabricate our electrokinetic microactuator arrays produces typical pore sizes of 1 µm and smaller, and thus should provide a theoretical frequency response limit around 1 MHz.

A different limit applies when the double layer thickness becomes comparable to the pore radius w, since then the electrolyte throughout the pore contains a largely uniform concentration of ions. Electrokinetic forcing then acts to induce motion directly throughout the fluid, and thus becomes a body force. The pore flow that results from a sinusoidally applied electric field is then equivalent to the oscillatory flow induced in a pipe by a sinusoidally varying pressure gradient.

This also has an exact solution that can be used to assess the frequency response limits applicable under those conditions. However, for the double layer thicknesses encountered in our work, this does not appear to be the limiting case.

These considerations suggest that electrokinetic microactuator arrays with a 1 μm porous matrix in the electrokinetic channels can meet the requirements on spacing, flowrate, and frequency response for sublayer control on vehicles under realistic conditions.

4. Microactuator System Architecture

The integration of individual microactuators into a practical system for sublayer control requires an architecture concept that is matched to the requirements of the physical problem and to the processing capabilities than can be realistically integrated into such a system. Key elements of this system architecture are independent of the particular microactuators used, and can be applied to essentially any active sublayer control system.

Actuators

The system architecture being pursued in this study is fundamentally based on the local nature of the sublayer bursting process which these microactuators seek to affect. This allows electrokinetic microactuator arrays to be fabricated in *tiles* composed of a large number (e.g., 40×40) of *unit*cells, with each unit-cell composed of a much smaller number (e.g., 6×6) of individual sensor-actuator element pairs (see Dahm et al 2000). A sensor-actuator pair is typically located every 100 wall units along the spanwise and streamwise directions within each unit-cell. All interactions between the sensors and the actuators occur at the unit-cell level, and thus each unit-cell contains its own independent processing capability. Because of the relatively small unit-cell size that the dynamics of the sublayer bursting process allows, it may be possible to greatly reduce the required sensor capabilities and unit-cell processing capabilities.

Sensors

Detection of streamwise vortical structures in the sublayer is by wall shear stress sensors colocated with each microactuator in the unit-cell. The system architecture uses one wall shear stress sensor for each actuator, located between adjacent actuators. Many of the usual concerns about shear stress sensor calibration and accuracy can be relaxed in this system approach, since the role of each sensor is not to measure the wall shear stress distribution below the vortical structures, but rather simply to identify the presence of a vortical structure just prior to bursting with reasonably high probability of detection. Thus the instantaneous wall shear stress sensor outputs can be compared to a running average value obtained from a simple (e.g., RC) low-pass filter located on each unitcell. When the sensor output exceeds a preset multiple of the running average, then the state of the *i*-th sensor in the processing electronics is set to $S_i = 1$ (or to $S_i = \pm 1$ if the sensors have directional capability). Otherwise the input from the sensor is set to $S_i = 0$. The complete set of sensor states $\{S_i\}$ for $i = (1, 2, ..., n_S)$, where n_S is the number of sensors in each unit-cell, provides the input to the unit-cell processing electronics. The running average essentially eliminates the need for calibrating each sensor, and eliminates difficulties caused by changes in the vehicle speed and attitude or by the particular location of the sensor-actuator pair on the vehicle. Sensor drift over timescales significantly longer than the averaging time becomes irrelevant, and sensor accuracy does not need to be high since the sensor output is thresholded in this manner.

Processing

The role of the local unit-cell processing is to use the n_S sensor states $\{S_i\}$ on each clock cycle to determine the n_A

actuator states $\{A_i\}$, where $A_i = +1$, 0, or -1 corresponds respectively to positive volume flux (blowing), zero volume flux, or negative volume flux (suction). The actuators are not modulated; they are either on (± 1) or off (0), and thus the voltage of the top-layer electrode for each actuator is set to $A_i V_{ref}$. Here V_{ref} is the voltage of a common power bus that runs between the unit-cells (see §5). The processing circuit thus effectively acts as a three-state bridge between this power bus and the electrode contact for each of the microactuators in the unit-cell.

The set of sensor states $\{S_i\}$ implies a set of actuator states $\{A_i\}$. Functional approaches of the type $\mathbf{A} = f(\mathbf{S})$ may be appealing in their generality and rigorous connection to control theory, but are likely to require significantly more processing capability than can be readily accommodated within each unit-cell. Moreover, such an approach would overlook the fact that the physics of the sublayer structures greatly restrict this functional dependence and thus provide opportunities for considerable simplification. For example, since the processing is purely local at the unit-cell level and the unit-cell size can be made relatively small, it may be possible to use a simple look-up table approach (*e.g.*, a programmable logic array) that eliminates the need for complex processing. Such a look-up table approach can be implemented at various levels of approximation.

The simplest is to make use of the nominally streamwise structure of the sublayer vortices, and thereby reduce the number of spatial dimensions in both the sensor and actuator arrays to just one. This can be done by logically grouping the n_S sensors in the unit cell into nC_S columns along the streamwise direction, and then obtaining a single sensor column state CS_i for each column (e.g., by a majority rule among the sensor states $\{S_i\}$ within the column). Similarly, the n_A actuators are grouped into streamwise columns, and a single actuator column state CA_i is used to drive all the actuators in that column. This reduces the logic circuit requirements to setting the nC_A -element column state vector $\{CA_i\}$ from the *nC*_S-element column state vector $\{CS_i\}$. For the relatively small numbers of columns provided by the unitcell architecture, the number of possible sensor column vector combinations may be sufficiently small that each of the appropriate actuator column vectors can be explicitly determined from simple model-based considerations.

Alternatively, irrespective of whether the unit-cell processing is to be done in one or two spatial dimensions, since the lookup table remains static and is the same for all unit-cells it can be generated from a detailed simulation study. This might be done by a neural net approach that evolves to determine a look-up table which minimizes the wall shear stress within a unit-cell from discrete thresholded sensor inputs S_i . Such an approach to generating the look-up table may be able to incorporate recent advances in applications of control theory to wall shear stress reduction (*e.g.*, Kim 2001).

5. Microactuator Fabrication and Testing

Several early actuator arrays were fabricated and used to test various aspects of electrokinetic microactuator performance as well as to develop practical mass fabrication approaches. These have evolved the design from initial tests with elementary packed channel actuators, to small arrays of fully functioning microactuators, to unit-cell sized components and full-scale dense arrays.

Elementary Packed Channel Actuators

Initial tests were done with simple capillaries packed with glass beads of various diameters to verify the scaling principles relevant to electrokinetic pumping under steady (DC) applied fields. The scalings in \$3 were confirmed experimentally in tests using 100 µm glass capillaries filled with various electrolytes. These showed that miniaturization

by constructing additional interfacial surface (and hence additional double layer area) within the channel interiorallows large increases in pressure rise p to be achieved in plugged actuators while causing essentially no reduction in volume displacement rate Q for open actuators. This was accomplished by filling the actuators with glass spheres having diameters as small as 0.5 µm, creating effective interstitial channels with submicron scales. The dependence of pressure rise and flowrate on the applied voltage V and channel length L were also verified. The performance advantages of miniaturization should continue to apply down to the Debye length scale. Further tests verified the dependence of performance on electrolyte type and concentration as suggested by the ionic mobility in (7).

MEKA-0 Microactuator Array

Based on the results with elementary packed channel actuators, the initial 3×3 MEKA-0 microactuator array in Fig. 3 was fabricated and tested. This number of actuators was smaller than the typical unit-cell, but allowed examination of unit-cell fabrication and initial performance testing with unsteady applied fields. The array was sized for the UAV application in Fig. 2, consisting of individual microactuators with 1000 µm diameter and 2000 µm center-to-center spacing. The channels were mechanically drilled into a 3 mm thick glass substrate. A ring electrode was formed around the periphery of each microactuator channel using standard metallization and photoetching techniques. Due to chipping that occurred in the drilling process the resulting edge quality was relatively poor (see Fig. 4), however the resulting ring electrodes were of acceptable quality. The bottom surface electrode was common for all channels.

The MEKA-0 array was used to test the DC pumping capability of such an electrokinetic microactuator array. Results for the volume of electrolyte displaced over time at two different applied voltages are shown in Fig. 5, where the dependence on electric field strength in (8) is verified.

MEKA-1 – MEKA-4 Microactuator Arrays

Several further arrays were fabricated to assess laser drilling of the electrokinetic channels, explore design issues associated with larger unit cells, and examine alternate substrate materials. MEKA-1 was a 10×10 array fabricated in glass using CO₂ laser drilling. Individual electrokinetic channels were 2000 µm in diameter with 5 mm center-tocenter spacing. The channels were filled with the same porous polymer matrix as for the MEKA-0 array. A leadout pattern was designed for this array that would permit metallization of unit cells with 100 actuators. MEKA-2 was a 3×3 hydronautical-scale array consisting of 100 µm diameter electrokinetic channels with 200 µm center-to-center spacing. Fabrication was in glass using the same CO₂ laser drilling process. MEKA-3 and MEKA-4 arrays were fabricated in acrylic substrate, and explored compatibility of the polygel components with the substrate material.

MEKA-5 Full-Scale Hydronautical Array

MEKA-5, shown in Figs. 6-11, is a hydronautical array produced as a technology development step to demonstrate fabrication of full-scale dense arrays of electrokinetic microchannels and their integration with a top-layer containing the basic unit-cell structure. The array is fabricated in 7 cm \times 7 cm tiles. Each tile contains 25,600 individual electrokinetic



Figure 3. Initial electrokinetic microactuator array (MEKA-0), consisting of a single 3×3 unit-cell, fabricated in glass for initial testing. Individual actuators are 1000 μ m in diameter and filled with porous silicon matrix having approximately 1 μ m pore size. Top and bottom surface metallization and leadouts are also visible (see also Fig. 4).

microactuators, grouped into 1600 unit-cells (40×40 unitcells per tile), with each unit-cell composed of a 4×4 array of microactuators. Every 5th row and column of microactuators in the tile is skipped to provide room for unit-cell processing electronics.

Figures 6-8 show the center layer of the three-layer MEKA-5 hydronautical array tile. Each of the 25,600 individual electrokinetic microactuators has a 250 μ m microchannel diameter and 350 μ m center-to-center spacing between microactuators within a unit cell. The channels are fabricated in 250 μ m thick mylar material to provide high electric field

strength with low voltage differences across the center layer, and a flexible substrate that allows conformal application to vehicle surfaces. The electrokinetic polygel matrix material was filled in the liquid state in the microchannels by a twocomponent polymerization process. Curing produced a porous polygel matrix with pore sizes in the range of 1 μ m. Figure 9 shows an SEM image of the typical pore structure. Pore sizes vary significantly, but are typically 1 μ m and smaller, indicating a 1MHz theoretical frequency response limit. The 10 kHz loss-less response demonstrated with such polygel channels (see Fig. 5) is more than sufficient for the 1kHz frequency response requirements for sublayer control



Figure 4. Photomicroscope views of microactuator channels in MEKA-0 array (prior to polygel filling) with top and bottom surface metallization and electrode leadouts, showing edge imperfections from drilling in glass. Subsequent arrays were laser drilled in various substrates to examine mass fabrication options. MEKA-5 array in Figs. 6-11 was fabricated in a thin conformal mylar center layer.



Figure 5. Measured DC and AC performance of electrokinetic microactuators, showing DC volume displacement versus time at two different applied voltages (across 3 mm thick MEKA-0 array)(*left*) and variation in equivalent DC flowrate with AC frequency f(right). Ideal loss-less AC performance would correspond to f^{-1} rolloff indicated by straight line. Note that small (1 µm) polygel pore size produces essentially ideal AC performance to at least 10 kHz; theoretical frequency response limit for 1 µm pore size is approximately 1 MHz.

on large hydronautical vehicles.

The top layer of the MEKA-5 array is MEMS fabricated and provides the 25,600 individual microactuator electrodes and leadouts grouped into the unit-cell architecture (see Fig. 10). The layer is fabricated by a three-mask MEMS process consisting of a cavities mask, an electrodes mask, and a nozzles mask. The cavities mask is formed in SU-8 and provides the necessary separation between the top of the polygel within each microchannel in the center layer and the corresponding top-layer electrode. The electrodes mask is patterned in platinum and provides the top-layer electrode for each microactuator and the leadout to a contact at the unit-cell edge, as shown in Fig. 11. The nozzles mask is etched in polyamide and provides a 50 µm nozzle through which pumping occurs. Fabrication of the complete top-layer was done via MEMS Exchange in The University of Michigan fabrication facilities.

The architecture for arrays like MEKA-5 is based on a 4 ÿ 4 unit-cell composed of wall shear stress sensors and electrokinetic microactuators. The top surface electrode for each microchannel has a leadout that runs to a contact at the edge of the unit-cell. All the unit-cells within the tile share a common ground electrode in the bottom layer. A power bus for the entire tile, held at constant reference voltage V_{ref} , runs along horizontal and vertical lines between the active areas of adjacent unit-cells (see Fig. 11). This makes the array highly fault tolerant to damage. The look-up table logic circuit provides a three-state bridge between the electrode contact for each of the microactuators and the corresponding closest power bus line. Thus on each clock cycle, the actuator state vector $\{A_i\}$ obtained via the programmable logic array from the sensor state vector $\{S_i\}$ sets the voltage $A_i V_{ref}$ of the top electrode for each actuator. This produces blowing on some actuators, suction on some actuators, and no action on the remaining actuators. The space between adjacent unit cells on the MEKA-5 array suffices to accommodate the relatively simple circuitry needed to implement this system architecture.

The MEKA-5 array represents the current state-of-the-art in electrokinetic microactuator array fabrication for sublayer control of turbulent boundary layers on full-scale vehicles. The individual microactuator size and performance, their arrangement into dense 25,600-element tiles with unit-cell architecture, and fabrication of a top layer with electrodes and leadouts, demonstrate key steps required to produce a fully functional hydronautical-scale microactuator array. A future



Figure 6. Tile layout of MEKA-5 hydronautical-scale array, conisting of 25,600 electrokinetic microactuators on a 7×7 cm tile, grouped into 40×40 unit-cells, each composed of a 4×4 arrangement of individual microactuators with 250 µm diameter and 350 µm center-to-center spacing.



Figure 7. Unit-cell arrangement for MEKA-5 hydronautical array, showing partial view of microchannel layout. Filled center layer is shown in Fig. 8. Every 5th row and column in the tile is left open to provide space for redundant common power bus lines and unit-cell look-up table circuitry that connects individual microactuator top-surface electrodes within each unit-cell to power bus (see Fig. 10).

MEKA-7 array will contain colocated wall shear stress sensors with each of the individual microactuators as a further technology development step, and a subsequent MEKA-8 array will include the look-up table logic circuitry that interconnects the sensors and the actuators.

MEKA-6 Laboratory Demonstration Array

The MEKA-0 array was used to demonstrate pumping at the required equivalent DC pump rates using electrokinetic microchannels filled with the porous polygel matrix material. The purpose of the MEKA-6 array is to conduct a wind tunnel demonstration of streamwise vortical structure manipulation via electrokinetic pumping. The experiments, which are currently being set up, will use a synthetically-generated streamwise vortex over a flat-plate body, and will induce lateral displacements of this structure by pumping from an electrokinetic actuator.

A unique Dual Stereo PIV (DSPIV) system has been assembled for these measurements, which will allow highlyresolved measurements of all nine components in the velocity gradient tensor field $\mathbf{u}(\mathbf{x},t)$ (see Fig. 12). This permits direct visualization of the streamwise vortical structure and its displacement, as well as the wall shear stress signature below the vortical structure. The basic layout of the DSPIV system is shown in Fig. 13. The system uses four frequencydoubled Nd:YAG lasers (Spectra-Physics) to provide beams



Figure 9. SEM photograph showing porous polymer matrix material used to obtain electrokinetic pumping in microactuator channels. Pore sizes are typically 1 μ m or smaller, leading to very high frequency response of EK pumping.



at 532 nm (green) with roughly 10 nsec pulse length. Two of these beams are used to pump a dye laser, which provides output centered around 623 nm (red). The green and red beams from two of the lasers are formed into parallel light

Figure 8. Photograph showing part of thin (250 μ m thick) mylar center layer of MEKA-5 hydronautical-scale array, with 250 μ m diameter electrokinetic microchannels filled with polygel matrix material.



Figure 10. Unit-cell electrode layout in MEKA-5 array, showing layout of top surface electrodes within each unit-cell. Unit-cell look-up table circuitry connects individual electrodes to common voltage bus and sets polarity for each actuator.



Figure 11. Microphotographs of MEMS top layer for MEKA-5 full-scale hydronautical array, showing platinum electrodes with leadouts to contacts within each unit cell. Complete MEMS top layer in each MEKA-5 tile contains 1600 such 4 × 4 unit cells.

sheets that intersect the vortical structure. Each of the green and red light sheets is double-pulsed by time-separating the corresponding pulses from the Nd:YAG lasers. Two stereo PIV systems (LaVision) are used to record particle images in the green and red light sheets. Optical filters allow each pair of cameras to see only one color. The two SPIV systems are slaved together and operated via a custom master-slave software arrangement developed for this application by LaVision. Processing of the two separate stereo PIV image pairs produces the velocity field $\mathbf{u}(\mathbf{x},t)$ and, more importantly, the full velocity gradient field $\mathbf{u}(\mathbf{x},t)$. Figure 14 shows the wind tunnel arrangement and the DSPIV system for these experiments.

9. Concluding Remarks

Microactuator arrays based on the electrokinetic principle have several characteristics that make them potentially suitable for practical sublayer control on full-scale aeronautical and hydronautical vehicles. They involve no moving parts and can achieve high frequency response due to the fundamental principle on which they operate. The equivalent DC pumping rate of such microactuators has been shown to meet the requirements for sublayer control under conditions applicable to full-scale hydronautical vehicles. The AC frequency response of such microactuators easily exceeds the 1 kHz requirements for sublayer control on hydronautical vehicles, and the ultimate frequency limit may be in the MHz range. Large dense arrays of such electrokinetic microactuators can be fabricated with a three-layer design, in which electrokinetic pumping occurs in a center layer with microchannels formed in a substrate material using laser drilling. These channels can be filled with a 1 µm-scale porous polymer matrix material that provides the electrokinetic double-layer when wetted by an appropriate electrolyte. The bottom layer forms a common electrolyte reservoir and provides a common electrode for all channels. The top layer is MEMS-fabricated to provide a separate electrode for each microactuator, and can be combined with wall shear stress sensors and comparatively

simple processing electronics to produce a fully functional array. A system architecture has been developed based on he inherently local nature of the sublayer dynamics, which allows segmenting tiles into individual unit-cells with comparatively few sensors and actuators. This local unit-cell approach allows considerable simplifications in the sensorand processing requirements. Sensor outputs are referenced to a running average to eliminate effects of drift and the need for calibration. Thresholding of the sensor outputs and the use of three discrete actuator states, together with the relatively small unit-cell size, allows the processing electronics to be accomplished by a simple look-up table implemented with a programmable logic array. The array serves as a three-state bridge between each actuator electrode and a common power bus that runs between all the unit-cells in the tile, making the array highly fault tolerant to damage.



Figure 12. Parallel green and red laser light sheets for dualstereo PIV measurements, showing velocity gradients obtained within each sheets and between the two sheets.



Figure 13. Schematic showing lasers and imaging cameras assembled for dual-stereo particle image velocimetry (DSPIV) measurements of streamwise vortical structure manipulation via electrokinetic actuators. Two closely-spaced double-pulsed laser sheets, one green and one blue, are viewed by two pairs of LaVision stereo PIV cameras and a master-slave arrangement of data acquisition systems.



Figure 14. Experimental arrangement for dual-stereo particle image velocimetry (DSPIV) demonstration of streamwise vortical structure manipulation via electrokinetic actuators, showing wind tunnel and DSPIV measurement system (*left*) and closeup of DSPIV system for vorticity and shear stress measurements.

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