THE FLUID MECHANICS OF MICRO ELECTRO MECHANICAL SYSTEMS(M E M S)

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Abstract: Manufacturing processes that can create extremely small machines have been developed in recent years. Micro electro mechanical systems (MEMS) refer to devices that have characteristic length of less than 1 mm but more than 1 micron, that combine electrical and mechanical components and that are fabricated using integrated circuit Batch-processing techniques. Electrostatic, magnetic, pneumatic and thermal actuators, Motors, valves, gears, and tweezers of less than 100-pm size have been fabricated. These have been used as sensors for pressure, temperature, mass flow, velocity and sound, as actuators for linear and angular motions, and as simple components for complex systems such as micro-heat-engines and micro-heat-pumps. The technologies progressing at a rate that far exceeds that of our understanding of the unconventional physics involved in the operation as well as the manufacturing of those minute devices. The primary objective of this article is to critically review the status of our understanding of fluid flow phenomena particular to micro devices. In terms of applications, the paper emphasizes the use of MEMS as sensors and actuators for flow diagnosis and control.

Technologies for micromachining are reviewed in the context of their application in fluid systems. Four micromachining technologies are bulk rnicro machining, surfacemicro machining, wafer bonding, and high aspect-ratio micro structures (HARM). Two examples of micro machined devices for flow sensing and control are described. The first is a floating-element shear-stress sensor. and the second is a micro machined valve. Issues important to the application of micromachining are summarized in this paper.

Introduction:

Definition: Fluid mechanics is the science of the mechanics of liquids and gases. It involves many of the same principles of solid Staticsand Dynamics, but fluids is a more complex subject because solids involve the study of forces on discrete bodies, while in fluids bodies flow together.

- The analysis is based on the fundamental laws of mechanics, which relate continuity of mass and energy with force and momentum.
- An understanding of the properties and behavior of fluids at rest and in motion is of great importance in engineer

Knowledge of fluid mechanics in needed to properly design many engineering projects, including water pipe systems, storm water drainage systems, aircraft, brake systems, heating and air conditioning systems, golf balls, boats, and cars. Therefore, most of you will use Fluid Mechanics in your work.

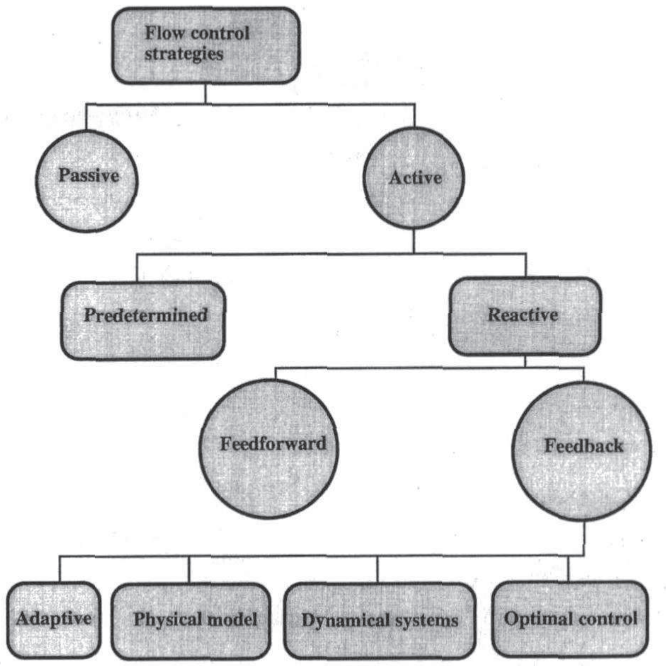
Historical development of Fluid mechanics:

- Ancient civilizations: irrigation, ships
- Ancient Greece: Archimedes –buoyancy (3rdcentury B.C.)
- Ancient Rome: aqueducts, baths (4th century B.C.)
- Leonardo (1452-1519): experiments, research on waves, jets, eddies, streamlining, flying
- Newton (1642-1727): laws of motion, law of viscosity, calculus
- 17th & 18th century engineers: solutions to frictionless fluid flows (hydrodynamics), empirical equations (hydraulics)
- Late 19th century: dimensionless numbers, turbulence At some of (1904): proposes idea of
  Flow fields of low-viscosity fluids divided into two zones:
  A thin, viscosity-dominated layer near solid surfaces
  An effectively inviscidouter zone away from boundaries
  Explains paradoxes
  Allow analysis of more complex flows.
- 20th century: hydraulic systems, oil explorations, structures, irrigation, computer applications and fluid flow phenomena particular to microelectronic devices
- Beginning of 21st century:
  No complete theory for the nature of turbulence
  Still a combination of theory and experimental data

By Using Fluid mechanics is used to design the following one's

Significance	used to design of
Weather & climate	Water supply system –Waste water treatment, Dam spillways
Aerodynamics	Aircrafts, rockets,computer disk drives,
Combustion	valves, flow meters–Shock absorbers, brakes –automatic transmissions
Energy generation	–ships, submarines, breakwaters, marinas
Geology	–Bearings, Artificial organs
Hydraulics and Hydrology	–Windmills, turbines -pumps,HVAC systems
Sports & recreation	–Sport items: Golf balls, Race cars

Classification of flow control strategies:



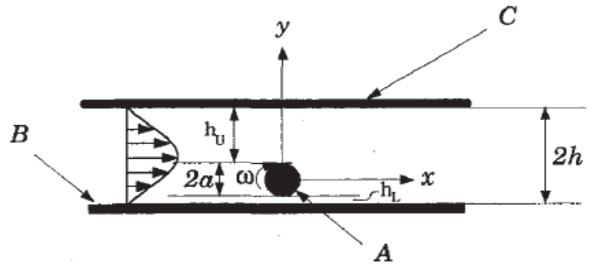
Introduction to Micro devices for Flow Control: MEMS integrates electronics and mechanical components and can therefore executesense-decision-actuation on a monolithic level. Micro sensors/micro actuators would be ideal for the reactive flow control concept advocated in the present subsection. Methods of flowcontrol targeted toward specific coherent structures involve nonintrusive detection and subsequent modulation of events that occur randomly in space and time. To achieve proper targeted control of these quasi-periodic vertical events, temporal phrasings well as spatial selectivity are required. Practical implementation of such an idea necessitates the use of a large number of intelligent, communicative wall sensors and actuators arranged in a checkerboard pattern., characteristics and energy consumption of such elements required to modulate the turbulent boundary layer which develops along a typical commercial aircraft or nuclear submarine.

An upper-bound number to achieve total turbulence suppression is about one million sensors/actuators per square meter of the surface, although as argued earlier the actual numberneeded to achieve effective control could perhaps be one or two orders of magnitude below that.

The sensors would be expected to measure the amplitude, location, and phase or frequency of the signals impressed upon the wall by incipient bursting events. Instantaneous wall-pressure or wall-shear stress can be sensed, for example. The normal or in-plane motion of a minute membrane is proportional to the respective point force of primary interest. For measuring wallpressure, microphone-like devices respond to the motion of a vibrating surface membrane or an internal elastomeric. Several types are available including variable-capacitance (condenser or electrolyte), ultrasonic, optical (e.g., optical-fiber and diode laser), and piezoelectric devices.A potentially useful technique for our purposes has been tried at MIT (Warrenton et al., 1987; Young et al., 1988; Haritonidis et al., 1990a; 1990b). An array of extremely small (0.2 mm in diameter) laser-powered microphones(termed microphones) was machined in silicon using integrated circuit fabrication techniques, and was used for field measurement of the instantaneous surface pressure in a turbulent boundary layer. The wall-shear stress, though smaller and therefore more difficult to measure than pressure, provides a more reliable signature of the near-wall events.

Micro pumps: There have been several studies of microfabricatedpumps. Some of them use non-mechanical effects. The Knudsen pump uses the thermalcreepeffect to move rarefied gases from one chamber to another. Ion-drag is used in electro hydrodynamic pumps.

Schematic of micro pump:

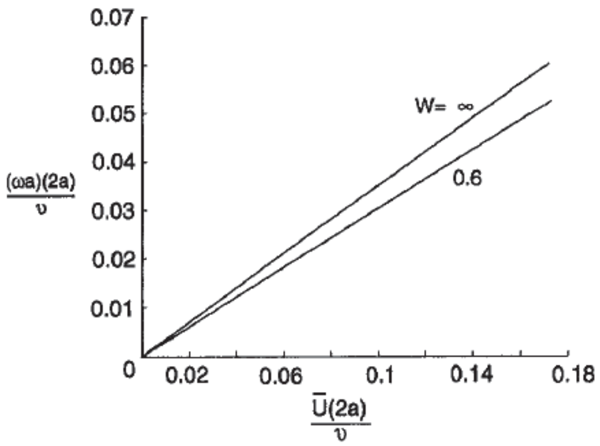


These relay on the electrical properties of the fluid and are thus not suitable for many applications. Valve less pumping by ultrasound has also been proposed (Moroney et al., 1991), but produces very little pressure difference. Mechanical pumps based on conventional centrifugal or axial turbo machinery will not work at micro machine scales where the Reynolds numbers are typically small, on the order of 1 or less. Centrifugal forces are negligible and, furthermore, theKatter condition through which lift is normally generated is invalid when inertial forces are vanishingly small.

In general there are three ways in which mechanical micro pumps can work:

1. Positive-displacement pumps. These are mechanical pumps with a membrane or diaphragm actuated in a reciprocating mode and with unidirectional inlet and outlet valves. They work on the same physical principle as their larger cousins. Micro pumps with piezoelectric actuators have been fabricated. Other actuators, such as thermo pneumatic, electrostatic, electromagnetic or bimetallic, can be used These exceedingly minute positive-displacement pumps require even smaller valves, seals and mechanisms, a not-too-trivial micro manufacturing challenge. In addition there are long-term problems associated with wear or clogging and consequent leaking around valves. The pumping capacity of these pumps is also limited by the small displacement and frequency involved. Gear pumps are a different kind of positive-displacement device.
2. Continuous, parallel-axis rotary pumps. A screw-type, three-dimensional device for low Reynolds numbers was proposed by Taylor (1972) for propulsion purposes and shown in his seminal film. It has an axis of rotation parallel to the flow direction implying that the powering
3. motor must be submerged in the flow, the flow turned through an angle, or that complicated gearing would be needed.
4. Continuous, transverse-axis rotary pumps. This is the class of machines that was shown that a rotating body, asymmetrically placed within a duct, will produce a net flow due to viscous action. The axis of rotation can be perpendicular to the flow direction and the cylinder can thus be easily powered from outside a duct. A related viscous-flow pump was designed by OdeU and Kovasznay(1971) for a water channel with density stratification. However, their design operates at a much higher Reynolds number and is too complicated for micro fabrication.

Micro turbines: De Courtye (1998) have described the possible utilization of the inverse micro pump devices a turbine. The most interesting application of such a micro turbine would be as a micro sensor for measuring exceedingly small flow rates on the order of nanoliter/s (i.e.,microflow metering for medical and other applications).The viscous pump described in operates best at low Reynolds numbers and should therefore be kinematicallyreversible in the creeping-flow regime. A micro turbine based on the same principle should, therefore, lead to a net torque in the presence of a prescribed bulk velocity. The results of three-dimensional numerical simulations of the envisioned micro turbines are summarized in this subsection.



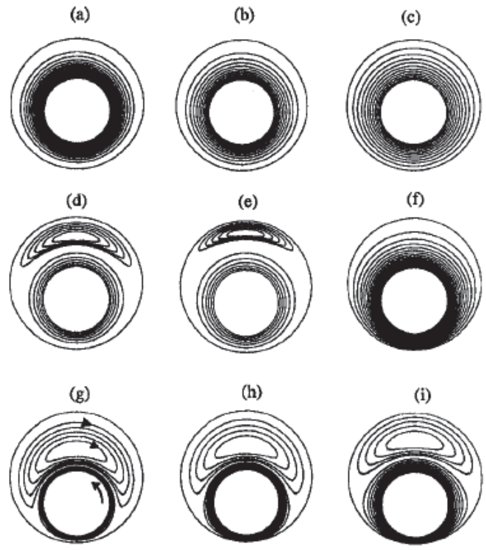
Turbine rotation as a function of the bulic velocity: The Reynolds number for the turbine problem is defined in terms of the bulk velocity, since the rotor surface speed is unknown in this case, where *U* is the prescribed bulk velocity in the channel, *a* is the rotor radius, and *v* is the kinematic viscosity of the fluid.

The turbine characteristics are defined by the relation between the shaft speed and the applied load. A turbine load results in a moment on the shaft, which at steady state balances the torquedue to viscous stresses. At a fixed bulk velocity, the rotor speed is determined for different loads on the turbine. Again, the turbine characteristics are linear in the Stokes (creeping) flow regime, but the side walls have weaker, though still adverse, effect on the device performance as compared to the pump case. For a given bulk velocity, the rotor speed drops linearly as the external load on the turbine increases. At large enough loads, the rotor will not spin, and maximum rotation is achieved when the turbine is subjected to zero load.

Micro bearings: Many of the micro machines use rotating shafts and other moving parts which carry a load and need fluid bearings for support, most of them operating with air or water as the lubricating fluid. The fluid mechanics of these bearings are very different compared to that of their larger cousins. Their study falls in the area of micro fluid mechanics, an emerging discipline which has been greatly stimulated bytes applications to micro machines and which is the subject of this paper.

Macro scale journal bearings develop their load-bearing capacity from large pressure differences which are a consequence of the presence of a viscous fluid, an eccentricity between the shaft and its housing, a large surface speed of the shaft, and a small clearance to diameter ratio. Several closed-form solutions of the no-slip flow in a macro bearing have been developed. Wannier (1950) used modified Cartesian coordinates to find an exact solution to the bi harmonic equation governing two dimensional journal bearings in the no-slip, creeping flow regime.

Kamal(1966) and Ashino and Yoshida (1975) worked in bipolar coordinates; they assumed a general form for the stream function with several constants which were determined using the boundary conditions. Though all these methods work if there is no slip, they cannot be readily adapted to slip flow. The basic reason is that the flow pattern changes if there is slip at the walls and the assumed form of the solution is no longer valid.



Effect of slip factor and eccentricity on micro bearing lines

Micro bearings are different in the following aspects: (1) being so small, it is difficult to manufacture them with a clearance that is much smaller than the diameter of the shaft; (2) because of the small shaft size, its surface speed, at normal rotational speeds, is also small; and (3) air bearings in particular may be small enough for non-continuum effects to become important.

(The micro turbo machines being developed presently at MIT operate at shaft rotational speeds on the order of 1 million rpm,and are therefore operating at different flow regime from thatconsidered here.) For these reasons the hydrodynamics of lubrication is very different at micro scales. The lubrication approximation that is normally used is no longer directly applicableand other effects come into play. From an analytical point of view there are three consequences of the above: fluid inertia is negligible, slip flow may be important for air and other gases, and relative shaft clearance need not be small.

Micromachining technologies: The micromachining technologies can be broadly classified into four general area; bulk micro rnachining, surface micromachining, wafer bonding, and high aspect-ratiomicrostructure technology (HARM).

The oldest and most familiar method of micromachining involves the selective masking and etching of the bulk of a material. Most of this technology has centered around the use of single-crystal silicon as the material given its excellent properties and the existing technology base of integrated circuits.

Bulk micromachining methods usually involve etching through most of a silicon wafer (250-750 um thick), which translates to relatively large structures (of order several millimeter). Surface micro machining uses thin film deposition and selective etching to fashion micrornachined devices with thicknesses on the order of one micron, and lateral dimensions of the order 100 um. However(1988) has written a review of this process technology is a simplified schematic of a surface micromachining process. A thin film spacer material is deposited and patterned. and followed by the deposition and patterning of a structural material on a substrate. The substrate and thin films are next immersed in which selectively removes the spacer material without

Etching either the structural material or the substrate.

This process has been exploited in a large". Amount of micromechanical devices, and in some instances has been combined with bulk micromachining. The advantages of the surface micromachining method are the relative small size of the devices fabricated, and the ability to use materials other than silicon as the mechanical material. A large number of different materials have been demonstrated using surface micro machining including polycrystalline silicon, silicon nitride, metals, and polymers. This diversity of materials can also be a disadvantage since the mechanical properties and stresses of these thin films is often not well understood.

High aspect-ratio microstructures (HARM): High aspect-ratio microstructures (HARM) is a terminology applied to a class of devices fabricated by methods which permit extension of the microstructure vertically by tens to hundreds of microns. The most commonly recognized technology in this class is called LIGA The LIGA process entails formation of an extremely high aspect-ratio pattern in a thick photosensitive material by exposure with a synchrotron x-ray source. Vertical structures hundreds of microns high with lateraltapers of less than several microns have been demonstrated.

Plating is performed through the patterned material to fort metal microstructures. These plated structures can then be used as molds for injection molding or stamping processes. The use of anx-ray exposure process is a limit to the availability of this technology, although there have been several demonstrations of similar processes using deep UV lithography, which is more commercially accessible. In this case the thicknesses are limited to tens of microns and the aspect ratio is not as high .

Conclusions: Micromachining can be an enabling technology in fluid systems. Recent advances in technology. CAD. material science. and packaging are making micromachining more accessible inthose not familiar with the technology. This increased access will facilitate the use of micro machined structures in more applications. Sufficient caution to issues of materials,processdesign, packaging, and system partitioning will enhance the likelihood of success.

Micro electro mechanical systems(MEMS) have witnessed explosive growth during the last decade and are finding increased applications in a variety of industrial and medical fields. The physics of fluid flows in micro devices and some representative applications have been explored in this paper. While we now know a lot more than we did just few years ago, much physics remains to be explored so that rational tools can be developed for the design, fabrication and operation of MEMS devices.

The traditional Navier-Stokes model of fluid flows with no slip boundary conditions works only for a certain range of the governing parameters. This model basically demands two conditions.

1. The fluid is a continuum, which is almost always satisfied as there are usually more than 1 million molecules in the smallest volume in which

appreciable macroscopic changestake place. This is the molecular chaos restriction.

2. The flow is not too far from thermodynamic equilibrium, which is satisfied if there is sufficient number of molecular encounters during a time period small compared to the smallest time-scalefor flow changes. During this time period the average molecule would have moved a distance small compared to the smallest flow length-scale MEMS are finding increased applications in the diagnosis and control of turbulent flows. The use of micro sensors and micro actuators promises a quantum leap in the performance of reactive flow control systems, and is now in the realm of the possible for future practical devices. Simple, viscous-based micro pumps can be utilized for micro dosage delivery, and micro turbines can be used for measuring flow rates in the nanoliter range. Both of these can be of value in several medical applications.

Much nontraditional physics is still to be learned and many exciting applications of micro devices are yet to be discovered.

Future Scope: Much nontraditional physics is still to be learned and many exciting applications of microelectronic devices are yet to be discovered.

The future is bright for this emerging field of science and technology and members of the Mechanical Engineers should be in the forefront of this progress. Like Richard Feynman was right about the possibility of building. mite-size machines, but was somewhat cautious in forecasting that such machines, while "would be fun to make," may or may not be useful.

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