

# Microcantilever: An Efficient Tool for Biosensing Applications

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**Abstract**—Most of the biosensing applications involving analysis and detection of a particular specimen demands fast, easy to use, less expensive, highly reliable and sensitive method for the recognition of biomolecules. The reason behind this increasing demand is that most of the available laboratory equipment require large space, are highly expensive and have other preconditions. Most of the viscometers available for measuring the rheological properties of blood require cleaning after each use which can be challenging due to the capillary geometry. The substitute to this is microcantilever that has emerged as an ideal candidate for biosensing applications. Microcantilever is capable of being used in air, vacuum or liquid medium. This paper consists of seven sections in which working principle of a cantilever, different modes of vibration, their comparative analysis, analytical equations of hydrodynamic equations exerted by the fluid on the cantilever and their impact on the resonant frequency and quality factor, applications of microcantilever in liquid medium specifically in biomedical field are discussed.

**Index Terms**—Microcantilever, dynamic mode, resonant frequency, biosensing, rheology.

## I. INTRODUCTION

MEMS (Microelectromechanical systems) is one of the most promising technologies in which several mechanical devices like sensors, actuators, transducers implanted in semiconductor chips are consolidated with computers [1]. The attractive features of MEMS devices are: they are interdisciplinary in nature, exhibits batch production, less expensive, highly miniaturized structure, highly reliable, better performance than other available technologies. Different biosensors, blood pressure sensors, microviscosity sensors, microcantilevers, micropumps, microvalves, micro flow sensors, optical switches, airbag sensors, all come under the category of MEMS devices [2]. MEMS biosensors are utilized for studying intermolecular interactions, for microfluidic rheometry [3] i.e. measuring rheological (mechanical) properties of

different fluids, in Diagnostic and Translational applications [4]. The Global Positioning system can be used for tracking purposes and much more.

Since we are focusing on biosensing applications, for that purpose MEMS-based microcantilever sensor is studied. In biomedical applications, selection of biocompatible material for a specific application is very important.

### A. Biocompatible materials used in medical practices

Though there are numerous fields where MEMS system finds its applications. Since we are focusing on biosensing applications, it becomes important to have an idea of biocompatible materials [5]. Before that, it is necessary to understand what biocompatibility is. Biocompatibility is the ability of a material to perform with appropriate host response in a specific situation. Alternatively, it is the ability to be intact with a living system without producing adverse effects. Fig.1. shows different types of biocompatible materials.

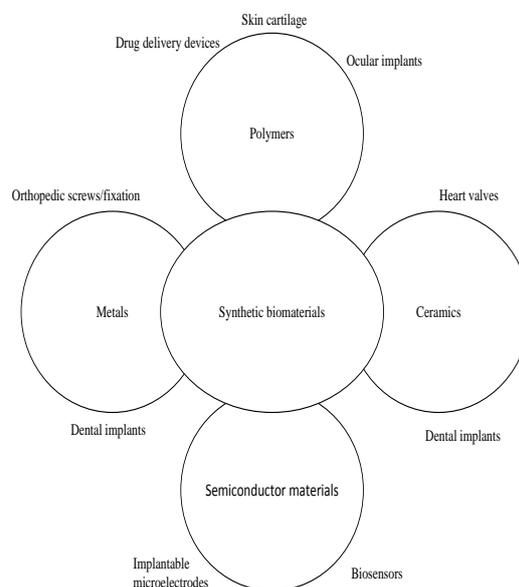


Fig.1. Types of biocompatible materials.

## II. MICROCANTILEVER

Microcantilever is a beam of solid material say, silicon, nickel, etc. in the submillimeter range that is kept fixed at one end and allowed to vibrate freely at another end. The vibrations of the cantilever in a particular medium say, air, vacuum or liquid are studied and are then utilized in measuring various parameters involved in the applications. Microcantilevers are the devices that have

greater potential as microsensing platform [14]. The features like high mass sensitivity, a high degree of parallelization, easy implementation, non-toxic procedures, better limit of detection, fast response, low fabrication cost, label-free detection etc., makes them an ideal candidate for biosensing applications. The various applications of MEMS are shown in Table 1. [15]. And the different types of biocompatible materials for different applications are shown in Table 2.

Table 1. Various applications of MEMS.

Field of application	MEMS devices	Purpose	Advantages	References
In telecommunication	Optical MEMS, tunable capacitors, RF MEMS switches, high Q inductor.	For voltage controlled oscillators, splitters, and couplers, optical attenuators, micro-lenses, displays.	Improved efficiency of optical assembly and alignment accuracy.	[6], [7]
In Healthcare	Pressure sensors, MEMS inertial sensor, capacitive sensors.	For tonometric blood pressure measurement, surgery, kidney dialysis equipment, respirators, in pacemakers.	Increased signal output and stability, a sensitivity of 2mV/mm Hg 100 mm Hg and resolution of 0.5 mm Hg. Microfluidics enables reduction of fluid sample size, up to thousands of tests per chip.	[8], [9]
In automotive industry	Accelerometer, airbag sensors, break force sensors.	Collision detection, intelligent tyres.	3-axis accelerometer consumes less power and is useful for accurate tilt measurement and operating temperature varies from -40 <sup>0</sup> C to +105 <sup>0</sup> C. 3-axis digital gyroscope operating temperature varies from -40 <sup>0</sup> C to +85 <sup>0</sup> C, is used for multiple applications(Pitch, Roll, Yaw)	[10],[11]
In defense	Embedded sensors, chemical sensors for soldiers, microactuators.	Missile guidance, surveillance, data storage, identification friend or foe.	A chemical sensor for soldiers detects chemical agents below harmful thresholds, small lightweight, rugged. MEMS-based Friend or foe identification has 360 <sup>0</sup> coverage, fast response, low probability of intercept.	[12],[13]

Table 2. Biocompatible materials and its area of applications

Biocompatible materials	Area of application
Titanium	Dental implants, bone implant, pacemaker boxes, surgical instruments
Ni-Ti alloys	Orthodontics
PIB, EPCO	Measuring concentration of contaminants in harmful water
Silicone-hydrogel	Contact lenses
PDMS	Cerebrospinal fluid monitoring

Microcantilever works in both static and dynamic modes which are discussed in next section. The cantilever can be used as a sensing device in any environment say, air, vacuum, liquid. In the field of biology, microcantilever can be used for the detection of PSA

(Prostate-Specific Antigen), detection of myoglobin, detecting DNA hybridization, detection of single vaccine virus particle, detection of low-density lipoproteins, detection of Escherichia coli. In the field of chemistry and environmental monitoring, cantilevers are used for the detection of humidity, temperature and heat changes, infrared light and UV radiations, harmful contaminants in water, to estimate changes in fluid pressure, analyte vapors in the gas phase and much more. Fig.2. [16] shows the applications of microcantilever in different fields.

## III. GENERIC OPERATION OF MICROCANTILEVER

Microcantilever has two modes of operation: static mode and dynamic mode [17]. In static mode, the top surface of the cantilever is coated with antigen sensitive

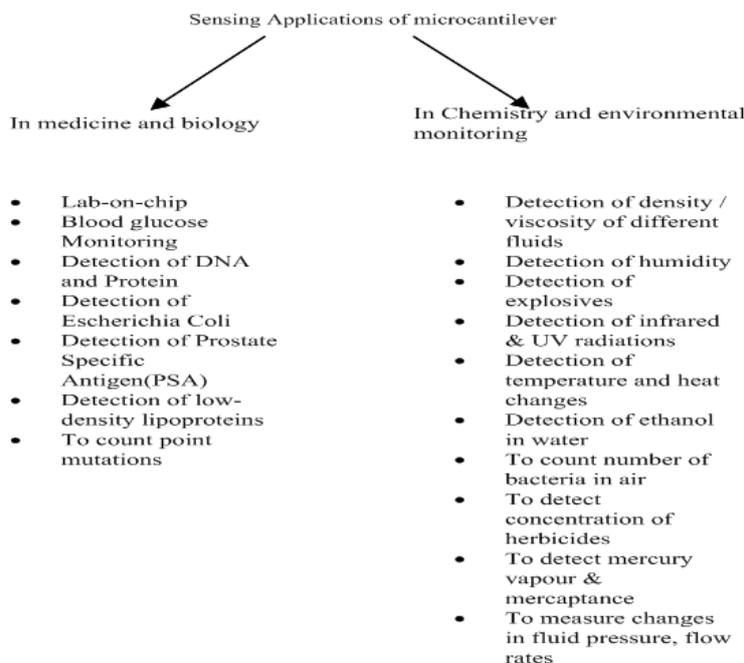


Fig.2. Sensing applications of microcantilever [16].

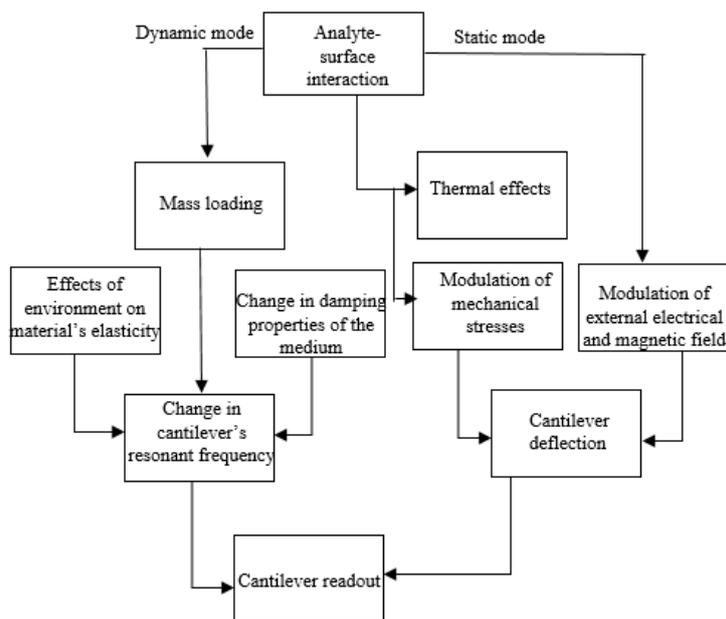


Fig.3. A flowchart depicting cantilever's mode of operation and transduction principle (Adapted from [19]).

film and the other side of the cantilever is coated with the non-reactive film so as to avoid any hindrance during the antigen-antibody interaction. Alternatively, static mode is sensitive to surface stress [18]. Whereas in dynamic mode both the top and the bottom surface of the cantilever is coated with an active film. Instead of coating both the surfaces of the microcantilever, it is possible to study dynamic behavior (resonant frequency and quality factor) of the cantilever by coating either surface. In dynamic mode, the inertia force is adequate to cause the structure to vibrate. The analyte-antibody interaction causes the change in the total mass which in turn changes the resonant frequency. In static mode, the load is applied slowly as a result of which the inertia force can be

ignored. Microcantilever can be made to operate in any medium say, air, water, and vacuum. When we are using the microcantilever in the liquid medium, then cantilever's dynamic mode of operation is preferred. The reason behind this is that the molecules to be detected do not have attributes that lend themselves to be detected, so dynamic mode is favored over static mode where the frequency of cantilever changes in response to analyte binding. Fig.3. is the flowchart depicting cantilever's mode of operation [19]. The change in cantilever's resonant frequency is sensitive to environments' effects on material's elasticity, mass loading and damping properties of the medium. And in the case of static mode, the cantilever's deflection is sensitive to thermal effects,

modulation of mechanical stress and external electrical and magnetic field. The most interesting thing about microcantilever sensor is that it can be used to measure the mechanical properties of fluid [20]. By mechanical properties we mean, the fluid’s viscosity, its density. The idea that the cantilever can be used for measuring the rheological properties comes from factuality that the dynamic response of cantilever is contingent on the

medium of operation. The conspicuous or determining factors in resonating microcantilevers are resonant frequency and quality factor. So, by tracking the change in resonance frequency and quality factor, we can determine the rheological properties of any kind of fluid. Table 3.shows different deflection detection methods of the microcantilever.

Table 3. Microcantilever deflection detection method.

Deflection detection methods	Working principle	Advantages	Disadvantages	References
Piezoresistive deflection detection method	Stress is recorded by implanting piezoresistive material near cantilever’s top surface.	Allows to integrate readout system on chip	Deflection resolution is small (1nm)	[21]
Capacitive deflection detection method	Change in capacitance due to analyte-antibody interaction on the surface of the cantilever is recorded.	Highly sensitive and provides outright displacement.	Inefficient while measuring large deflections.	[22]
Optical deflection detection method	Deflection of low power laser beam at the surface of the cantilever is recorded using photoelectric position detector.	Measures deflection in sub-nanometer range	Irregular response in liquid cell environment	[23]
Interferometry deflection detection method	Interference signal which consists of reference laser beam and the laser beam reflected by cantilever is recorded with the help of photodiode.	Highly sensitive	Less sensitive in liquids	[24]

IV. DIFFERENT MODES OF VIBRATION

Microcantilever vibrating in any medium exhibits different types of vibrational modes. The nature of these modes depends upon the nature of the force being applied to the cantilever’s surface [25] [26] [27].

A. Transverse mode

When the microcantilever is subjected to the force which is acting perpendicularly to the cantilever surface and is parallel to the axis at the fixed end, the cantilever is said to be vibrating in the transverse mode. This mode is also termed as the out-of-plane bending mode. Fig.4. represents the transverse mode. It is clear that the cantilever is having zero deflection at fixed end and is exhibiting maximum displacement of 3.37 μm at free end.

The expression for nth order resonant frequency in the transverse mode is given as:

$$f_{Tr}^n = \frac{t}{4\pi} \frac{\lambda_n^2}{L^2} \sqrt{\frac{E}{3\rho_c}} \tag{1}$$

where  $\lambda_n$  is the eigenvalue which can be calculated from  $1 + \cos(\lambda_n)\cosh(\lambda_n) = 0$ , n is positive integer. The first five eigenvalues calculated are 1.8751, 4.6941, 7.8548, 10.9955, 14.1372.

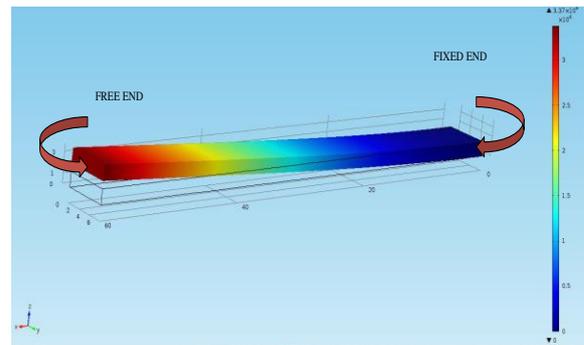


Fig.4. The geometry of a microcantilever having dimensions (60\*6\*1.5) μm vibrating in the transverse (out-of-plane) direction with undamped natural frequency (5.7762e5Hz).

The eigenvalues are calculated using the formula:

$$\lambda_n = \frac{\pi(2i-1)}{2} \text{ for } i < 5 \tag{2}$$

B. Lateral mode

When the force being applied on the surface of the microcantilever is in the direction parallel to the surface of the cantilever and perpendicular to the axis at the fixed end, the cantilever is said to be vibrating in the lateral mode. This mode is also termed as the in-plane flexural mode. Fig.5. represents the lateral mode. It is clear that the displacement is zero at the fixed end and is having maximum value of 3.36 μm at the free end.

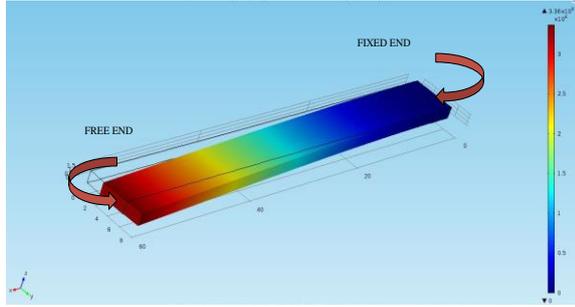


Fig.5. The geometry of a microcantilever having dimensions (60\*6\*1.5)  $\mu\text{m}$  vibrating in the lateral (in-plane) direction with undamped natural frequency (2.2871e6Hz).

The expression for nth order resonant frequency of microcantilever vibrating in the lateral mode is given as:

$$f_{La}^n = \frac{w\lambda_n^2}{4\pi L^2} \sqrt{\frac{E}{3\rho_c}} \quad (3)$$

The eigenvalues ( $\lambda_n$ ) calculated above are same for in-plane mode.

### C. Torsional mode

When the nature of the cantilever vibration is such that its one edge of the free end is vibrating in the y-direction and another edge in  $-y$  direction, then the cantilever is said to be vibrating in the torsional mode. Fig.6. represents torsional mode. It is clear from the figure that at the fixed end the displacement is zero and at the free end, it is having maximum deflection of 3.91  $\mu\text{m}$ .

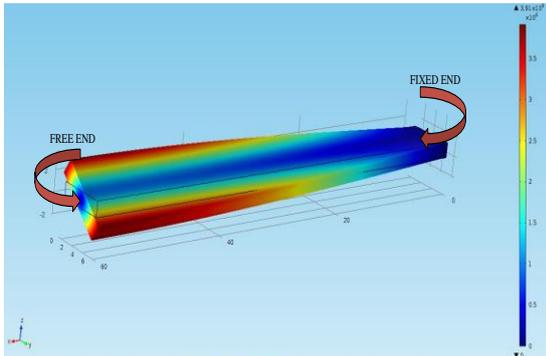


Fig.6. Geometry of microcantilever having dimensions (60\*6\*1.5)  $\mu\text{m}$  vibrating in the torsional mode with undamped natural frequency (1.0169e7Hz).

The expression for nth order resonant frequency of microcantilever vibrating in the torsional mode is given as:

$$f_{To}^n = \frac{(2n-1)}{4L} \sqrt{\frac{G\xi}{\rho_c I_p}} \quad (4)$$

where G is given by:

$$G = \frac{E}{2(1+\nu)} \quad (5)$$

$\nu$  depends upon the chosen material

$I_p$  is the polar moment of inertia given by:

$$I_p = \frac{tw^3 + wt^3}{12} \quad (6)$$

$\xi$  is the damping coefficient given by:

$$\xi = \frac{1}{3} t^4 \left[ \frac{w}{t} - \frac{192}{\pi^5} \sum_{n=1}^{\infty} \left( \frac{1}{n^5} \tanh \frac{n\pi w}{2t} \right) \right] \quad (7)$$

Table 4. Symbols used in above equations

Symbol	Meaning
E	young's modulus
L,w,t	length, width, and thickness of the beam.
$\lambda_n$	The eigenvalue of nth mode.
$\rho_c$	beam density.
G	shear modulus.
$I_p$	polar moment of inertia.
$\xi$	damping coefficient
$\nu$	Poisson ratio.

## V. DIMENSIONS AND MATERIAL OF MICROCANTILEVER

The material chosen for the cantilever is silicon because its Young Modulus is small as compared to other materials [28]. Young Modulus basically indicates the elasticity of the material. The lower value of elasticity indicates higher sensitivity. For this reason, silicon is preferred over other materials.

Table 5. Mechanical Properties of Silicon material.

Property	Value
Young's Modulus	131e9Pa
Poisson's ratio	0.27
Density	2330kg/m <sup>3</sup>

Table 6. Dimensions of microcantilever (Adapted from [29]).

Dimension	Value
Length	60 $\mu\text{m}$
Width	6 $\mu\text{m}$
thickness	1.5 $\mu\text{m}$

## VI. OVERVIEW OF APPLICATION OF MICROCANTILEVER IN LIQUID MEDIUM

The idea that the cantilever can act as an ideal candidate for measuring rheological properties of fluid [30] [31] [32] [33] originate from the fact that the cantilever's dynamic response is contingent on the medium of operation. The dynamic response of the cantilever can be viewed in the matter of resonant frequency and quality factor.

### A. Selection of mode of operation

As discussed earlier, for sensing applications, microcantilever can be operated either in static or dynamic mode. Static mode is responsive to stress induced on the cantilever surface and the dynamic mode is responsive to change in mass of microcantilever. During analyte-antibody interaction, molecular constituents do not provide useful information that is necessary for detection. For this reason, in liquid phase sensing applications, mass sensitive sensors are used. Thus, when microcantilever operates in a dynamic mode, their resonant frequency changes in response to analyte binding and the properties of the fluid are measured accordingly.

### B. Selection of mode of vibration

As discussed earlier, microcantilever mainly has three modes of vibration, namely, transverse, lateral and torsional. When our operating medium is air or vacuum, in that case, transverse mode of vibration is preferred. But as we change our operating medium from air to liquid, then working with transverse mode becomes difficult or quite inefficient. The performance of the microcantilever degrades by considerable damping. Because when the cantilever is immersed in a fluid, it suffers resistance being offered by fluid [34]. Consequently, both resonant frequency and the Quality factor of the beam decreases drastically when the operating medium i.e. air is replaced by water.

Table 7. Comparison of vibrational mode for liquid phase sensing application.

Transverse	Lateral
50% shift in resonant frequency.	5-10% shift in resonant frequency.
The Quality factor is not good.	The Quality factor is 5 times larger.
Gravimetric sensitivity is poor.	Gravimetric sensitivity is improved by when immersed in water.
Limit of detection is commendable.	Limit of detection is around 100ppb compared to the out-of-plane.
Flexural rigidity is small.	Flexural rigidity $\left(\frac{b^3}{h^3}\right)$ is greater than the transverse flexural mode.

L.A. Beardslee et al. [35] investigated a cantilever which was 400  $\mu\text{m}$  long, 90  $\mu\text{m}$  wide and 20  $\mu\text{m}$  thick for both lateral (in-plane) and transverse (out-of-plane) vibrations. The response of the cantilever operated in vacuum came to be 154.6kHz (Q=680) and that in the water came to be 96.1kHz (Q=20) i.e., shifted by 38% when operating medium air is replaced by water. Whereas the in-plane vibrating cantilever shifted from 636.7kHz to 596.0kHz i.e., shifted by 7% only. It is thus concluded that the in-plane mode is least affected by fluid damping and mass loading caused by surrounding fluid. Hence concluded that lateral flexural mode is preferred over transverse flexural mode for sensing applications in

the liquid medium. The increased resonant frequency and decreased the effective mass of beam in the case of lateral mode results in increased mass sensitivity which in turn leads to the lower limit of detection in liquid phase biosensing.

Table 7.shows the comparative analysis of vibrational mode for liquid phase chemical sensing applications.

### C. Geometrical consideration for design of liquid phase sensor

At the micro-scale, the cantilever's vibrations instead of depending only on the microstructure's properties and surrounding medium properties also depend on the structure's geometry. The dynamic behavior of cantilever is investigated in terms of beam geometry and medium property.

Following are the design considerations for liquid phase sensor [36] [37] [38]:

1. Shorter, wider, thicker microcantilevers are best for biosensing applications as it yields highest Q-factor while vibrating in the in-plane mode in liquid [39].Q-factor increases with increase in device thickness.
2. The beam cross sectional area should be assumed uniform all over the beam length.
3. The beam length should greatly exceed the width of the microcantilever beam.
4. The amplitude of vibration should be considered considerably smaller than any length scale in geometry.

### D. Fluid-structure interaction of microcantilever

There are several flexible structures say, microcantilever, micropumps, microplates, microvalves, micro flow sensors, microviscosity sensors that undergo deformation through several means such as fluid pressure, phase change, electrostatic force, magnetostatic force, friction. All these microfluidic devices involve microfluidic structure interaction [40].

While analyzing the cantilever operating in the viscous medium, our first task is to study the effect of hydrodynamic force on the microcantilever vibrations [41] [42]. Hydrodynamic forces are the forces that the fluid exerts onto the body of the structure e.g. Drag and lift force.

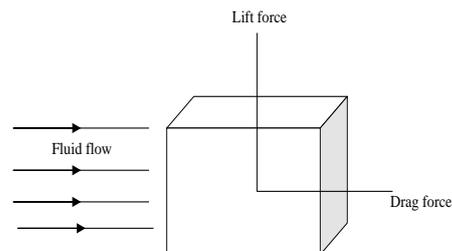


Fig.7. Schematic of lift and drag force components when fluid flow passes a body.

When the structure is allowed to settle in a liquid medium, the fluid flow endeavors a force on structure's surface as shown in fig.7. The component of force that is acting in the direction parallel to the fluid flow direction

is called drag force and the component of force that is acting in the direction perpendicular to the fluid direction is labeled as lift force [43]. The hydrodynamic force shown in fig. 8 is the resultant of the pressure (lift) force and the shear (drag) force.

$$F_{hydrodynamic} = F_{shear} + F_{pressure}$$

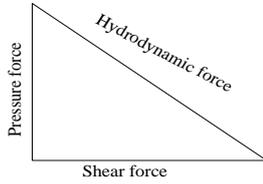


Fig.8. The hydrodynamic force acting on cantilever beam; shear and pressure force.

#### E. Equations governing fluid-structure interaction of microcantilever

When the cantilever is settled in a liquid medium, the motion of the cantilever suffers resistance being offered by the fluid. The dynamic behavior (resonant frequency and quality factor) of the cantilever that depends on the properties of the medium in which they are operating are calculated. This enables us to measure the mechanical properties of different types of fluid.

The Euler-Bernoulli equation of motion before the application of an external force is given as:

$$EI \frac{\partial^4 y(x,t)}{\partial x^4} + \rho_b A \frac{\partial^2 y(x,t)}{\partial t^2} = 0 \quad (8)$$

Where,

$$I = \frac{bh^3}{12} \quad (\text{in case of transverse mode})$$

$$I = \frac{b^3h}{12} \quad (\text{in case of lateral mode})$$

In the presence of external force, the equation of motion is modified as:

$$EI \frac{\partial^4 y(x,t)}{\partial x^4} + \rho_b A \frac{\partial^2 y(x,t)}{\partial t^2} = F_y(x) e^{j\omega t} \quad (9)$$

When microcantilever is allowed to vibrate in the viscous medium, then an additional force is exerted on the surface of the cantilever. Consequently, the beam equation is written as:

$$EI \frac{\partial^4 y(x,t)}{\partial x^4} + \rho_b A \frac{\partial^2 y(x,t)}{\partial t^2} = F_y(x) e^{j\omega t} + F(x,t) \quad (10)$$

This additional hydrodynamic force,  $F(x,t)$  [44] is written as:

$$F(x,t) = -g_1 \frac{\partial v(x,t)}{\partial x} - g_2 \frac{\partial^2 v(x,t)}{\partial t^2} \quad (11)$$

In the frequency domain, (4) is expressed as:

$$F_{fluid} = -[j\omega g_1(x,\omega) - \omega^2 g_2(x,\omega)] y(x,\omega) \quad (12)$$

$\omega$  = frequency of vibration,  $y$  = microcantilever deflection.

$g_1$  is given as:

$$g_1 = M_L (2\pi f_l) \left( b_1 \frac{\delta}{w} + b_2 \left( \frac{\delta}{2} \right)^2 \right) \quad (13)$$

$g_2$  is given as:

$$g_2 = M_L \left( a_1 + a_2 \frac{\delta}{w} \right) \quad (14)$$

$$M_L = \frac{\pi \rho_f w^2}{4}$$

$\rho_f$  = fluid density.

$w$  = width of the cantilever.

$a_1 = 1.0553$ ,  $a_2 = 3.7997$ ,  $b_1 = 3.8018$ ,  $b_2 = 2.7364$  are ‘‘Maali’s Parameters’’ [45].

The boundary layer thickness or skin depth can be expressed as:

$$\delta = \sqrt{\frac{2\mu}{\rho_f (2\pi f_l)}} \quad (15)$$

The amount of fluid excited by the vibrating beam is directly proportional to the skin depth [46]. The resonant frequency [47] and quality factor incorporating the effect of hydrodynamic force are expressed as:

$$f_l = f_{o,vacuum} \frac{1}{\sqrt{1 + \frac{Lg_2}{m}}} \sqrt{1 - \frac{1}{2Q_{total}^2}} \quad (16)$$

$$f_{o,vacuum} = 0.1615 \left( \frac{b}{L^2} \right) \left( \sqrt{\frac{E}{\rho_b}} \right) \quad (17)$$

where  $f_{o,vacuum}$  = undamped resonance frequency in the vacuum.

$m$  = mass of the cantilever.

$f_i$  = resonant frequency.

$b, L$  = beam width and length respectively.

The quality factor of cantilever immersed in a liquid comprehends fluid damping as well as internal damping effects.

Thus the quality factor can be expressed as the contribution of these two main components:

$$\frac{1}{Q_{total}} = \frac{1}{Q_{int}} + \frac{1}{Q_{fluid}} \quad (18)$$

$Q_{int}$  is the internal quality factor of the microstructure and  $Q_{fluid}$  is the quality factor contributed by the fluid.

When the cantilever vibrates in out-of-plane mode, fluid-induced losses tends to dominate. So it is possible to replace fluid-induced losses. Consequently,  $Q_{total}$  is approximately equal to  $Q_{fluid}$ . The fluid dependent quality factor, using results of Sader is given as [48]:

$$Q_{fluid} = 2\pi f_{o,vacuum} \frac{\sqrt{1 + \frac{Lg_2}{m}}}{\frac{Lg_1}{m}} \quad (19)$$

In order to model the fluid, the incompressible form of Navier-stokes' equation is used. This is because in the

$$\eta = \frac{2a_1 b h \rho}{f_o (b_1 a_2 - a_1 b_2)} \frac{\left[ b_1 (f_{vacuum}^2 - f_o^2) + 2\xi a_2 f_{vacuum}^2 - \sqrt{b_1^2 (f_{vacuum}^2 - f_o^2)^2 + 4\xi^2 f_{vacuum}^2 [a_2^2 \xi f_{vacuum}^2 - (a_2 b_1 - 2a_1 b_2)(f_{vacuum}^2 - f_o^2)]} \right]}{\left[ (a_2 b_1 - 2a_1 b_2)(f_{vacuum}^2 - f_o^2) - 2a_2^2 \xi f_{vacuum}^2 + a_2 \sqrt{b_1^2 (f_{vacuum}^2 - f_o^2)^2 + 4\xi^2 f_{vacuum}^2 [a_2^2 \xi f_{vacuum}^2 - (a_2 b_1 - 2a_1 b_2)(f_{vacuum}^2 - f_o^2)]} \right]} \quad (22)$$

$$\rho_f = \frac{2h\rho}{\pi b f_o^2 a_1 (a_2 b_1 - a_1 b_2)} \left( (a_2 b_1 - 2a_1 b_2)(f_{vacuum}^2 - f_o^2) - 2\xi a_2^2 f_{vacuum}^2 + a_2 \sqrt{b_1^2 (f_{vacuum}^2 - f_o^2)^2 + 4\xi^2 f_{vacuum}^2 [a_2^2 \xi f_{vacuum}^2 - (a_2 b_1 - 2a_1 b_2)(f_{vacuum}^2 - f_o^2)]} \right) \quad (23)$$

where the damping ratio in the fluid  $\xi$  is given as:

$$\xi = \frac{g_1 f_o}{4\pi f_{vacuum} m_L \sqrt{1 + (g_2 (f_o) / (m_L))}} \quad (24)$$

And the eigenfrequency ( $f_o$ ) in the fluid is given as:

$$f_o = \frac{f_{vacuum}}{\sqrt{1 + (g_2 (f_o) / (m_L))}} \quad (25)$$

flow the wavelength of microcantilever's vibration greatly exceeds the width of the cantilever [49]. Hence the fluid is considered incompressible.

Assuming the velocity gradient of fluid and beam to be small, the fluid's equation of motion is given as [50]:

$$\rho_f \frac{\partial u}{\partial t} = -\nabla P + \eta \nabla^2 u \quad (20)$$

Where  $\rho_f \frac{\partial u}{\partial t}$  is fluid's inertial forces and  $\eta \nabla^2 u$  is the fluid's viscous forces.

The Renolds number is defined as the ratio of fluid's inertial forces to the fluid's viscous forces and is expressed as:

$$Re = \frac{\rho_f w b^2}{4\eta} \quad (21)$$

Higher the value of Renolds number, lower will be the viscosity of the fluid and vice-versa.

The analytical expressions of viscosity and density that depends on Maali's parameters, the resonant frequency in the vacuum, the dimensions, the density of the cantilever,  $\xi$  and eigenfrequency are given as [51]:

Table 8. Symbols used in above equations.

Symbol	Meaning
$g_1, g_2$	Fluid coefficients.
$f_{vacuum}$	Undamped resonant frequency.
Re	Renolds number.
$f_o$	Eigenfrequency in the fluid.
$\rho_f$	Fluid density.
$\eta$	Fluid viscosity.
$\xi$	Damping coefficient
$m_L$	Mass of the cantilever.
$a_1, a_2, b_1, b_2$	Maali's parameters.
EI	Flexural rigidity.
$Q_{fluid}$	Quality factor due to the fluid.
$\delta$	Boundary layer thickness.
P	Pressure at a particular point in the fluid.
u	Velocity at a particular point in the fluid.

## VII. MICROCANTILEVER IN BIOMEMS APPLICATIONS

As discussed earlier, microcantilever finds its application in different fields [52] [53] [54] [55] [56] [57]. Some of the biosensing applications are discussed below:

### A. MEMS pressure sensor

Measurement of pressure in various organs say heart, urinary bladder, eye etc. is very important to get an indication of patient health. In Ref. [58] embedded system has been designed to monitor the health status of the patient. Lawrence Yu et al [59] have discussed the fully implantable pressure sensor for pressure measurement without having any infection risks posed by catheters or wires. These fully implantable MEMS pressure sensors can also be used for IOP monitoring of Glaucoma patient. CardioMEMS manufactured a heart failure monitoring system that utilizes HF pressure sensor that is having attractive features [60]. It does not require a battery (externally powered), no lead and is smaller in size (3.5\*2\*15mm) say, millimeters. Michael A. Fonseca [61] have designed a flexible wireless passive pressure sensor that is capable of measuring pulse pressures ranging between 12-37mmHg and mean pressures ranging from 70-120mmHg in animals.

### B. Cantilever biosensors for magnetic detection of virus

In the case of a patient who is suffering from AIDS, it is very important to monitor the sequence of HIV (Human Immunodeficiency Virus) so as to stop the infection from spreading and improving the living condition and life expectancy of the patient. Though monitoring the sequence of HIV is not an easy task. It requires highly expensive and time-consuming procedures. With a view of the prevailing situation, Microcantilever came into the picture being highly sensitive, smaller in size, cheap, portable, robust. It helped doctors to monitor the progression of HIV. In Ref. [62], cantilever (500\*100\*0.9mm) for detection of magnetic nanoparticles have been discussed which exhibited static deflection as low as 2e-3nm.

### C. Cantilever biosensors for detection of specific protein

The cantilever can be used for detection of specific protein. For example, in the case of the tumor where normal cells are stimulated to produce angiogenesis (the development of new blood vessels) signaling molecules. The resulting new blood vessels allow cancer cells to attack nearby tissues and thereby forming new colonies of cancerous cells called metastases. Yu et al. [63] have demonstrated that the angiopoietin-1 and 2 promotes or inhibits tumor angiogenesis. So for the detection of Angiopoietin, the microcantilever is chosen. Carlo et al [64], designed cantilever (1200\*800\*7mm) for which the measured frequency shifts and relative frequency changes for Ang-1 at 25 µg/ml came to be  $(-1.52 \pm 0.94)10^2$ .

### D. Cantilever for measuring glucose level in blood

The determining factor to identify if a person is suffering from diabetes is glucose level. There are

available different laboratory diagnostic equipment for monitoring the glucose level that employs collection and analysis of blood which causes pain and tension to the patients. The alternative to these procedures is using a non-invasive technique for the measuring glucose level in blood. Paper [65] presents a cantilever (1000\*100\*10µm) that is coated with selective antigen (probe molecule) anayte-antibody interaction is studied. When the antigen present in the saliva comes in contact with the surface of the cantilever, the glucose level can be estimated by tracking the change in resonance frequency.

### E. MEMS inertial sensor

Nowadays MEMS Accelerometers are used for biosensing application in defibrillators and pacemakers. In case a person's heart beats unusually very fast, in that situation, there are chances of cardiac arrest. The function of defibrillators is to provide electrical shocks to allow the normal heart beat. The function of a pacemaker is to maintain the heart beat under abnormal conditions. Endevco Corporation modeled 40366 accelerometers [66] that are considered ideal for implantable medical device applications. The implantable devices include rate responsive heart pacemakers and defibrillators. This accelerometer fulfills all the requirements desired in medical applications i.e. highly reliable, repeatable, smaller package size.

## VIII. CONCLUSION

Cantilever explores the wide area of applications. The cantilever-based sensor platform proved to be the best option over available time consuming, expensive analytical instruments. Microcantilever is the first successful mass production product for inertial applications. It has got very rich understanding and its theory is well developed. It can be produced in semiconductor fabrication lab. It is possible to propose new innovative structure for such devices. It is hoped that microcantilever based devices can be integrated with other biomedical devices for monitoring and measuring bio-interest quantities in big way, in coming future. Cantilever's ease of preparation, being independent of the environmental changes gained the attention of researchers. Microcantilevers have greater potential as microsensing platform, have high mass sensitivity, better limit of detection, low fabrication cost. Microcantilever finds huge opportunity in medical and biotech applications due to the availability of compatible materials and sizes and being capable of electronics integration. In addition to different areas of application discussed above, cantilever also finds its application in cell culture, filtration products, materials characterizations, chip cooling, microphones, gas flow metering. Though a large number of bioMEMS devices are already available in the market but the research is still going on for designing more promising devices. Despite ample advantages, there are certain challenges in MEMS for medical applications like packaging where MEMS chip requires electrical connect, mechanical stress management, Application Specific

Integrated Circuit (ASIC), small form factor. Also, for both MEMS function and biocompatibility, hermeticity is required to determine productiveness of the seal in MEMS packages. For sterilization, there are limitations on certain materials like Ethylene oxide which can be absorbed by plastic, gamma, e-beam which cause damage to electronics and few plastics. Besides this, MEMS devices still have a huge opportunity in medical and biotech applications.

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