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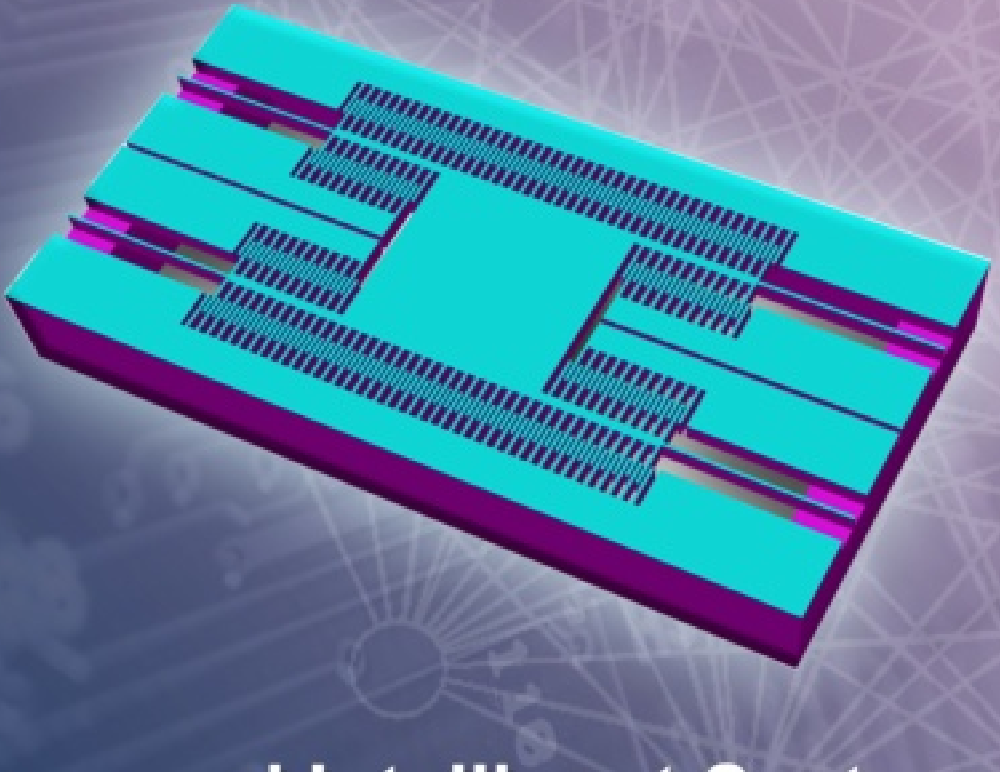

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# Simulation of Liquid Material for Microfluidic-based Acoustic Sensor

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**Abstract:** This work investigates the performance of two different liquid materials, i.e. Propylene Carbonate and Methanol to be used in microfluidic-based acoustic sensor. Both liquids were selected based on several important liquid properties including surface tension and permittivity. By using these materials as the fluid element, the damping effect and flow response between both materials were then simulated to investigate their influence on the sensitivity resolution and response. The work was performed through Finite Element Model (FEM) using ANSYS 12.1. The damping analysis shows that the Propelyne Carbonate had less damping effect than Methanol, by comparing them to the air backing structure. This suggests that the Propylene Carbonate is a preferred material. However, in flow response analysis, Methanol demonstrates a better performance with about 18 times higher. This trade off behaviour urges that other factors such as application type, device dimension and sensitivity also need to be carefully considered before realising such sensor device. *Copyright © 2012 IFSA.*

**Keywords:** Microfluidic-based, Acoustic sensor, Damping effect, Flow response.

## 1. Introduction

Acoustic microsensing starts to get attention due to the advancement in IC technology which enables the fabrication of microdevice. Capacitive micromachined ultrasonic transducer (cMUT) is an example of microdevices realized through this technology advancement. Research in cMUT has been an ongoing active research for various type of application since then. It uses capacitive sensing mechanism in order to convert the acoustic wave to a signal suitable for further processing. For a conventional cMUT, the variation of separating distance between the membrane and substrate in response to acoustic signal creates a capacitive change which is then converted into electrical signal through a respective readout circuitry. Previous research has covered many research parameters such as structure dimension (size of electrodes, location of electrodes, gap height) and structure material (electrode, membrane and substrate) [1-3]. However, the conventional structure sometimes suffers from several disadvantages such as reliability issues and tedious fabrication processes [4]. Apart from that, conventional microfabrication process also involves sacrificial layer release process where a suitable resist material should be deposited before that layer can be selectively removed [5]. Selective etching requires a tight parameter controlled procedures in order to accurately remove the unwanted part of the sacrificial layer.

These constraints and disadvantages, hence, becomes the motivation of this work. In conjunction to this, a new structure of capacitive acoustic sensing is proposed as to overcome these drawbacks. The structure manipulates the microfluidic technology to reduce the fabrication steps and avoid some complex processes in realizing such microdevice. It also capable to overcome some difficulties faced due to limited number of related microfabrication facilities. The higher value of dielectric permittivity of microfluidic material also becomes an added advantage as this factor could increase the capacitive sensing mechanism. The availability of various suitable liquids makes the selection wide open.

## 2. Background

### 2.1 2.1. Device Structure

Fig. 1 shows the structure of the device. It is filled with a liquid in order to generate the capacitive changing mechanism when liquid flow occurs inside the microchannel. The structure is based on the feasibility studies on several designs that share similar concept and had been successfully fabricated. The implementation of liquid movement in response to acoustic signal is exploited from work by [6]. The work that mimics a human cochlea structure however requires many fabrication steps to realize the overall structure. Microfluidic fabrication technique through softlitography process is proposed as it is found to have less fabrication steps. In order to suit to the process, Polydimethyldioxane (PDMS) is selected as a sensing membrane. The suitability of PDMS as a membrane is based on work by [7] and [8]. The [7] had analyzed several acoustic properties of the PDMS based membrane such as the acoustic impedance and pressure response. The work [8] shows the practicality of PDMS to be fabricated as a membrane through softlitography process.

### 2.2.Device Operation

During operation, an incoming acoustic signal will exert some pressure on the membrane which causes the membrane to deflect downward. As a result, this downward deflection of the membrane will force the liquid into a microfluidic channel inlet. As the signal ceases, the liquid will move backward, creating a back and forth movement inside the microchannel. The movement is assumed to be depending on the sinusoidal varying acoustic pressure signal. For sensing mechanism, the electrode is fabricated at the bottom layer of the microchannel. Therefore, the liquid movement inside the microchannel thus creates a capacitive effect that is strongly depends on the overlapping area variation between the liquid and electrodes. The flow of the liquid inside the device is assumed to be laminar based on [9]. Similar to cMUT, the sensing sensitivity is partly determined by the amount of membrane deflection in response to acoustic signal. This deflection determines the amount of displaced liquid which will be flowing into the microchannel. For a complete unit, the capacitance variation needs to be converted into electrical signal through a suitable capacitive detection circuit.

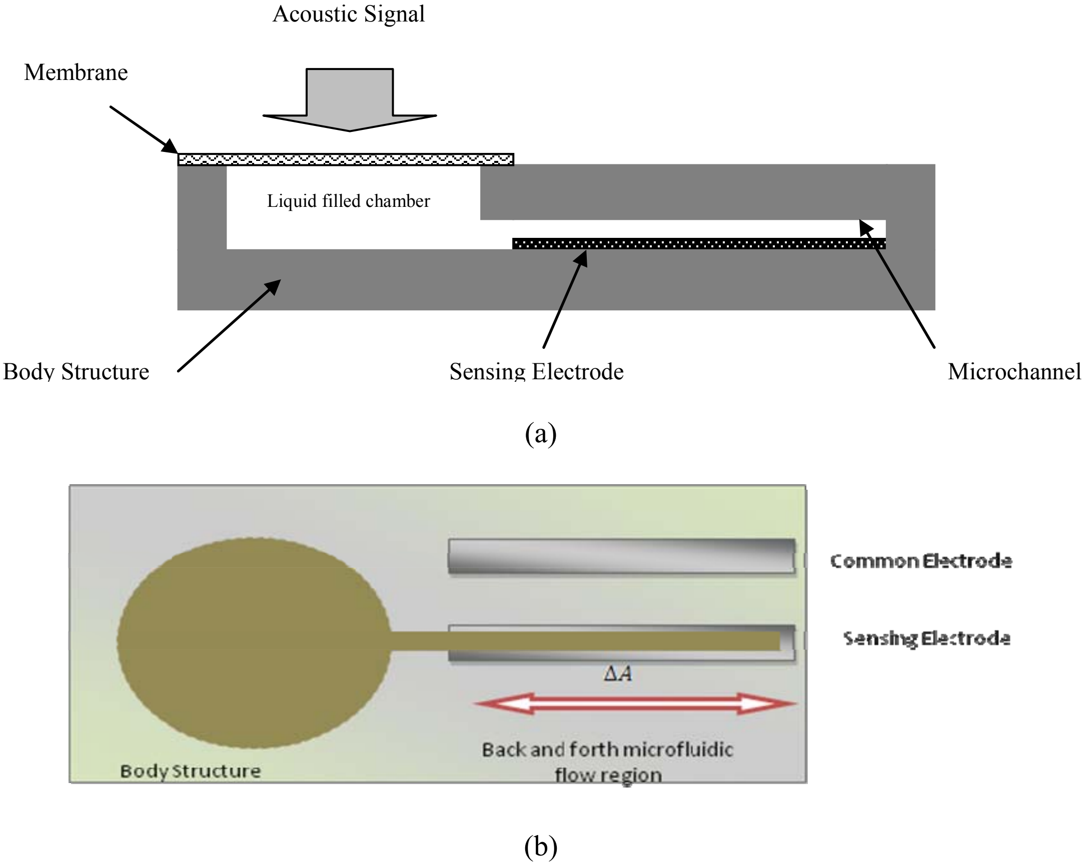

**Fig. 1.** Microfluidic-based acoustic sensor: (a) Side view; (b) Top view.

## 3. Methodology

Apart from the membrane material, selection of the liquid material also has a direct impact to the overall performance of the device. This is due to the permittivity value of the liquid which can affect the capacitance value obtained. Work by [10] proposed two liquid candidates suitable for the device, i.e. Propylene Carbonate and Methanol. These liquids are selected based on the analysis performed on surface tension, permittivity, boiling point and melting point of the materials. Besides the advantages of implementing microfluidic-based sensor, this fluid will also inevitably introduces damping, which reduces the deflection amount of the sensing membrane. So this work is intended to investigate on the damping effect of these liquids as well as their flow behavior in response to the pressure signal applied onto the PDMS membrane.

### 3.1. Damping Effect

In order to investigate the damping effect of liquid backing layer upon the vibration of the membrane, the process was divided into two steps. The first step was to compute the damping parameter of the backing layer, and the second step was to perform the harmonic analysis of the whole structure based on the damping parameter obtained from the first step.

### 3.1.1. Damping Ratio Analysis

Squeeze film analysis is an analysis performed to extract the behavior of a thin film under the effect of force or pressure acting on it perpendicularly. In this work, the thin film was assumed to represent the backing layer of the device structure. The backing layer would create some sort of resistance that opposes the movement or vibration of the membrane structure. The resistance was due to the viscosity of the material used as the backing layer and was known as viscous damping. The squeeze film analysis enables the extraction of several damping parameter associated with the backing layer, which was treated as thin film structure including the damping ratio. Using ANSYS 12.1, the damping ratio of different backing material was extracted by using the modal projection technique. The modal projection technique was initiated by building a structure of membrane and thin film and the model was then meshed accordingly.

Next, the modal analysis was performed to extract the Eigen frequency of each mode. Through modal analysis, the number of interest mode had been specified in order for the software to extract the frequencies associated with each mode. Other than damping ratio, several other damping parameter could also been extracted using this technique such as the damping coefficient, stiffness coefficient and stiffness ratio. The dimension of the thin layer (backing layer) is shown as in Table 1.

**Table 1.** The thin film geometry.

| **Dimension** | **Selected Value** |
|---|---|
| Size of Thin Film (μm) | 500 × 500 |
| Thickness of Membrane (μm) | 2 |
| Gap Thickness (μm) | 50 |

In this simulation work, apart from two liquid materials selected as backing layers, the damping ratio of air backing layer was also obtained as a reference. The performance of both liquids as backing layer were then compared to the air backing structure to study their effect on how much the membrane deflection would decrease when the gap was filled with liquid material. As the viscosity and density affects the damping, these properties become the key properties that had been varied in simulation. The properties of material used as backing material are depicted in Table 2.

**Table 2.** Material properties of liquid materials.

| **Material** | **Density ( kg/μm$^3$ )** | **Kinematic Viscosity (μm$^2$/s )** |
|---|---|---|
| Propylene Carbonate | $1.21\times10^{-15}$ | $1.40\times10^{6}$ |
| Methanol | $0.79\times10^{-15}$ | $0.74\times10^{5}$ |
| Air | $1.20\times10^{-18}$ | $1.50\times10^{7}$ |

Through modal projection technique, the damping parameter such as the damping ratio of each material at different modes was extracted. Then, the parameter was plotted against the eigenvectors to study its pattern across the first mode to the fifth mode.

### 3.1.2. Harmonic Analysis with Damping Ratio

Harmonic analysis was performed to investigate the response of membrane vibration at certain range of frequency. Through this analysis, frequency at which the maximum membrane deflection occurred can be obtained. The maximum deflection was important in estimating the sensitivity of the device, while the frequency response was useful especially to determine the operational frequency range. This analysis was significant in order to investigate the best frequency range that the sensor could operate.

In this analysis, PDMS was chosen as a membrane material due to its higher deflection response compared to the commonly used $Si_3N_4$ with response to pressure. Table 3 shows the structural properties of PDMS used in this FEM modeling.

**Table 3.** PDMS Specifications.

| Dimension | Selected Value |
|---|---|
| Young Modulus (MPa) | 0.87 |
| Poisson Ratio | 0.49 |
| Density(kg/um$^3$ ) | $9.7\times10^{-19}$ |

In this analysis, the data obtained from the damping ratio analysis was included in order to study the effect on the membrane deflection at their resonance. However, only the damping ratio associated with the first mode was selected as it produces the maximum membrane deflection.

### 3.2. Flow Response

Simulation was based on finite element model performed using ANSYS 12.1. Apart from laminar flow, the flow also assumed to be incompressible where the density of the flow material does not affected by the applied pressure. FLUID141 was used to represent the liquid. The effect of flow in response to sound pressure was performed by applying specific pressure on the membrane structure. The applied pressure represents the acoustic pressure which causes the membrane deflection. The effect of pressure onto different liquid was analyzed by varying their density and viscosity (Table 2). Table 4 shows the structural dimension of the device

**Table 4.** Structure design specifications.

| Membrane Diameter (µm) | Gap Height (µm) | Microchannel Height (µm) |
|---|---|---|
| 600 | 100 | 20 |

In the analysis, the main goal was to investigate the pressure and flow behavior that occur across the device. Through ANSYS, post processing menu was used to collect all nodal solutions after being simulated. Pressure distributions across the device and velocity vector were extracted from this menu. The relationship between the pressure and velocity was used to investigate the flow response of the critical region. The region that became our main concern was at the beginning of microchannel. This region was important as it would influence the overall flow inside microchannel. A node from this region was then selected as the node of interests. Velocity of the node was plotted against the applied pressure in which the gradient of the plot represents the flow response of the interests region. From the pressure- velocity response, we can estimate how fast the reaction between these liquids. The steeper gradient indicates that the faster the response signal would be between these liquids. In the mean time, for specific pressure, the higher velocity indicates that the higher capacitive changes (due to higher overlapping area between liquid and electrode) would be when responding to the applied pressure. The velocity at a particular point also enables us to predict the occasion of turbulence phenomenon.

## 4. Results and Discussions

### 4.1. Damping Effect

### 4.1.2. Damping Ratio Analysis

Fig. 2 shows the damping ratio of thin film structure using three different backing materials. Note that throughout the first to fifth mode, the plotting shares the same pattern where the highest damping ratio is at the first mode and decreases towards higher mode. The first mode value then will be used in the next simulation due its maximum value. For liquid backing, Propylene Carbonate material offers lower damping ratio as compared to methanol. For the first mode vibration, the damping ratio of Propylene Carbonate is 0.002, which is two times higher than that of air backing. Meanwhile, for methanol the damping ratio is seven times higher than that of air, which is 0.007. The differences in damping ratio are resulted from different value of viscosity and density of the fluids. The second and the third mode demonstrate the same value of damping ratio and this is due to the symmetrical properties of modal vibration in both modes, where they also share the same modal frequencies. Next, it can be seen that the higher the vibration mode, the difference in damping ratio between all materials become less. This pattern is observed where all type of fluid materials have similar damping ratio at the fifth mode. So, at higher modes, the material properties such as the viscosity and density have less effect on the damping ratio.

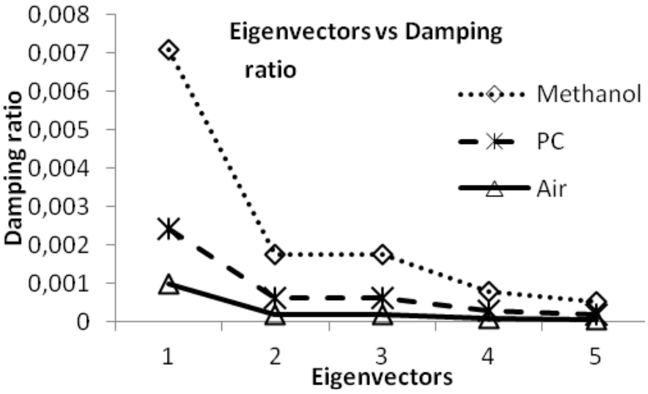

**Fig. 2.** The damping ratio across different modes for 3 different backing materials.

### 4.1.2. Harmonic Analysis with Damping Ratio

Fig. 3 shows the harmonic analysis for three different materials backing with the damping ratio included. The damping causes the membrane deflection to decrease by a certain amount. Taking the air backing material as a reference, the application of liquid backing yields a reduction of 50 % and 70 % for Propylene Carbonate and Methanol, respectively.

This pattern agrees with the value obtained from the damping ratio analysis. Apart from this effect, the damping ratio also exhibits other phenomenon. Different material causes the resonance frequency to be shifted at some degree. Propylene Carbonate shifts the resonance to 475 kHz while methanol shifts to 625 kHz. This plot suggests that as the damping ratio increases, the amount of deflection will decrease with the resonance frequency to be shifted to a higher value. As the damping ratio is depending on the viscosity and density, the selection of material for backing layer could be based on these parameters. The lower the kinematic viscosity, one should expect that the resistance to the membrane deflection will be higher, thus producing a less deflected membrane displacement. In this configuration, the detection sensitivity can be predicted based on the resulted deflection of the membrane. As the amount of liquid entering the microchannel depends on the total volume displaced by the membrane deflection, the more the membrane deflected will result a higher volume of liquid to enter the microchannel, thus increasing the capacitive change inside it. This sensing effect also could be contributed by a proper selection of materials with higher permittivity, which excluded in this work.

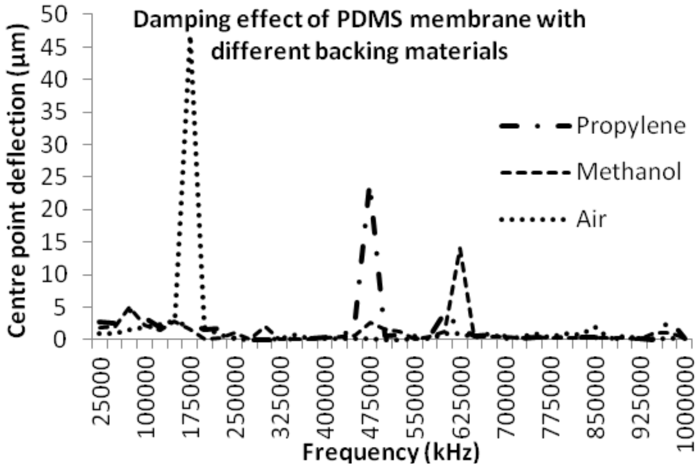

**Fig. 3.** Harmonic analysis of three different materials with damping ratio included.

## 4.2. Flow Analysis

### 4.2.1. Pressure Distribution

By using the same dimension and applied pressure, both materials show the same pattern of pressure distribution. The change of pressure begins from the mid-point of the device reservoir structure and continues toward the microchannel end. This means that the area is the only region that the flow activity will be significant (Fig. 4).

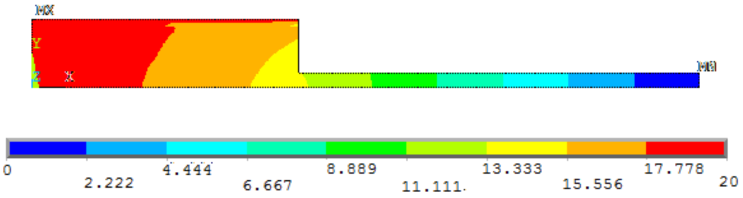

**Fig. 4.** Pressure distribution inside the device at selected device dimension.

### 4.2.2. Velocity Contour

Contour plot gives us information on how the velocity varies across the channel. Fig. 5 exposed several regions with their velocity range. The region near the entrance of microchannel seems to have the highest value. Therefore this region is critical in determining the threshold value when the turbulence will occur. The detail on the flow direction and magnitude will be discussed next.

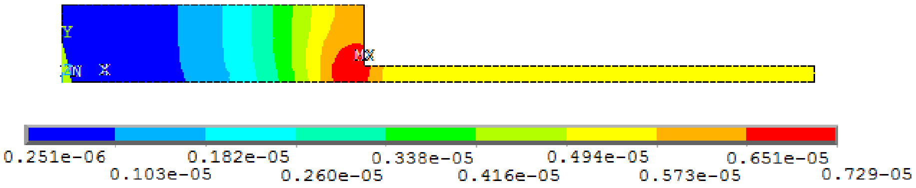

**Fig. 5.** Contour plot of the velocity across the devices.

### 4.2.3. Velocity Vector

Fig. 6 shows the liquid flow vector based on the previous given condition. The result enables the flow direction and magnitude to be determined. The flow direction for both liquids is found to have the same laminar pattern. However, the flow is found to exhibit different magnitude upon the same applied pressure. It is maximum near the microchannel starting point due to the flow entering a smaller microchannel entrance. By selecting any node inside this region, the value can be obtained to evaluate their respective flow response.

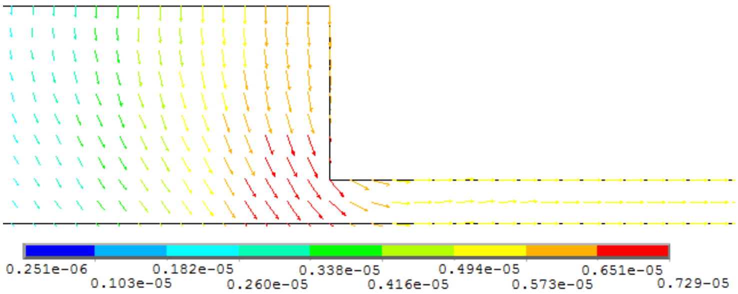

**Fig. 6.** Flow direction of both materials.

### 4.2.4. Flow Response

The Fig. 7 shows the relationship between the applied pressure and velocity of the flow of a node inside the critical region for both electrolytes. The obtained velocity range for both liquid is found to be very small, thus indicating that the flow will be in laminar form.

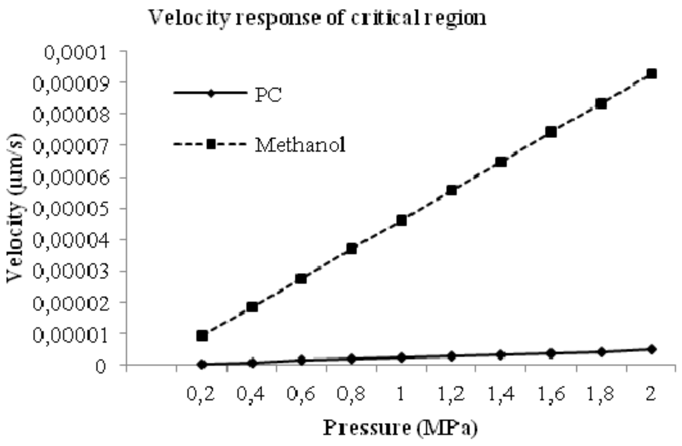

**Fig. 7.** Flow response comparison of both materials.

The response of the flow to the applied pressure is measured from the gradient of the graph. Methanol has $4.64\times10^{-5}$ μm/MPa, while Propylene Carbonate gives $2.45\times10^{-6}$ μm/MPa. This indicates Methanol has a response of about 18 times higher compared to Propylene Carbonate. The significance of obtaining such response is to predict how fast the capacitive sensing will take place in response to an incoming acoustic pressure signal.

## 5. Conclusions

Based on these simulation results, each liquid material seems to have a superior performance in each criterion under consideration. In terms of flow response, Methanol offers a better result with higher flow velocity at microchannel. This could be resulted from the lower surface tension between the liquid and microchannel material. On the other hand when it comes to the damping effect, Propylene Carbonate offers less damping effect to enable the higher deflection of the membrane. Higher membrane deflection can also be considered as a factor that contributes to higher detection sensitivity. This finding thus demonstrates a trade off possibilities between the liquid material properties and the behaviour that influence the sensor's performance. The conflict in selecting the liquid that contributes to the better sensitivity suggests that other factors also need to be considered such as the type of application, range of operation frequency, dimension of the device and also the expected sensitivity.

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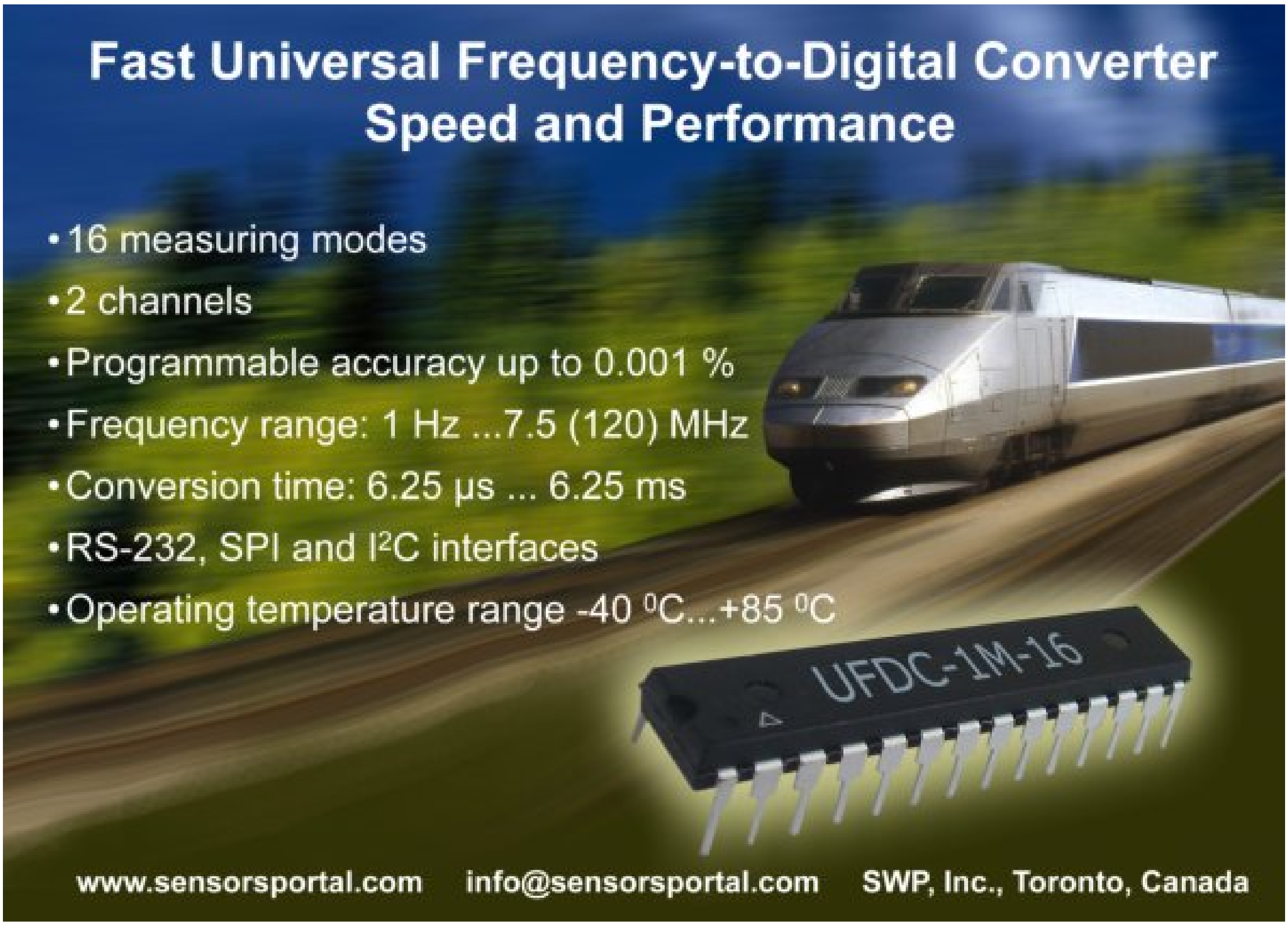

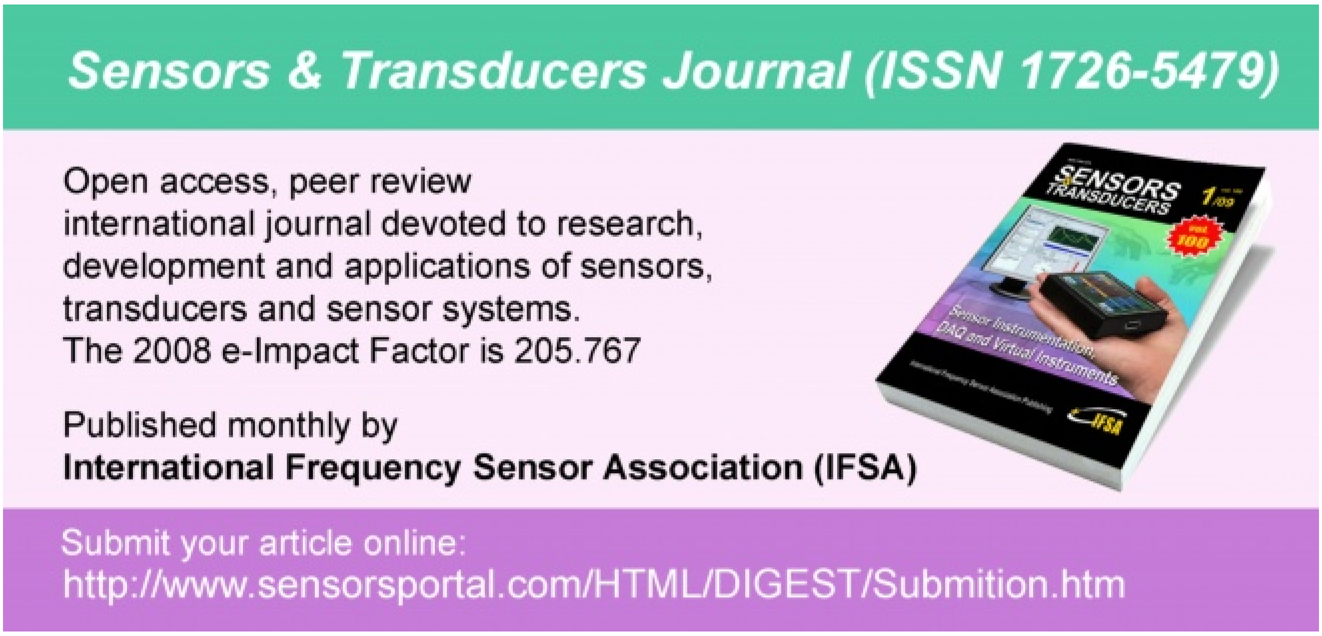

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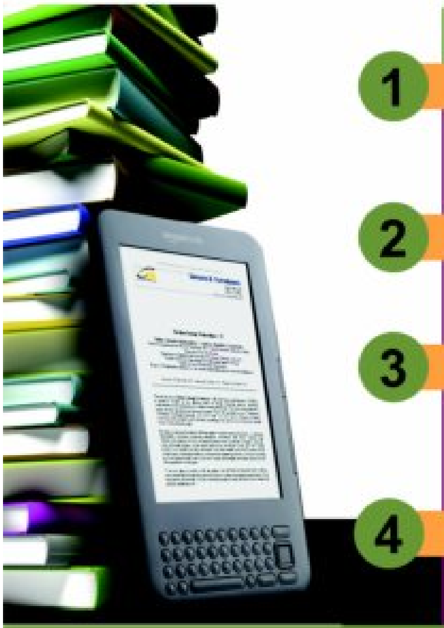

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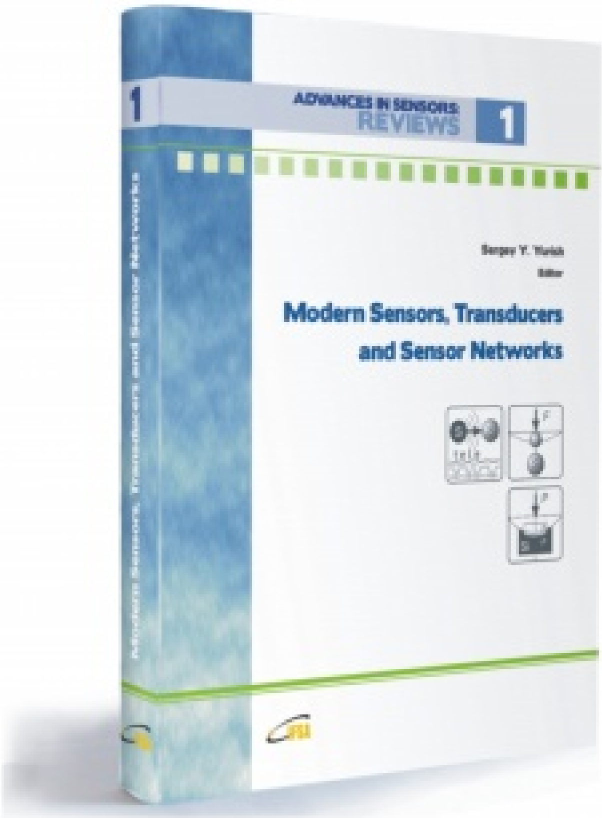

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