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Multiple Exhaust Gas Sensor for Automobiles

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Abstract: The exhaust gases of automobiles causes many serious health and environmental issues. The existing challenge is to reduce the released unburnt fuel and to create a smart fuel injection control which will result in better performance and fuel efficiency. This can be made possible only with the ability to sense and analyze the exhaust in real time. The objective of the project is to develop an integrated exhaust gas sensor using MEMS technology. It can sense four main harmful constituents of the exhaust gases from an automobile. The gases that can be sensed are Carbon- monoxide (CO), Nitrogen dioxide (NOx), Hydrocarbons (HC) and Carbon-dioxide (CO_2). The four gas sensors are integrated into a single package. The main sensing element is the micro cantilever used as a resonator. The measurement value of the change in the resonant frequency of the cantilever beam gives the amount of the corresponding gas present in the given sample. Simulation is done to derive the relation between the mass of the cantilever beam and its corresponding resonant frequency. COMSOL Multiphysics is the numerical solver used here. This design will also help us to design a real time exhaust gas monitoring system.

Keywords: Cantilever, COMSOL, GasSensor, Micro electromechanical systems (MEMS), Resonator.

1. INTRODUCTION

The exhaust of petrol and diesel engines vary in their composition. It is important to find the effect of each of its composition and to eliminate all the harmful products. Due to recent technological advancements, Lead has been completely eliminated from automobile exhaust emissions. Similarly sulphur dioxide emission can be curbed by reducing the sulphur content in the fuel. The exhaust gases have a very harmful impact on human being as well as other living organs. This effect can be studied from the below mentioned list.

A. *Carbon monoxide:* It results from the incomplete combustion of combustibles containing carbon. It is colourless, odourless, explosive and highly toxic. Carbon monoxide prevents red blood corpuscles (erythrocytes) from transporting oxygen. Even a relatively low concentration of carbon monoxide in the air we inhale is incurable. In normal concentrations in the open, carbon monoxide will oxidize to carbon dioxide CO_2 within a short period of time.

B. *Nitrox Oxide:* They are compounds of nitrogen N_2 and oxygen O_2 (NO, NO_2, N_2O, etc.). Nitrogen oxides are composed by high pressure, high temperature and a glut of oxygen in the engine during the combustion cycle. Several oxides of nitrogen are adverse to health. Action taken to curtail fuel consumption has unfortunately, frequently led to a increase in nitrogen oxide concentrations in fatigue emissions because a more adequate combustion process creates higher temperatures. These high temperatures in turn ungenerous higher nitrogen oxide emission.

C. *Hydrocarbons:* They are unburnt fuel components which occur in the exhaust emissions after incomplete combustion. Hydrocarbons (HC) occur in a variety of forms (e.g. C_6H_6, C_8H_{18}) and each has different effects on the human organism. Some hydrocarbons infuriate the sensory organs while others are carcinogenic (e.g. benzene).

D. *Carbon Dioxide:* Carbon dioxide is a colourless, non-combustible gas. It is produced by the incineration of fuel containing carbon (e.g. petrol, diesel). Carbon mingles with oxygen induced into the engine.

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The deliberate on climatic change (global warming) has amplified public consciousness to the subject of CO_2 emissions. Carbon dioxide CO_2 depletes the ozone layer which protects the earth aligned with the sun's UV rays (greenhouse effect) [4].

2. EXISTING SYSTEM

The existing system requires every personal vehicle to be checked for pollution every year. Vehicles complying with the pollution control board standards are issued a clearance certificate. The pollution check is done at special authorized centers, which have gas analyzers installed. The driving cycle is executed on the roller dynamometer. While this phase is under way, the main blower induces fatigue gas together with the filtered ambient air in a stable air mass flow. This means that the amount of air-fatigue gas blend induced stays stable. When the vehicle produces higher exhaust emissions during an acceleration phase, less ambient air is induced. When the vehicle produces lesser exhaust emissions, extra ambient air is drawn in. A constant quantity of this air-exhaust gas blend is withdrawn continuously and pumps into one or more collecting bags. The collected exhaust components are considered referred to the total distance enclosed and output is provided in grams per kilometer. The main drawback is that it is not a real time system. So, the actual emission can vary even if a vehicle had emissions under limits while testing. Moreover any control that can be implemented needs a feedback of real time values to work on. The Existing Exhaust Gas Analyzing System is shown in Figure 1.

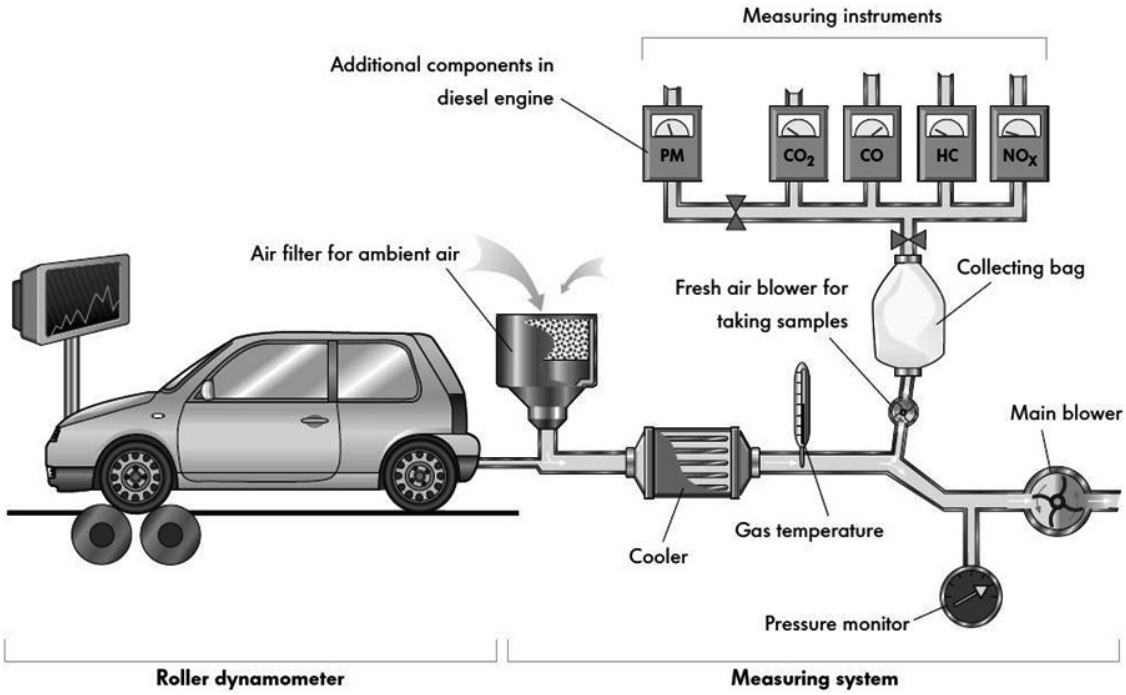

Figure 1: Existing Exhaust Gas Analyzing System

3. PROPOSED SYSTEM

The main focus of the design is to make the monitoring System real time. The small size and integrated circuit (IC) compatibility of the MEMS sensors can be employed to complete this task [5]. Micro-device also provide higher sensitivity, faster response and are powerful anti-disturbing capability [1], [6], [7]. Most gas sensing applications make use of micro-cantilever with a chemically sensitive material [7], [8]. Polymers are the preferred sensing elements as the adsorption and desorption of the gas analyte on to the polymer layer are reversible [7].Cantilever systems are broadly classified into two: the static and the resonant type. In the first type, the bending deflection of the beam gives the measure of the mass of gas

adsorbed. In the second type, the resonant frequency corresponds to the mass of adsorbed gas. Frequency measurement is found to be more reliable as it is originally in digital form and can be transmitted more safely [9]. The cantilever beam coated with the polymer layer forms the micro-cantilever resonator. The polymer is selected according to the desired gas to be sensed and their corresponding selectivity towards it. The micro-cantilever resonator integrates an electro-thermal driving unit and a piezo-resistive detecting unit [6].

A. Measuring principle

The exhaust gas reacts with the polymer layer coated on the cantilever beam and get adsorbed to its surface. This causes a mass loading and in turn changes the resonant frequency of the structure. The frequency shift $\Delta\omega$ due to the adsorbed gas is expressed in terms of mass of the cantilever m and the fundamental resonant frequency ω_0 by [6], [10].

$$\Delta\omega \approx -\frac{1}{2}\frac{\omega_0}{m}\Delta m \tag{1}$$

If we consider the volume of the polymer deposit on the micro-cantilever as V_{poly} and the fascination of the analyze in the polymer stage as C_{poly}, then the mass load due to the polymer analyte interaction will be

$$\Delta m = C_{poly}V_{poly} \tag{2}$$

If C_{gas} is the concentration of the analyze in the gas phase, then the proportion between the equilibrium concentration of the analyze in the polymer phase and in the gas phase is the coefficient *K* given by [6], [11]

$$K = \frac{C_{poly}}{C_{gas}} \tag{3}$$

The final measurement model of the sensor is given by

$$\Delta\omega \approx -\frac{1}{2}\frac{\omega_0 K V_{poly}}{m}C_{gas} \tag{4}$$

The model shows that the measure of resonant frequency shift gives the concentration of the specific gas. Moreover the relationship is linear [6]. This is the measurement model of the gas sensor based on a polymer-coated micro-cantilever resonator. It can be see the concentration of the specific gas can be measured by detecting the resonant frequency shift of the micro-cantilever. The measurement is approximately linear.

B. Design

The cantilever beam is designed with a length of 1000 μm, a width of 400 μm with a thickness of 10 μm [6]. An air column of length 1500 μm and width 400 μm with a thickness of 400 μm was considered for the simulation of the chemical reaction.

4. SIMULATION

The design of the cantilever beam and simulation of various environments were done using COMSOL Multiphysics® 4.3. The designed model is simulation mainly consisted of two different studies. The first study was conducted to validate the relation between the resonant eigen frequency and the corresponding mass of the gas adsorbed over the cantilever beam. The second study incorporated transport of dilute species physics to find the distribution of adsorption over the polymer layer for two gas individually.

A. Eigen Frequency Study

The Eigen frequency physics of COMSOL help us to find the eigen frequencies of the given structure. The cantilever beam is defined to be made of silicon. One end of the beam is fixed. Mass loading is done

vertically perpendicular on the top boundary the beam. The apply mass will be stimulate the of the gas analyte adsorbed onto the cantilever beam. The structure was meshed to form 2000 finite elements. The study is computed to obtain the first six Eigen frequencies of the structure as shown in Figure 2 & 3. For further study we considered only the first eigen frequency of the cantilever beam.

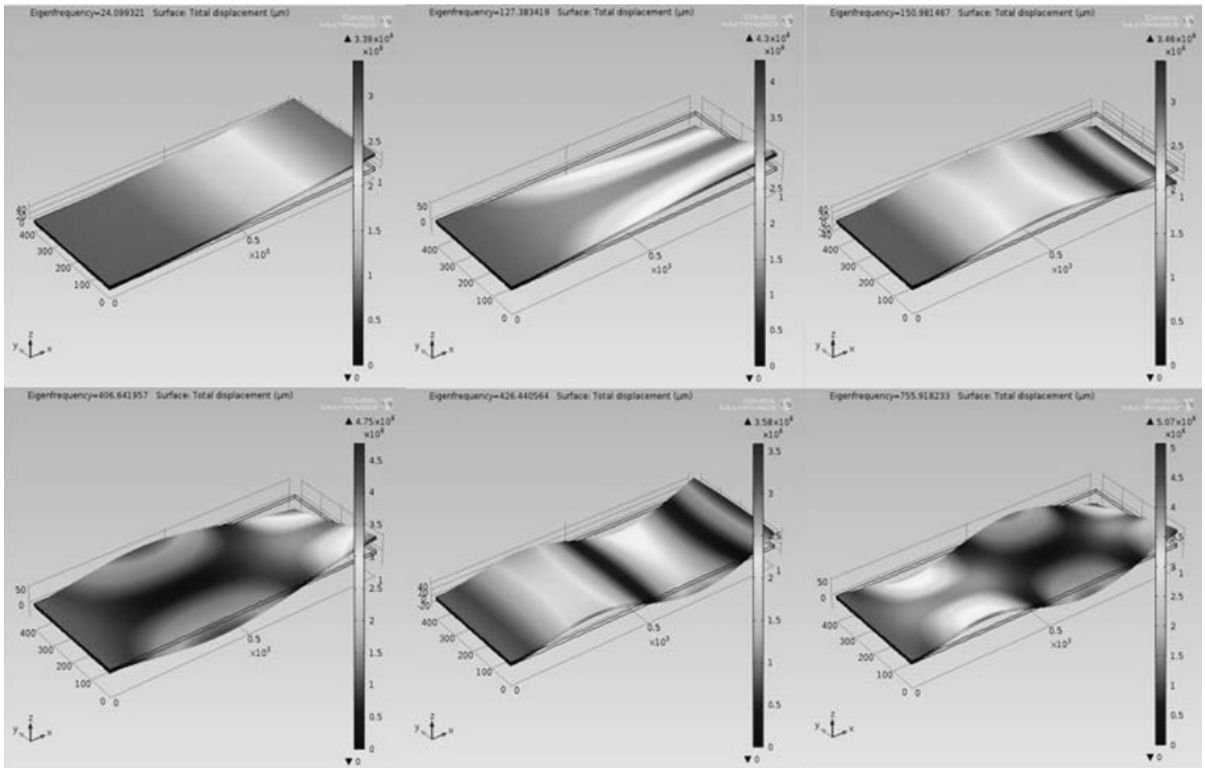

Figure 2: First Six Eigen Frequencies of the structure for NOx gas

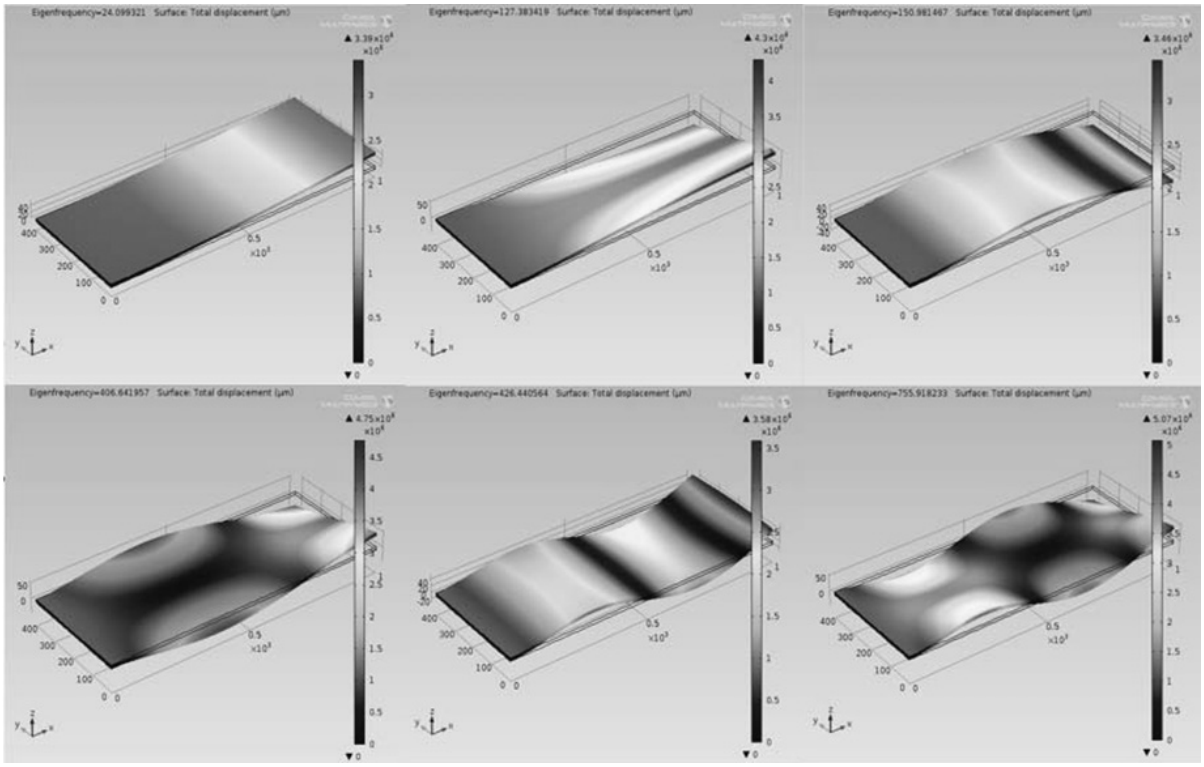

Figure 3: First Six Eigen Frequencies of the structure for HC gas

The applied mass is diverse between five different values to find its relation with eigen frequency. For zero mass, the resonant frequency is found to be at 14124 Hz.

With an increase in the applied mass, the frequency reduces linearly to a value of 9166 Hz for an applied mass of 0.032 kg. The relation between the applied mass and the eigen frequency of the structure was plot using origin software and is provided in Figure 4.

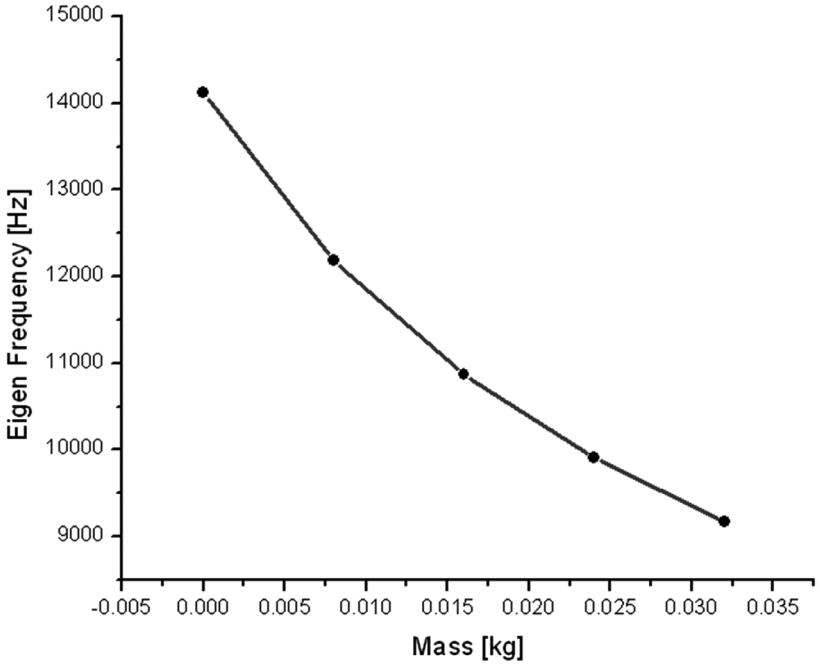

Figure 4: Mass VS Eigen frequency

Table 1
Adsorption Governing Constants

Name	*Expression*	*Description*
c0	1000[mol/m^3]	Initial concentration
k_ads	10^{-6}[m^3/(mol*s)]	Forward rate constant
k_des	10^{-9}[1/s]	Backward rate constant
Gamma_s	1000[mol/m^2]	Active site concentration
Ds	10^{-11}[m^2/s]	Surface diffusivity
D	10^{-9}[m^2/s]	Gas diffusivity
v_max	1[mm/s]	Maximum velocity
delta	0.1[mm]	Channel width

B. Transport of Dilute Species Study

The Transport of dilute species physics of COMSOL helps us to simulate the chemical reactions between the polymer layer coated onto the cantilever beam and the gases exhausting out of an automobile. For our study, let us consider the target gas analyte to be NOx. BaCO3 is found to be a good trapping material for NOx [2], [12].Poly-glycolic acid is found to be good trapping material for HC. The reaction between the sensing layer and the gas analyte is provided by a set of equations and constants. The governing constants are provided in Table 1. The rate surface reaction and the inlet velocity profile equations govern the chemical reaction. Consider c to be the channel concentration of the analyte and cs to be the surface concentration of the analyte. The surface reaction rate is defined by

$$R = k\_ads*c*(Gamma\_s-cs)-k\_des*cs \quad (5)$$

The inlet velocity profile is given by the equation

$$v\_lam = v\_max*(1-((x-0.5*delta)/(0.5*delta))2) \quad (6)$$

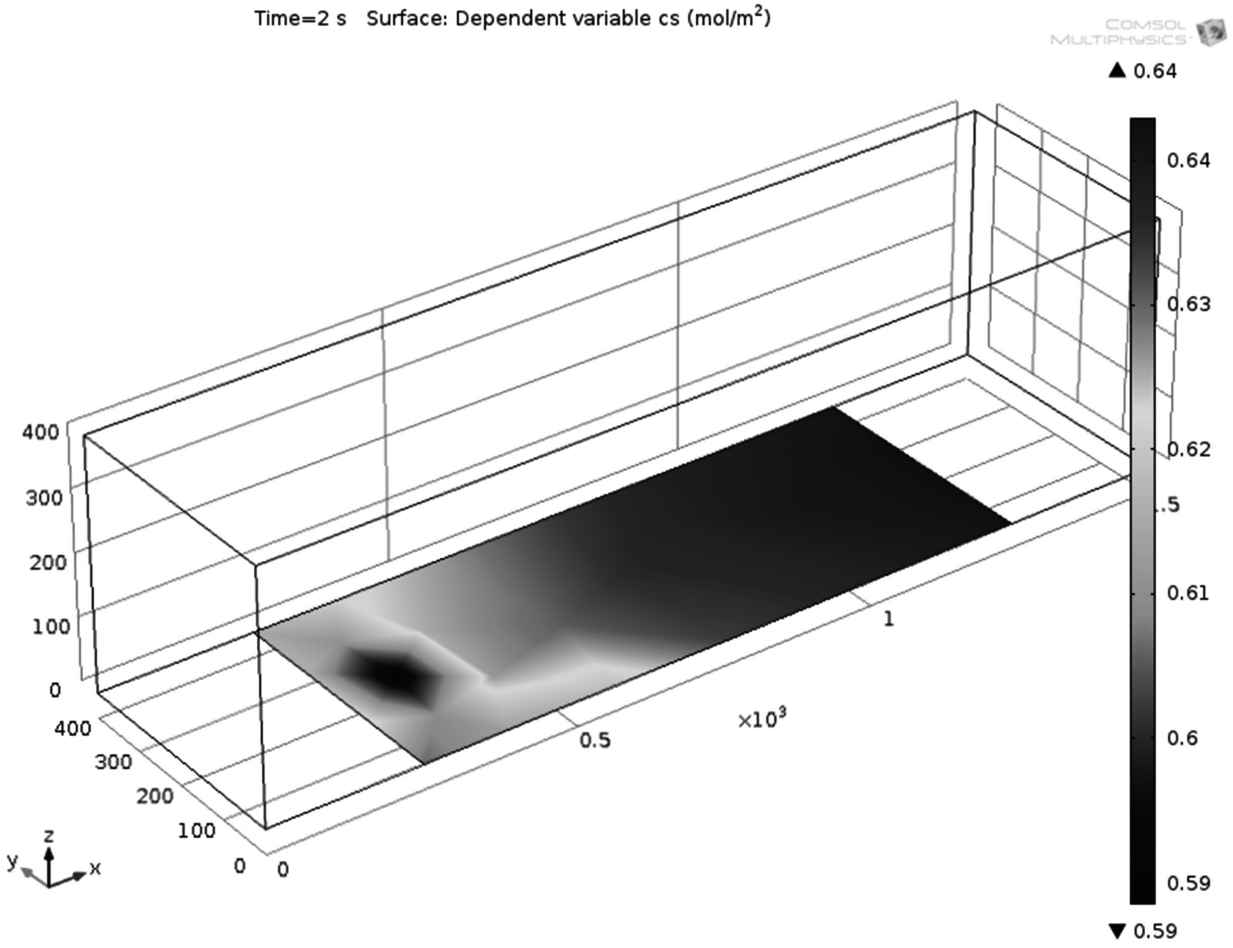

Figure 5: Surface Concentration at T = 2s for NOx

The reactive surface is placed at the bottom of the gas flow path and 250 μm away from the inlet. The initial concentration of the gas analyte on the beam is assumed to be c_0.The structure is meshed to form 580 finite elements. The result shows the concentration distribution of the gas analyte over the cantilever beam after two seconds as shown in Figure 5. The concentration distribution can then be imported into the first eigen frequency study to get more accurate results.

5. INTEGRATION OF SENSORS

The single sensor design was extended into a double sensor design. The materials used to sense the two gases for HC & NOx .The sensing beam is positioned at an angle to the inlet in order to improve the sensitivity of the design. Two cantilever beams are used to two gases and kept parallel to each other. The beam will be kept some oriented to ensure the higher sensitivity of sensors. But the driving and detecting units coupled together to facilitate the setup to be accommodated into single package.

6. CONCLUSION

The result obtained from the simulation validates the working principle of the sensor. The relation between the mass of the gas present in exhaust gas and the measured resonant frequency of the cantilever is found

to be almost linear. This confirms the feasibility of the design using a micro-cantilever beam for the use of sensing exhaust gases in automobiles.

Further work can be done to optimize the position of the reacting bed with respect to the inlet of the gas analyte. This work can also be expanded to design a four in one integrated sensor to monitor all the four main harmful gases like CO, CO2, NOx, and HC in real time.

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