Design of MEMS Based Mini-Catamaran

Shirshendu Chatterjee
Institute of Radiophysics and Technology
University of Calcutta, Kolkata
iamshirshendu98@gmail.com

Abstract

A design is presented for a Micro-ELectro-Mechanical-System(MEMS) based Mini-Catamaran, which works on the concept of Machian Propulsion. The MEMS based boat works utilizing steam as the power source s giving it high stability and high speed. The Mini-Catamaran is designed with the Micro-Boiler using MEMS heater situated on each boat on either side of the platform. The operation of the controlled through a GPS based command system. Instead of using fuel or gas, the boat works with the use of steam formed by the Micro-Boiler. Simultaneous exhaust and suction of the water due to heating in both MEMS will elevate the speed, with higher level of control and precision.

Keywords— MEMS, Micro-Boiler, Catamaran, Micro-heater

I. Introduction

In the present technological era, the need for miniaturization of devices has become the prime factor for establishing various state-of-art technologies. Several types of miniature machines have been fabricated earlier, although there has been a particular inclination in the areas of microsensors and microactuators.[1, 2, 4] This miniaturization of devices has been gradually taken place in the area of Naval and Defence technologies. Similar to boats used in navy for defence purposes, the need for mini-boats have become a target of interest for spying and environmental monitoring purposes. There have been a number of attempts to miniaturize actuators and sensors related to water, attracting increased interest with the investigation of new floating methods and propulsion mechanisms for environmental applications such as water quality monitoring etc.

In recent years, many studies have been conducted on various kinds of microrobots which are able to move on water [5]-[15] and have been reported by several research groups. The previous studies mostly focused on water strider robots, and studies on other propulsion mechanisms were also conducted. But, these researches had major drawbacks such as a large volume, low speed, and short lifetime. The development of stable device was needed which would further increase the scope for industrial as well as defence applications.

In this paper, we describe our MEMS based micro-boiler which is incorporated in a Mini-Catamaran boat with the engines as the actuator and a electronic control system to control the boat. This Catamaran boat can be used for defence applications which show high perseverance with relatively high speed due to its two engines.

Catamaran has a greater advantage over traditional single or monohull boats as it comprises of two boats connected by a platform. This serves as an important factor giving it higher stability, speed compared to others. Using this structure, modifications has been made in this paper using MEMS based Micro-boiler as the engine which along with propulsion also helps the boat to steer in any direction as per required.

This is the first approach using Catamaran as a boat and using Micro-Boilers for movement and steering purposes. The proposed model can be a subject to different modifications when it comes to the electronic system which controls the operation of the boat. This model can have a large application in industry as well as defence domains.

II. Innovation in Design

The Micro-Boiler is designed based on the use of steam as the propulsion mechanism for the Catamaran boat. This steam propulsion theory is known as Machian Propulsion. Though several attempts to miniaturize boat propulsion mechanism[9]-[14] have been made earlier, our approach has capability to be the most stable and high speed micro-actuator used as a propulsion engine.

I. *Design*

In Fig 1. the proposed structure of the MEMS based actuator is shown which works as the engine for the Catamaran. It consists of separately fabricated top and bottom silicon substrates that are bonded in the final stage of fabrication. The water cavity is prepared by bonding the two wet-etched substrates, and the micro engine has two propulsion nozzles at the bottom of its rear side. On the top substrate,micro-heater is fabricated which helps to heat up the water in boiler cavity which in turn is converted to steam for the propulsion of the boat.

The Micro-Boiler shown in Fig.1 is not only responsible for the propulsion of the catamaran, but it also controls the steering of the boat in the desired direction. It, will be seen in section III, that the speed of ejection of the water from the propulsion nozzles is much greater than that of the inflow, thus helping the boat to move forward. Taking in account of the thermodynamics of the system, it can be seen that as the temperature of the heater increases, more faster is the change of water into steam thus faster speed is attained. Thus, there is a direct relation between the temperature of the heater to the speed of the boat. Exploiting this phenomenon, we can achieve the control to steer the boat in preferred direction by increasing the current delivered to the heater, increasing temperature thus increasing speed. The dual Micro-boiler thus can be subjected to differential heating which in turn helps the boat to steer.

Thus, we can see dual Micro-Boiler incorporated in the boats will not only give the Catamaran much higher speed, but also give us the availability to steer the boat just by changing the input current. Now, the reason for using Catamaran rather than any other boats is described clearly in section IV.

II. *Architecture and Dimensional Details*

The heater is the integral part for the Micro-Boiler which serves as the engine of the Catamaran. It was seen that for micro-heaters the geometry played a major effect on its distribution of temperature.[20]. There can be several types of design which can be incorporated for the fabrication of the Micro-heater which are chosen as per requirement.

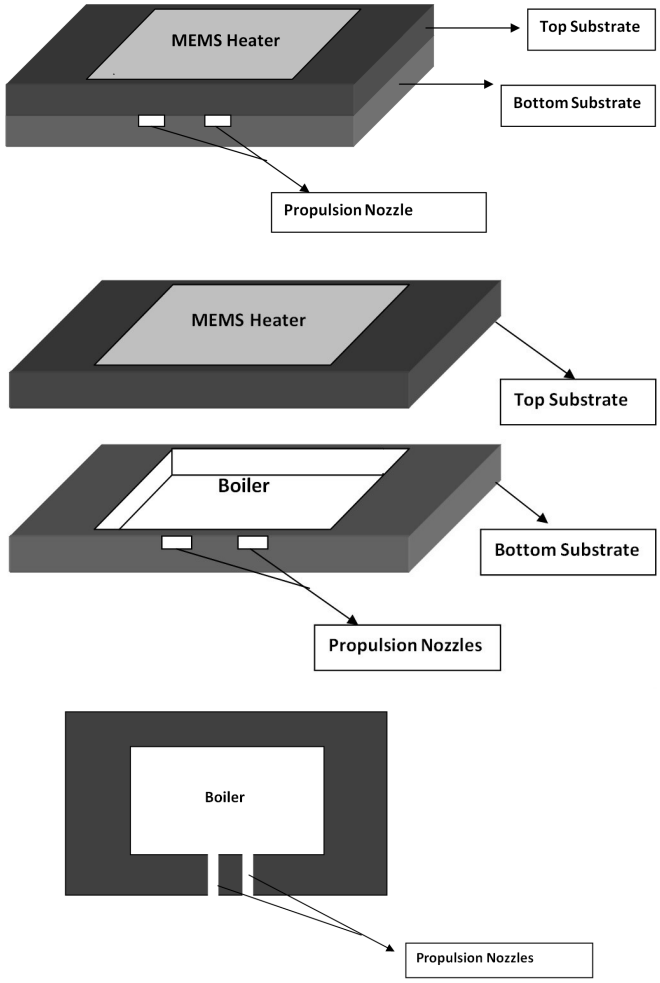

Figure 1: *Structure of the proposed micro-engine for Catamaran.*

The micro heater that is used in this paper has a combination of parallel and meandering geometries, which is seen to have the most uniform temperature distribution and which serves good for our requirement for the engine.

The dimension of the micro-heater which is used will have a overall length and width of 480μm in Fig 2. The width of the heating element made of gold will be of 30

μm, the gap between the gold in meandering structure is 10 μm.Gold is used as heating element due to its high melting point ($\sim$ 1,064 °C), high resistance to oxidation.It has a high electrical conductivity, has a stable temperature coefficient of resistance, and also good chemical and thermal durability. Micro-heater using gold serves as to be more robust compared to other materials when the devices operate at relatively high temperature.

After fabrication of the heater the boiler part comes into the picture. The bottom substrate consisting of the boiler is of the same size of the substrate used for the heater. The etched out cavity formed to serve as the boiler for water intake will be of the same size of the cavity in the heater.

III. Principle of Operation

We have used the theory of Machian propulsion[16] which is based on propulsion by generation of steam. As the water keeps coming into the cavity, the heater turned on. When heat is applied to the boiler, water in the boiler evaporates, producing steam. The expanding steam is suddenly pushed out of the boiler and pushes some of the water out the cavity through the propulsion nozzles, propelling it forward.The boiler or the cavity being dry, cannot, therefore, generate any more steam. The momentum of the column of water in the exhaust tube keeps it moving outward, so that the pressure inside the boiler drops down below the atmospheric pressure.

The pressure outside the boiler now forces water back into the boiler. This water then boils and the cycle of alternate suction and ejection repeats. The water expelled from both tubes during the first phase of the cycle, and drawn in from both tubes during the second phase of the cycle.

Thus as discussed above, Catamaran is propelled forward by the alternate suction and ejection of the fluid across its pipes' orifice, thus having the net mass flux being zero. Yet, there is a net forward thrust developed because, during the outflow, the flow is an axi-symmetric jet confined to a narrow domain and does not diverge much for reasonable distances.

The flow during suction can be thought of as similar to the flow induced by a sink flows through pipes simultaneously. The inflow is of the same magnitude but it does not produce an equal and opposite thrust and is much smaller compared to the thrust produced during ejection as shown in Fig.3.

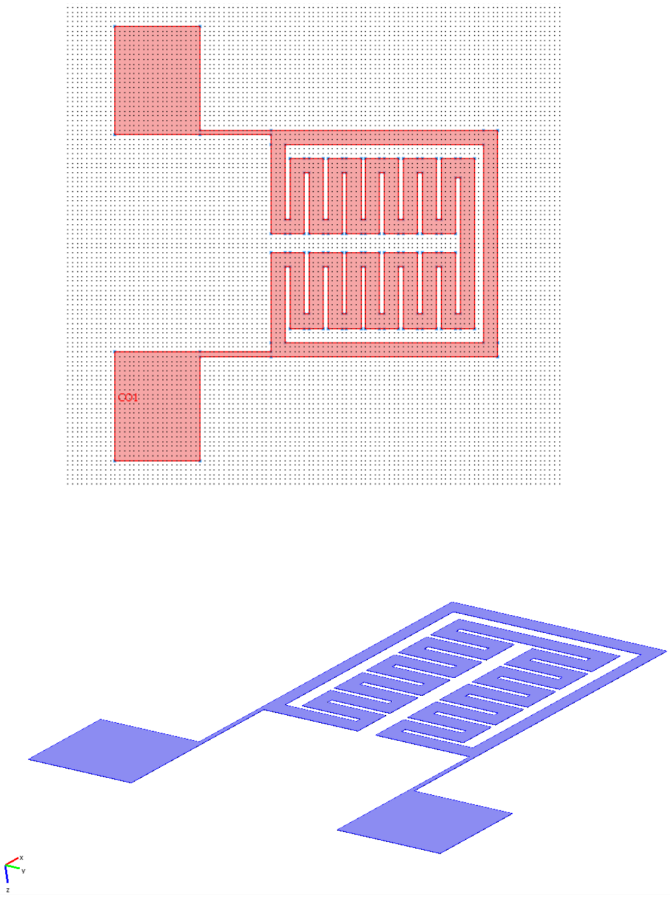

Figure 2: *Structure of the parallel and meandering MEMS heater*

The inflow is of the same magnitude but it does not produce an equal and opposite thrust and is much smaller compared to the thrust produced during ejection as shown in Fig.3. The difference between how the inflow and outflow is critical in the study of fluid mechanics. It can be easily seen that we cannot 'suck out' a candle but we can easily 'blowout' a candle even though the average velocity near the lips is nearly the same for both of the situations. The asymmetry of the shapes of the inflow and the outflow is a consequence of the viscosity of water, whereas the catamaran would be able to operate in an ideal fluid. Furthermore, as they pass through the orifices,the outflowing and the inflowing water carry the same momentum but in opposite directions, relative to the boat. The important difference is that the momentum of the outflow is expelled, whereas the momentum of the inflow is soon transferred to the boat.

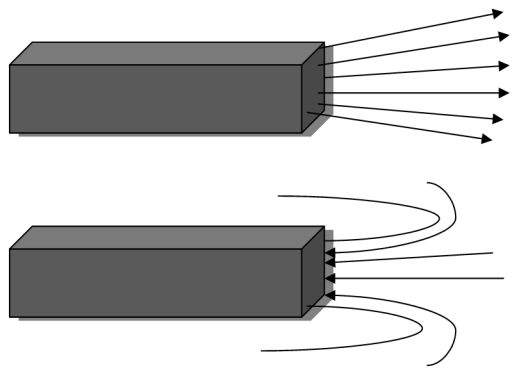

Figure 3: *Outflow and Inflow of water from an orifice*

IV. Design of Catamaran

For the application of this actuator, we propose a design of the catamaran to be used in defence applications for water monitoring as well as spying operations.

I. Why Catamaran?

We know, the catamaran consists of two boats with one adjoining platform. This design of boat has been extensively used for its higher stability. Exploiting it's advantages, a mini version of this catamaran is designed which can run through the dual MEMS engine with Micro-Boiler defined above with slight modifications.

In designing boats of small dimension, packing electronic system with engine inside the boat can become a difficult task to accommodate. This problem is solved by the platform between the boats of the catamaran thus giving ample space for the placement of the engine as well as a electronic system which gives the catamaran a higher advantage over other boats.

Another most important use of the Catamaran is the use of dual Micro-Boiler. This option is only available because of the use of two boats which is connected together. The dual Micro-Boiler is the main attraction of using this boat as it not only serves as a engine but also helps the boat to steer in any preferred direction when required as discussed above. This versatility of the dual Micro-Boiler proves to have higher advantage and efficacy than any other models.

As seen in Fig.4, our proposed design of the catamaran have two MEMS engines incorporated on each boats. Each boat have two orifices which extend till the opening of the propulsion nozzles of the MEMS engine. Steering rudder is also added to the boat for redundancy of the Micro-Boilers to steer.

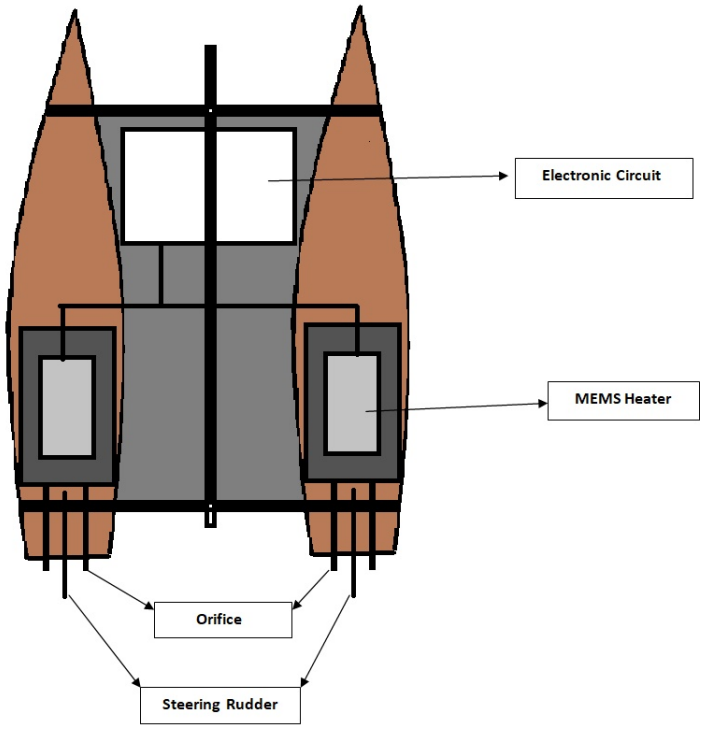

Figure 4: *Design of the proposed Mini-Catamaran*

II. Power Source

Now, identifying a satisfactory method for supplying electrical power to the controllers and actuators is a major step in the design process. For the boat the use of a micro power supply can prove to be advantageous for heating as well as for the light weight. Like any power supply system, the micro power supply must be composed of three parts-

1. Energy Source
2. Energy Capture
3. Energy Storage and delivery

We know that the most useful and readily accessible energy source is light energy. Light energy can be obtained from sun. Using a photovoltaic cell to capture the energy, light can be harnessed to produce an electrical current. The electrical current produced by the photovoltaic cells

Table 1: *Material Properties of layers of micro-heater*

Material	Si	Si_3N_4	SiO_2	Au	SiC
Young's Modulus(GPa)	140	297	74.8	79	137
Density(kg/μm^3)	2.33 e-15	2.9 e-15	2.27 e-15	1.93 e-14	3.1 e-15
Poisson's Ratio	0.17	0.27	0.2	0.415	0.14
Thermal Conductivity(pW/μmK)	150 e+6	22 e+6	1.4 e+6	3.10 e+8	12 e+7
Specific Heat(pJ/Kg.K)	7.12 e+14	17.0 e+13	1.0 e+15	1.3 e+14	15 e+13
Dielectric Constant	1.19e+1	8.0	3.9	6	10.8
Electrical Conductivity(s/m)	-	-	-	4.10 e+7	1e+2
Melting Point($^\circ C$)	1414	1480	1600	1064	2730

can be used to drive the MEMS heater to perform. First, the current can be routed directly to the controllers that would, in turn, route current to heater when needed.

This configuration would be sufficient assuming that lighting conditions were always optimal, but would not allow for any auxiliary power, should light levels drop below the operating threshold.

In order to ensure operation in non-optimal lighting, a method of power storage is necessary. The second and more desirable way to configure the photocells is in conjunction with a battery. The photocell would charge the battery, and the battery would drive the engine. Further, the photocell could temporarily be used along with the battery if higher voltages or currents are required.

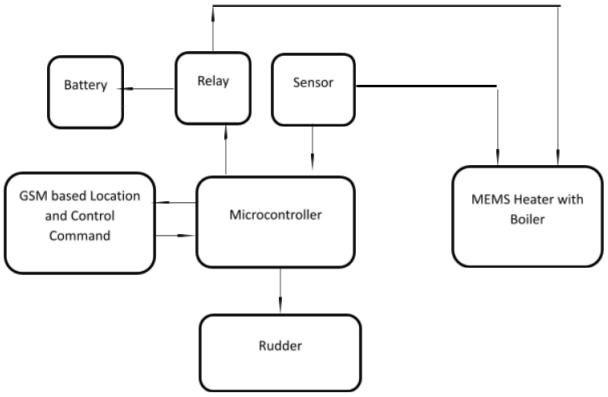

Figure 5: *Block Diagram of the control system to monitor operations on the Catamaran*

To control such operations an electronic system is a must which will be placed on the platform of the catamaran. This will be externally controlled using GPS based control command for finding it's location and movement. This signal is captured by microcontroller to control different operations. The battery will be switched on through the microcontroller thus switching on the Micro-Boiler through relay. The temperature of the heater can also be sensed through a sensor which in turn gives microcontroller to control the current to be delivered as and when required for a particular desired temperature. After the Catamaran starts moving, it's movement can also be controlled thorough GPS based control system using command given to the microcontroller. The block diagram of the whole process is shown in Figure 5.

V. Fabrication Feasibility

I. Fabrication Procedure-

The boiler and the heater are to be fabricated separately and then placed together. When both substrates are completely processed, they will bonded using epoxy.

I.1 Fabrication of MEMS Heater-

The fabrication of MEMS heater with different geometry and structure has been stated before in different works.[20, 21]. The fabrication procedure of our MEMS heater has been motivated by some works.

The MEMS Heater will be designed on a 1000 μm x 1000 μm substrate area of a silicon-100 substrate. The first fabrication process step involves the deposition of a 0.3 μm - thick silicon nitride (Si_3N_4.) layer onto the silicon substrate surface using the low-pressure chemical vapor deposition process. This Si_3N_4 layer is deposited to act as a membrane that can support the micro-hotplate structure. Then the deposited Si_3N_4 layer is etched using the wet

etching method to form a base structure for the micro-hotplate. In this etching process, phosphoric acid can be used as etchant.

After this, a 0.5 μm -thick silicon oxide (SiO_2) layer is deposited onto the Si_3N_4 membrane and is etched using the wet etching method to give it a shape as the micro-hotplate. The use of the SiO_2 layer is to insulate the Si_3N_4, membrane and the heating element. After that a 0.2 μm gold layer which is the heating element is deposited onto the SiO_2 layer using the sputtering method. This gold layer is patterned to form various micro-heater shapes with parallel and meandering geometry. A 0.8 μm -thick SiO_2 and a 0.2 μm -thick silica carbide (SiC) layers are deposited onto the patterned gold layer to ensure that the heat from the gold heating element is distributed uniformly across and along the micro-hotplate. After that, these two layers etched to have a shape as the micro-hotplate. Another 0.5 μm -thick SiO_2 insulating layer is deposited onto the onto the SiC layer to insulate it from any electrical contact. Finally, the last step is the creation of a cavity at the back side of the device (silicon substrate) to isolate the Si_3N_4 membrane from the substrate. The purpose of this is to reduce the heat dissipation from the heater to the Si substrate. Anisotropic wet etching will be used in this process.

I.2 Fabrication of the boiler-

The bottom substrate consists of two propulsion nozzle and a deep cavity. Firstly, silicon oxide is grown by thermal oxidation and is patterned on the front of the bottom substrate by wet etching using a buffered oxide etchant. TMAH etching is performed to form the two propulsion nozzle and deep cavity.

VI. Conclusion

This paper has proposed a design for a catamaran using Micro-Boiler working with the use of Machian Propulsion theory. The Micro-Boiler uses a heater with a cavity in the middle and two propulsion nozzles. The MEMS based Micro-Boiler is powered by a battery. The Catamaran uses two MEMS engine on each boats and an electronic control system based on GPS technology. The steering operation of the boat is controlled by differential heating of the dual Micro-Boiler. The Catamaran proposed can have various application for defence and spying and can sustain in water due to high stability, speed and also due to use of renewable energy.

VII. About the author

Shirshendu Chatterjee is a 4^{th} year B.Tech student at the Institute of Radiophysics and Electronics, University of Calcutta.

VIII. Acknowledgement

I wish to thank STARC-DRDO for giving this oppurtunity. I wish to extend my special thanks to Prof. Anirban Bhattacharyay, Institute of Radiophysics and Electronics, University of Calcutta for his guidance and help in organization and gradual development of the idea.

References

[1] H. Fujita, "Microactuators and Micromachines," Proceedings of the IEEE, vol. 86, pp. 1721-1732, (1998).

[2] J. H. Smith, J. J. Sneigowski, P. J. McWhorter, and A. D. Romig, "Intelligent Microsystems: Strategy for the Future," in Semiconductor International, (1998)

[3] Olivas, J.D., Bolin, S. Advancements in MEMS materials and processing technology. JOM 50, 38–43 (1998).

[4] K. E. Petersen, "Silicon as a mechanical material," in Proceedings of the IEEE, vol. 70, no. 5, pp. 420-457, (1982)

[5] Hu, D., Chan, B. Bush, J., The hydrodynamics of water strider locomotion. Nature 424, 663–666 (2003).

[6] Gao, X., Jiang, L. Water-repellent legs of water striders. Nature 432, 36 (2004).

[7] Y. S. Song and M. Sitti, "Surface-Tension-Driven Biologically Inspired Water Strider Robots: Theory and Experiments," in IEEE Transactions on Robotics, vol. 23, no. 3, pp. 578-589, (2007)

[8] C. Luo, H. Li and X. Liu, Propulsion of microboats using isopropyl alcohol as a propellant, J. Micromech. Microeng. 18 067002 (2008)

[9] Y. Mita, Y. Li, M. Kubota, W. Parkes, L. I. Haworth, B. W. Flynn, J. G.Terry, T. B. Tang, A. D. Ruthven, S. Smith, and A. J. Walton: Proc. 38th European Solid-State Device Research Conf., 2008, p. 306.

[10] S. K. Chung, K. Ryu, and S. K. Cho: Appl. Phys. Lett. 95 014107(2009).

[11] S. K. Chung, K. Ryu, and S. K. Cho: Proc. 22nd Int. Conf. Micro Electro Mechanical Systems, p. 1083 (2009).

[12] Won, J.M., Lee, J.H., Lee, K.H. et al. Propulsion of water-floating objects by acoustically oscillating microbubbles. Int. J. Precis. Eng. Manuf. 12, 577–580 (2011)

[13] K. Visvanathan, F. Shariff, S. Y. Yee, and A. S. Basu: 15th Int. Conf.Solid-State Sensors, Actuators and Microsystems, p. 1293 (2009).

[14] Gou, X. Ye, and Y. Okuda: Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, 2006, p. 2430.

[15] Hu, D.L., Prakash, M., Chan, B. et al. Water-walking devices. Exp Fluids 43, 769–778 (2007).

[16] A. Jenkins, Eur. J. Phys. 32 1213(2011)

[17] Hwang, Woo-Jin , Shin, Kyu-Sik , Roh, Jay , Lee, Dae-Sung , Choa, Sung-Hoon. Development of Micro-Heaters with Optimized Temperature Compensation Design for Gas Sensors. Sensors (Basel, Switzerland). 11. (2011)

[18] Sharadha, V. Arakeri, Jaywant. Propulsion of the putt-putt boat — I. Resonance. 9. 66-73 (2004).

[19] Santosa, Pramudya , Utama, I Ketut. An Investigation into Hybrid Catamaran Fishing Vessel: Combination of Diesel Engine, Sails and Solar Panels. IPTEK Journal of Proceedings Series.(2014)

[20] O. Sidek, M. Z. Ishak, M. A. Khalid, M. Z. Abu Bakar and M. A. Miskam, "Effect of heater geometry on the high temperature distribution on a MEMS micro-hotplate," 2011 3rd Asia Symposium on Quality Electronic Design (ASQED), pp. 100-104, (2011)

[21] Lee, Kook-Nyung ,Lee, Dae-Sung , Jung, Suk , Jang, Yun-Ho , Kim, Yong-Kweon, Seong, Woo-Kyeong. A High-temperature MEMS Heater Using Suspended Silicon Structures. Journal of Micromechanics and Microengineering. 19. (2009)