Enhanced and self-tuned motive force for locomotion of a nanorobot: Possible solution from nature

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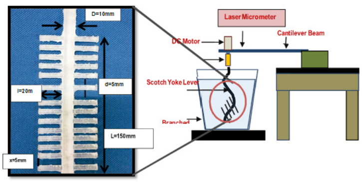
Locomotion of bacteria in fluid at small scale is accomplished by cilia and flagella present on its surface. In nature, presence of cilia exhibits various applications such as movement of egg for fertilization in female, mucus and dust removal from lungs and circulation of cerebrospinal fluid in brain. In literature, artificial cilia has been fabricated and used for mixing and movement of fluid in microfluidic applications. In the present study, the branches (cilia) on flagella (paramecium) has been employed as tree branch concept for designing of artificial nanoswimmer and experiments have been performed at scaled up level in silicon oil medium to mimic human body environment. The effects of primary branches have been investigated by fabricating the branched flagella using flexible PDMS (polydimethylsiloxane) biocompatible material suitable for human body and biological applications. It has been observed that by increasing number of primary branches from 14 to 28, increase in deflection approximately 23% has been observed. The observed deflection is correlated to the thrust force developed by the propulsion of flagellated nanoswimmer. The thrust force generated due to planar wave actuation of flagella is being picked up by laser micrometer in terms of displacement of cantilever beam. The work also provides a theoretical model that supports the experimental results. The concept of self- tuning also have been studied through statistical analysis probability density function (PDF) which means variations in deflection data can be decreased by increasing number of primary branches.

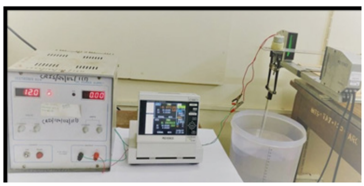
The current study focus on how branched density affects the output performance in terms of self-tuning and thrust force generation for different model of nanoswimmer. Two designs of nanoswimmer have been investigated experimentally to prove the hypothesis and results are leading towards possible design by improving the efficiency of nanoswimmer. The statistical analysis is performed to endorse the self-tuning and thrust force conception of designed nanoswimmer *via* probability density function (PDF) and root mean square (RMS) plot of recorded deflection from experimental study. In literature, the effect of viscosity also can be seen to examine the increase in thrust force for nanoswimmer which is also being considered in the present work.

Conclusion: A tree branch structure is mimicked to design different models of nanoswimmer. Two designs have been explored and experimental investigations have been performed to study the performance of planar mode of propulsion of natural bacteria and quantitatively analysis is being carried out to see the influence of branching on thrust force generation. Effect of number of primary branches can be seen clearly by changing the spacing between branches. In first design (I) (Figure 2) 28 branches have been studied experimentally and then 14 branches by removing the branches at alternate position over the length of flagella as shown in design (II) (Figure 2). Deflection is being recorded and statistical data analysis is applied to see the effect of branches for self-tuning means to lower the variations in the recorded data points which can be indicated in PDF plot. RMS plot for 28 branches and 14 branches represents the more deflection approximately 41% and 52% on increasing viscosity 350cSt to 15000cSt which corresponds to high thrust force at low Reynolds number regime. As the number of primary branches increases from 14 to 28 in 15000cSt silicon oil environment, the deflection of cantilever beam increases by 23%. The thrust force on increasing number of branches from 14 to 28 as observed through numerical modelling. Enough energy can be harness for on board powering of nanoswimmer which can be employed by converting mechanical motion into electrical by means of electrostatic, electromagnetic and piezoelectric conversion techniques by exploiting the proposed design of nanoswimmer. Primary branches at an angle need to investigate further to improve the

performance of an artificial nanoswimmer.

Keywords: Nanoswimmer, tree-branching, PDMS, self-tuning.





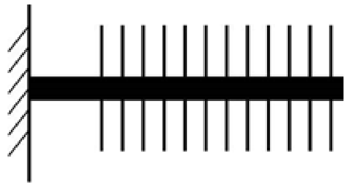
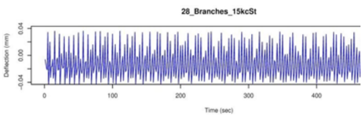
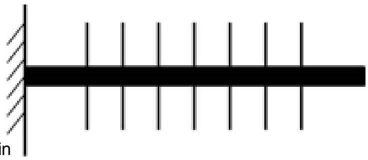


Figure 1: (a) Schematic diagram of experimental set up; (c) Scaled up prototype for experimental investigation using Planar mode of propulsion





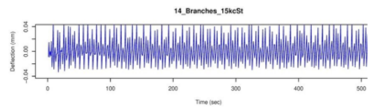
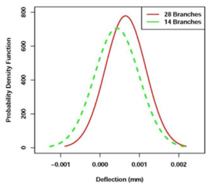
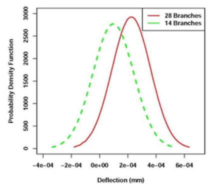


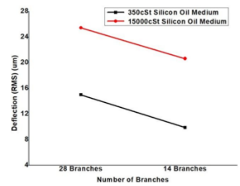
Figure 2. Design (I) and (II) are showing increase in spacing between branches by decreasing number of branches from 28 to 14; (a) and (b) are presenting the record of deflection of cantilever beam attached to nanoswimmer in 15000cSt silicon oil medium



(a) 15,000cSt Silicon Oil medium



(b) 350cSt Silicon Oil medium



(c) Different viscosity of Silicon Oil Medium

Figure 3. (a) and (b) showing the effect of branches in different viscosity of silicon oil in terms of probability density function (Gaussian Curve and peak point on the curve is indicating mean value for 28 and 14 branches on flagella; (c) root mean square value of deflection to see the difference in deflection recorded for different model of nanoswimmer

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