# A Synthetic Microswimmer with an Acoustically-Actuated Flagellum

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**Abstract:** A model for actuating a synthetic microswimmer with a flexible flagella using an acoustic field to excite an oscillating wave in the flagellum is presented in this paper. In order to create the largest possible wave amplitudes, the wavenumber of the fluid is matched to the wavenumber of the microswimmer's flagellum at a particular modal frequency. An analytic model of this approach shows that a stiff material, such as nickel, is most appropriate for this coupling. However, 3D numeric simulation suggests that amplitudes of the wave produced by this coupling are on the order of sub-angstrom and are too small to create cell-like swimming. Further study is needed to understand the system of a microswimmer in fluid, and associated 2nd-order effects, to drive larger oscillatory amplitudes.

**Keywords:** microswimmer, flexible flagellum, acoustic actuation, biomimetic swimming.

## 1. Introduction

Micro-robotic, flagellum-driven, swimmers have significant potential use in medical applications and biological studies. We see two motivations for the bio-inspired approach. First, the strategies employed by natural systems suggest solutions to engineering problems that may not occur to the human designer, particularly in regimes where we have no direct physical experience (e.g. microscale swimming at low Reynold's numbers). Second, engineered model systems are a platform for scientific study; in an engineered system it is possible to control experimental parameters that may be impossible or difficult to modify in animal experiments. However, by using a physical system rather than a computational model, certain complexities of the true environment can be retained [1].

For example, the rheological properties of complex fluidic environments are predicted to couple to flagellar mechanics in complex ways, possibly resulting in a speed enhancement for swimming microorganisms. This predicted enhancement results from the interplay between the dynamic material properties of the fluid (viscoelasticity) and the solid flagellar structure (geometry and elasticity). Due to the high degree of variability and lack of control over swimming cells, there exists a significant need for engineered flagellated swimmers whose waveform dynamics can be controlled to understand the ability, adaptation and evolution of cell motility in complex fluids.[2] In addition to swimming, flagellar and ciliary synchronization has been observed in a number of natural systems including sperm motility and cilia, whereby hydrodynamic and mechanical interactions between elastic, actuated flagellar appendages result in coordinated motion. Thus, local, physical interactions can lead to large scale synchronization (cilia) and potentially an increase collective swimming efficiency (sperm).[3] A tunable, engineered system is ideal for studying the collective motion of swimming cells. Hydrodynamic and steric interactions between swimming cells are known to lead to large scale collective swimming patterns in bacteria and sperm. While such pattern formation has been well characterized in recent years, an understanding of the mechanisms leading to such behavior is not fully formed. [4]

In terms of engineering applications, such a swimmer could be useful for minimally invasive exploration of small regions that cannot be probed by conventional means. [1] In the medical field, a "micro-robot" might also be used for selective drug delivery or micro surgery.[5, 6] A microscopic swimmer platform capable of swimming in Newtonian and non-Newtonian fluids where one could attach a cargo, sensors, or the like, to the swimmer's body is ideal.

However, power delivery and communications are problematic for microswimmers, because power sources and actuators present fabrication challenges at the micro scale. Therefore, the use of an external power source, such as ultrasound, could be used to excite motion and simultaneously image with backscattered waves. Medical ultrasound, in the range of 1 MHz to 200 MHz, is an approved technology that enables imaging within the human body and appears to be a promising source of energy to power the swimmer. Results from preliminary models suggest that it is possible to excite a traveling wave in a flexible flagellum and propel a microswimmer through a fluid at low Reynolds numbers.

## 2. State of the Art

The literature sights many examples of passive microswimmers that are actuated by magnetic fields [7-28] and viewed using optical microscopes. Nelson et. al. produced several stiff, magnetically actuated, helical flagellum and used them to carry out various tasks. [10, 13-15, 20, 23-27] Their original swimmer was created in 2009, measured about 3 microns in diameter and 48 microns long and was capable of swimming at over 1 micron per second. [10] Another notable magnetically actuated microswimmer was created by Dreyfus et. al. which swam at 5 microns per second by beating a flexible flagellum made from 1 micron diameter, magnetic nano-particles strung together by DNA molecules to be about 25 microns long. [7, 17]

Apart from magnetically actuated swimmers, several flagellum-driven microswimmers have been produced with flexible flagella driven with a variety of biological methods. Williams et. al. developed a cast PDMS, sperm-like swimmer that was driven by a cardiomyocyte (cardiac cell). [29] PDMS was cast into a flagellum about 2mm long with the cardiomyocytes cultured where the head of the structure meets the flagellum. The cardiomyocytes contract rhythmically, and make the flagellum beat, propelling the swimmer at a maximum recorded velocity of 10 microns per second. Also in the biologically actuated realm is the work by Magdanz et. al. By capturing a bovine sperm cell in an 8 x 50 micron tube, they created a swimmer that was self-propelled and steered with a magnetic field. [30, 31]

As seen from this brief review, the majority of flagella-propelled microswimmers are either driven magnetically or by biological means. However, there is little research in the design, fabrication and characterization of flexible-flagella swimmers on the micro scale actuated using an acoustic field. Several swimmers in the literature are driven acoustically [32-39] either by oscillating bubbles or oscillating stiff metallic rods, but these do not rely on an undulatory swimming motion. Parmar et. al., [39] are the only work we are aware of that describes flexible, acoustically actuated structures. In this work, a 3D printed flexible flagellum was demonstrated that was capable of rotating 180 degrees in a 1 MHz acoustic field. More work in this area needs to be done.

## 3. Approach

We propose a single-flagellum microswimmer that is acoustically actuated and imaged by medical ultrasound acoustic fields (1MHz to 200MHz). This microswimmer will serve as a platform to perform tasks at the micro scale and swim through fluid media. Locomotion will be achieved by the coupling of an incoming acoustic plane wave to a traveling wave in the body of the swimmer, as seen in Figure 1. The resulting scattered waves will be used to image the device to allow for control where optics is not appropriate.

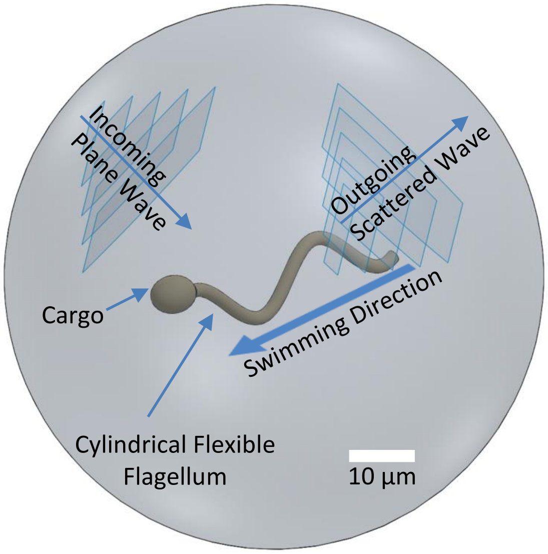

*Figure 1: Conceptual representation of the acoustic actuation of a cylindrical flagellum.*

Preliminary work has been done to model the flagellum as a fixed-free cylidrical beam. A key design tool that has been used to limit the design space is the assumption that the best acoustic coupling will occur where the wave number of the fluid $\beta_{fluid}$ will match the wave number of the structure $\beta_{beam}$. For example, we can calculate a slender bending geometry which will create a match between the bending wavenumber in the structure and the fluid wavenumber (for a wave impinging with grazing incidence), at a specified resonance frequency $\omega$.

$$\beta_{fluid} = \beta_{beam}$$

$$\frac{\omega}{c} = \left( \frac{\left(\rho_{beam} + \rho_{fluid}\right) A\omega^2}{EI} \right)^{1/4} \qquad (1.1)$$

Where $\rho$ is density, $c$ is the speed of sound in the fluid and $A$, $E$ and $I$ are the cross-sectional area, elastic modulus and area moment of inertia of the structure, respectively. In equation 1.2 we also take into account the added mass of the fluid $\rho_{fluid}$, which, for a perfect fluid, is equal to the mass of the displaced fluid. [40] This simplification is only valid for incompressible, inviscid fluids, and bears further study. However, as a starting point, this result is such that it allows development of an analytic expression for the structural dimensions. A time frequency is chosen in the range appropriate for medical ultrasound. The diameter of the flagellum is then calculated from (1.1) to match the fluid wavenumber. Finally, the length L of the flagellum is calculated to match a this wavenumber to a resonant mode of the structure, presuming that this will result in the largest amplitude of motion.

$$\omega = \left(\frac{N}{L}\right)^2 \sqrt{\frac{EI}{\left(\rho_{beam} + \rho_{fluid}\right) A}} \qquad (1.2)$$

Here, N is the eigenvalue of the chosen mode for a bending beam and depends on the choice of boundary conditions. For 50 MHz, the 4th mode of a fixed/free beam results in the dimensions listed in the table below.

| Material | Radius (µm) | Length (µm) |
|---|---|---|
| SU8 | 10.6 | 52.5 |
| PDMS | 577.9 | 52.5 |
| Nickel | 3.18 | 52.5 |

*Table 1: Resulting diameters calculated cylindrical beam excited at 50 MHz.*

From Table 1, we can see that polymers like SU8 and PDMS are not appropriate for this application because they will not create high aspect ratio cylinders on the order of cellular flagella. Indeed, the entire model assume slender structures, so the SU8 and PDMS results where the aspect ratio is 0.5 or greater cannot be appropriately modeled with this set of equations. The simple model immediately suggests that stiffer materials such as Nickel may need to be used.

Finally, it is important to point out that the standing wave response we are designing for here will not produce forward swimming. A traveling wave will be required to produce biomimetic swimming. This, in turn, will necessitate the investigation of tapered structures or other variations in structural properties along the length, as well as a good understanding of damping mechanisms. Ongoing work begins from the simple analytical starting point we have described here to explore three dimensional numerical models of structures in real fluids, which will then motivate our physical designs.

## 4. 3D Simulation

As a starting point for verification of the analytic model by way of 3D numerical analysis, a straight, fixed-free, cylindrical rod was used as the model of the flagellum. The rod was prescribed a simple nickel material model with a Young's modulus E of 207GPa, Poisson's ratio of 0.31 and density of 8880 kg/m$^3$. The rod was placed in a cylindrical control volume with a simple water model where the wavespeed is 1500m/s and the density is 1000kg/m$^3$. An impinging plane wave with an amplitude of 1Pa was released from one end of the control volume and cylindrical wave radiation boundary condition on the cylindrical surface. The far end of the control volume had a plane wave boundary for the waves to exit without reflections. On the swimmer itself is a hard boundary at the fixed end and free on all other surfaces. The velocity of the free structure is matched to that of the fluid at the boundary to couple the motion of the solid and fluid domains and the geometry was meshed with 2$^{nd}$–order tetrahedral elements with 6 elements across the wavelength of the plane wave and the radius of the flagellum.

Results of this simulation show the dependence of the amplitude of the standing wave in the flagellum to the incident angle and frequency of the impinging wave. From Figure 2, we see that maximum displacement is achieved at an angle of incidence of 40 degrees for a 50MHz plane wave. Placing the swimmer at 40 degrees to the incident plane wave, a frequency sweep was performed from 50MHz to 200MHz while varying the radius and length of the flagellum to match the frequency. Figure 3 shows that maximal displacement of the flagellum is achieved as the frequency is lowered. The analytic model in Figure 4 shows that the dimensions of the swimmer are still small at low ultrasonic frequencies; however they start to become larger than 'cell-scale' below 100MHz.

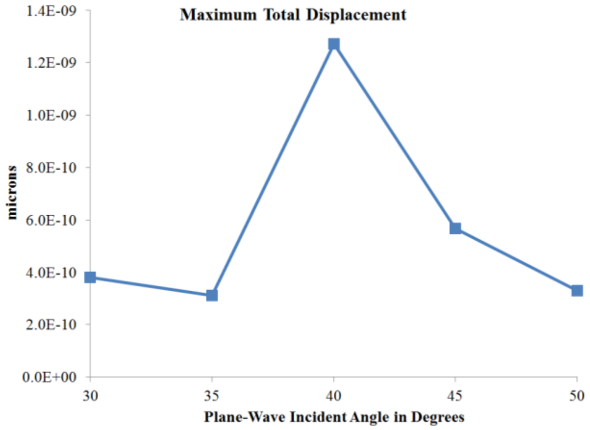

*Figure 2: Maximum displacement of the flagellum as a function of incident angle of the impinging 50MHz plane wave. Flagellum dimensions are defined by equations (1.1) and (1.2) at 50MHz.*

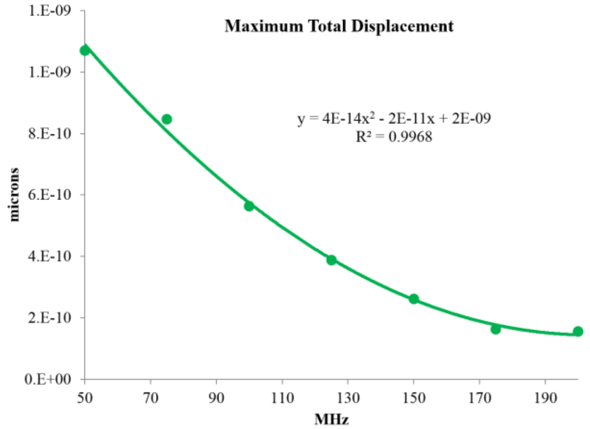

*Figure 3: Maximum displacement of the flagellum as a function of frequency sweep from 50MHz to 200MHz for a flagellum of radius and length dependent on a 40 degree incident plane wave.*

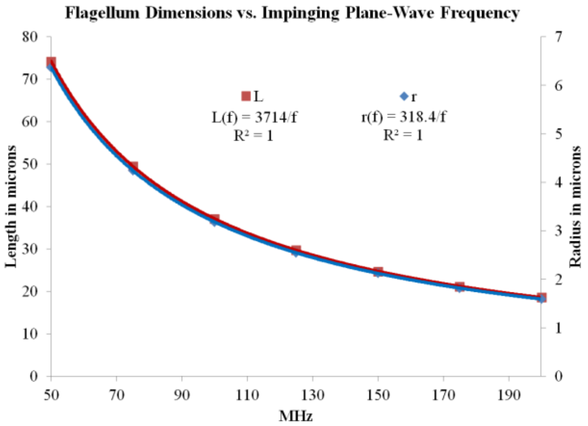

*Figure 4: Analytic solution to radius and Length of the flagellum dimensions decrease as the inverse of the impinging plane wave frequency.*

## 5. Conclusions and Future Work

The analytic model described in section 3 shows that it is possible to excite a mode in the flagellum of a microswimmer in order to get large amplitudes in the flagellar structure. The model also shows that, in order to achieve the proper aspect ratio, the material of the flagellum should be stiff (e.g. Nickel, etc.). However, from the results of the 3D fluid-structure coupled model in section 4, it appears that the amplitude of the motion of the microswimmer flagellum is very small; on the order of $10^{-5}$Å for a 1Pa plane wave. If the acoustic pressure were increased by 1000 times, to 1kPa, the displacement would scale to $10^{-2}$Å: Still not feasible for cell-like swimming.

It may still be possible to increase the amplitude by determining the actual modal frequency of the system in water. A substantial increase in amplitude would occur if the swimmer is excited at the exact resonance frequency of the system. Other important features of the system to investigate are second-order acoustic effects, such as acoustic streaming around the flagellum and radiation pressure on the cargo that the flagellum may push. The flagellum will have to be designed to overcome any significant forces that are produced by these effects.

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