

A Synthetic Microswimmer with an Acoustically-Actuated Flagellum

OBJECTIVE

The goal of this project is to design, build and characterize a micro-scale device that travels in a manner resembling cell-like swimming using medical ultrasound as the actuation and imaging method. This synthetic microswimmer will serve as a platform to perform tasks at the micro scale and swim through fluid media.

MOTIVATION

Inspiration from natural systems suggests solutions to engineering problems that may not occur to the human designer, particularly in regimes where we have no direct physical experience such as micro-scale swimming at low Reynold's numbers. Micro-robotic, flagellum-driven swimmers have significant potential for use in medical applications and biological studies. We see two motivations for the bio-inspired, acoustically-actuated approach:

- 1. Engineering model systems** as platforms for scientific study makes it possible to control experimental parameters that may be impossible or difficult to modify in animal experiments.
- 2. 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.

DISCUSSION

The analytic model shows that for 50 MHz, the 4th mode of a fixed/free beam results in the dimensions listed in the table below. We see that 'soft' materials will only couple at dimensions that are not appropriate for this application. As seen in the plot to the right, dimensions of a nickel microswimmer flagellum are proportionate to the inverse of the drive frequency.

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

A frequency sweep was conducted near the analytical resonant frequency. A more realistic estimate of the resonance which includes compressibility effects is lower than predicted analytically by about 20%. The peak amplitude of the motion of the microswimmer flagellum is very small; approximately $3 \cdot 10^{-4} \text{Å}/\text{Pa}$ (that is, for a 1Pa incident plane wave). Realistic ultrasound levels in water are approximately 1 kPa, suggesting maximum achievable motions on the order of 0.3 Å. This is too small for flagellar swimming.

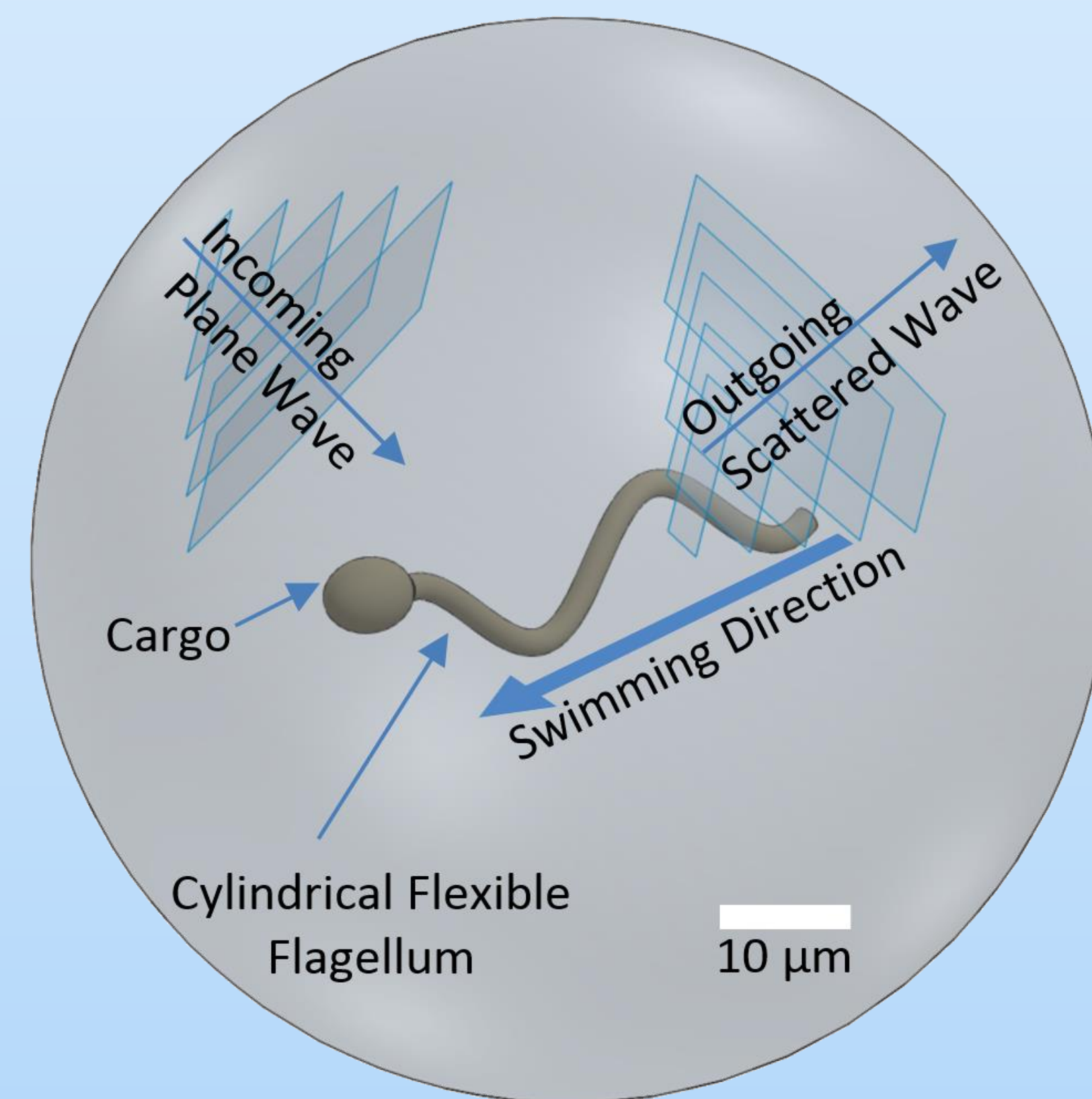
Other important features of the system to investigate are second-order acoustic effects, such as acoustic streaming around the flagellum and radiation pressure on the cargo that the flagellum may push. The flagellum will have to be designed to overcome any significant forces that are produced by these effects.

APPROACH

Cell-like locomotion will be achieved by the coupling of an incoming acoustic plane wave to a traveling wave in the body of the swimmer, however a standing wave is modeled here to determine the feasibility of this acoustic coupling as a power delivery method. Acoustic coupling, and the largest magnitude of motion, will occur where the projected wave number of the fluid β_{fluid} will match the wave number of the fluid loaded flagellum structure β_{beam} . We also take into account the added mass of the fluid ρ_{fluid} , which, for a perfect fluid, is equal to the mass of the displaced fluid.¹ 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.

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

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

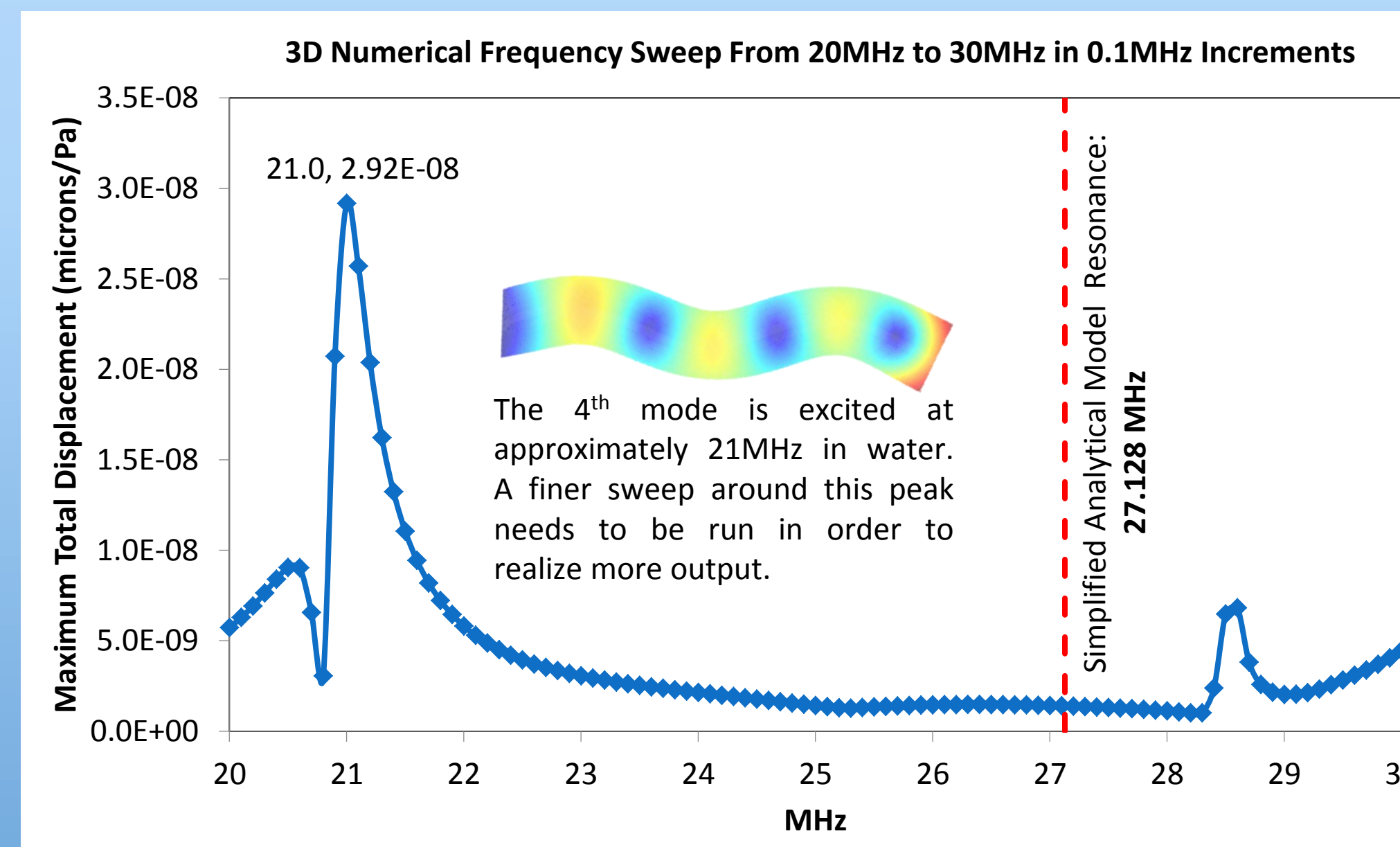


The diameter of the flagellum is then calculated where this wavenumber matching occurs at a particular resonant frequency ω appropriate for ultrasound (1MHz to 200MHz) and angle of incidence θ . The length L of the flagellum is calculated to match this wavenumber to an eigenmode of the structure N , presuming that this will result in the largest amplitude of motion.

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

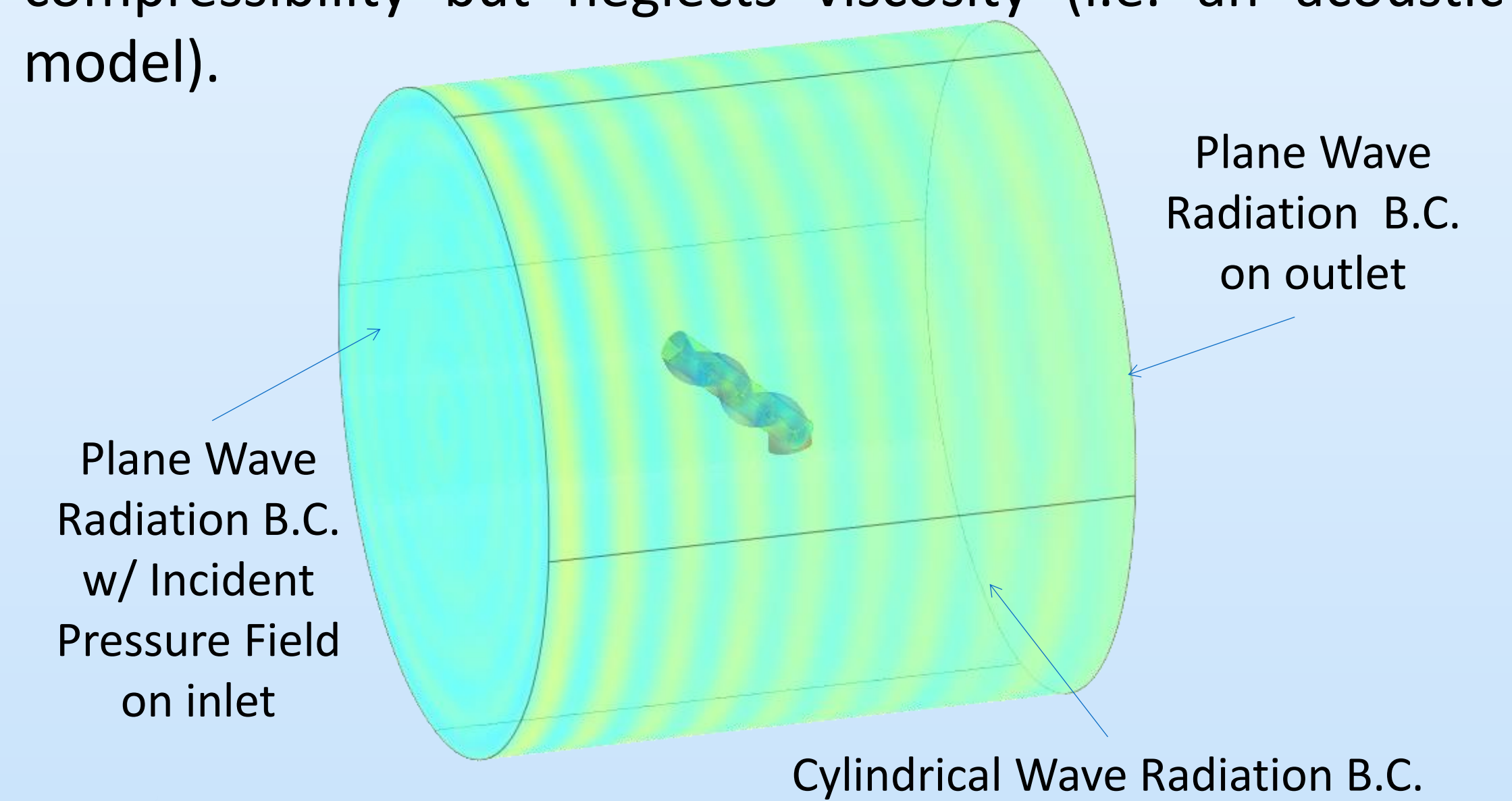
A standing wave response will not produce forward swimming, therefore asymmetry of the structure and impedance matching with the fluid is required for energy to flow in one direction generating a traveling wave. Ongoing work begins from this simple analytical starting point where three-dimensional numerical models of structures in real fluids are explored.

¹ S.-s. Chen, *Flow-induced vibration of circular cylindrical structures*. Washington: Hemisphere Pub. Corp, 1987.



3D MODEL

A 3D numeric simulation was used to understand how variation in impinging plane wave frequency and angle of incidence affects the coupling of the vibration of the fluid to the structure of the swimmer's flagellum. A nickel cantilever beam, surrounded by a cylindrical control volume of water, was used to represent the system. A simple water model was used that includes density and compressibility but neglects viscosity (i.e. an acoustic model).



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. 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. Maximal displacement of the flagellum is achieved as the frequency is lowered. So – larger swimmers operating at lower frequencies may perform better – further investigation is needed.

