# Tracing the Kilohertz Rotation of Nanofabricated Nanomotors Propelled by Ultrasound

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Nanomotors propelled through fluids by ultrasound (Fig. 1) have emerged as a novel nanotechnology with potential biomedical applications including diagnosing disease, delivering drugs, and performing surgery.[3] Such nanomotors are typically metal nanorods (Fig. 2) fabricated by electrodeposition guided by a nanoporous template. Under acoustic actuation, nanorods have been observed to translate and rotate along and around the long axis. Nanomotor rotation is highly relevant to related biomedical applications, but is difficult to directly measure for optically featureless metallic nanorods, and has not yet been quantified.

Here, we model the conditions under which nanoparticles qualify as tracers of the vortical flow fields around nanomotors, and we measure the microvortex advection of tracer nanoparticles around nanomotors. In this way, we infer the rotational frequencies of nanomotors. In an acoustic resonator driven at $\approx 3$ MHz with an energy density of $< 10$ J/m$^3$, we discover that nanomotors can rotate at frequencies of up to $\approx 10$ kHz, resulting in tangential velocities at the nanomotor surfaces of $\approx 10$ mm/s and shear rates of $\approx 10^4$ 1/s. We find that statistical variation in nanorod length and diameter dominates the uncertainty in our measurement of nanomotor rotational frequency (Fig. 3) and strongly influences the interaction of a nanomotor with the surrounding microfluidic environment.

Our study results in several important advances towards understanding the behavior and fulfilling the potential of this active nanotechnology. First, rotation is the major mode of nanomotor motion in our experimental system, dissipating by far the most energy by hydrodynamic interaction and establishing the fastest measured rotation of an autonomous nanoscale object at low Reynolds number. Second, precision nanofabrication is absolutely essential in future applications of nanomotors, as variation in nanorod dimensions limits our ability to control the hydrodynamic interaction of nanomotors with other objects and one another.

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[3] W. Wang, L. A. Castro, M. Hoyos and T. E. Mallouk, ACS Nano 6 (7), 6122-6132 (2012).

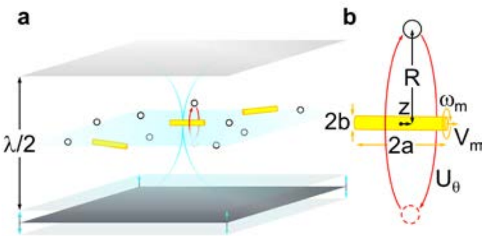


***Figure 1: Experimental Schematic:*** **a,** Ultrasound propels gold nanomotors around the nodal plane of a half-wavelength layered acoustic resonator. Microvortical fluid flows advect polystyrene nanoparticles around rotating nanomotors. **b**, The nanomotor is modeled as a cylinder with length 2a, diameter 2b, translational velocity $V_m$, and rotational frequency $\omega_m$. The nanoparticle is located at a radius R from, and position z along, the long axis of the nanomotor, around which the nanoparticle is advected with a tangential velocity $U_\theta$. We input our measured values of a, b, R, z, and $U_\theta$ into a hydrodynamic model of the vortical flow field around a rotating rod at low Reynolds number[4] to infer the unknown value of $\omega_m$.

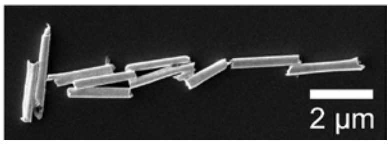


***Figure 2: Nanorod Characterization:*** A scanning electron micrograph shows an ensemble of gold nanorods treated as cylinders with lengths of 2a = (2.19 ± 0.28) μm and diameters of 2b = (316 ± 39) nm (average ± standard deviation). Individual nanorods show variation in nanoscale structure.

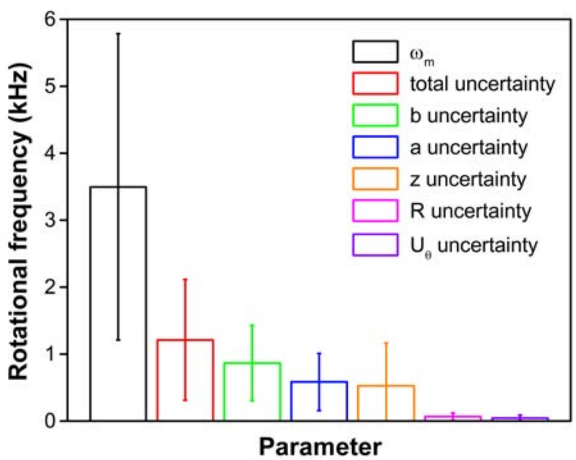


***Figure 3: Rotation Inference:*** An analysis of uncertainty elucidates our measurements of kilohertz rotation and informs future biomedical applications of nanomotors. Each of the five measured values that we input into our hydrodynamic model contributes differently to the total uncertainty in our inference of the rotational frequency $\omega_m$ of a nanomotor. Rotational frequency $\omega_m$, total uncertainty, and the individual uncertainty contributions of the five measured values are plotted as average values with vertical bars denoting one standard deviation. In the case that nanomotor length 2a and diameter 2b are characterized as an ensemble average and standard deviation, these two parameters account for > 85 % of the total uncertainty in our inference of nanomotor rotational frequency $\omega_m$. The distributions of nanorod length 2a and diameter 2b result from variation in electrodeposition and nanopore size used to template the nanorods. These results clearly show that precision nanofabrication is essential to accurately characterize and fully control the microvortical flows around rotating nanomotors in future biomedical applications.

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[4] A. T. Chwang and T. Y. Wu, J. Fluid Mech. **63**, 607-622 (1974).