Deformation of soft helices by viscous axial flows: a twisting to bending transition

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The study of fluid-structure interactions between helix-shaped particles and viscous flows is of importance for both fundamental science and technological applications. Helical structures are common among microorganisms, such as E. coli bacteria, who propel themselves through viscous media by rotating helically shaped flagella. The chirality of such structures induces breaking of the time-reversal symmetry associated with viscous flows. Possible applications include swimming micro-robots for targeted delivery or flow micro-sensors. We have recently developed a fabrication method for micron-sized soft helices with precise and full shape control, based on in-situ modification of the helical pitch (see top images of fig. 1.a). This allows systematic study of the fluid-structure interactions.

In this work, we examine the elastic extension of clamped helices immersed in viscous axial flows (see fig. 1.a). We show that the previously established scaling [1] is correct but fails to address the influence of the helical pitch. We study this influence and highlight an effective stiffening as the pitch increases, meaning that, all other things being equal, close-coiled helices are easier to stretch than open-coiled ones (see qualitative illustration in fig. 1.a and detailed plot in fig. 1.b). This stiffening is explained by a transition from a regime dominated by twisting of the filament and perpendicular drag forces at small pitch to a regime dominated by bending of the filament and parallel drag forces at large pitch. Theoretical modeling, based on Kirchoff rod theory and resistive-force theory, and backed by numerical simulations, qualitatively predicts the stiffening but fails quantitative agreement.

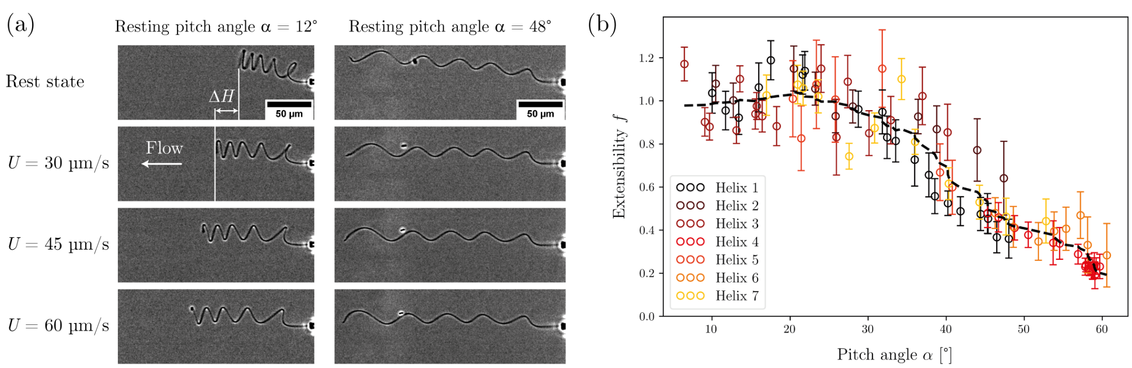

Figure 1. (a) Comparison of the flow-induced elastic elongation of a PMMA-made helix for two different resting pitch angle. The images are taken using phase-contrast microscopy. We measure the axial extension ΔH as a function of the flow velocity U. (b) Dimensionless extensibility as a function of the resting pitch angle for 7 different PMMA-made helix, and filtered-mean of all experimental points. The dimensionless extensibility f is defined as $f = \Delta H \times C/\eta U R^2 L^2$ as to isolate the influence of the pitch [1], with R helical radius, L filament length, η fluid viscosity and C filament twisting modulus.

References

1. M. Kim & T. R. Powers, Deformation of a helical filament by flow and electric or magnetic fields, *Physical Review E*, **71(2)**, 021914 (2015).