Electronic Supplementary Information for "Stiffness-Modulated Motion of Soft Microscopic particles Over Active Adhesive Cilia"

Amitabh Bhattacharya[1] and Anna C. Balazs*[2]

1 Mechanical Engineering Department, Indian Institute of Technology, Bombay, Powai, Maharashtra, 400076, India

2 Department of Chemical and Petroleum Engineering, 1249 Benedum Hall, University of Pittsburgh, Pittsburgh, PA, 15261, USA

At the end of Section 3.2 in the manuscript, we mention the importance of tacky cilia-particle adhesion in our system. Specifically a bond formed on the particle surface can apply a force component that is parallel to the surface. This kind of tacky interaction would not have been possible if the cilia-particle interaction consisted of only conservative forces between smooth surfaces (e.g. [1]). To illustrate the role of the tackiness in the bonds, we perform the following analysis. We first calculate the force $\mathbf{F}^{\mathrm{Cil},e}$ from the cilia acting on each triangular element (with index e) on the particle surface. For a given element e, $\mathbf{F}^{\mathrm{Cil},e}$ is calculated by averaging $(\mathbf{F}^{\mathrm{Bond}i}+\mathbf{F}^{\mathrm{Exc},i})$ over the nodes belonging to the element. We then decompose the force from the cilia into components that are perpendicular and parallel to the surface. Specifically, if the outward surface normal for element e is n^e, then $\mathbf{F}^{\mathrm{Cil},e}=\mathbf{F}^{//,e}+\mathbf{F}^{\perp,e}$, where $\mathbf{F}^{\perp,e}=(\mathbf{F}^{\mathrm{Cil},e}\bullet\mathbf{n}^e)\mathbf{n}^e$, and $\mathbf{F}^{//,e}=\mathbf{F}^{\mathrm{Cil},e}-(\mathbf{F}^{\mathrm{Cil},e}\bullet\mathbf{n}^e)\mathbf{n}^e$. At any instant in time, we can measure the x component of the net tangential and perpendicular forces acting on the particle, given by $F_x^{\mathrm{Tang}}=\sum_e F_x^{//,e}$ and $F_x^{\mathrm{Norm}}=\sum_e F_x^{\perp,e}$ respectively.

In Figure SI.1, we plot the values of F_x^{Tang} and F_x^{Norm}, averaged separately over the effective and recovery strokes, for 15 actuation cycles, over all the random seeds. Clearly, for all adhesion levels, forces tangential to the particle surface form a significant proportion of the total force from the cilia in the x direction. For higher adhesion levels, it can be seen that the tangential forces dominate. These trends can be explained by the tackiness of the bonds, and the fact that, after the bonds form, the lower surface of the floppy particle is approximately parallel to the x direction (e.g. Figure 8 (b) in the text). The larger number of bonds formed at the lower surface of the floppy particle are then able to apply a proportionally higher force on the particle in the x direction. This would not have been possible if the bond forces were purely conservative; in that case, within the cilia-particle contact area, forces from the cilia could mainly point in the direction normal to the surface (i.e. $\pm y$ direction). Such bonds would "slip" when pulled parallel to a smooth surface, due to lack of tackiness.

In Figure SI.2, we show plots for similar calculations that have been performed for the rigid particle. Here, we can see that the role of the tacky bonds is significantly less across the range of adhesion levels. Since the rigid particle retains its spherical shape, therefore the normal component of the bond force is able to play a larger role in transporting the rigid particle.

Therefore, our results show that tacky adhesion plays a large role in enabling modulation of particle velocity by its stiffness. Indeed, we performed similar simulations earlier, in which only conservative cilia-particle bond forces were used, but we were unable to observe a significant modulation of particle velocity by its stiffness (we do not report those results in any detail here).

References

(1) Sauer, R. A. *Computer methods in biomechanics and biomedical engineering* **2009**, *12*, 627–40.

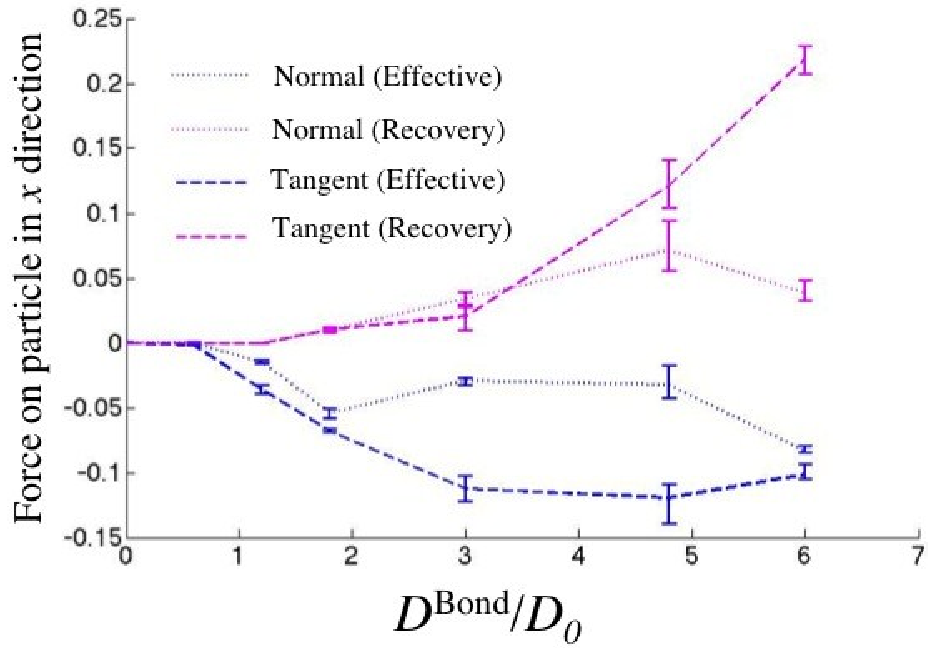

Figure SI.1: Plots of force on particle from cilia in the *x* direction, for the floppy particle $E^{\text{Part,*}}$=0.26. The forces can be due to cilia-particle bond forces normal to the surface (dotted), and tangential to the surface (dashed). The forces have been averaged over the effective (blue) and recovery (magenta) parts of the actuation cycle.

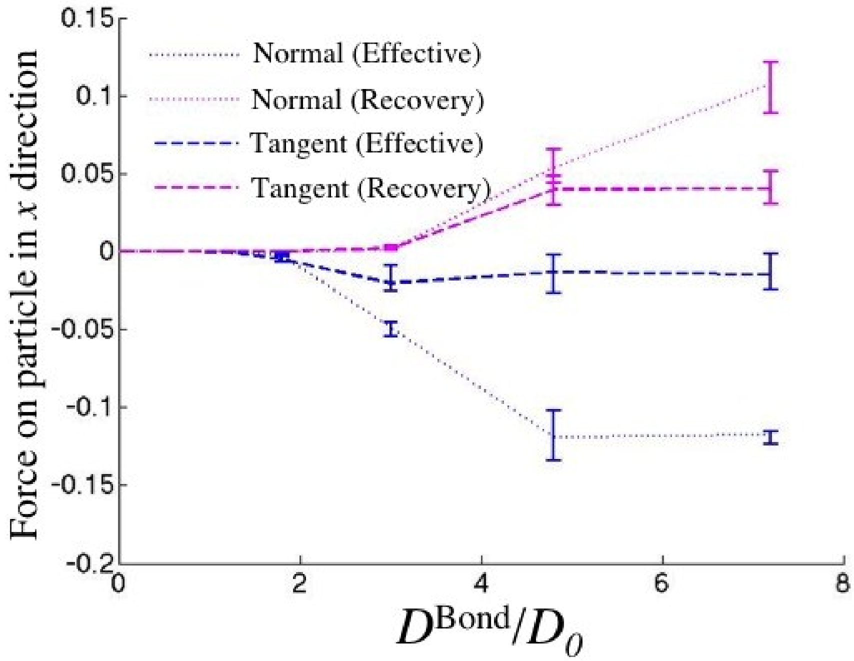

Figure SI.2: Plots of force on particle from cilia in the *x* direction, for rigid particle $E^{Part,*}$=5.2. The forces can be due to cilia-particle bond forces normal to the surface (dotted), and tangential to the surface (dashed). The forces have been averaged over the effective (blue) and recovery (magenta) parts of the actuation cycle.