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Simulating Biofilm Deformation and Detachment with the Immersed Boundary Method

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Abstract. We apply the immersed boundary (or IB) method to simulate deformation and detachment of a periodic array of wall-bounded biofilm colonies in response to a linear shear flow. The biofilm material is represented as a network of Hookean springs that are placed along the edges of a triangulation of the biofilm region. The interfacial shear stress, lift and drag forces acting on the biofilm colony are computed by using fluid stress jump method developed by Williams, Fauci and Gaver [*Disc. Contin. Dyn. Sys. B* 11(2):519–540, 2009], with a modified version of their exclusion filter. Our detachment criterion is based on the novel concept of an averaged equivalent continuum stress tensor defined at each IB point in the biofilm which is then used to determine a corresponding von Mises yield stress; wherever this yield stress exceeds a given critical threshold the connections to that node are severed, thereby signalling the onset of a detachment event. In order to capture the deformation and detachment behaviour of a biofilm colony at different stages of growth, we consider a family of four biofilm shapes with varying aspect ratio. For each aspect ratio, we varied the spacing between colonies to investigate role of spatial clustering in offering protection against detachment. Our numerical simulations focus on the behaviour of weak biofilms (with relatively low yield stress threshold) and investigate features of the fluid-structure interaction such as locations of maximum shear and increased drag. The most important conclusions of this work are: (a) reducing the spacing between colonies reduces drag by from 50 to 100% and alters the interfacial shear stress profile, suggesting that even weak biofilms may be able to grow into tall structures because of the protection they gain from spatial proximity with other colonies; (b) the commonly employed detachment strategy in biofilm models based only on interfacial shear stress can lead to incorrect or inaccurate results when applied to the study of shear induced detachment of weak biofilms. Our detachment strategy based on equivalent continuum stresses provides a unified and consistent IB framework that handles both sloughing and ero-

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sion modes of biofilm detachment, and is consistent with strategies employed in many other continuum based biofilm models.

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1 Introduction

The subject of this work is the flow-induced deformation of a biofilm colony, which is a mesoscale collection of bacterial cells held together by an extracellular polymeric network (EPS) that is secreted by the cells. The dimensions of a biofilm colony can be anywhere from tens to hundreds of microns, whereas the size of an individual bacterial cell making up the colony is on the order of 1–5 microns; our focus is on continuum models that treat the biofilm as a viscoelastic solid continuum rather than incorporating the dynamics of individual bacteria. The flow-induced deformations of the biofilm colony affect the fluid dynamic forces acting on it, and thereby altering both the extent and the mode of detachment (i.e., sloughing or erosion) that may be experienced by the biofilm. We are particularly interested in understanding whether biofilm colonies gain any protection against detachment when they are in close proximity to other colonies. To this end, our aim is to develop a robust numerical method for simulating the interaction between a biofilm colony and the surrounding fluid that is capable of capturing the different modes of biofilm detachment.

Our approach is based on the immersed boundary (or IB) method in which a mesoscale biofilm colony is replaced by a network of Hookean springs as done in the previous biofilm IB studies reported in [1, 73, 74]. On the microscale, a biofilm is a spatially heterogeneous mixture of multiple components (bacteria cells, EPS and fluid) as discussed in [24]. One modeling approach that reflects this description is a microscale bottom-up approach as in [67] that represents the biofilm by bacteria placed at experimentally determined positions and connected by Hookean springs, where the springs represent acutal/plausible EPS connections between bacteria. In a general setup that lacks such microscale data on bacterial positions, we have instead employed a mesoscale approach. In our IB framework, the mechanical response of a biofilm continuum mimics that of a viscoelastic solid, where the elastic contribution comes from the Hookean spring network and the viscous contribution derives from the viscous fluid permeating the network. By using a uniform triangulation of the biofilm domain, we approximate the multi-component biofilm as a continuum having spatially homogeneous mechanical properties. Despite this approximation, the primary focus in our work is taking a closer look at modeling biofilm detachment and developing a novel approach using an equivalent continuum stress to initiate detachment in a manner that is consistent with other continuum mechanics based models such as [16].