sor John Frangos of the Department of Chemical Engineering at Pennsylvania State University. This probably reflects the fact that study of mechanical forces is not predominantly within the domain of chemical engineering—or even of engineering more broadly. Indeed, one of the positive features of this book is that it should alert our community to the excellent work going on in this particular aspect of biochemical and biomedical engineering by investigators from other disciplines. My own viewpoint is that chemical engineers remain uniquely well suited for quantitative research in cell biology, especially in its contemporary molecular approach, as regulation of cell function is ultimately chemical in nature. Even when mechanical forces are the original stimuli, it is my prejudice that these forces act by eventual translation into cellular biochemical processes. Thus, I believe that the crucial issue in studying effects of *mechanical* forces on cells is how they modulate *chemical* regulatory systems. A few relevant examples exist already, such as polymerization of cell cytoskeleton precursors and binding of substratum-bound ligands to cell adhesion receptors, in which mechanical forces appear to alter chemical reaction rates, presumably by modification of molecular interaction energies.

Despite the 1993 publication date of this book, it is yet too early for this molecular perspective to be prominent in a collection of research on mechanical force effects on cells. However, Professor Frangos has done an excellent job of organizing contributions from leading groups to cover the spectrum of current information in this area. It is, of course, typical for multiauthor volumes to be uneven in clarity and approach. Nonetheless, all 11 chapters are reasonably well written and technically sound, and should be found useful by anyone interested in this subject for summaries of the present state of understanding of various topics. A few of the chapters are especially noteworthy and highly recommended for their emphasis on offering authoritative insights, going beyond basic description. These include Chapter 2 on the role of the cytoskeleton in mechanochemical signal transduction by Don Ingber, Chapter 4 on mechanically-sensitive ion channels by Peter Davies, Chapter 5 by Frangos on cell secretion products under fluid shear conditions, Chapter 6 on shear stress effects on endothelial cell morphology by Bob Nerem, and interrelated Chapters 9 and 10 by Larry McIntire and Terry Papoutsakis, respectively, on fluid mechanical effects on cells in suspension and in bioreactors. (These chapters also have coauthors, but for the sake of brevity [and with sincere apologies to them] I have mentioned only the senior investigators.) Other helpful contributions include Chapter 1 by Roger Tran-Son-Tay on methods for measuring physical forces and Chapter 3 by Albert Banes on mechanical deformation of cells. The remaining chapters summarize information that may be beneficial for purposes of literature survey but do not, in my limited personal opinion, provide significant aid to increased conceptual understanding of their topics.

Along with the guide to special attractions listed above, it might be worthwhile to a potential buyer to offer a few additional, minor comments in order to sketch a fuller picture of what will be found in the book. Absent a true introductory chapter, the Preface by Editor Frangos spells out the motivation for the project, but it does not go further to relate the individual chapters within a global context nor does it frame the outstanding questions to be addressed. Chapter 1 on force measurement methods is variable in detail, showing great depth in some assays but very little in others, without apparent correlation to current utility. Chapter 2 advocates the intriguing and appealing theory known as "tensegrity," based on the analogy of Buckminster Fuller's geometric mechanics to cells. Chapter 4 lays out the evidence for "shear-activated" membrane channels very nicely and admits that the fundamental mechanism is still unknown. Chapter 5 contains one of the best discussions I have read examining concisely alternative mechanisms for shear stress regulation of intracellular processes. Chapter 6 is the epitome of what one looks for in an expert review, focusing on ongoing issues. Chapter 8, by Lowell Langille, on effects of blood flow on artery walls, contains the greatest degree of emphasis on *in vivo* physiology. Chapter 10 is extremely thorough in considering various possible mechanisms causing cell damage in bioreactors, including both suspension and surface-anchored cells. Finally, Chapter 11, by Paul Todd, on the influence of gravity on cells, is interesting, but fails to make a compelling argument for centrality, at least in the case of cells in culture as opposed to whole tissues.

It should be clear that I see this volume as a valuable addition to the library of anyone interested in mammalian cell function. I know that I will frequently refer to particular chapters in it when I need to recall information on some topics and to refresh insights on mechanical force effects on mammalian cells in either bioprocessing or health care technology applications.

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Microhydrodynamics: Principles and Selected Applications

By Sangtae Kim and Seppo J. Karrila, Butterworth-Heinemann, Boston, 1991, 507 + xxiii pp., $69.95.

In the briefest and broadest terms, this book can be regarded as addressing the linear relation between motions and forces that applies to low-Reynolds-number particulate flow. It does so with clarity of presentation, and with sufficient scope and depth to encompass the roles of an excellent advanced graduate text and of a timely and timeless reference for research.

Overview

Whether hydrodynamics represents the primary focus or one of several interacting phenomena, fundamental understanding and applications-oriented modeling of the mechanics of colloidal dispersions and noncolloidal suspensions, electrophoretic separations, filtration and membrane transport processes, sedimentation, coagulation, and site-specific reactions rely on hydrodynamic coefficients in the creeping-flow regime, at various levels of accuracy and of geometric detail. This information is usually utilized in one of two equivalent linear forms that relate the kinematical characterization of the motion of the particles relative to the surrounding fluid (linear and angular velocity, ambient rate of strain) to dynamical quantities (forces, torques, stresslets). Resistance relations regard the forces as being determined by prescribed motions; mobility relations yield directly the motions resulting from given applied forces:

$$\begin{bmatrix} \text{Forces} \\ \hline \text{Torques} \\ \hline \text{Stresslets} \end{bmatrix} = \mu \begin{pmatrix} \text{Grand} \\ \text{resistance} \\ \text{tensor} \end{pmatrix} \cdot \begin{bmatrix} \text{Relative linear velocity} \\ \hline \text{Relative angular velocity} \\ \hline \text{Ambient rate of strain} \end{bmatrix}$$

$$\begin{bmatrix} \text{Relative linear velocity} \\ \hline \text{Relative angular velocity} \\ \hline \mu^{-1}\text{ (Stresslets)} \end{bmatrix} = \begin{pmatrix} \text{Grand} \\ \text{mobility} \\ \text{tensor} \end{pmatrix} \cdot \begin{bmatrix} \mu^{-1}\text{ (Forces)} \\ \hline \mu^{-1}\text{ (Torques)} \\ \hline \text{Ambient rate of strain} \end{bmatrix}$$

Whether written for one or many particles, the above general forms always remain the same. The generality and impact of resistance and mobility tensors throughout the realm of particulate flows cannot be overestimated. Buried within this abstract formulation—and embodied in individual matrix entries that are usually the products of enlightened asymptotics, dogged algebraic tenacity, or arduous numerics—are the physics of screened interactions, lubrication forces, alignment and rotation of fibers, coiling or stretching of polymers and proteins, and intraparticle and interparticle hydrodynamic coupling that can have significant effects on sedimentation and diffusion.

In some celebrated cases, such as the renormalization of screening interactions in dilute suspensions and porous media, the collective macroscopic behavior of swarms of particles has been characterized in terms of two-particle interactions and other simple(r) subproblems, which require hydrodynamic coefficients in a small "grand" resistance or mobility matrix, and thereby shed light on overall aspects of vastly larger such matrices. Significant results on rheology (including electrorheological behavior), sedimentation, fractal aggregates, and viscous resuspension at much higher concentrations have come from (massive) Stokesian dynamics simulations involving many particles. What is gradually emerging from the accumulating literature in particle-scale hydrodynamics can be regarded as a database on collective macroscopic behavior, which has not yielded to decades of continuum mechanics—the latter often based on purely macroscopic postulates or on *ad hoc* or too grossly stylized representations of subcontinuum structure. It is in this context that *Microhydrodynamics* establishes its pedagogic mission and its computational presence.

Three themes running through the tome of Kim and Karrila warrant explicit mention. First, the emphasis on fundamental solutions (Stokeslets and other hydrodynamic singularities) for representing hydrodynamic coefficients and flow fields and for deriving theorems results in a very unified presentation that is inherently phrased in the language and approach of current analytical and numerical research. [A similar emphasis can be seen, for example, in the chapter devoted to basic Stokes hydrodynamics in *Colloidal Dispersions* by Russel, Saville, and Schowalter (Cambridge Univ. Press, 1989).] The increasing prevalence of boundary integral equations, multipole expansions and singularity methods in computational Stokes flow has not been due only to their mathematical and computational advantages; it can be attributed equally to the infusion of physics brought by the fundamental solution(s) they all have in common. In the discernable movement away from volumetric discretization techniques, computational Stokes flow has thereby been enriched beyond physically sterile formalisms of numerical approximation. Never before have there been better opportunities for analyzing the physical interpretations of truncation errors or for splicing asymptotics together with numerics, often seamlessly in the course of one calculation or simulation. Significantly, Kim and Karrila make a point, at strategic places, of developing the correspondence between different formulations involving fundamental solutions (integral representation theorems, multipole expansions, image systems, slender-body asymptotics) and of establishing connections of these with venerable traditions that are perhaps, ever so gradually, receding into the background—stream functions and Lamb's general solution.

Second, in combination with the Faxen laws, singularity representations yield hydrodynamic coefficients almost immediately, with little or no conceptual or numerical "post-processing" of the flow field itself. As indicated above, it is the coefficients in the resistance and mobility tensors, and not the pointwise velocity fields, that are frequently of primary interest in applications. Thus, one frequently witnesses the authors carrying approximations to orders just sufficient for elegantly extracting the coefficients without wasting unnecessary algebraic labor.

Finally, the book emphasizes spherical and ellipsoidal shapes of suspended particles as vehicles for introducing and illustrating various analytical, asymptotic and numerical techniques. Indeed, these simple shapes occupy a central and exalted position in the history of theoretical Stokes flow, not merely due to a celebrated parade of pioneering analytical and asymptotic solutions. Their widespread utility in microstructural constitutive modeling for suspensions and porous media stems from the fact that observable macroscopic behavior can often be attributed to very gross geometric features of suspended particles or dissolved macromolecules, whose long-range hydrodynamic effects (intimately connected with properties of the basic singularities) largely dominate over the collective impact of finer-scale details of shape. In extremely crowded microstructures, the opposite end of the spectrum, interactions are often dominated by lubrication forces and are therefore essentially captured by asymptotic approximations for nearly touching spheres. Rotational transport processes and dissipation in elongational flows, as well as their rheological consequences, are determined largely by overall measures of nonsphericity, so that the effects of suspended fibers or uncoiled polymers are well modeled using ellipsoids and rigid or flexible dumbbells. Thus, for an exceptionally wide range of systems, phenomena and applications, much effort has justifiably been dedicated to the characterization of nearly any particle, colloid or macromolecule, no matter how bizarre its shape, in terms of a hydrodynamically "equivalent" sphere. And when the simplest of geometric conceptions cannot meaningfully be applied, this fact represents a significant and distinguishing feature, for which recourse is then made to the next simplest model that can hope to snare the recalcitrant physics: an (axisymmetric) spheroid, rodlike or disklike.

(This unifying approach fades at higher Reynolds numbers: one can take bets on how long an aeronautical engineer will remain in employment after proposing any scheme for modeling a fighter jet as an aerodynamically equivalent sphere.) Also noteworthy is the completeness with which the authors extend results for rigid particles to the more complicated case of viscous droplets and bubbles.

Contents and description

This book is divided into four parts. The first three parts progress systematically from basic hydrodynamical principles to single-particle problems and then to hydrodynamic interactions involving two or more particles or wall effects. This portion of the book emphasizes analytical and asymptotic methods. The fourth part—substantially more research-oriented, for which some prior familiarity with functional analysis and integral equations is desirable if not absolutely necessary—develops a completed double-layer representation to obtain (well-posed and well-conditioned) boundary integral equations of the second kind for complex multiparticle geometries. There is a bibliography at the end of each of the four parts: with some overlap they contain 49, 93, 76 and 72 citations, respectively, to research papers, monographs and significant dissertations in the scientific, engineering and mathematical literature of the field. Collectively, they represent a comprehensive and judicious sampling of relevant history and modernity—spanning from revered origins (Basset, 1888; Sampson, 1891; Smoluchowski, 1911, 1921; Jeffery, 1915, 1922; Faxén, 1922, 1924; Oseen, 1922, 1924; Hückel, 1924; Odqvist, 1930; Lamb, 1932; Lorentz, 1937; Burgers, 1938) to the leading edge of computational simulations. Useful features that assist navigation through the text include an "Organization Scheme" of seven pages following the preface and an eight-page table of notation at the end. The five-page index is sufficiently detailed, in combination with the table of contents, for specific results to be isolated; there is no author index. Well-crafted exercises (some of them really qualifying as small projects) are provided after all the chapters, except for the first and eleventh. These cover the range from analytical and asymptotic solutions to function-analytic proofs, to fairly heavy computational tasks. It may pay to purchase an extra ream of paper before starting on them.

This book embodies an unusual feature that may very well set a trend for scientific publications in the future: the provision and maintenance of an electronic login address ("doug.cae.wisc.edu," IP number 128.104.193.67) through which readers can find updated errata and amplifications on the text and exercises, including actual programs, organized by chapter in subdirectories of "pub/microhydro." This conceptual "service contract" accompanying the book is most useful.

Highlights from Parts I-III

Progressing through multipole expansions and spatially distributed "singularity solutions," Chapter 3 sets a universal stage upon which the flow field around an arbitrary particle can be regarded as being generated by an abstract linear functional that describes some internal "smearing out" of singularities. This approach allows a very elegant derivation of the Faxén laws (attributed to E. J. Hinch). Multipole expansions for spherical particles and droplets are related to Lamb's general solution and the Stokes stream function in Chapter 4. For single- and two-particle geometries, Chapters 5 and 7 introduce the general resistance and mobility tensors and the corresponding axisymmetric scalar functions. Jeffery orbits, rheological effects of rotary diffusion, and electrophoretic transport are discussed in a concise manner. Centered primarily around spherical geometries, Chapter 6 addresses time-dependent Stokes flow at arbitrary Strouhal number, also utilizing fundamental solutions. Oscillatory solutions and the main features (Basset history integral, virtual mass) of general motions are derived, along with the relevant Faxen laws and low-frequency asymptotics.

Chapter 8 describes the method of reflections for far-field interactions. Clearly illustrated with examples is the important point that mobility functions are accurate to higher order than resistance functions constructed from the same number of reflections, whereby, "contrary to one's initial perception and the approach in the older literature, when applying the method of reflections, one should first solve the entire collection of mobility problems and then invert these if the resistance solutions are also required" (p. 197). (The very concrete utility of this fact in large-scale Stokesian dynamics simulations of concentrated suspensions is not, however, mentioned in Parts III & IV.) Noteworthy features include: (i) an excellent overview, in the admirably short space of four pages, of screening interactions and renormalization in suspension rheology; (ii) a discussion of hydrodynamic interactions between spheres and spheroids undergoing electrophoretic motion. Chapter 9 develops lubrication approximations for nearly touching particles or droplets, particularly with a view toward cataloging the forms of singular or regular behavior of squeezing vs. shearing motion in the various cases. Chapters 10 and 12 extend the method of reflections to hydrodynamic interactions between spheres of vastly different size and to wall effects.

Drawing together a wealth of analysis from the literature, supplemented with some new numerical results, Chapter 11 provides 11th-order far-field expansions and lubrication approximations for a nearly complete set of scalar resistance and mobility functions for two spheres of unequal size. This very useful compilation alone should justify the presence of *Microhydrodynamics* on many shelves of specialists and nonspecialists alike. Chapter 13 develops basic elements of a general boundary-multipole collocation method for numerical solutions involving fairly simple particles such as spheres and spheroids. Here, the coefficients in a multipole expansion are determined by imposing, simultaneously on all particles, the boundary conditions at a sufficient number of discrete points to yield a determinate system of linear equations.

Highlights from Part IV

Part IV addresses the computational modeling of many-body quasistatic Stokes flows for applications in which the geometry of individual particles warrant detailed and accurate resolution, as opposed to far-field/near-field asymptotic splicing or effective-medium approximations. Specific aspects of the formulation anticipate and take advantage of foreseeable developments in massively parallel computational hardware. For example, in Chapter 19 a remarkable connection is drawn between hydrodynamic screening in suspensions and the possibility of limiting information flow between processors that represent widely separated particles (asynchronous iteration).

Although boundary integral techniques in Stokes flow are not new, the treatment is significant for several reasons. Based, as it is, on integral equations of the second kind, it attacks the issue of well-posedness head on, for which the resultant ill conditioning of discretized equations in first-kind formulations has heretofore been carefully tiptoed around for simple geometries or else numerically outpowered with high-precision arithmetic. Attributing some key ideas to a seminal paper of Power and Miranda (*SIAM J. Appl. Math.*, **47**, 689, 1987), the development in *Microhydrodynamics* is also enriched by original contributions and innovations of the authors. Among other features, function-analytic proofs here take on a uniquely physical flavor. If one central message is proclaimed from the rooftops by Part IV, it is that mathematical rigor has tangibly useful consequences for numerics and the resulting elucidation of the physics of low-Reynolds-number particulate flows. The underlying details can perhaps be skipped, but the resulting theorems must not be. Given a numerical landscape in which *ad hoc* mesh refinement frequently represents the only practical attack on questions of convergence, the authors have waved an exemplary banner.

Distributions of point forces (single-layer potentials) over the surfaces of particles can represent the most general surrounding flow field, but yield ill-posed integral equations. As is discussed in Chapter 15, second-kind integral equations based on (more abstract) hydrodynamic double-layers are well posed (and therefore much better suited to accurate numerics), but suffer from the inability to represent net forces or torques. Thus, the "range-defficient" representation must be augmented with one or more point-force and point-torque solutions within each particle. Chapters 16 and 17 are devoted primarily to the conceptual *peristroika* by which (i) the resulting indeterminacy is removed to yield a unique solution, and (ii) the discretized matrix version of the second-kind integral equation can be solved by fast iterative means. Significant computational examples appear in Chapters 18 and 19, including benchmark implementations on multiprocessor arrays.

Although Part IV is self-contained and follows logically from the material covered earlier in the book, it is written at a discernably higher level than the first three parts. It is essentially a short research monograph grafted onto an advanced graduate text and so warrants some comments of assessment separately from the rest of the book. The summary of relevant facts from integral equations (§14.2) represents an effective selection *vis-a-vis* material relegated to mathematical references. Approached by a reviewer who has experience with numerics based on fundamental solutions (but not expertise with boundary element methods), the details were comprehensible with some background reading and with particular effort required for the conceptual juggernaut of Chapters 16 and 17. The theorems and main results are, however, stated with clarity and succinctness, so that the main elements and their computational consequences can be extracted by readers wishing to skip the details. Of particular merit throughout is the illustration of conceptual and numerical aspects with analytical or asymptotic solutions for the double-layer densities of spheres, spheroids and other simple geometries. With reference to illustrative computational examples and programs supplied via the anonymous ftp server "doug," the presentation is geared so that readers can gain sufficient familiarity with the second-kind formulation to implement it for their own research problems. In this and in its translation of mathematical rigor into numerical gains, Part IV succeeds resoundingly.

If a suggestion could be made in the event of a future edition, it would be to base the discussion of Wielandt deflations (§§17.3–17.6) more heavily on the analogy with matrix operations, which was used so effectively in presenting the bordering scheme in §16.3. This is the approach used by Pozrikidis in his more recent monograph *Boundary Integral and Singularity Methods for Linearized Viscous Flow* (Cambridge Univ. Press, 1992), in which some motivating ideas are credited (p. 121) to Kim and Karrila. The above commentary is made partly also because arguments utilizing the analogy with the Jordan-block decomposition of matrices are quite central throughout (§§14.2, 15.3, 17.3, 17.4), but diluted in the absence of a more concrete correspondence with linear algebra.

In surveying the literature on boundary integral methods in fluid mechanics, one can detect a marked movement toward second-kind formulations over the last few years. The present book, the product of two authors who have made significant advances in the field, has contributed leadership and vision to this movement. A recent paper by Liron and Barta (*J. Fluid Mech.*, **238**, 579, 1992) presents a short and direct derivation of an integral equation of the *second kind* written immediately for the *single-layer potential* (*surface traction*). [The equivalence of this approach to the developments in Part IV has been pointed out by Kim and Power (*J. Fluid Mech.*, **257**, 637, 1993).] Second-kind formulations in Stokes flow have also recently been derived by less similar means (Davis, *J. Fluid Mech.*, **213**, 51, 1991; *Quart Appl. Math.*, **XLIX**, 507, 1991; *Phys. Fluids A.*, **4**, 7, 1992). Clearly, significant things are afoot—fueled by the concrete computational benefits of mathematically well-posed formulations. In this context, *Microhydrodynamics* stands as a seminal and guiding work.

Overall commentary

This book is well organized and comprehensive within its scope of low-Reynolds-number particulate flow. One area could, however, have received more attention—an assessment that is not intended to violate the age-old taboo against judging a book by what it does not contain (particularly for a title that advertises *selected* applications). The treatment of transient Stokes flow in Chapter 6 seemed like the perfect starting point for a discussion of Brinkman media, which are (i) governed by exactly analogous equations and (ii) play a central role in modeling heterogeneous media owing to their embodiment of hydrodynamic screening. Indeed, one of the authors has participated in the development and implementation of such a renormalization scheme for calculating the permeability of dilute, fixed beds of spheres (Kim and Russel, *J. Fluid Mech.*, **154**, 253, 269, 1985). This is not a criticism of Chapter 6; it was just going so well when it ended that this reviewer would have liked to see it continue for another 20 pages or so.

In overall character, this book is unavoidably a highly mathematical work, but its (inherently interdisciplinary) interest and utility should not be restricted to theoreticians, because it comprehensively compiles an immense volume of hydrodynamic information—in formulas and physically-oriented rules of thumb—that will be downright useful to anyone in the area of particulate flow. The book is replete with pithy, well-organized summaries and tables of exact and asymptotic solutions and also of relevant literature. Within the scope that chemical engineering has established in this country, the theoretical aspects will appeal to a specialized, yet remarkably broad, audience for two reasons: (i) colloidal phenomena and microstructured fluids are of technological importance in their own right and owing to the role they play in such timely areas as materials processing; (ii) theoretical modeling on the particulate scale contributes materially to the engineering of microstructure and the analysis of data in this field. Specific sections—notably, the presentations of singularity solutions in §3.3, the application of reflections to resistance and mobility problems in §§8.2, 8.3, the lubrication theory of §§9.2, 9.3, and the analysis of the image system of a Stokeslet near a rigid sphere (§10.2)—represent monuments to analytical valor. In many places shines a mastery of harmonics of every description.

The blend of analytical and asymptotic mathematics, physical insight and enlightened numerics crafted by Kim and Karrila is of the spirit that has burned brightly in some of the most significant achievements in particulate flow and heterogeneous media over the past two decades. Written in a direct, purposeful and marginally conversational style, the presentation conveys the enthusiasm of active researchers. Above all, *Microhydrodynamics: Principles and Selected Applications* will stand out as an eloquent and enduring statement of significant hydrodynamic principles—a major source of information and inspiration for many years to come.

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