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Nature-inspired microfluidic propulsion using magnetic artificial cilia

Khaderi, Syed Nizamuddin

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Bibliography

- AINLEY, JOSEPHINE, DURKIN, SANDRA, EMBID, RAFAEL, BOINDALA, PRIYA & CORTEZ, RICARDO 2008 The method of images for regularized stokeslets. *Journal of Computational Physics* **227** (9), 4600–4616.
- ALEXEEV, ALEXANDER, YEOMANS, J. M. & BALAZS, ANNA C. 2008a Designing synthetic, pumping cilia that switch the flow direction in microchannels. *Langmuir* **24** (21), 12102–12106.
- ALEXEEV, A., YEOMANS, J. M. & BALAZS, A. C. 2008b Designing synthetic, pumping cilia that switch the flow direction in microchannels. *Langmuir* **24**, 12102–12106.
- ALLMAN, D.J. 1984 A compatible triangular element including vertex rotations for plane elasticity analysis. *Computers and Structures* **19** (1-2), 1 – 8, special Memorial Issue.
- ANNABATTULA, R. K., HUCK, W. T. S. & ONCK, P.R. 2010 Micron-scale channel formation by the release and bond-back of pre-stressed thin films: A finite element analysis. *Journal of the Mechanics and Physics of Solids* **58**, 447–465.
- BAAIJENS, FRANK P. T. 2001 A fictitious domain/mortar element method for fluid-structure interaction. *International Journal for Numerical Methods in Fluids* **35** (7), 743–761.
- BALTUSSEN, M. G. H. M., ANDERSON, P. D., BOS, F. M. & DEN TOONDER, J. M. J. 2009 Inertial flow effects in a micro-mixer based on artificial cilia. *Lab Chip* **9**, 2326 – 2331.
- BATHE, KLAUS-JURGEN 1996 *Finite Element Procedures*. Prentice-Hall, Inc.
- BATHE, KLAUS JURGEN & HO, LEE WING 1981 A simple and effective element for analysis of general shell structures. *Computers and Structures* **13** (5-6), 673 – 681.
- BATOZ, J. L., BATHE, K. J. & HO, L. W. 1980 A study of three-node triangular plate bending elements. *International Journal for Numerical Methods in Engineering* **15**, 1771–1812.
- BELARDI, J., SCHORR, N., PRUCKER, O. & RUHE, J. 2011 Artificial cilia: Generation of magnetic actuators in microfluidic systems. *Advanced Functional Materials* Accepted.
- BELARDI, J., SCHORR, N., PRUCKER, O., WELLS, S., PATEL, V. & RUHE, J. 2010 Fabrication of artificial rubber cilia by photolithography. In *Second European Conference on Microfluidics - paper no. 112*.
- BLAKE, J. R. 1971a Infinite models for ciliary propulsion. *Journal of Fluid Mechanics* **49** (02), 209–222.

- BLAKE, J. R. 1971*b* A note on the image system for a stokeslet in a no-slip boundary. *Mathematical Proceedings of the Cambridge Philosophical Society* **70** (02), 303–310.
- BLAKE, J. R. 1971*c* A spherical envelope approach to ciliary propulsion. *Journal of Fluid Mechanics* **46** (01), 199–208.
- BLAKE, J. R. 1972 A model for the micro-structure in ciliated organisms. *Journal of Fluid Mechanics* **55** (01), 1–23.
- BLAKE, J. R., LIRON, N. & ALDIS, G. K. 1982 Flow patterns around ciliated microorganisms and in ciliated ducts. *Journal of Theoretical Biology* **98**, 127 – 141.
- BLAKE, J. R. & SLEIGH, M. A. 1974 Mechanics of ciliary locomotion. *Biological Reviews* **49**, 85–125.
- BRENNEN, C. 1974 An oscillating-boundary-layer theory for ciliary propulsion. *Journal of Fluid Mechanics* **65** (04), 799–824.
- BRENNEN, CHRISTOPHER & WINET, HOWARD 1977 Fluid mechanics of propulsion by cilia and flagella. *Annual Review of Fluid Mechanics* **9**, 339–398.
- BRUSS, HENRIK, BRASK, ANDERS & KUTTER, JORG P. 2004 Nanofluidic components for electrokinetic micropumps. In *The Second International Workshop on Nanophysics and Nanotechnology*, pp. 149–156.
- CHANG, SUK TAI, PAUNOV, VESSELIN N., PETSEV, DIMITER N. & VELEV, ORLIN D. 2007 Remotely powered self-propelling particles and micropumps based on miniature diodes. *Nature Materials* **6**, 235–240.
- CHEN, LINGXIN, MA, JIPING, TAN, FENG & GUAN, YAFENG 2003 Generating high-pressure sub-microliter flow rate in packed microchannel by electroosmotic force: potential application in microfluidic systems. *Sensors and Actuators B: Chemical* **88**, 260–265.
- CHEN, Z. S., HOFSTETTER, G. & MANG, H. A. 1998 A galerkin-type be-fe formulation for elasto-acoustic coupling. *Computer Methods in Applied Mechanics and Engineering* **152** (1-2), 147 – 155, containing papers presented at the Symposium on Advances in Computational Mechanics.
- CHILDRESS, STEPHEN 1981 *Mechanics of swimming and flying*. Cambridge university press.
- COOK, ROBERT D., MALKUS, D.S., PLESHA, M.E., MALKUS, DAVID S. & PLESHA, MICHAEL E. 2001 *Concepts and Applications of Finite Element Analysis*. John Wiley and Sons.
- COOPER, G. M. & HAUSMAN, R. E. 1992 *The Cell: A Molecular Approach*. John wiley and Sons.
- DARNTON, N., TURNER, L., BREUER, K. & BERG, H. C. 2004 Moving fluid with bacterial carpets. *Biophysical Journal* **86**, 1863–1870.
- DAUPTAIN, A., FAVIER, J. & BOTTARO, A. 2008 Hydrodynamics of ciliary propulsion. *Journal of Fluids and Structures* **24** (8), 1156 – 1165, unsteady Separated Flows and their Control.
- DONEA, J., GIULIANI, S. & HALLEUX, J.P. 1982 An arbitrary lagrangian-eulerian finite element method for transient dynamic fluid-structure interactions. *Computer Methods in Applied Mechanics and Engineering* **33** (1-3), 689 – 723.

- DOWNTON, M. T. & STARK, H. 2009 Beating kinematics of magnetically actuated cilia. *EPL (Europhysics Letters)* **85** (4), 44002.
- DREYFUS, R., BAUDRY, J., ROPER, M. L., FERMIGIER, M., STONE, H. A. & BIBETTE, J. 2005 Microscopic artificial swimmers. *Nature* **437**, 862–865.
- EHLERS, K M, SAMUEL, A D, BERG, H C & MONTGOMERY, R 1996 Do cyanobacteria swim using traveling surface waves? *Proceedings of the National Academy of Sciences of the United States of America* **93** (16), 8340–8343.
- EVANS, B. A., SHIELDS, A. R., CARROLL, R. LLOYD, WASHBURN, S., FALVO, M. R. & SUPERFINE, R. 2007 Magnetically actuated nanorod arrays as biomimetic cilia. *Nano Letters* **7** (5), 1428–1434.
- FAHRNI, FRANCIS, PRINS, MENNO W. J. & VAN IJZENDOORN, LEO J. 2009 Micro-fluidic actuation using magnetic artificial cilia. *Lab on a Chip* **9**, 3413 – 3421.
- FULFORD, G.R. & BLAKE, J.R 1986 Muco-ciliary transport in the lung. *Journal of Theoretical Biology* **121** (4), 381 – 402.
- GARDINER, M. B. 2005 Importance of being cilia. *HHMI Bulletin* **18**, 32–37.
- GAUGER, E. M., DOWNTON, M. T. & STARK, H. 2009 Fluid transport at low Reynolds number with magnetically actuated artificial cilia. *The European Physical Journal E* **28**, 231–242.
- GERE, J. M. & TIMOSHENKO, S. P. 1984 *Mechanics of materials*. Brooks/Cole Engineering Division.
- GERSTENBERGER, AXEL & WALL, WOLFGANG A. 2008 An extended finite element method/lagrange multiplier based approach for fluid-structure interaction. *Computer Methods in Applied Mechanics and Engineering* **197** (19-20), 1699 – 1714, computational Methods in Fluid-Structure Interaction.
- GERSTENBERGER, A & WALL, W A 2010 An embedded dirichlet formulation for 3d continua. *International Journal for Numerical Methods in Engineering* **82** (5), 537–563.
- GHOSH, RAJAT, BUXTON, GAVIN A., USTA, O. BERK, BALAZS, ANNA C. & ALEXEEV, ALEXANDER 2010 Designing oscillating cilia that capture or release microscopic particles. *Langmuir* **26**, 2963–2968.
- GOLESTANIAN, RAMIN & AJDARI, ARMAND 2008 Analytic results for the three-sphere swimmer at low Reynolds number. *Physical Review E* **77** (3), 036308.
- GRAY, J. 1922 The mechanism of ciliary movement. *Proceedings of the Royal Society of London, B* **93** (650), 104–121.
- GROVER, WILLIAM H., SKELLEY, ALISON M., LIU, CHUNG N., LAGALLY, ERIC T. & MATHIES, RICHARD A. 2003 Monolithic membrane valves and diaphragm pumps for practical large-scale integration into glass microfluidic devices. *Sensors and Actuators B: Chemical* **89** (3), 315 – 323.
- GU, WEI, ZHU, XIAOYUE, FUTAI, NOBUYUKI, CHO, BRENDA S. & TAKAYAMA, SHUICHI 2004 Computerized microfluidic cell culture using elastomeric channels and Braille displays. *Proceedings of the National Academy of Sciences of the United States of America* **101** (45), 15861–15866.

- GUERON, S. & LEVIT-GUREVICH, K. 1999 Energetic considerations of ciliary beating and the advantage of metachronal coordination. *Proceedings of the National Academy of Sciences of the United States of America* **96** (22), 12240–12245.
- GUERON, S., LEVIT-GUREVICH, K., LIRON, N. & BLUM, J. J. 1997 Cilia internal mechanism and metachronal coordination as the result of hydrodynamical coupling. *Proceedings of the National Academy of Sciences of the United States of America* **94** (12), 6001–6006.
- HALBERT, SA, TAM, PY & BLANDAU, RJ 1976 Egg transport in the rabbit oviduct: the roles of cilia and muscle. *Science* **191** (4231), 1052–1053.
- HAPPEL, JOHN & BRENNER, HOWARD 1986 *Low Reynolds Number Hydrodynamics: with special applications to particulate media*. Martinus Nijhoff Publishers.
- HARRISON, D. J., FLURY, K., SEILER, K., FAN, Z., EFFENHAUSER, C. S. & MANZ, A. 1993 Micromachining a miniaturized capillary electrophoresis-based chemical analysis system on a chip. *Science* **261**, 895–897.
- HOMSY, ALEXANDRA, KOSTER, SANDER, EIJKEL, JAN C. T., VAN DEN BERG, ALBERT, LUCKLUM, F., VERPOORTE, E. & DE ROOIJ, NICO F. 2000 A high current density dc magnetohydrodynamic micropump. *Lab on a Chip* **5** (4), 466–471.
- HUGHES, THOMAS J. R. & LIU, WING KAM 1981 Nonlinear finite element analysis of shells: Part i. three-dimensional shells. *Computer Methods in Applied Mechanics and Engineering* **26** (3), 331 – 362.
- HUSSONG, J., BREUGEM, W. P. & WESTERWEEL, J. 2011a A continuum model for flow induced by metachronal coordination between beating cilia. *Journal of fluid mechanics* Under review.
- HUSSONG, J., SCHORR, N., BELARDI, J., PRUCKER, O., RUHE, J. & WESTERWEEL, J. 2011b Experimental investigation of the flow induced by artificial cilia. *Lab on a chip* **11**, 2017–2022.
- IBANEZ-TALLON, INES, HEINTZ, NATHANIEL & OMRAN, HEYMUT 2003 To beat or not to beat: roles of cilia in development and disease. *Hum. Mol. Genet.* **12**, R27–35.
- JACKSON, JOHN DAVID 1974 *Classical Electrodynamics*. John Wiley and Sons.
- JANG, JAESUNG & LEE, SEUNG S. 2000 Theoretical and experimental study of magnetohydrodynamic micropump. *Sensors and Actuators A: Physical* **80**, 84–89.
- JEON, N.L., DERTINGER, S.K.W., CHIU, D.T., CHOI, I.S., STROOCK, A.D. & WHITESIDES, G.M. 2000 Generation of solution and surface gradients using microfluidic systems. *Langmuir* **16** (22), 8311–8316.
- JOG, C. S. & KELKAR, P. P. 2006 Non-linear analysis of structures using high performance hybrid elements. *International Journal for Numerical Methods in Engineering* **68**, 473–501.
- JOHNSON, R E & BROKAW, C J 1979 Flagellar hydrodynamics. A comparison between resistive-force theory and slender-body theory. *Biophys. J.* **25** (1), 113–127.
- KHADARI, S. N., BALTUSSEN, M. G. H. M., ANDERSON, P. D., IOAN, D., DEN TOONDER, J. M. J. & ONCK, P. R. 2009 Nature-inspired microfluidic propulsion using magnetic actuation. *Physical Review E* **79** (4), 046304.
- KHADARI, S. N., BALTUSSEN, M. G. H. M., ANDERSON, P. D., DEN TOONDER, J. M. J. & ONCK, P. R. 2010 The breaking of symmetry in microfluidic propulsion driven by artificial cilia. *Physical Review E* **82**, 027302.

- KHADERI, S. N., CRAUS, C. B., HUSSONG, J., SCHORR, N., BELARDI, J., WESTERWEEL, J., PRUCKER, O., RUHE, J., DEN TOONDER, J. M. J. & ONCK, P. R. 2011*a* Magnetically-actuated artificial cilia for microfluidic propulsion. *Lab Chip* **11**, 2002–2010.
- KHADERI, S. N., DEN TOONDER, J. M. J. & ONCK, P. R. 2011*b* Fluid flow in microchannels due to asymmetric and out-of-phase motion of magnetically-actuated artificial cilia, submitted .
- KIM, Y. W. & NETZ, R. R. 2006 Pumping fluids with periodically beating grafted elastic filaments. *Physical Review Letters* **96** (15), 158101.
- KINOSITA, H. & MURAKAMI, A. 1967 Control of ciliary motion. *Physiological Reviews* **47**, 53–82.
- KLONOFF, DAVID C. 2007 Benefits and limitations of self-monitoring of blood glucose. *Journal of Diabetes Science and Technology* **1**, 130–132.
- KOPP, M. U., DE MELLO, A. J. & MANZ, ANDREAS 1998 Chemical amplification: Continuous-flow pcr on a chip. *Science* **280**, 1046–1048.
- KOST, G. J., TRAN, N. K., TUNTIDEELERT, M, KULRATTANAMANEEPORN, S. & PEUNGPOSOP, N. 2006 Katrina, the tsunami, and point-of-care testing. *American Journal of Clinical Pathology* pp. 513–520.
- KUNDU, P. K. & COHEN, I. M. 2008 *Fluid mechanics*. Academic press.
- LAI, H. & FOLCH, A. 2011 Design and dynamic characterization of single-stroke peristaltic pdms micropumps. *Lab Chip* **11**, 336–342.
- LANCZOS, C. 1952 *The variational principles of mechanics*. University of Totonro Press.
- LANGELIER, SEAN M., CHANG, DUSTIN S., ZEITOUN, RAMSEY I. & BURNS, MARK A. 2009 Acoustically driven programmable liquid motion using resonance cavities. *Proceedings of the National Academy of Sciences* **106** (31), 12617–12622.
- LASER, D J & SANTIAGO, J G 2004 A review of micropumps. *Journal of Micromechanics and Microengineering* **14** (6), R35–R64.
- LAUGA, E. & POWERS, T. R. 2009 The hydrodynamics of swimming microorganisms. *Reports on Progress in Physics* **72**, 096601.
- LEMOFF, ASUNCION V. & LEE, ABRAHAM P. 2000 An ac magnetohydrodynamic micropump. *Sensors and Actuators B: Chemical* **63**, 178–185.
- LIAO, CHIA-SHENG, LEE, GWO-BIN, LIU, HSIAO-SHENG, HSIEH, TSUNG-MIN & LUO, CHING-HSING 2005 Miniature RTPCR system for diagnosis of RNA-based viruses. *Nucleic Acids Research* **33** (18), e156.
- LIGHTHILL, JAMES 1976 Flagellar hydrodynamics. *SIAM Review* **18** (2), 161–230.
- LIRON, N. 1978 Fluid transport by cilia between parallel plates. *Journal of Fluid Mechanics* **86** (04), 705–726.
- LITSTER, SHAWN, SUSS, MATTHEW E. & SANTIAGO, JUAN G. 2010 A two-liquid electroosmotic pump using low applied voltage and power. *Sensors and Actuators A: Physical* **163** (1), 311–314.
- VAN LOON, R., ANDERSON, P.D., VAN DE VOSSE, F.N. & SHERWIN, S.J. 2007 Comparison of various fluid-structure interaction methods for deformable bodies. *Computers & Structures* **85** (11-14), 833 – 843.

- VAN LOON, R., ANDERSON, P. D. & VAN DE VOSSE, F. N. 2006 A fluid-structure interaction method with solid-rigid contact for heart valve dynamics. *Journal of Computational Physics* **217**, 806–823.
- MALONE, AMANDA M. D., ANDERSON, CHARLES T., TUMMALA, PADMAJA, KWON, RONALD Y., JOHNSTON, TYLER R., STEARNS, TIM & JACOBS, CHRISTOPHER R. 2007 Primary cilia mediate mechanosensing in bone cells by a calcium-independent mechanism. *Proceedings of the National Academy of Sciences* **104** (33), 13325–13330.
- MALVERN, LAWRENCE E. 1977 *Introduction to the Mechanics of a Continuous Medium*. Prentice-Hall.
- MANZ, A., EFFENHAUSER, C. S., BURGGRAF, N., HARRISON, D. J., SEILER, K. & FLURY, K. 1994 Electrosmotic pumping and electrophoretic separations for miniaturised chemical analysis systems. *Journal of micromechanics and microengineering* **4**, 257–265.
- MANZ, A., GRABER, N. & WIDMER, H. M. 1990 Miniaturized total chemical analysis systems—a novel concept for chemical sensing. *Sensors and Actuators B* **1**, 244–248.
- MARMOTTANT, P. & HILGENFELDT, S. 2003 Controlled vesicle deformation and lysis by single oscillating bubbles. *Nature* **423**, 153–156.
- MASUD, A., THAM, C. L. & LIU, W. K. 2000 A stabilized 3-d co-rotational formulation for geometrically nonlinear analysis of multi-layered composite shells. *Computational Mechanics* **26**, 1– 12.
- MITRAN, S. M. 2007 Metachronal wave formation in a model of pulmonary cilia. *Computers and Structures* **85**, 763774.
- MURASE, M. 1992 *Dynamics of cellular motility*. John Wiley and Sons.
- NAJAFI, ALI & GOLESTANIAN, RAMIN 2004 Simple swimmer at low Reynolds number: Three linked spheres. *Phys. Rev. E* **69** (6), 062901.
- NGUYEN, N. T. & WHITE, R. M. 1999 Design and optimization of an ultrasonic flexural plate wave micropump using numerical simulation. *Sensors and Actuators A: Physical* **77** (3), 229 – 236.
- NIEDERMAYER, THOMAS, ECKHARDT, BRUNO & LENZ, PETER 2008 Synchronization, phase locking, and metachronal wave formation in ciliary chains. *Chaos: An Interdisciplinary Journal of Nonlinear Science* **18** (3), 037128.
- OH, KIESEOK, CHUNG, JAE-HYUN, DEVASIA, SANTOSH & RILEY, JAMES J. 2009 Bio-mimetic silicone cilia for microfluidic manipulation. *Lab on a Chip* **9** (11), 1561–1566.
- VAN OOSTEN, CASPER L., BASTIAANSEN, CEES W. M. & BROER, DIRK J. 2009 Printed artificial cilia from liquid-crystal network actuators modularly driven by light. *Nature Materials* **8**, 677 – 682.
- PESKIN, CHARLES S. 2002 The immersed boundary method. *Acta Numerica* **11** (-1), 479–517.
- PILARSKI, PATRICK M., ADAMIA, SOPHIA & BACKHOUSE, CHRISTOPHER J. 2005 An adaptable microvalving system for on-chip polymerase chain reactions. *Journal of Immunological Methods* **305** (1), 48 – 58, the 8th International Workshop on Human Leucocyte Differentiation Antigens.
- POLYANIN, A. D. 2001 *Handbook of Linear Partial Differential Equation*. CRC, section 1.1.2-5.

- POZRIKIDIS, C. 2002 *A practical guide to boundary element methods*. Chapman & Hall/CRC.
- PURCELL, E. M. 1977 Life at low Reynolds number. *American Journal of Physics* **45** (1), 3–11.
- QIAN, BIAN, JIANG, HONGYUAN, GAGNON, DAVID A., BREUER, KENNETH S. & POWERS, THOMAS R. 2009 Minimal model for synchronization induced by hydrodynamic interactions. *Phys. Rev. E* **80** (6), 061919.
- VAN RIJSEWIJK, L. 2006 Electrostatic and magnetic microactuation of polymer structures for fluid transport. Master's thesis, Eindhoven University of Technology.
- ROSSI, ANTHONY F. & KHAN, DANYAL 2004 Point of care testing: improving pediatric outcomes. *Clinical Biochemistry* **37** (6), 456 – 461, special Issue: Proceedings of the IX International Congress on Pediatric Laboratory Medicine.
- ROTH, YEHUDAH, KIMHI, YOSEF, EDERY, HABIB, AHARONSON, EPHRAM & PRIEL, ZVI 1985 Ciliary motility in brain ventricular system and trachea of hamster. *Brain Research* **330** (2), 291 – 297.
- SALE, W S & SATIR, P 1977 Direction of active sliding of microtubules in Tetrahymena cilia. *Proceedings of the National Academy of Sciences of the United States of America* **74** (5), 2045–2049.
- SALSAC, A. V., BIESEL, D. BARTHES & TALLEC, P. LE 2010 Coupling of finite element and boundary integral methods for a capsule in a stokes flow. *International Journal for Numerical Methods in Engineering* pp. 829 – 850.
- SATIR, P & SLEIGH, M A 1990 The physiology of cilia and mucociliary interactions. *Annual Review of Physiology* **52** (1), 137–155, PMID: 2184754.
- SCHILLING, E.A., KAMHOLZ, A.E. & YAGER, P. 2002 Cell lysis and protein extraction in a microfluidic device with detection by a fluorogenic enzyme assay. *Analytical Chemistry* **74** (8), 1798–1804.
- SCHNEIDER, S. 2008 Fe/fmbe coupling to model fluidstructure interaction. *International Journal for Numerical Methods in Engineering* pp. 2137 – 2156.
- SCHORR, N., BELARDI, J., PRUCKER, O., WELLS, S., PATEL, V. & RUHE, J. 2010 Magnetically actuated polymer flap arrays mimicking artificial cilia. In *Second European Conference on Microfluidics - paper no. 105*.
- SHIELDS, A. R., FISER, B. L., EVANS, B. A., FALVO, M. R., WASHBURN, S. & SUPERFINE, R. 2010 Biomimetic cilia arrays generate simultaneous pumping and mixing regimes. *Proceedings of the National Academy of Sciences* .
- SING, CHARLES E., SCHMID, LOTHAR, SCHNEIDER, MATTHIAS F., FRANKE, THOMAS & ALEXANDER-KATZ, ALFREDO 2010 Controlled surface-induced flows from the motion of self-assembled colloidal walkers. *Proceedings of the National Academy of Sciences* **107** (2), 535–540.
- SMITH, D.J., GAFFNEY, E.A. & BLAKE, J.R. 2008 Modelling mucociliary clearance. *Respiratory Physiology and Neurobiology* **163**, 178188.
- SMITH, D. J., GAFFNEY, E. A. & BLAKE, J. R. 2007 Discrete cilia modelling with singularity distributions: Application to the embryonic node and the airway surface liquid. *Bulletin of Mathematical Biology* **69**, 1477–1510.

- SQUIRES, T. M. & QUAKE, S. R. 2005 Microfluidics: uid physics on the nanoliter scale. *Reviews of Modern Physics* **77**, 977 – 1026.
- STONE, HOWARD A. & SAMUEL, ARAVINTHAN D. T. 1996 Propulsion of microorganisms by surface distortions. *Phys. Rev. Lett.* **77** (19), 4102–4104.
- STRATHMANN, R. 1973 Function of lateral cilia in suspension feeding of lophophorates (brachiopoda, phoronida, ectoprocta). *Marine Biology* **23**, 129 – 136.
- STUDER, VINCENT, PEPIN, ANNE, CHEN, YONG & AJDARI, ARMAND 2004 An integrated ac electrokinetic pump in a microfluidic loop for fast and tunable flow control. *The Analyst* **129** (10), 944–949.
- SVENSSON, S., SHARMA, G., OGDEN, S., HJORT, K. & KLINTBERG, L. 2010 High-pressure peristaltic membrane micropump with temperature control. *Microelectromechanical Systems, Journal of* **19** (6), 1462–1469.
- TAMM, S. L. & HORRIDGE, G. A. 1970 The relation between the orientation of the central fibrils and the direction of beat in cilia of opalina. *Proceedings of the Royal Society of London. Series B, Biological Sciences* **175**, 219 – 233.
- TEC PLOT 2008 Tec360 user manual.
- TIMONEN, J. V. I., JOHANS, C., KONTTURI, K., WALTHER, A., IKKALA, O. & RAS, R. H. A. 2010 A facile template-free approach to magnetodriven, multifunctional artificial cilia. *ACS Applied Materials and Interfaces* **2**, 22262230.
- DEN TOONDER, JAAP, BOS, FEMKE, BROER, DICK, FILIPPINI, LAURA, GILLIES, MURRAY, DE GOEDE, JUDITH, MOL, TITIE, RELJME, MIREILLE, TALEN, WIM, WILDERBEEK, HANS, KHATAVKAR, VINAYAK & ANDERSON, PATRICK 2008 Artificial cilia for active micro-fluidic mixing. *Lab on a Chip* **8** (4), 533–541.
- VILFAN, ANDREJ & JÜLICHER, FRANK 2006 Hydrodynamic flow patterns and synchronization of beating cilia. *Phys. Rev. Lett.* **96** (5), 058102.
- VILFAN, MOJCA, POTOCNIK, ANTON, KAVCIC, BLAZ, OSTERMAN, NATAN, POBERAJ, IGOR, VILFAN, ANDREJ & BABIC, DUSAN 2010 Self-assembled artificial cilia. *Proceedings of the National Academy of Sciences* **107**, 1844–1847.
- WEST, JONATHAN, KARAMATA, BORIS, LILLIS, BRIAN, GLEESON, JAMES P., ALDERMAN, JOHN, COLLINS, JOHN K., LANE, WILLIAM, MATHEWSON, ALAN & BERNEY, HELEN 2002 Application of magnetohydrodynamic actuation to continuous flow chemistry. *Lab Chip* **2**, 224–230.
- WHITESIDES, GEORGE M. 2006 The origins and the future of microfluidics. *Nature* **442**, 368–373.
- WOOLLEY, DAVID M. 2010 Flagellar oscillation: a commentary on proposed mechanisms. *Biological Reviews* **85** (3), 453–470.
- WU, JIE, LIAN, MENG & YANG, KAI 2007 Micropumping of biofluids by alternating current electrothermal effects. *Applied Physics Letters* **90** (23), 234103.
- Y. BOURQUIN, J. REBOUD, R. WILSON & COOPER, J. M. 2010 Tuneable surface acoustic waves for fluid and particle manipulations on disposable chips. *Lab Chip* **10**, 1898 – 1901.
- YEO, L. Y. & FRIEND, J. R. 2009 Ultrafast microfluidics using surface acoustic waves. *Biomechanics* **3**, 012002.

-
- ZENG, S., CHEN, C., SANTIAGO, J. G., CHEN, J., ZARE, R. N., TRIPP, J. A., S., F. & FRECHET, J. M. J. 2002 Electroosmotic flow pumps with polymer frits. *Sensors and Actuators B: Chemical* **82** (2-3), 209 – 212.
- ZIENKIEWICZ, O. C. & TAYLOR, R. L. 2002 *The finite element method*. Butterworth-Heinemann.

