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James Lighthill: The Collected Works

James Lighthill's unexpected and untimely death in July 1998 has robbed the Applied Mathematics Community of one of its most illustrious leaders. Ironically, it now seems, a four-volume set of Lighthill's Collected Works was published by Oxford University Press in the previous year, edited by Yousuff Hussaini. A complete bibliography of Lighthill's scientific publications up to 1996 is included, about two-thirds of which are reproduced. In his General Introduction the Editor foresees that with Lighthill's 'acumen, and his mental stamina unabated' a fifth volume will eventually be needed. Sadly that can now be compiled. This article is in the nature of a biographical review of the Collected Works.

Lighthill burst onto the fluid mechanics research scene as a teenager. He had entered Trinity College, Cambridge at the early age of 17 in 1941, graduating in 1943 under wartime regulations. He had hoped that war service would be carried out at the Royal Aircraft Establishment, Farnborough where his future wife Nancy Dumaresq had been drafted. In the event he served the remaining two years in a group headed by Sydney Goldstein at the National Physical Laboratory, Teddington. His first paper (I,A1)*, published on 21 January 1944 two days before his twentieth birthday, was on supersonic aerofoil theory, in which he drew together, and extended, earlier work on sharp-nosed aerofoils. He returned to Cambridge for one year before leaving for Manchester in 1946, but not before eleven papers had been published from the work carried out at the NPL. One of the most delightful of these (1945, II, D26) describes a new method for designing aerofoils with given velocity distributions.

Goldstein had been appointed as Beyer Professor of Applied Mathematics at Manchester, and he attracted Lighthill there as Senior Lecturer. When Goldstein left in 1950 Lighthill succeeded him to the Beyer Chair at the age of 26, a position he was to hold until 1959.

World War II had provided a stimulus for research in fluid dynamics in general, and aerodynamics in particular, with increasing emphasis on high speed flows. Lighthill's first post-NPL investigation (1947, I, B10), in four parts, was concerned with the hodograph transformation, showing how this can be extended from steady compressible fluid flows with free boundaries to those with solid boundaries. Several other landmark papers have the same origins. The method of strained co-ordinates (1949, I, B13) for rendering solutions uniformly valid is one. Other investigations using perturbation methods were subsequently incorporated (I, B17) in Section E of *General Theory of High Speed Aerodynamics* (Princeton University Press, 1954), later published as a separate *fascicule* by the Press in 1960. Perhaps the most famous papers of this period are his two papers, published in 1952, on sound generated aerodynamically (III, H47); the second, which deals with the sound field of a jet, was particularly timely, since jet-propelled civil aircraft were soon to be commonplace. His paper (1953, II, F38) on the interaction between a boundary layer and a supersonic mainstream in which there are weak compressive disturbances, contains the essence of the ideas for the development more than a decade later, by others, of the so-called 'triple deck'. A major research contribution was an invited survey article on 'Viscosity effects in sound waves of finite amplitude' in *Surveys in Mechanics* (Cambridge, 1956) (I, C20). This volume commemorated G. I. Taylor's 70th anniversary. Taylor had discussed the effects of viscosity and heat conduction on the

* Volume number, section and paper number

propagation of a surface of discontinuity in a gas in 1910. Lighthill elaborated upon this theme, but also included the effects of relaxation. Gas imperfection, dissociation, ionization and radiation were not considered in detail. However, with hypersonic flow, associated with re-entry problems, becoming a reality, this article led not unnaturally to his work on the theory of dissociating gases (1957, I, C21), developed for both equilibrium and quasi-equilibrium flows. Not all of Lighthill's work during the Manchester period was associated with aerodynamics and high-speed flows. His studies of the propagation of shock waves stimulated an interest in wave motion in general, and water waves in particular. His paper with Benjamin on cnoidal waves and bores (1954, III, J56) represents an early revival of the use of the Korteweg–deVries equation. The following year, with Whitham (1955, III, J57), he developed a theory of kinematic waves. These are waves of a rather special type in which a 'flow' is related to a 'density'; the theory was applied to flood movement in rivers, and traffic flow. Anisotropic waves formed the subject of a later paper (1960, I, C22); in the mathematical part of this paper a technique is developed for asymptotically evaluating Fourier integrals in many dimensions. This is applied to the solution of partial differential equations representing anisotropic or dispersive wave motions or both. The physical vehicle chosen is the propagation of magnetohydrodynamic waves, although others have subsequently applied it to areas as diverse as atmospheric lee waves and elastic waves. Two other papers of this period are worthy of mention, if only because they represent an early indication of future research directions. One (1952, IV, L70) concerns propulsion by 'squirming' motion at low Reynolds number, the other (1960, IV, L71) an inviscid theory of the swimming of slender fish.

The Manchester period lasted for only 13 years. These were years of astonishing and seminal productivity. New areas of research in fluid mechanics were opened up, to be exploited by others, not least by a succession of graduate students who spanned that period. To the surprise of most, in 1959 Lighthill was appointed as Director, the youngest to date at the age of 35, of a major government research laboratory, namely the renowned Royal Aircraft Establishment at Farnborough.

In what he described as a 'sabbatical quinquennium' Lighthill demonstrated administrative skills to match those of his research. He familiarised himself with the work of all departments in an establishment that at the time employed 8000 people, 1400 of whom were scientists and engineers. He enjoyed the interdisciplinary nature of the RAE and declared of his Directorship in an after-dinner speech at the annual meeting of the Fluid Dynamics Division of the American Physical Society in November 1960 (1962, I, C24) that '. . . at present I wouldn't give it up for anything!' Exciting developments accompanied his tenure as Director. For example, the Anglo-French Supersonic Treaty was signed in 1962 ensuring the future of the supersonic transport project; blind landing systems were in the final stages of development; on the materials side carbon-fibre research was reaching its climax; a new Structures Laboratory was being planned, dedicated to fatigue testing of Concorde. At this time the highly regarded RAE research publications consisted of Technical Reports (TR) and Technical Memoranda (TM). To these Lighthill added the TM DIR series for his own research. Sadly, none of these survive in the Collected Works, presumably because they were superseded by external publication. Notable amongst his publications during this period are his contributions on bodies in shear flows in *Incompressible Aerodynamics* (OUP, 1960), not reproduced, and the first two chapters, better described as essays, in *Laminar Boundary Layers* (1963, II, F43). Three important lectures were subsequently published, the Ludwig Prandtl Memorial Lecture (1961) on strained co-ordinates, not reproduced, the Royal Society Bakerian Lecture on sound generated aerodynamically (1962, III, H50) and the Wright Brothers Lecture on jet noise (1963, III, H51). Wave motion was of continued interest with contributions to upper atmosphere aerodynamics (1960, I, C23) and wind-generated waves (1962, III, J59). It was while Director of the RAE that he perceived a real need for a professional institute to serve the interests of the Applied Mathematics community. The Institute of Mathematics and its Applications was launched in 1964, with Lighthill as its first President. His Presidential Address on ‘Group velocity’ was subsequently published by the IMA (1965, III, K64).

Following his five-year term at Farnborough, Lighthill was appointed in 1964 as Royal Society Research Professor, a chair he chose to hold at Imperial College. For his inaugural lecture in 1965 he returned to a familiar theme, namely ‘Waves in Fluids’. This was subsequently published by the College, but does not feature in the Collected Works. However, he gave the same lecture at the Courant Institute in the following year, which was subsequently published in *Communications in Pure and Applied Mathematics* **20** (1967) 267–293. The scientific content of each is the same, but the IC version contains a more extensive introduction, aimed at the local audience. In it he explains why he chose not to identify with a particular department, but to adopt the role of a ‘roving research professor’. The main reason cited is his interdisciplinary experience, at the RAE, which amongst other things made up for ‘all those battles with the Whitehall machine’. Lighthill’s sojourn at Imperial College lasted for five years. Back now to research, unencumbered by teaching or administration, major papers flowed. In addition to research on wave motion (1965, III, K65), (1967, III, K66, K67) he embarked on a study of rotating fluids. His first paper (1966, III, J60) was a survey, based on a lecture given at an IUTAM symposium, in which he derives all the leading results of rotating-fluid theory, using vorticity principles as the sole theoretical tool, in a non-rotating frame of reference. A later paper (1969, III, J61) addresses the response of the Indian Ocean to the onset of the Southern Monsoon. But it was, significantly, during this period that his interest in the life sciences was revived. This resulted, in collaboration with Colin Caro, in the establishment of the Physiological Flow Studies Unit at Imperial College. Two papers relating to flow in the capillaries were published, not reproduced, and a major survey article on the hydrodynamics of aquatic animal propulsion (1969, IV, L72). Twenty classes within ten phyla of the animal kingdom are discussed. The article serves as a prime example of its author’s astonishing ability to embrace a new field of study, and apply to it with profit the principles of his own discipline.

In 1969 Lighthill returned to Cambridge as Lucasian Professor of Mathematics, a position he was to hold for ten years. During that decade of the 1970s he continued to pursue research on rotating fluids (1970, III, K68), acoustics (1972, III, H52), (1978, III, H53) and wave motion. The latter includes an analysis of a resonant-duct wave-energy device (1979, III, J62), and his authoritative book on *Waves in Fluids* (CUP, 1978). However, it is to the life sciences, specifically biofluiddynamics, that Lighthill’s major effort was devoted during this period. In particular, it is in a series of survey articles that he fully exposed the richness of the subject. To do this, it had been necessary to ‘immerse myself in the zoological literature and the language of zoologists’ (IV, L75). The first of these (1972, IV, M86) was based on lectures given at ICMS Udine in 1971 and is a general survey of flows within the human body including the lungs, the urinary tract, the general systemic circulation, and microcirculation, of the blood. In July 1973 he gave a lecture course on *Mathematical Biofluiddynamics* at a Research Conference of the National Science Foundation held at Rensselaer Polytechnic Institute. These lectures were subsequently incorporated into a book of the same title (SIAM, 1975). This included earlier work, for example (IV, L72) and (IV, M86) referred to above, and represents a then state-of-the-art survey of aquatic and aerial animal locomotion, and physiological fluid flows. In it he claims to have been only ‘able to scratch the surface of this important new field’ but hopes to have shown that there are rich veins there for those ‘who are prepared to dig deep’ which, of course, Lighthill himself did. In a lecture given to the 13th Congress of Theoretical and Applied Mechanics he returns to, and updates, the theories of aquatic animal locomotion (1973, IV, L72). On a return to Rensselaer in 1975 to give the John von Neumann Lecture, he gave a two-year update on flagellar hydrodynamics (1976, IV, L78). This survey of low-Reynolds-number biofluiddynamics encompasses those organisms at about the lowest levels of organisation in the animal and plant kingdoms, namely the protozoans, the bacteria, the algae and the fungi. Aerial locomotion was the subject of a lecture to the British Hydromechanics Research Association (1974, IV, L77). (Note that the correct reference of this paper should be *Swimming and Flying in Nature* (T. Y. Wu, C. J. Brokaw and C. Brennen, editors) pp. 423–491 (New York: Plenum Press 1975), and that it also appears in the *IMA Bulletin, Tenth Aniversary Issue* (1974) pp. 369–393. This last article does not feature in the Collected Works. In *Scale Effects in Animal Locomotion* (T. J. Pedley, editor) pp. 365–404 (New York: Academic Press 1977), he contributed a chapter on the scaling of aerial locomotion (IV, L79). In these wide-ranging and defining survey articles it is not always easy to detect Lighthill’s original contributions: easier in fact to define those of his students and collaborators who were introduced to this new field of endeavour by him. But there are two research papers, independent of the surveys, which should be mentioned. The first analyses the Weis–Fogh mechanism of lift generation (1973, IV, L76). This is the famous ‘clap and fling’ mechanism by which the chalcid wasp generates circulation about its wings, and therefore lift. The second provides a modification of the actuator-disk model, which makes it aerodynamically self-consistent, to describe hovering flight bounded below by horizontal ground.

In 1979 Lighthill again showed his capacity to surprise, by relinquishing the Lucasian Chair in favour of the Provostship of University College London. Once again his superb administrative skills were much in evidence as he guided a large and complex organisation through the financial blizzards visited upon the UK university sector by a government which, to quote Oscar Wilde, ‘knows the price of everything, and the value of nothing’. That University College has survived with an enhanced academic reputation is a testimony to these skills. It is, therefore, a little unfortunate that the Inaugural Frederic Constable Lecture on *Academic innovation* is listed (1980, J. R. Soc. Arts), but not reproduced, in the Collected Works. Research during this period inevitably slowed, but administrative burdens did not prevent advances being made. For example, internal biofluiddynamics found a new focus in the fluid mechanics of the cochlea in the inner ear (1981, IV, M87), (1983, IV, M88). Whilst external biofluiddynamic investigations resulted in a four-part contribution (1990, IV, L82) on the biofluiddynamics of balistiform and gymnotiform locomotion, as distinct from the earlier studies of anguilliform and carangiform modes of propulsion. Basically, the new modes of motion studied are those for which the body and any caudal fin remain rigid, with propulsion effected by undulations or oscillations of the median fins. Wave motion remained a major interest, epitomised by a paper on the wave loading on off-shore structures (1986, III, J63). Also, there was a brief diversion to chaos (1986, II, G46).

Formal retirement, which came in 1989, gave rise to a predictable increase in research activity, from a base in the UCL Mathematics Department. Prominent in this was a renewed interest in aeroacoustics generated by an invitation from the Editor of the Collected Works to take part in a workshop at ICASE Virginia in 1992, and his introductory lecture is reproduced in them (1992, III, H54). (Curiously this paper is duplicated, in a different format.) This renewed activity resulted in Lighthill being invited to give the Inaugural Theodorsen Lecture in 1993 on the aeroacoustics of high-speed jets (1994, III, H55) (again duplicated). Papers from this period also include an up-to-date survey of biofluiddynamics (1993, IV, L84), an analysis of the swimming of the clupeoid fish (1993, IV, L85) and further contributions to our understanding of the hearing process (1991, IV, M89), (1992, IV, M90). The very last paper cited, but not reproduced, is on flagellar motion and is published in an issue of this Journal celebrating the centenary of a paper on slow viscous flow by H. A. Lorentz (*J. Eng Math*. **30** (1996) 35–80). This paper epitomises the Lighthillian approach to fluid mechanics. In it he presents, *inter alia*, the anatomy of the spirochete and demonstrates how its swimming motion may be modelled by a helical distribution of superposed stokeslets and rotlets. These yield a flow field confined to a region close to the outer cell body's helical shape, with a powerful jet-like interior flow through the coils of the swimming cell. Another contribution, listed but unfortunately not reproduced, is to *Twentieth Century Physics* (L. M. Brown, A. Pais and B. Pippard, editors) pp. 795–912 (Bristol and Philadelphia: IOP Publishing 1995). In Chapter 10 Lighthill charts the successful developments of fluid mechanics from the beginnings of this century. Not unnaturally Prandtl and Taylor are perceived as heroes, with their authority stamped upon the first half of the twentieth century. That being so, the pages of these Collected Works identify Lighthill as one of their natural heirs, as he strode majestically through its second half.

Professor Hussaini, and Oxford University Press, have performed a valuable service to the fluid mechanics community by bringing together Lighthill's scientific papers, up to 1996, in these Collected Works. The papers are organised in twelve sections each identified with a particular theme; they are reproduced without change of pagination, with each identified by a bold number in the margin. The difficulty this creates is minor. There is a chronological list of publications, in addition to the section-by-section breakdown. A complete *Curriculum Vitae* lists the honours and distinctions bestowed upon Lighthill, including some two dozen honorary doctorates, but unaccountably omitting his election to the Fellowship of the Royal Society in 1953.

Two published books that are listed have not emerged in the above discussion: these are his *Introduction to Fourier Analysis and Generalised Functions* (CUP, 1958) and *An Informal Introduction to Theoretical Fluid Mechanics* (OUP, 1986), both of which are advanced undergraduate texts. Lighthill was an inspirational teacher of undergraduates in both Manchester and Cambridge. Before leaving Manchester he had taught every course that was the responsibility of the Applied Mathematics Sector, including service courses. Anyone who encountered him in any one of his capacities as administrator, researcher or teacher could appreciate his brilliance. Some had the good fortune to know him in more than one of these capacities. He was active to the end. Just before Easter, 1998, he gave an invited lecture at the BAMC on 'One hundred years of shock waves', and in July at the Euromech conference in Manchester on 'Steady and unsteady separated flows', entitled 'Boundary layers and upstream influence 45 years ago'. This closing chapter of his life accurately mirrored Prandtl and Taylor's contributions at the beginning of the century.

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