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DAVID CRIGHTON
1942–2000

A commentary on his career and his influence on aeroacoustic theory

By JOHN E. FFOWCS WILLIAMS
Emmanuel College, Cambridge CB2 3AP, UK

FIGURE 1. This picture shows David Crighton in his element, and George Batchelor rather shocked by it – but given away by the glint in his eye.

David Crighton was struck down by cancer in his fifty-eighth year. He was then at the height of his career and was one of the most admired personalities in fluid mechanics. He had specialized in wave theory, helping to understand and solve problems of practical importance using the full power of mathematical method. Efforts to control the sound and vibration caused by unsteady flow were never far from his thinking, and Crighton's contribution to those efforts has changed significantly the way the subject is viewed. Having first attracted him into the field and never losing my interest in the way he was influencing it, it is natural that I should comment on the technical developments while looking back on Crighton's professional life. The subject has changed a great deal and there are now many more researchers involved in its study, many of whom rely on techniques that Crighton pioneered – really powerful mathematical methods. But the basic problems remain: powerful flows are noisy.

David Crighton had gone straight from his undergraduate days at Cambridge to teach mathematics to part-time students, declining the opportunity to do research which was the normal choice of people that bright. He rocketed to the top of the career grade at Woolwich Polytechnic where his teaching talent was immediately recognized, but very soon he was missing the prospect of research and looked around for a way of doing both; he needed to find a research supervisor and a project that he could start, without letting down his colleagues at Woolwich. His search brought him into my office at Imperial College where I was having a marvellous time teaching and researching in areas strongly supported by the American Navy. Good ideas were always supported. David told me that he would like to study turbulence, talks at Cambridge by Ian Proudman and George Batchelor having made a deep impression on him. But I regarded turbulence as a subject to be avoided, telling him that it only remained interesting as long as it remained un-understood. But the consequences of turbulence were quite a different matter and I would be happy to collaborate with him on research into the coupling of turbulence with other effects. Aerodynamic sound was a good possibility because that was my own speciality and Crighton had already begun to think that Proudman's ideas on pressure fluctuations in homogeneous turbulence could be extended to cover the compressible case. Not easily, I thought; homogeneous turbulence would produce a homogeneous, and therefore infinite, volume of sources, giving an infinite sound level everywhere. That set him thinking, and very soon we had agreed to work together. His first paper, showing how the infinity of Olbert's paradox was checked by dissipative effects, was published by the Cambridge Philosophical Society. Crighton had proved that such effects had no likely application on a terrestrial scale, he had been weaned off the homogeneous turbulence problem and he had been caught by the research bug.

Crighton resigned from Woolwich Polytechnic to join the maths department at Imperial College as a research assistant on a Navy grant. Gas bubbles in water had well established acoustical properties that Murray Strasberg, working at the David Taylor Model Basin, wished to extend to include the effects of turbulence. That was the subject of the grant on which Crighton was hired. Sound is very weakly coupled to low Mach number flow, and most of the unsteady pressures in flow have little to do with sound. An isolated bubble will vibrate in response to the unsteady pressure in a sound wave, and that vibration will scatter a tiny part of an incident wave's energy to radiate outwards from the bubble. Bubbles are driven into vibration by turbulent pressure fluctuations also, their volumetric oscillation making sound very much more effectively than the turbulence does. Crighton also noticed that a distribution of bubbles would lower the speed at which sound travels by a very large factor, and that the effective Mach number of bubbly flow would therefore be increased dramatically. Both these effects imply that bubbles in underwater flows are a very bad thing from a noise point of view. That interesting thought attracted a great deal of attention when it was published in the *Journal of Fluid Mechanics* – but we were in trouble! We had, in our enthusiasm, published too quickly and the publication clearance we anticipated from the Navy was not, in fact, forthcoming.

In developing aerodynamic noise theory to handle the inhomogeneous two-phase flow problem, several interesting issues had had to be faced, to do with which of the several parameters in the problem were important, and important in which region of parametric space. Ways were needed for dealing with the large variations that occur in crossing clouds of bubbles. Crighton's technique was to consider definite models, ones that could be posed and solved for precisely, and he thereby broke away from the tendency to rely on statistical descriptions that had previously been normal in the subject.

Since so very little could be said with confidence about turbulence, aeroacoustic thinking concentrated more on the wave aspects of the problem. The sources of waves were difficult to handle, but the diffraction, the refraction and the scattering of waves as they moved away from their sources to travel to the distant field, might well be more easily modelled. At high enough frequency, ray theory is best and easy to deal with. But noisy subsonic flows tend to make sound of longer wavelength than the size of the flows, and inhomogeneities can alter fundamentally the way they generate sound. Sound could have a back-reaction and might even alter the flows themselves, though it would be hard to tell, knowing so little about turbulence.

Lighthill's acoustic analogy defined flow sources as quadrupole, with the inefficiency of quadrupoles determining most of the effects that characterize the subject. Turbulence and its equivalent quadrupoles were usually approximated by unsteady incompressible flows, with the only known exact examples involving concentrated vorticity embedded in otherwise irrotational flow. Müller and Obermeier's calculation of the sound produced by a pair of line vortices spinning around each other was a singular example, confirming in a definite deterministic model the dimensional scaling of Lighthill's analogy. That analogy had also been extended to include the scattering properties of sharp-edged surfaces – surprising properties that became much easier to understand once Crighton got involved. He solved a new type of aeroacoustic example by working out the sound of a line vortex moving around the edge of a semi-infinite rigid screen. He had posed and solved the first non-trivial deterministic model that addressed the processes of both generation and diffraction of flow-induced waves. Crighton went on to become a master of the matched asymptotic expansion techniques that Crow had first used to clarify the foundations of the acoustic analogy. Crighton applied them to model definite new hydro-acoustic processes which had potentially significant applications, so his research attracted a great deal of interest amongst aeronautical and naval scientists. His paper with Leppington that proved that the scattering properties of a sharp-edged screen were much more to do with the extensive nature of the screen than with the sharpness of the edge was typical of his work in breaking new ground and drawing general conclusions. The precision of the analysis and the clarity of its exposition were very convincing. Crighton was using powerful mathematical methods to derive precise solutions to model problems and through them he was adding to the growing feeling that the difficult and far more complicated practical situations were beginning to be understood.

David Crighton had a very highly developed understanding of how surface vibration interacted with flows to determine the main characteristics of their radiated noise. That subject was a continuing theme of his research from his earliest studies as a student. He discarded the common modal-based approach to vibration, to solve instead for the detailed time-accurate motion that resulted from unsteady fluid stresses. The near-surface flows are often very intricate, their structure being set by a balance between conflicting processes, the balance being different in different parts of parametric space. Flexible surfaces bring in an additional set of parameters, making the fluid/surface-vibration problem very rich indeed in its range of behaviour. Crighton's lectures on this subject were often akin to a geographical tour of newly discovered features in the various different parametric regions.

Sometimes the energy of flow-coupled vibration lay mainly in the supporting mechanical structure, sometimes it was in the fluid, and Crighton enjoyed exploring problems where it could be made to pass from one to the other by the scattering effect of surface inhomogeneities. This area, too, was one where his work had an immense influence on today's perception of the subject. Never is the problem of flow-induced vibration more important than in the response of submarine structures to flow. It is especially important to know whether any distinctive features of the sound might point to identifiable characteristics of a vessel. Crighton, who lectured extensively to expert international audiences, always enjoyed the attentive following of naval scientists.

The range of effects found when flow and waves interact on surfaces is even greater when the surfaces bound moving fluid, or the surface is an interface between two fluids in relative motion. Instabilities arise; waves can grow exponentially with their effects dominating over those that initially triggered the instability. That process occurs in many important practical flows, in the shear layer just downstream of the nozzle exit in a jet, for example. It is possible that the development of disturbed vortex sheets might have features in common with high Reynolds number shear layers; Crighton thought they did. Because the semi-infinite vortex sheet downstream of a semi-infinite screen was definite enough to be amenable to precise modelling and solution, he began to study it very early on in his research career and carried on later, with research students and others. Orszag and Crow had pointed to the importance of knowing what conditions apply in the flow at the trailing edge where the vortex sheet is born, and what effects limit the singularity of potential theory at that point, and how they are to be incorporated into a Kutta condition. Crighton extended their work and by modelling the problem in a definite way and solving it precisely, helped build the confidence with which others now calculate routinely the unsteady flows that interact with the sharp edges found in practice at cavity openings and at the trailing edges of aerofoils.

Fourier decomposition, matched asymptotic expansions and the Wiener–Hopf technique were the three main mathematical tools which Crighton used in his work, and which he taught to others. He enjoyed pointing out to me the limitation of confining my interest to only the first term in an expansion. Indeed on one occasion he was greatly amused by Derek Moore who, on being told by Crighton of his success in evaluating the thirteenth term in an expansion, remarked that the supervisor would only be interested in the sign of the first term. The importance of viscosity in particular regimes near surfaces or near sharp edges, but its irrelevance in others parts, makes matching techniques a natural choice. So too does the dominance of compressibility in the radiation field while being negligible around the source. Aeroacoustics abounds in examples of these features in situations that are completely beyond the scope of precise analysis, or even computation. Crighton's work had a direct application to them, and having always been interested in aeroplanes he enjoyed the aeronautical relevance of his work.

His work on waves went much further than the aeronautical context. He was fascinated by the balance often found in nature between nonlinear steepening and the dispersive effects in waves. He was an expert on Burgers' equation and the Korteweg–de Vries equation, and highly adept at finding physically relevant applications for them. The internal structure of shock waves and the propagation of nonlinear sound, both narrow and broad band, provided good research material, as did solitons, and as indeed did the characters that studied them: few who heard Crighton lecturing on Scott Russell's fascination with the solitary wave could ever forget the experience.

The vibration of ship and aircraft structures, which are frequently modelled as an array of periodically supported panels which are coupled to one another by movement or bending at their supports, is a heavily worked area of study. It received renewed attention once it was realized that irregularities in the periodic supports

FIGURE 2. Professor Ernst-August Müller being served champagne by David Crighton and me at a celebratory meeting in Göttingen marking Müller's retirement from Director of the Max Plank Institute. Krishnamurty Karamcheti is standing by with cigars and dimly lit behind him stands Willi Möhring.

could actually prevent the transmission of vibration along the structure. Crighton was closely involved with that work and a welcome member of both the British and American teams that sought to benefit from the effect in underwater applications. What Crighton was able to model was the effect of fluid loading on this mechanical equivalent of Anderson's localization principle. He studied how a vibrational wave incident on the edge of a panel that adjoined but was mechanically isolated from its neighbour, and which would, in the absence of fluid loading, not enter into the adjoining panel, could actually jump over the mechanical stop. Fluid loading would couple the mechanically isolated structures. He made good use of the fact that those coupled fluid/structure waves, whose phase speed was only slightly lower than the speed of sound in the fluid, had most of their energy in the fluid. Though they are evanescent, slightly subsonic surface waves extend far out into the fluid. Crighton emphasized the fact that any abrupt interruption of the surface could have little effect and the wave would tend to go on unchanged. Fluid coupling really matters. Crighton understood its practical importance and he developed the theory that makes its effect easy to understand.

It takes very much more than mathematical ability to earn the reputation that Crighton gained. He was one of those fortunate people who saw the best side of things and took the most complimentary views of other's muddled thinking. He liked people and they liked him. It was a real pleasure to collaborate with him and he seemed to add value wherever he worked. That was so from his early student days. He became my research student in a period when I was directing the Anglo-French research programme to control the noise of Concorde during its take-off and landing at airports, and it was natural that many of his research problems were related to that exciting project.

Concorde's supersonic jets were noisy and the noise suppression technology available in the aircraft industry had been found wanting, making the manufacturers search for new ideas and be receptive to the need for fundamental but directed research. The supersonic turbulent shear layers surrounding the propulsive jets were quite different from the simplistic models of turbulence used in the acoustic analogy, from which most conceptions of the problem were derived at that time. The exhaust flow was very hot and unsteady, containing the burning residue of the unburnt fuel. The strong compression and expansion waves set up at the nozzle exit created an axial grating of scatterers that make noise out of the travelling eddies as would a finger running over the teeth of a comb. The jet flow was swirling as it left the turbines and it was fast enough to generate sound waves very efficiently. The eddies moved supersonically making their own ballistic shock waves, or Mach waves. Reducing the jet noise without impairing jet thrust and the aeroplane's ability to climb was the target for the intensive research programme during which very many ideas were tested, but few of which held any possibility of producing the required suppression of more than 10 decibels with negligible thrust penalty. Engine flight tests revealed many aspects that ran counter to contemporary thinking. The noise ahead of the aircraft was just as big a problem as that behind, and tended to increase with increasing flight speed. The frequency spectrum changed in flight but not in a way consistent with Doppler shifts based on eddy convection or aircraft flight speed. It was very important to model the various source possibilities and to use the models with the flight experiments to get a better idea of where the principal noise was coming from, and to determine the sensitivity of the source, and the changes that might be made in the engines.

Crighton was a very useful member of the Concorde research team, into which he soon became completely integrated. He was the first to model effects of flight on diffraction processes, and his work was central to the understanding of what came to be known as the excess noise problem. The whole question of how flight effects might be anticipated, based on the results of static testing, was another major theme of his work. He got involved in highly idealized models to examine fundamental but crucial questions. It was far from clear whether or not the noise could be changed by stimulating the shear flow to alter the mixing process. It was not known then, and very probably not known today, whether increasing or reducing the rate of jet spread was desirable from a noise point of view. Bechert, at the University of Berlin, and Moore at Rolls Royce had independently discovered that seeding the jet with sound upstream of the nozzle could induce a coherent structure into the jet turbulence, and it was observed that that changed the jet noise. That property was soon modelled in studies that treated the main jet as a weakly disturbed laminar flow, whose instability waves were receptive to external seeding. Crighton showed how the instability might change in elliptically shaped jets, and indeed his results gave some clues to the superior performance of the fish-tail type of jets built into the production design.

Crighton's interest in nonlinear waves dates from this period also. The pure tones of the turbine that were heard near the engine suffered considerable spectral broadening while travelling to a distant observer. In part this was because the sound had to cross the turbulent interface in escaping from the jet, and in part it was due to atmospheric turbulence that scattered and broadened the spectrum of sound as it travelled. Also, though, the sounds were loud enough to experience nonlinear propagation effects.

Concorde's sonic boom was also distorted during its travel to the ground, both by turbulence in the atmosphere, and because of the real gas effects that give sound in air slight dispersive properties that show up over very long distances. Crighton was quick to learn from the considerable body of nonlinear wave work that had been done in response to the Navy's underwater needs, and he built on that work, continuing to produce new ideas right until the end.

The shielding of sound by stratified flow and by parts of an aircraft capable of forming acoustic shadows, was an obvious possibility that gave rise to theoretical modelling which helped to interpret strange experimental results that were both definite and significant. Ribner had long realised the importance of flow refraction in jet noise, but the difficulty of interpreting the Doppler effects of source motion raised new questions of which relative velocity was important: was it relative to the local flow or to the surrounding atmosphere? Crighton was one of many who worked on that problem, and his work was distinctive in meeting head-on the question of how to deal with instabilities of the basic flow. He succeeded in deriving from laminar flow models some convincing similarities with the deterministic features found in shear layer turbulence. By the early seventies there were several people who really understood the way sound interacts with stratified flow and also understood how helpful that knowledge was in interpreting jet noise experiments. My impression is that the differently focused current expertise has yet to improve on that position.

There was another quite separate form of practical contact that deeply influenced Crighton's work. While still at Imperial College he agreed to join in a project aimed at teaching modern analytical methods in acoustics to Admiralty scientists engaged on sonar work. Lecture notes were written in support of lectures, given one day a month over a twelve month period, to an audience containing scientists who knew much more about the problem that the lecturers did, and they provided very interesting feedback. The course was a very successful one in which lasting professional friendships were made. This rapidly moving advanced course found Crighton enjoying the lecturing experience just as much as he enjoyed research. He particularly enjoyed, and was very good at, explaining to interested experts the techniques and the results of mathematical analysis. His ability to help and communicate his ideas clearly to scientific professionals, so gaining their enthusiastic support, were probably his greatest career skills. Practical problems were brought to him and he really enjoyed helping to solve them. The Admiralty course was repeated several times and taken to scientific venues in Europe and to the USA, being given twice at Stanford, where again many good friends were made and fruitful collaborations were born. The course notes were eventually published in the book *Modern Methods in Analytical Acoustics*, a book containing six splendid chapters by Crighton on his favourite technical subjects.

David Crighton was a research assistant for seven years until 1974 when, out of the blue for him, he was appointed to succeed T. G. Cowling as Professor of Applied Mathematics at Leeds University. That was a brilliant appointment for both Crighton and the University.

Crighton threw all his energy into raising the profile of the Department and the morale of his staff. He involved his research students and colleagues on problems deriving from practical situations and he took a very active part in the national committees distributing research support and representing the teaching profession. He travelled a very great deal, earning international acclaim and growing into one of the best known figures in the profession. His leadership brought about a veritable transformation of the department. When he left Leeds eleven years later to succeed George Batchelor at Cambridge, he left a highly motivated team and a well-supported

FIGURE 3. David Crighton and Manfred Heckl seeing something much funnier than the others during Manfred's retirement celebration in Berlin. Hans Fernholz is paying attention also but I am far too grand to be amused!

and confident department. His research students thrived on his continued interest in the subject he had done so much to promote. The asymptotic solution of model equations in nonlinear acoustics, the nonlinear propagation of broad-band jet noise, models of feedback in shear layers, developments of the Korteweg–de Vries equation, spinning modes in turbulent jets, the vibration of fluid-loaded structures, wave propagation over large ranges, and asymptotic methods for simplifying calculations of propeller noise: all these were subjects he developed with his students at Leeds in a most productive phase of his career.

His eventual return to Cambridge was inevitable. He was the best possible choice for the Chair, which was considered by many to be the plum appointment in British applied mathematics. Once at Cambridge he devoted his energy to taking the Department of Applied Mathematics and Theoretical Physics to even greater heights. It had been fantastically successful ever since its foundation by George Batchelor who had given DAMTP an enviously distinctive place in history. When Keith Moffatt, who succeeded Batchelor, handed the reins over to Crighton the department was internationally admired for the quality and breadth of its work. But Crighton achieved at Cambridge much the same success he had enjoyed at Leeds. He brought to Cambridge the same inspiration and dedication to inspire colleagues and he led his Department to significant expansion. Crighton became recognised as a brilliant leader. He served on many of the most influential bodies affecting mathematical education and he chaired the Science and Engineering Research Council's Mathematics Committee. He brought to Cambridge a new determination to exploit the power of modern computers, and he

FIGURE 4. This picture of David and Ed Kerschen is a good illustration of how much fun meetings with David could be.

served as editor of both the *Proceedings of the Royal Society* and the *Journal of Fluid Mechanics*. He was President of the Institute of Mathematics and its Applications, President of the European Mechanics Society, and chaired the European Mechanics Council. He was extremely busy, but thrived on it. He never seemed short of time for his students, and he was the friendliest of colleagues, never losing the ability to recognise the strengths in people and making encouraging observations that bypassed problems.

At Cambridge he was chosen by Jesus College as their Master, an appointment that put him at the heart of the traditional structure that holds so much of the University's ability to attract the best students and deliver the individual attention that they find so stimulating. That gave him and his wife, Johanna, enormous pleasure. The Mastership required him to mix with students from all disciplines and, in particular, it gave him an opportunity to encourage the College's strong musical tradition. Crighton was an expert on Wagner and he was such a frequent presence at Bayreuth and wrote with such authority about the performances that Wagnerian enthusiasts could be forgiven for thinking music to be his primary interest and not mathematics. It certainly was a great interest, but applied mathematics and the waves of fluid mechanics interested him more.

Aeroacoustics today is quite a different subject from that which first captured Crighton's interest. Though noise control is important on environmental grounds, it is not nearly so excitingly important as it was in the sixties when the very existence of major aircraft and submarine projects depended on it. Three new developments are changing the perception of the subject. The enormous advance in computer power has made it possible to compute the solution to almost any well-defined problem in unsteady flow. Asking the right questions is much more important these days than answering them. Helicopter noise is one area where there has been great progress, a noise that is in the main caused by the deterministic motion of fluid around the rotating blades. The flow near the blade tips is complex and transonic, and provides an ideal application for modern CFD. Computational evaluation of the radiation integrals also allows knowledge of the local flows to be translated into accurate predictions of their radiated noise. This is a field in which it is now feasible to examine the acoustic performance of quite radically new designs. So, if quiet high-performance helicopter blades are possible, they can probably be found on the computer without going to the expense and trouble of testing them, and without exposing to general view the patently stupid ideas that are bound to be contained in the set of radically different arrangements that will be explored in searching for the genuinely quieter rotor.

Jet noise is quite a different story because it involves turbulence, still not understood enough to be sure that calculations of its noise mean very much. Of course it is possible to specify conditions within some computational box, and solve the intricate details of the Navier–Stokes equations within that box, the accuracy of the solution depending on the effort made by the programmer and the capacity of the computer. That the calculation is uncheckable might not be so important – but the inability of such computations to point to ways of making the flow quieter certainly is. There is still a very long way to go before CFD calculations of unsteady jet-like flows are convincing enough to form a useful means of exploring the radically different jets that might possibly be quieter.

The second major change that has come about is the realization that unsteady boundary conditions can actually affect the wave-making ability of flow. Large eddy structures in turbulence are definitely sensitive to boundary conditions and those large eddies may well be important sources of noise. There is still a very long way to go before that effect is understood well enough to become the basis of useful technology, but my guess is that one day it will. This is an area where the dynamics of weak disturbances to laminar shear flow bear an interesting analogy with the real case. How close that analogy is only time will tell, but it is very important indeed that it be explored, and the techniques for exploring it are very much those that Crighton pioneered.

The coupling between instability waves on diverging flows and the sound that they radiate into the surrounding atmosphere is a wonderfully rich source of research problems. Gone are the days when the quadrupole sources of aerodynamic sound could be reasonably regarded as given and incapable of receiving back-reaction from the sound. That view had been enormously helpful in understanding the low-speed jet noise problem, but that is a problem that has by now lost most of its interest: it is too noisy a flow to merit much further attention. Future emphasis should be on finding flows in which the noise sources are sensitive and for devising means of changing them. Deterministic models bearing a plausible similarity to real flows offer a much more direct way of exploring such possibilities than do direct simulations of the turbulent flows found in practice.

The third main development is the way that active control is changing the picture. Sound is essentially linear, and two sounds combine into sound which is the arithmetic sum of the individuals. If the pressure peaks of one sound coincide with the troughs of another, then the combination is quieter. When the second sound is deliberately constructed so that its troughs match the peaks of another exactly, that sound has become known as anti-sound, and the technology for active control of sound by this technique is very well advanced. The degree of suppression obtainable in this way depends on the accuracy with which the inverse of the principal sound can be reproduced at the right place and at the right time. Active cancellation seems to be feasible even for broad-band random noise, with twenty decibels of attenuation being quite practical. Far greater attenuation levels are achievable when active controllers are applied to silencing unstable flows. The broad-band noise of such flows comes from an instability wave that has grown till it is checked by the spectral-broadening nonlinear effects. A controller makes the flow linearly stable, so cutting off the input to the nonlinear noisy process and very great attenuation levels are then realized. Combustion-driven instabilities have been around for more than half a century, being a major problem in rocket motors and now providing one of the biggest current problems in large gas turbines. Models of these instabilities point to the importance of the linear instability that is inevitable when the unsteady sound pressure in a flame provokes unsteady burning which generates more in-phase unsteady pressure: an exponentially increased sound level is then inevitable.

Several successful applications of active control have already been reported and it does seem likely that it is a subject set to grow in importance. That is a good prospect because there are many techniques for approaching deterministic models of these unstable flows, so a reliable body of knowledge should be forthcoming: the technological importance of the subject is such that it is bound to attract the necessary funding. It may even be possible to change the fundamental properties of the high-speed shear layer to stabilize it and make it silent. That was the topic of many of my conversations with Crighton during the terminal phase of his illness. He was sceptical but really amused by my enthusiasm for the idea, and characteristically he was working hard on it and was actually reviewing the subject of active control of sound for the *Annual Review of Fluid Mechanics* just before he died.