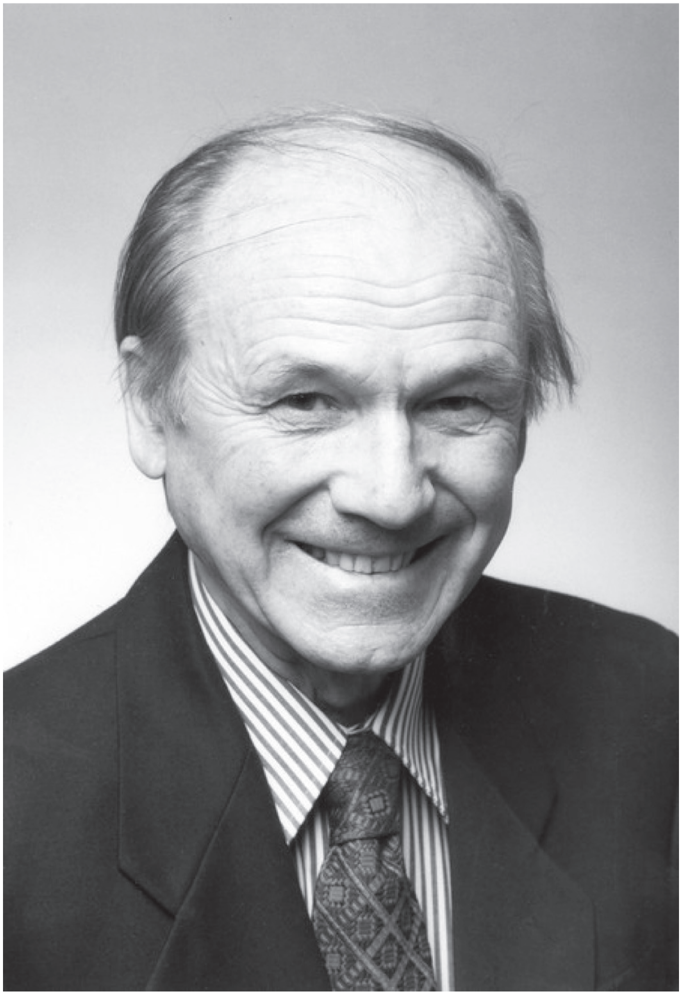

Anatol Roshko

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Anatol Roshko, 1923–2017

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Abstract

We present a brief account of Anatol Roshko's research and educational contributions to fluid mechanics, focusing on the spirit of his transformative ideas and legacy.

INTRODUCTION

Anatol Roshko, the Theodore von Kármán Professor Emeritus at the California Institute of Technology (Caltech), died on January 23, 2017, at the age of 93 at his home in Altadena, California, three miles north of the Caltech campus. Roshko was born on July 15, 1923, in Bellevue, Alberta, Canada. He received a Bachelor of Science degree in engineering physics from the University of Alberta in 1945, and after a brief tour in the Royal Canadian Artillery, he came to the Guggenheim Aeronautical Laboratories at the Caltech, which is now known as the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT). He earned his Master's (1947) and PhD (1952) degrees at Caltech and spent the rest of his professional career there, starting as a research fellow (1952–54) and continuing as a senior research fellow (1954–55). He was then appointed assistant professor (1955–58), associate professor (1958–62), and professor (1962–85). Roshko was named von Kármán Professor in 1985 and retired in 1994. From 1985 to 1987, he served as acting director of GALCIT.

An accomplished theorist, modeler, and experimentalist, Roshko made contributions to problems of separated flow, bluff body aerodynamics, shock wave–boundary layer interactions, shock tube technology, and the structure of turbulent shear flows. With his advisor, pioneering aerodynamics researcher Hans W. Liepmann, he coauthored the classic textbook *Elements of Gasdynamics* (Liepmann & Roshko 1957a), which became a worldwide resource (translated into Russian, Spanish, and Japanese) and has been used by generations of graduate students.

Roshko was a consultant to government laboratories and companies including the Office of Naval Research, McDonnell Douglas, Rockwell International, and General Motors. He helped organize the Wind Engineering Research Council and served on its executive board from 1970 to 1983.

Roshko was a member of the National Academy of Sciences and the National Academy of Engineering; a fellow of the American Academy of Arts and Sciences, the American Institute of Aeronautics and Astronautics (AIAA), the American Physical Society (APS), and the Canadian Aeronautics and Space Institute; and an honorary member of the Indian Academy of Sciences. His many awards include a Distinguished Alumni Award from the University of Alberta, the Reed Aeronautics Award and the Fluid Dynamics Award from the AIAA, the APS Fluid Dynamics Prize, and the Timoshenko Medal of the American Society of Mechanical Engineers (ASME).

In discussing Roshko's contributions to research and education, we cite several published papers but also refer to some documents that are not in the public domain. The latter include a collection of letters on the occasion of Roshko's retirement (Caltech 1995). They provide first-hand accounts of Roshko's impact on colleagues and testimonials from the past.

MAN WITH IDEAS

Roshko did not come from a privileged background. He grew up in the small city of Bellevue where his father worked in a coal mine. There were fifteen students in his high school's graduating class. Despite its small size and limited resources, Roshko praised its educational quality and his teachers: "Bellevue High School provided me with an excellent education in the basics, up to introductory calculus. The town was an ethnic pot, it was poor, everyone in it was poor, but the three high school teachers had University degrees!" (Roshko 1999, p. 431).

Fascinating insights into Roshko's ideas at the time can be gathered from his diaries, drawings, and even exam questions that he designed for himself. This material was graciously made available to us by his family. The exam titled "Air Trails—January 1937" (Roshko was 13) included the questions, "What are the four forces acting upon a plane in flight? Explain each," "What is the

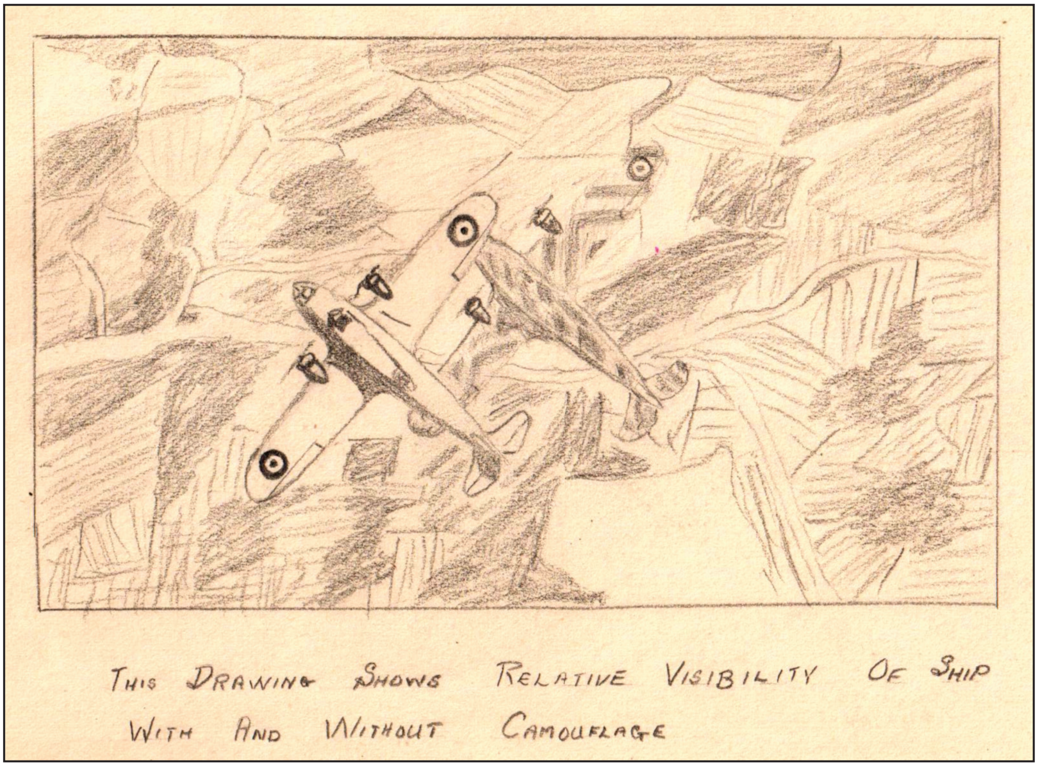

Figure 1

One of Anatol Roshko's drawings when he was a teenager.

angle of incidence?," "What is the angle of attack?," "Where is the center of pressure along the airfoil?," "Name the type of flaps; draw each one," and "What is the purpose of slots in airfoil?" Here we see the emergence of Roshko the educator. Several of his drawings, from around the same time, depicted aircraft of the Canadian Air Force. The one reproduced in **Figure 1** has the title, "This drawing shows relative visibility of ship with and without camouflage." It shows two twin-engine aircraft (possibly Bristol Beauforts), one standing out sharply against the ground and the other barely visible as its camouflage blends with the ground's patterns. This perhaps foretells the strong role that visualization would later play in Roshko's research. It also reveals an artistic side to the man, which was integral to many aspects of his career and life.

Roshko kept meticulous diaries in the early 1940s. With profound respect for his privacy, we feel that we can share certain passages that reveal some of the initial conditions that propelled him to such intellectual heights. The following excerpts are from January 2, 1942, when he was 18. They are reproduced as written, with only minor edits to punctuation for readability:

> Sure would be nice if I could just go wandering all over the world wherever I want, or else have a nice cabin way back "somewhere" where I could have all the time in the world to monkey around with something, build something, invent something; or else get behind the controls of some plane and tear around like mad—how right is that essay "Labor and Leisure"—the end of man is an action. Every time I think of it I wonder if I'm doing the right thing going to Varsity—always have the feeling that there's "something"??? I'd want to be doing, but darn it, what is it? That's why I think I'd rather take engineering than Physics. It seems more dynamic. Jeez, do I hate the thought of becoming a fat,

> middle-aged, conservative, "gentleman." And how I'd like to be something, do something startling—Columbus, Lindbergh. How easy it is now to see how far it is to the top. Before and after writing the Grade XII exams I thought how nice it would be to win one of the U.A. Matric scholarships but don't think I ever believed I had much chance of doing it. I really thought it would be an "ultimate" or something. But now I've got it, it doesn't seem like very much. Think now it would be nice to win the governor-general's gold medal at varsity but suppose that after, I would feel the same way about it. That's why I'd like to take Physics—maybe get the medal or even something like a Rhodes Scholarship or something (jeez what goofy thinking). Don't feel that I could ever really do anything in Physics, like think of a new theory or something, always think I could do more in aviation.

These passages, and the diaries as a whole, paint the picture of a gentle, caring, but unsettled spirit who was trying to grasp the big picture and his role in it and wanting to make a mark. His love of aeronautics, so evident by these writings, drawings, and exams, provided him with the answers that would eventually bring him to Caltech in 1945.

It was perhaps Roshko's modest roots that instilled in him a sense of economy in the way he approached research and education. He selected carefully a finite number of research problems of technological significance. He dissected them into layers, going after the physics with a passion for understanding. The use of nondimensional parameters is prevalent in his works, as is the role of flow visualization (Roshko 1992b). More generally, Roshko was interested in the big picture: nailing down the main drivers for the flow behavior and reducing the results in a form that would be practical. He was skeptical of preoccupations with things that he considered nonessential. A remark by Robert Breidenthal captures the influence of Roshko's approach: "Your indirect influence may be as strong as your direct scientific contributions. Largely due to you, flow visualization enjoys its present respectability.… It made it much easier for those of us following in your wake to attempt a similar approach, especially in the face of the current trend of the worship of complexity" (Caltech 1995, p. 18). Fred Browand added, "The choice of a suitable problem upon which to invest one's time is of the utmost importance, although most people seem to disregard this aspect of research.… Your problem selections have held up well over the years. Invariably, your selections are sufficiently limited in scope so that real progress in understanding can be achieved; yet, they are sufficiently fundamental so that new understanding will contribute to a host of related problems" (Caltech 1995, p. 21).

Roshko viewed the trend towards big, multi-investigator research consortia with wariness. In his acceptance speech for the ASME Timoshenko Medal titled "Small is Good," he said (Roshko 1999, p. 432),

> Also troubling is that bigness seems to be crowding out some of the culture that has served Applied Mechanics so well, i.e., the abstraction of well-posed scientific questions from important but messy practical ones (a phrase which I've borrowed from Garry Brown). As someone (Prandtl?) remarked, "there is nothing so practical as a sound scientific theory." It is idealized models, leading to analytical descriptions, that reveal the innermost workings of nature, and they help develop the "intuition" which engineers need to do their "dirty" work. This culture should not diminish; it is already small.

TEACHER, MENTOR

It may seem odd to start our discussion of Roshko's contributions with his role as an educator, but we feel that this is fitting his legacy and, more generally, the legacy of GALCIT. Roshko viewed education as integral to his mission and a cornerstone for excellence. His paper on GALCIT's contributions to education (Roshko 2002a) began with the sentences (p. 1), "The principal contribution of GALCIT has, of course, been its graduates. They have distinguished themselves in the aerospace industry, in academia, in government institutions and the military."

Roshko has educated and inspired generations of students through his teaching of graduate courses, notably Ae101 "Fluid Mechanics" and Ae204 "Technical Fluid Mechanics." Ae204 was developed with Donald Coles to provide students with foundational yet practical means to solve real-world turbulence problems. In "Small is Good," Roshko (1999, p. 432) wrote,

> Observing engineers solve tough technical problems, with imperfect technologies at their disposal, gave me a healthy respect and admiration for how they get their jobs done, and it often left me with feelings of inadequacy to help. I also realized how inadequate even our best students may be feeling as they stepped out into the real world. This led to the introduction, with Don Coles, of a new course in our curriculum, officially called Technical Fluid Mechanics but unofficially Dirty Fluid Mechanics, the kind you can't find in textbooks. This enabled us to pass on to our future engineers and researchers some extra help; at the same time it impacted our own research. . . .

Wilhelm Behrens (Caltech 1995, p. 8) recalled,

> I, for one, remember fondly the class I took from you called at the time "Dirty Fluid Mechanics". . . . It is quite remarkable how often one has to tackle problems that involve flow separation and reattachment, attached, semifree and free shear flows, usually in very complex geometries. Most of the time one cannot wait for lengthy numerical analyses, where you have to assume some turbulence model which may or may not apply. Then we fall back on methodologies you taught us, using relevant experimental data of generic classes of problems, similarity rules, and solving simplified, approximate equations, yet retaining the essence of the important physical mechanisms.

The book *Elements of Gasdynamics*, which Roshko coauthored with Hans W. Liepmann (Liepmann & Roshko 1957a), is widely considered to be the bible of compressible flow. There are many excellent textbooks in this field; what sets *Elements of Gasdynamics* apart, and makes it a classic, is the special rapport the authors develop with the reader. The book conveys something beyond technical expertise: the intimate relation, analytical and experimental, that the authors had developed with the subject matter, and their profound dedication to teaching this material to their students. The thoughtfulness of the exposition, clarity of the concepts, economy of writing, and superb exercises make this book a unique educational resource. Commenting on meeting Roshko at a conference in the mid-1960s, Albin Szewczyk recalled (Caltech 1995, p. 104), "I thought to myself not only had I met the author of this bible but also the guy who created the exercises at the end of the book that could be turned into theses and over which I had many a sleepless night."

As with his selection of research problems, Roshko chose a relatively moderate number of graduate students under his advisorship. The present authors are privileged to have belonged in this group. The relationship with Roshko extended beyond formal academic mentorship. He cared deeply about our wellbeing and treated us like family. For many of us, this extended into a lifelong friendship. Roshko's supervision was typically hands-off, giving general guidance but letting students develop their own intellectual independence. When the inevitable mistakes happened, Roshko would gently suggest the path to recovery. There was one central piece of advice: "You have to ask the right questions."

Roshko's program was adequately funded but not flush with money. He was not a "big operator." One of us (M.G.) remembers an occasion when, as a graduate student, he needed a water tunnel to complete his thesis about flow over cavities. There was no money to procure one, so Roshko challenged him to build one of his own. They sat down together and he helped M.G. with the design. It turned out so well that the tunnel was brought from JPL (Jet Propulsion Laboratory) to the subbasement of Kármán Laboratory, where it has been used for more PhD theses than any other tunnel in the aerospace laboratories at Caltech. Despite his economical way of approaching research, Roshko was a person of the highest generosity and selflessness. There were no bounds to the time, patience, support, and empathy he gave his students. His generosity extended to encouraging students to publish by themselves, without his name as a coauthor.

BLUFF BODY AERODYNAMICS

Roshko's love affair with the fluid mechanics of bluff bodies is ironically entangled with the topic of grid turbulence, a subject that Roshko neither showed interest in studying at the time nor pursued during his long and distinguished research career in fluid mechanics. At the time of his arrival at GALCIT in 1945, grid turbulence research in Hans Liepmann's group was still active but had shifted from its original objective of finding isotropy to other aspects of turbulent flows. The topic of isotropic turbulence was one of the main research assignments given to Liepmann by von Kármán, and it had occupied a large portion of his research efforts since his arrival at GALCIT in 1942. By the 1950s, Liepmann had concluded that isotropic turbulence was rarely found in nature and was too difficult to create in the laboratory; thus, most of Liepmann's students were assigned to study the more realistic and fascinating questions of turbulent shear flows (Narasimha et al. 2013). It was in this context that Roshko was assigned the task of finding out how much of the imprint of a wire mesh would remain in the turbulence as it evolved downstream of the grid-generated turbulence. Roshko started with a single wire and found the vortex wakes so fascinating that he never got beyond them (Narasimha et al. 2013). He quickly abandoned the initial grid turbulence aspect of his assignment.

Roshko obtained his PhD in 1952. The title of his thesis was "On the Development of Turbulent Wakes from Vortex Streets" (Roshko 1952). In this iconic piece of work, Roshko presented the first in-depth investigation of various flow regimes in the wake of circular cylinders at Reynolds numbers (Re) from 40 to 10,000. Almost all of his findings hold today just as he reported them more than 60 years ago. He divided the Reynolds number range of periodic shedding into a stable range of Re = 40–150, where vortex streets are formed and no turbulent motion is developed, and a second transition range of Re = 150–300, in which turbulent velocity fluctuations accompany the periodic formation of vortices. He correctly identified the laminar–turbulent transition in free shear layers, which emanates from the separation points on the cylinder as the source of turbulent velocity fluctuations. Roshko was the first to find that, in the stable range, the vortex street has a periodic spanwise structure. Perhaps the most remarkable finding in this work was the linear relationship between the Strouhal number and the Reynolds number in a range of Re = 60–2,000, a finding that he demonstrated by introducing a new dimensionless frequency, now known as the Roshko number (see Roshko 1954b, figure 10). Of utmost interest in this finding was his ability to successfully measure flow velocity using the Roshko number. This innovation was the subject of a US patent filed by himself and Hans Liepmann (Liepmann & Roshko 1957b). That patent is the basis for many of our current commercial flow metering devices.

In his early days at GALCIT, Roshko was also intrigued with Kirchhoff's free streamline model for flows with large separation as a means to break out of d'Alembert's paradox of zero-drag prediction for bluff bodies in ideal flows. The Kirchhoff model still grossly underestimated drag of bluff bodies in crossflows. He saw the potential improvement of Kirchhoff's free streamline model as a viable approach to obtaining a minimally empirical solution for the prediction of bluff body drag. Roshko had correctly identified that the main factors influencing base pressure and the resulting drag on bluff bodies were the velocity on the free streamline at separation (U_s), the width of the separated flow region, and the role of vortex dynamics in forming this region (Roshko 1954a, 1955a). This is how he arrived at a base pressure parameter that depended on the dynamics of the wake. He showed that, for a cylinder of a given cross-sectional shape, the drag coefficient C_D and the wake width were functions of his proposed base pressure parameter. He subsequently had the ingenious idea of using a splitter plate to cut off the communication between the two separated boundary layers in order to stop the vortex shedding and thus to create a steady-state base flow to test his proposed correction to Kirchhoff's model (Roshko 1954a, 1955a). Another important proposal from his 1955 work was the introduction of a universal Strouhal number based on the wake width and U_s, which he found to have a value of 0.16 for all cylinders.

Another pioneering contribution of Roshko was the investigation of cylinder drag and shedding frequency at very high Reynolds number (Roshko 1961). This involved a crash program shortly after the closing and before the dismantling of the Southern California Cooperative Wind Tunnel, a large pressurized facility (**Figure 2**). Reynolds numbers of up to 10^7 were achieved, compared to the highest value of 2×10^6 in wind tunnel measurements previously reported in the literature. Roshko discovered a high–Reynolds number transition in which C_D increases from its low supercritical value to a value of 0.7 at $Re = 3.5 \times 10^6$ and then becomes constant. He called this transition "transcritical." Additionally, for $Re > 3.5 \times 10^6$, definite vortex shedding occurs, with a Strouhal number of 0.27. Roshko attributed the increase in C_D, from the low supercritical value, to the separation point moving forward. He used his concept of universal Strouhal number to demonstrate that the wake width remains smaller than the cylinder diameter and that the vortex shedding is similar to that in the subcritical regime.

Figure 2

A high–Reynolds number experiment Anatol Roshko (*left*) conducted circa 1960 in the Southern California Cooperative Wind Tunnel before its dismantling. Image courtesy of the California Institute of Technology.

Two interesting continuations of his 1955 work are worth mentioning here. Roshko confided to M.G. that his work on Kirchhoff's free streamline model in conjunction with Riabouchinsky's (1926) closed cavity model prompted him to ponder a model for minimum drag for tandem bodies in crossflows. Keith Koenig's doctoral work on drag reduction methods for bluff bodies (Koenig & Roshko 1985) and Gharib et al.'s (1985) and Gharib & Roshko's (1987) works on axisymmetric cavity flows were results of suggestions made by Roshko with roots in his 1955 work, including his pioneering experiments on flow past rectangular cutouts (Roshko 1955b).

Roshko concluded that the relation of the drag coefficient to Reynolds number did not adequately reflect the actual sensitivity to Re. He correctly proposed a more revealing and fundamental approach based on changes of the base pressure coefficient, C_{pb}, with regard to the Reynolds number (Roshko & Fiszdon 1969, Williamson & Roshko 1990, Roshko 1993b). Roshko believed that the variation of C_{pb} with Re presented a formidable challenge for modeling across the whole Reynolds number range to the extent that, even with our current powerful computational capabilities, its numerical simulation would be difficult if not impossible.

Roshko's fascination with bluff body flows kept him engaged and dedicated to researching the various aspects of such flows. With John Cimbala and Hassan Nagib (Cimbala et al. 1988), he examined the persistence of Kármán vortices in the far wake of cylinders at $70 < \mathrm{Re} < 2{,}000$, which was the original objective of his own doctoral thesis. They discovered that Kármán vortices show a rapid decay followed by an intermittent growth and decay of lower-frequency (larger-scale) structures in the far wake. With Lorenz Sigurdson, Roshko investigated the effect of a periodic velocity perturbation on the separation bubble downstream of the sharp-edged blunt face of a circular cylinder aligned coaxially with the freestream (Sigurdson & Roshko 1988). They showed that the separation bubble could be considerably modified when forced at frequencies lower than the initial Kelvin–Helmholtz (K-H) frequencies of the free shear layer, and with associated vortex wavelengths comparable to the bubble height.

Flow–structure interaction was a topic that Roshko frequently visited through his consulting activities. However, his first serious attempt to investigate the role of frequency and amplitude of oscillations on the immediate wake region of circular cylinders started with Charles Williamson's postdoctoral work at GALCIT in the mid-1980s. Their work, elegantly summarized in an amplitude–wavelength plot (Williamson & Roshko 1988), depicted a comprehensive catalog of various vortex–body phase-locking modes they had observed along with other previous investigators. They also identified some critical wavelengths that, upon full synchronization, drastically changed the near-wake vorticity regions. They theorized that the modified vortex-pairing dynamics would have a major impact on the drag and lift forces on the body. Williamson & Roshko's work was limited to forced prescribed motions of cylinders. However, Roshko remained interested in this simple but fundamental question: Did their observed regimes apply to a free oscillation case? If so, they would be far more relevant for practical flow–structure issues. One fundamental issue that shaped his close collaboration with Anthony Leonard on the free oscillation of bodies that fluctuate in freestream was the question, What is the maximum attainable amplitude as one varies the parameters of the system? And what is the corresponding frequency of oscillation (Leonard & Roshko 2001; Shiels et al. 2001; Klamo et al. 2005, 2006)? More specifically, they were interested to see if there is a self-regulation mechanism that limits the range of amplitudes that these bodies would experience in their interaction with the near-wake vorticity field. It was Roshko's idea that the group investigate the case of zero mass, zero spring constant, and zero damping as a way of gaining insight into the latter question. Indeed, it was found by numerical simulation at $\mathrm{Re} = 100$ that the cylinder oscillated nearly sinusoidally at an amplitude of about one half the cylinder diameter and a frequency slightly lower than the Strouhal frequency of a fixed cylinder. (In this case, the fluid force on the cylinder had to be zero at all times, meaning that the force on the body due to the wake had to be exactly balanced by the added-mass force.) This finding, and the fact that some added spring constant produced higher amplitudes, ultimately led through several additional experimental and computational studies to the definition of a certain effective spring constant of about 2.5, which corresponds to a maximum amplitude over all parameters, including Reynolds number.

Roshko was also concerned about the effect of three-dimensionality on bluff body aerodynamics. He had suspected as early as 1954 that end effects, associated with aspect ratio, may impact the Strouhal number–Reynolds number relation (Roshko 1954b). He characterized such effects as extrinsic, and termed intrinsic the three-dimensionalities arising from natural instabilities (Roshko 1993b). Extrinsic and intrinsic three-dimensionalities can impact not just the shedding frequency but also the base pressure coefficient and, therefore, the drag coefficient. To isolate and understand the three-dimensional (3D) effects on flow around a cylinder, Roshko and colleagues compared experiments and 2D numerical simulations using vortex methods at Re = 5,000 (Chua et al. 1990). A striking result was that the drag coefficient of the 2D flow was $C_D = 3$, compared to $C_D = 2$ in the experiments. Roshko suggested that 3D effects cause a loss of spanwise phase coherence, resulting in a significantly lower base suction.

COMPRESSIBLE FLOWS

Shortly after joining Caltech, Roshko engaged in supersonic flow research by contributing to the design of a flexible nozzle for a small supersonic wind tunnel (Dhawan & Roshko 1951) that was implemented in the GALCIT supersonic wind tunnel. Soon thereafter, he participated in research to characterize the reflection of shock waves from boundary layers (Liepmann et al. 1951). This study brought to light the profound differences of shock reflection from a laminar versus a turbulent boundary layer. Roshko's first doctoral graduate student, Krishnamurty Karamcheti, studied acoustic radiation of high-speed air past rectangular cavities, thus extending the earlier low-speed work of Roshko (1955b). Karamcheti's PhD thesis included remarkable photographs revealing directional acoustic patterns (Karamcheti 1956). A key finding was that, for a given velocity, there is a minimum cavity width below which no sound emission occurs.

Roshko's first published works in compressible flow were motivated by the development in the early 1960s of the 17-inch shock tube at GALCIT for the study of rarefied gas dynamics. One of the challenges of operating shock tubes at low pressure is the severe decrease in flow duration, compared to the ideal situation, due to dissipative effects. Specifically, the thickening of the boundary layer results in a decrease in the distance between the shock front and the contact surface, resulting in a shorter run time. At the time, explanations for the phenomena were qualitative and estimates for the time loss were approximate at best. Roshko addressed this problem by developing an elegant analytical model for the laminar boundary layer development in the contact surface's frame of reference (Roshko 1960). He reduced the problem into similarity time and length parameters and developed an expression between the two that matched the experimental data. A maximum possible flow duration emerges from the analysis that increases linearly with the initial pressure and decreases strongly with shock Mach number. Roshko's engineering design skills became evident in the development of a novel device for bursting shock tube diaphragms. Instead of the common practice of scribing the diaphragm, which resulted in unpredictable bursting and lost pieces of the diaphragm, a cutter in a cruciform configuration slices the diaphragm in a leafing pattern and at precisely set pressures (Roshko & Baganoff 1961). Donald Baganoff, who worked on this project as a graduate student, recalled (Caltech 1995, p. 5), "I worked with [Roshko] on this problem using a makeshift setup on the roof of Guggenheim.

The noise that we made in bursting the test diaphragms and the disturbance that it must have caused on campus surely has not been exceeded since." Roshko's contributions were integrated into the design of the 17-inch shock tube, a world-class facility that was used by generations of researchers for at least four decades (Liepmann et al. 1962, Coles et al. 1969). Roshko was involved in extensive studies of the test time and its predictions by theoretical models (Roshko & Smith 1964).

An additional major thrust of Roshko's compressible flow work involved turbulent supersonic base flows, in conjunction with his consulting activity at the Douglas Aircraft Company. This was done in collaboration with Douglas engineer Gerald Thomke. Experiments were conducted in the Four-Foot Trisonic Wind Tunnel at Douglas Aerophysics Laboratory, a facility that enabled high unit Reynolds number. The focus was on understanding the turbulent reattachment region over a downstream-facing step, in particular, the relationship between base pressure and Mach number. Several challenges had prevented earlier studies from reaching a definitive conclusion, including uncertainty about the condition of the boundary layer and end effects of 2D models. The model tested in the Douglas tunnel was axisymmetric, which eliminated end effects, and its body was ducted (hollow), enabling a short distance from nose to step and resulting in a small boundary layer thickness compared to the step height. In addition, the large test section prevented wave reflections that could interfere with the wake. Roshko & Thomke (1966) measured surface pressure distributions throughout the region of separation and reattachment for several step heights and over Mach numbers from 2.0 to 4.5. One of the remarkable results was that the pressure distributions collapsed, for all step heights and Mach numbers, when plotted versus axial distance normalized by step height in the region of the steepest pressure rise, before the reattachment point. The scaling with step height suggested that the inner portion of the flow was influenced primarily by the linear growth of the separation shear layer. Downstream of the reattachment, the pressure distributions showed breaks that could be attributed to the interaction of the lip shock with the recompression shock. A follow-up study (Roshko & Thomke 1967) showed that the lip shock effect can be eliminated by boat-tailing the shoulder to alleviate the fast expansion there. The impact of these studies was aptly summarized by Mark Morkovin (Caltech 1995, p. 80): "Your results with Thomke on the local high heating in supersonic reattachment even influenced the local design of Martin Marietta's first maneuverable re-entry vehicle (the SV-5 in the Smithsonian)!"

The Douglas effort also encompassed the study of incipient separation in supersonic turbulent boundary layers and, in particular, the implementation of flare-induced separation (Roshko & Thomke 1976). Up to that time, there was a murky understanding of interaction length (the upstream distance from the corner where the pressure starts rising) and its dependence on the state of the boundary layer and Mach number, with no clear correlations. Following the philosophy of the earlier works, the design of a clean, elegant, well-defined experimental setup was instrumental in making significant inroads. Again, a hollow axisymmetric body was used, this time with compression corners formed by the attaching flares extending at a variety of angles. Simple scaling relations were developed for the interaction length as a function of the skin friction coefficient of the undisturbed boundary layer and the flare angle. These scaling relations, which involved a mix of physics and empiricism, correlated not only the present experimental results but also those of several previous studies.

When research funding dried up, the supersonic tunnel at GALCIT was decommissioned. Compressible flow remained an area of interest for Roshko, primarily in the context of mixing layers, which is covered in the next section. One of his last personal contributions was a short paper on maximum values of gas dynamic flux densities (Roshko 1993a), an analytical treatment whose simplicity and elegance would delight scholars of gas dynamics.

STRUCTURE OF TURBULENT SHEAR FLOWS

Roshko embarked on the study of mixing layers in the late 1960s, in collaboration with Garry Brown, who was then a research fellow at Caltech. A primary motivation was understanding the effect of Mach number on the shear layer spreading rate. It was generally agreed at the time that, in a single-stream shear layer, increasing the Mach number suppresses the spreading rate. However, quantitative and even qualitative agreement was lacking. The prevailing view was that the compressibility effect was connected to the increase in density (reduction in temperature) as the Mach number increases under adiabatic conditions.

To assess the effect of density at essentially incompressible conditions, Brown designed a unique shear layer facility, with optical access, in which variable density was achieved by using different gases, most often helium and nitrogen. Pressurization of the test section allowed for variation of the Reynolds number. Mean velocity was measured with Pitot and hot-wire probes, and mean density was measured with a novel aspirated probe (Brown & Rebollo 1972). As with the bluff body work, instantaneous visualization would play a key role and was implemented using a spark shadowgraph system. The first results from this experiment were presented in London in 1971, by invitation, at the AGARD (Advisory Group for Aerospace Research and Development) Conference on Turbulent Shear Flows (Brown & Roshko 1971). A central finding was that a large density difference had a relatively small effect on the spreading rate. In their concluding remarks, Brown & Roshko (1971, pp. 23–11) wrote, "A large, wave-like, structure, which increases in scale with distance from the origin of the shear layer is an essential feature of the uniform or variable density free shear layer at low Mach numbers." This statement would have profound consequences in the understanding of shear flow turbulence. The 1971 study was followed by the thesis work of Manuel Rebollo (Rebollo 1973), which generated a collection of shadowgraphs of astonishing detail, showing the persistence of vortical motions under a variety of Reynolds numbers, density ratios, velocity ratios, and pressure gradients. A related but somewhat distinct study by Davey & Roshko (1972) addressed the instability characteristics of variable-density shear layers composed of different freon gases and found overall agreement with the predictions of linear instability theory.

The findings from the shear layer experiments were consolidated in the paper by Brown & Roshko (1974), which is considered a milestone in the field of turbulence. The paper makes several seminal contributions, the foremost being that large-scale, essentially 2D, coherent structures are an inherent feature of the flow and persist at high Reynolds number. This discovery was the most astonishing to the authors, who stated (Brown & Roshko 1974, p. 782), "At first surprised to see such well defined structures, we attempted to eliminate them, looking for possible resonances, splitter plate, vibrations, etc., but none were found." The images of **Figure 3**, reproduced from Brown & Roshko (1974), show the persistence of coherent structures with increasing Reynolds number. As Roddam Narasimha remarked (Caltech 1995, p. 81), "Those pictures—whose significance dawned on me slowly after I left [Roshko]—have since become what surely must be among the most famous flow visualizations ever [.…] To say how greatly this work has influenced my own thinking would of course be trite, for it has profoundly affected everybody who works in turbulent flows."

Shadowgraph motion pictures allowed the tracking of eddies from frame to frame. The resulting spacetime trajectories indicated that the structures propagate with a fairly constant convective velocity U_c and, after a certain lifetime, amalgamate into larger eddies. Because of this interaction, the eddy spacing is not deterministic but has a distribution that peaks near $l = 3\delta_\omega$ for all the density ratios investigated, where δ_ω is the vorticity thickness. With regard to the shear layer growth rate, the paper provides physical insights into the correlation parameter

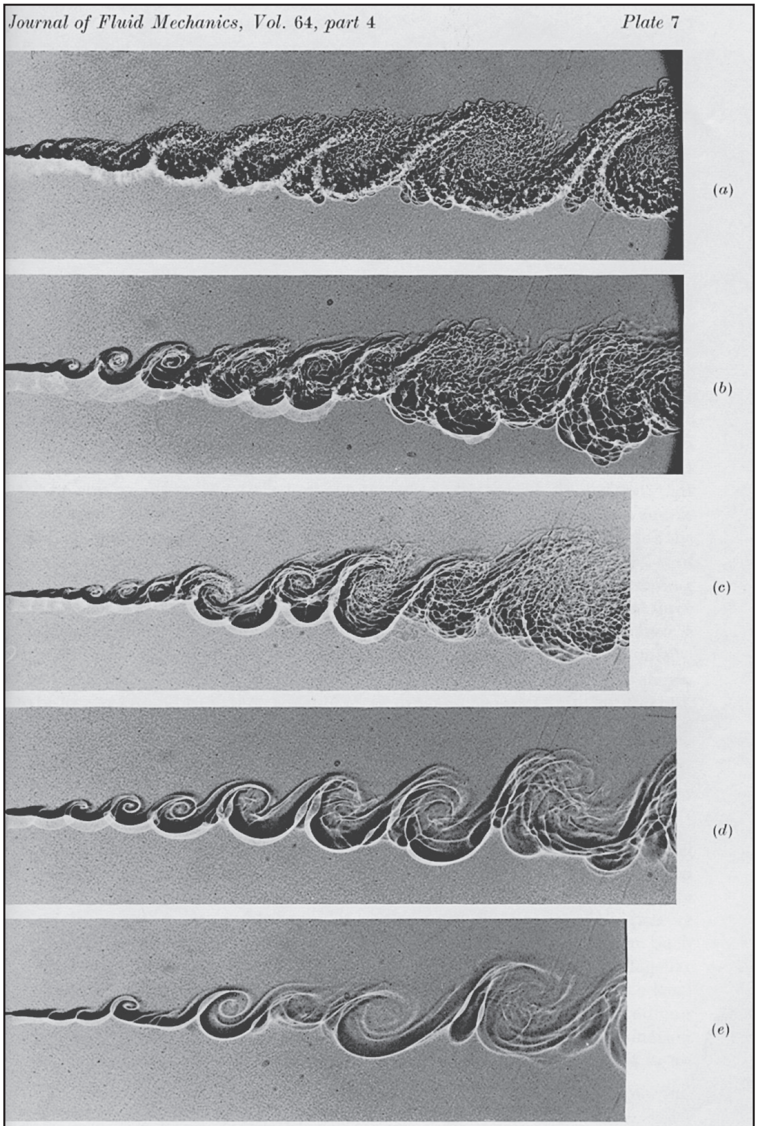

FIGURE 20. Effects of Reynolds number. Mixing layers between helium (upper) and nitrogen (lower) with $\rho_2 U_2^2 = \rho_1 U_1^2$. (a) Reynolds number is proportional to 8×10 (pressure = 8 atm, $U_1 = 10\,\mathrm{m\,s^{-1}}$); (b) 8×5; (c) 4×10; (d) 4×5; (e) 2×10.

Figure 3

The effect of Reynolds number on mixing between helium (*upper fluid*) and nitrogen (*lower fluid*) with equal dynamic pressures. Reynolds number increases by a factor of four from the bottom to the top image. Figure reprinted with permission from Brown & Roshko (1974).

$R = (U_1 - U_2)/(U_1 + U_2)$ proposed by Abramovich (1963) and Sabin (1965), where U_1 and U_2 are the fast and slow freestream velocities, respectively. The numerator (the velocity difference, ΔU) is interpreted as the temporal growth rate of an instability, while the denominator is related to the convection speed of the instability. This physical interpretation of R would serve well a few years later in the investigation of the effect of compressibility.

In his AIAA Dryden Research Lecture in 1976, Roshko presented eloquently the new view that had emerged from the GALCIT experiments (Roshko 1976). In the introduction, he stated (p. 1,349), "In recent years it has become increasingly evident that turbulent shear flows do contain structures or eddies whose description is more deterministic than had been thought, possessing identifiable characteristics, existing for significant lifetimes, and producing recognizable and important events." He stressed that the large organized structures are not affected by the small-scale turbulence at high Reynolds number, a theme that he would return to and refine in later years. He gave an insightful interpretation to axial space–time correlation by associating the correlation envelope to the probability that an eddy survives to a certain age. He described the entrainment process as an engulfing action of the large coherent eddies, whereby freestream, mostly irrotational, fluid is drawn in between vortices and ingested into the shear layer.

Shadowgraph views normal to the mixing plane revealed streamwise streaks at scales much smaller than the spanwise structure. A larger set of such visualizations in the same facility was performed by Konrad (1977), who proposed that, through their vortex stretching, the streamwise vortices form a mechanism by which the large spanwise structure becomes part of the cascade to small scales. The streamwise structures were found to be unstable above a critical Reynolds number, and this was associated with a rapid increase in molecular mixing. The term "mixing transition" was coined to describe this change. Nevertheless, the growth and development of the 2D large structures were basically unaffected by the streamwise structures. A reacting mixing layer experiment in a water tunnel by Breidenthal (1981) confirmed and quantified the phenomenon of mixing transition caused by the development of small-scale 3D motions in the flow. The results of the studies on streamwise structures, augmented by additional experiments, were integrated into a model by Bernal & Roshko (1986). In this model, the streamwise vortices originate from an internal instability of the main, spanwise vortices; they are not isolated but rather are "part of a warped vortex line threading its way up- and downstream between any two adjacent spanwise vortices, thus changing its streamwise directional sign on each pass" (Bernal & Roshko 1986, p. 521). Roshko (1991) elaborated on the complexity of mixing transition and distilled the findings of previous works with the goal of answering key questions, including the dependence on Reynolds number. Important insights were generated, but in his typical humility, Roshko concluded (p. 3), "The answers are tentative and incomplete." It is notable that Roshko also sought to understand the impact of large-scale structures on aero-optics. Wissler & Roshko (1992) used the Brown–Roshko apparatus to measure the deflection of a thin laser beam transmitted transversely through equal- and unequal-density mixing layers. Streamwise and spanwise deflections were found to be associated with the spanwise and streamwise structures, respectively.

The GALCIT shear layer work that started in the early 1970s is a fine example of the spirit of discovery and innovation fostered by Rosko and his collaborators. Motivated by the need to understand the effect of compressibility on shear layer spreading rate, the studies uncovered something of even wider impact. The benefit of flow visualization and, more generally, the focus on the big picture that Roshko advocated resulted in a totally new way to look at turbulence. Still, the effect of compressibility remained unresolved. The incompressible shear layer experiments showed conclusively that the density effect could not account for the large reduction in spreading rate seen in high-speed jets. In 1981 Roshko pursued an experimental program to address the instability of mixing layers with high compressibility. He selected D.P. for this project, who at the time was in his eighth month at GALCIT, as a Master's student, and had little idea about graduate research let alone turbulence. The initial plan, sketched sparsely on a single page by Roshko, was to study laminar-to-turbulent transition in supersonic shear layers. It was quickly realized that this would have required such low test section pressures that most diagnostics, including visualization, would be challenging. So, the focus shifted to understanding and modeling the spreading rate of supersonic mixing layers with a variety of freestream conditions, in analogy with the earlier incompressible experiments. A supersonic shear layer facility was designed and built that shared several elements of the Brown apparatus design: supply of dissimilar gases, variable geometry walls to adjust the pressure gradient, and windows for optical access. Several setbacks were encountered, including cracking of finely machined optical windows and inadvertent choking of the entire test section. Throughout, Roshko's calm encouragement and advice were central in moving the project forward. Initial spark schlieren images indicated layers barely growing with downstream distance. There was a definite large-scale turbulent structure, but it was not so defined as in the incompressible experiments. More quantitative measurements of growth rate were acquired by means of a small traversing Pitot probe. The resulting growth rate was correlated against the convective Mach number, $M_{c1} = (U_1 - U_c)/a_1$, that is, the Mach number of the fast freestream as seen in the frame of reference of the large-scale structure (or instability wave), which was an adaptation of a concept advanced by Bogdanoff (1983). The convective velocity U_c was defined based on the saddle point coherent structure model of Coles (1981), which requires equality of the total pressure in the convective frame. This results in M_{c1} and M_{c2} being equal or very close. Correlation of the growth rates versus M_{c1} resulted in a disappointing trend with no clear effect of compressibility. It became evident that several variables were changing at the same time: velocity ratio, density ratio, and M_{c1}. In an effort to isolate the effect of M_{c1}, the compressible growth rate was normalized by the incompressible value at the same density and velocity ratios. The formula for the incompressible growth rate followed the physical arguments of Brown & Roshko (1974) discussed above: $\delta \sim \Delta U/U_c$, where the Coles-inspired model for U_c accounted for the effects of both velocity ratio and density ratio. The normalized growth rate versus M_{c1} now showed a clear trend: a rapid reduction with increasing M_{c1}, flattening to around 0.2 for $M_{c1} > 1$. The normalized growth rate versus M_{c1} has since become the standard way to plot growth rates and has been used widely in experimental, computational, and theoretical investigations (Papamoschou & Roshko 1988).

In a series of papers and presentations in the 1990s and early 2000s, Roshko offered perspectives that unified and crystallized the findings of the GALCIT work on shear layers (Roshko 1992a, 2000, 2002b). These were followed by his last publication on this topic, with Garry Brown (Brown & Roshko 2012) bookending more than five decades of discovery (the collaboration with Brown extended to Roshko's very final days). In the following discussion, we summarize the principal ideas elucidated. The genesis of the turbulence is the K-H instability that develops when two parallel streams at different velocities come into contact. The resulting exponential growth of the velocity and vorticity perturbation thickens the mean velocity profile. A wave at fixed wavelength l finds itself developing in a mean flow of increasing thickness, δ; its growth rate will be cut off when δ/l reaches the neutral point on the amplification–wave number relation, at which point the wave has steepened into a vortical (coherent) structure. With increasing thickness, the shear layer becomes receptive to longer wavelengths, that is, larger structures. In a mean sense, the structures define the extent of the mixing region δ, and their evolution defines the growth rate $\mathrm{d}\delta/\mathrm{d}x$. The physical mechanism by which the coherent structures grow is amalgamation, which can take the form of pairing (primarily at low to moderate Reynolds number) or more generic merging (high Reynolds number). In incompressible flows, the pairing can be explained by the Biot–Savart law (Brown & Roshko 2012). While this generation and pairing of vortical structures had been seen in earlier works (Freymouth 1966, Winant & Browand 1974), these studies were done in the near field that is influenced by the initial conditions. The GALCIT experiments demonstrated that coherent structures persist in the far field, where the shear layer has lost memory of the initial conditions and depends only on global parameters: the fixed freestream conditions and the local thickness $\delta(x)$. The coherent structures thus "result from and exhibit the instability of the underlying, global mean flow" (Roshko 1992a, p. 8). Because in the far field there is no fixed, external reference scale, the large-scale structures are coherent but not deterministic. In particular, their spacing l has a distribution that Bernal (1988) has shown is lognormal. It is notable that the most probable wavelength, $l \approx 3\delta_\omega$, corresponds to the neutral point of the K-H amplification rate. Similar conclusions were drawn in Cimbala et al.'s (1988) study of the far wake. Dominant frequencies are associated with the neutral point on the amplification rate–wave number diagram. On the other hand, the far wake has a more pronounced 3D structure than does the shear layer; as a result, amalgamation processes in the wake are weaker and less definable than in the shear layer.

Roshko extended his research on turbulent structure to a more complicated geometry, the jet in crossflow (Fric & Roshko 1994). Flow visualization, combined with hot-wire measurements, again played a pivotal role in elucidating the flow physics. Smoke seeding and soap film flow enabled spectacular views of the turbulent structure on several planes. The origin and formation of the vortices in the wake were found to be fundamentally different from vortex shedding from solid bluff bodies. The flow around a transverse jet does not separate from the jet and does not shed vorticity into the wake. Instead, the wake vortices have their origins in the laminar boundary layer of the wall from which the jet issues. Roshko was also interested in the impact of large-scale structure on combustion, particularly on the liftoff height of turbulent jet flames. The study by Hammer & Roshko (2000) provides valuable insights on the relation between the local large-structure turbulence timescales and the oscillation of the liftoff height.

CONCLUSION

The present authors consider it a blessing to have been students of Anatol Roshko. For both of us, Roshko was a guiding star in our professional and personal lives. Our world is smaller without him, but his legacy will continue to inspire us and generations of engineers and scientists. We hope that this article makes a small contribution in this regard.

We would be remiss not to mention a person who had a profound influence on Roshko and was an inseparable part of the Anatol experience, his wife Aydeth. An accomplished sculptor, Aydeth Roshko would charm and delight anyone who ventured into Roshko's circle. International students, colleagues, and visiting researchers found hospitality and conviviality at the home of Anatol and Aydeth. She was a second mother to Caltech graduate students and their friends that passed through the threshold of the couple's home. Colleagues and students have fond memories of parties around the fireplace at Roshko's house and of hikes in the San Gabriel mountains above Altadena. Aydeth's passing in 2010 was devastating to Anatol; it was through his focus on science that he was able to recover, to the extent possible, from her loss.

In closing, we cite a passage in David Davenport's tribute to Roshko (Caltech 1995, p. 27):

> It might be said that for a person of Anatol's trim physique that the wake he leaves behind is much wider than bluff body theories would predict. His figurative, intellectual wake has washed up on students, researchers, wind engineers, aerodynamicists and beyond. His quiet spoken but reverberant statements on fluid mechanics have provided inspiring insights to many.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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