Professor Narasimha's contributions to fluid mechanics: a perspective

K.R. Sreenivasan
International Center for Theoretical Physics
Strada Costiera 11, 34014 Trieste, Italy

Extended Abstract

1. Introduction

Over the years, Professor Roddam Narasimha has played important roles, sometimes several of them at once. He has been on outstanding teacher, a world-class researcher, a dynamic leader [1], builder of institutions [2], and a person who has dispensed advice and wisdom to the highest circles [3]; his interests span education in a formal sense [4], history [5], philosophy [6], and so forth. His contributions in several of these spheres loom large, but, because of his modest style, it is hard to appreciate their extent unless one knows him well over a sustained period of time. A steady intellectual pursuit of his has been fluid mechanics, a subject to which he has contributed in various different ways. His published work [7], which forms the main topic of this brief article, is but a part of his overall contributions. The manner in which his research style captivated a number of his fellow workers [8], some of them his students, is nothing short of remarkable. That he never exercised that influence overtly, but did so largely by example and through unspoken moral authority, is a testimony to the natural element in which he finds himself as a mentor. He brought rigor and class to his research, and kindled similar aspirations lying dormant in others. For instance, after his return from Caltech, he initiated a number of his students and colleagues to the 'magic' of singular perturbation methods (among other subjects), especially with respect to the unclosed set of equations in turbulence [9]. That a world-class research effort has surrounded him without interruption for more than four decades, no matter how many diversions were pressed upon him, is in no small measure due to his tenacity, and to his tendency to hone the mastery of a subject by returning to it several times over [10]. He has influenced fluid dynamics research in India like no one before. Yet, his success is not "local" but one that measures well with the best elsewhere [11].

I was RN's student [12] at a time when many ideas were simmering in his group; some that took shape in later years were in gesticulation at the time. I have kept in touch with some of his work over the last thirty or so years, and so it seemed that I could write about it with relative ease. That was the plan. It has not turned out to be so. His work has covered a wide range, in most of which I cannot claim immediate expertise, and so the going has been slow. For this abstract, then, I shall do no more than state my intentions, which fall far short of expectations.

The main ingredients of his research are simple enough to list: transition between laminar and turbulent states [13], turbulent shear flows [14], and the shock structure [15]. He has worked seriously, and written eloquently, on many other problems that cannot be pigeonholed into these three, and so I should explain myself. Indeed, his work on the effects of surface curvature [16] and nonlinear vibration of strings [17] essentially established him as an independent research worker who could do first-rate work in what appeared at the time to be "Indian isolation". The paper on vibration is a class act in which one can see the stirrings of 'modern' ideas of nonlinear dynamics and chaos—for instance, Arnold tongues. RN did not pursue these ideas, and so did not reap the benefit of being a pioneer in those subjects. He did venture into chaos much later, and the work [18], though bearing his characteristic style, was not followed up beyond its immediate context. His attention was taken up by a number of problems such as flow control [19], transonic and supersonic flows [20], wind energy and rural technology [21], standard atmosphere for tropics [22], monsoon dynamics [23], inversion layer very near the ground (which he named the Ramdas layer [24]), reliability and maintenance of air fleet [25], and civil aviation in general [26]; all these subjects are richer today because he chose to work on them. But RN's contributions to the three subjects I mentioned earlier are more lasting and salutary because he pursued them with concentration and persistence. Perhaps with the exception of some atmospheric phenomena (see [22], [23] and [24]), he did not pursue the others with comparable vigor.

Below, I make a few cursory remarks about RN's work in these areas, leaving further expansion for the full paper. I will primarily discuss three papers, one in each category. My choice is purely personal: those were the first papers of RN that I myself read. They also represent, in my view, the best of his style: carefully analytical yet pragmatic at the same time.

2. Transition between laminar and turbulent states

RN started his research career on the transition to turbulence of a laminar boundary layer, for his Associates Thesis in the Aeronautics Department. The first two papers of [13] were the published outcome. The central theme of the work was transition intermittency, in particular the intermittency factor, γ, which is the fraction of time that the flow is turbulent-like at any point in the boundary layer. The thesis of the work was that, if one knew, in addition to γ, the transition Reynolds number—which is based on the length at which the laminar boundary layer breaks down—one could predict with good accuracy a number of boundary layer properties in the transition region. It was stated that other agents to which the transition phenomenon is susceptible play a minor role; for example, the effect of the boundary layer Reynolds number was regarded as subsumed mostly though the magnitude of transition Reynolds number. At the time, Emmons' turbulent spots had received attention, as was Schubauer & Klebanoff's later work at NBS; the concept of the intermittency factor was also well known. Emmons had already shown how the intermittency factor can be related to the so-called spot production function, $g(\mathbf{x};t)$, which is a measure of the density of spot production rate at a spatial position $\mathbf{x}$. But I believe it was RN that made a bold simplifying hypothesis on the spot-production rate, calculated the intermittency factor, and, in general, brought out its important role in transition.

The work had several clever ideas. First, the breakdown of the laminar flow in a boundary layer, which occurs randomly in time, was assumed to be localized and very nearly discontinuous along a line across the flow, i.e., g was a delta function centered around $x = x_t$. Using this idea, Narasimha (1957) (see [13]) was able to calculate the intermittency distribution in the boundary layer, and show that γ has a self-similar distribution—a marvelous achievement for anyone, especially for a beginner! Second, by hypothesizing that the boundary layer alternates between laminar and turbulent states, each at the appropriate Reynolds number, with γ representing the proportion of time spent in the turbulent state, Dhawan & Narasimha (1958), see [13], were able to calculate the mean velocity profiles and skin friction, and obtain analytical expressions for standard measures of the boundary layer thickness. It was also shown in this paper that the mean velocity profiles in the transition zone belong to a universal one-parameter family, with γ as the parameter. In addition to examining further consequences of these ideas, the paper ambitiously discussed the transition in supersonic boundary layers and contained a simple method for determining γ from Preston tube measurements.

Several interesting remarks of that paper have provided seeds for part of the transition work carried out subsequently in RN's group—for example, the effect of pressure gradients and the effects of relaxing the hypothesis of local breakdown.

RN made important contributions also to relaminarization, or the process by which a turbulent boundary layer undergoes transition to a laminar state. At the Indian Institute of Science, the work had its origin in the Ph.D. thesis of M.A. Badri Narayanan, a close collaborator of RN for many years, despite palpable differences in their styles. An important paper resulted from this work [M.A. Badri Narayanan, J. Fluid Mech. 31, 609-623 (1968)]. RN was involved in this work through numerous, and in the work that was reported in V. Ramjee's Ph.D. thesis [see M.A. Badri Narayanan & V. Ramjee, J. Fluid Mech. 35, 225-241 (1969)]. Soon, I took up the problem and coauthored a few papers with RN. He paid continuing attention to this subject through collaborations with P.R. Viswanath and A. Prabhu (see [12]). Without going into too many details here (because of my own connection to the subject), it should be said that it was RN who saw the best way to organize the myriad forms of relaminarization into a small number of themes. This helped us to understand the underlying unity of the subject.

3. Shock structure

I acquired some knowledge of Kinetic Theory of Gases in a course taught by S.M. Deshpande in Aeronautics, and of Statistical Mechanics in a course taught in Physics by A.S. Rajagopal. As I was preparing for research in that general area, one of the first papers I read was Narasimha (1968) of [15], on weak shocks; my particular research problem was to have been to tackle the structure of strong shocks.

What the paper teaches us is that whenever strict equilibrium does not obtain (which is almost always the case), the very fast molecules do not encounter collisions the same way as slow molecules do. They remain effectively in free-molecular flow (the effective Knudsen number for such molecules is high), so that the tails of the velocity distribution are not Maxwellian even when departures from equilibrium are small in some global sense, as in infinitesimally weak shocks. RN showed how the problem could be handled properly using the method of matched asymptotic expansions in which the small parameter is effectively the weak density jump across the shock. The inner solution is the classical Chapman-Enskog distribution determined by local parameters, and the outer solution, which is influenced by global conditions, contains long tails; these tails show an asymmetry between the upstream and downstream sides of the shock. An important result is that the fast molecules moving upstream towards the cold side present a precursor to the hot side. In this precursor region (which is far upstream of the shock in units of shock thickness), the rate at which equilibrium is approached is like $\exp[-|x|^m]$, where m is determined by some properties of intermolecular potential.

There are some similarities between this situation and the probability density function of velocity increments in the inertial range of hydrodynamic turbulence, but it is hard to take advantage of this similarity.

4. Fully turbulent state

RN's work with A. Prabhu on the modeling of distorted turbulent flows was a leap in simplicity: instead of detailed modeling of each term in the turbulent energy equation separately, this model subsumed them all by means of one relaxation term. By making a comparison between measurements and the computed results of the model, Prabhu showed that the model holds very well under fairly demanding situations. There were several directions in which the work could have progressed, such as introducing anisotropy of relaxation effects, connecting the relaxation times to the mean strain field, and so forth, but they were not taken up once Prabhu completed the thesis. It is astonishing that this simple idea, whose success in the kinetic theory of gases is well known, works as well as it does in highly distorted turbulence. Relaxation models have now been taken up again by others, especially because of the current interest in lattice Boltzmann methods, for which it is a natural step to take; in various modified forms, relaxation models work very well for rheological flows as well as Newtonian flows in very small apparatus (where slip effects can be important).

The paper I particularly wish to discuss now, also briefly, is the first on the list in [14]. This is perhaps the most cutting-edge paper on turbulence that came from RN's group. The Stanford work on bursting was published in 1967 (Kline et al., JFM **30**, 741). Its follow-up work by Kim, Kline & Reynolds was available as unpublished report in 1968 (and was later published in JFM **50**, 133, 1971). Preliminary results from RN's group were released in 1969 as one of the Aeronautics Department reports. In the JFM paper, the authors pushed forward the Stanford work in completely original ways that spanned a broad scope. On the one hand, the authors considered turbulent bursting, which they understood well to be an integral part of turbulent energy production; on the other hand, they continually attempted to link their findings to fine-scale intermittency. They seemed to be attempting to solve two key problems at once: turbulent energy production and dissipation. In the immediate sequel (the second paper in [14]), the authors appeared to have come to the conclusion that turbulence, produced in whatever form and in whichever flow, will remember its source, in so far as the interval between two successive events is of the order of a characteristic time of the large scale of turbulence—

but that it fast acquires a nearly universal form of spottiness that has little to do with its origin, and so is universal.

As has been remarked elsewhere [B.J. Cantwell, “Organized motion in turbulent flow”, Annu. Rev. Fluid Mech. **13**, 457-515 (1981)], what shocked the community and forced them to take notice of the paper was the finding that an essentially wall phenomenon, hitherto believed to scale with wall variables, was found to scale with outer variables. With some well-known exceptions, the community as a whole was not ready to accept it (it is unclear that it does so now, either), and curiosity soon led to controversy and division, and different types of results on the scaling of “bursting” began to appear: some supporting inner scaling, some supporting outer scaling, some extolling the virtues of mixed scaling, and some claiming no scaling at all! The fact appears to be that the phenomenon under consideration is sufficiently complex that not everyone was studying the same precise facets of it. The interpretation of the measurements was in itself not always immaculate.

While some specifics of the JFM paper have invited criticism of one sort or another, I think that there are two broad and lasting lessons to be learnt from it. First, some aspects of an inner phenomenon do depend on the outer scale. In a broader interpretation, this is the crux of anomalous scaling, which is now recognized as common in turbulence and other areas of condensed matter physics. Second, there is a certain virtue to discussing some turbulent phenomena in terms of “events” or “episodes” rather than merely in terms averages. In a larger sense, the emphasis on fractals and other descriptions of stochastic geometry attempt to do just that, albeit without invoking dynamics directly. In this sense, the paper brought about a qualitative change in our thinking of the subject.

5. Concluding remarks

It is hard to measure a person’s cumulative contributions in a hastily written essay such as this. RN’s students reflect them in some measure, and his influence will thus last for some time to come. I will close with a few words about his influence on me, personally. When I started working for RN, he drew me several times into little projects (e.g., collecting all existing data on the effects of free stream turbulence on the transition Reynolds number), and, through various discussions, deeply into the thesis works of Prabhu, Narahari Rao and others. The rich experience I had in working with him on sonic booms produced ten or so reports for the Department of Science and Technology. He allowed me to do anything I liked—experiment, theory or numerical work. At the end of some four or five years, I felt ready to tackle any problem; while that was no doubt to some degree a false supposition, that confidence has served me well. When my work on relaminarization had come to a stage, RN asked me to write up a draft. I argued that I had done nothing important and doubted if the work was worth publishing. A relatively long conversation with him taught me how to recognize the value of one’s own work. I cherish that tutorial. That, too, has served me well.

References and footnotes

[1] During RN’s tenure as Director of the National Aerospace Laboratory (1984-1993), he undertook many institutional changes that coincided with changes in governmental policies; as Director of the Institute for Advanced Studies since 1997, RN has overseen its transformation into a mature institution.

[2] Among other things, RN has been responsible for starting at the Indian Institute of Science the campus-wide seminar on Fluid Mechanics (the first speaker was Mack Head from Cambridge); and for getting off the ground the Asian Congress of Fluid Mechanics and the Center for Atmospheric Sciences as well as the journal Sadhana. He is the Founder- President of the Indian Society for Mathematical Modeling and Computer Simulation, and has served the Indian Academy of Sciences as its President.

[3] RN has served on various Boards of Directors such as Hindustan Aeronautics Limited, and as member of such important organizations such as the Defense Research and Development Council, the Scientific Advisory Committee to the Central Cabinet, the Space Commission, and the National Security Board. He has written valuable policy papers on Research and Development, Technology, Computing, Security, and so forth.

[4] His interest in higher education needs no special documentation. His interest in education formally can be witnessed in his support for Resonance, a monthly journal published since 1996 by the Indian Academy of Sciences. The journal carries articles in all areas of science aimed generally at the undergraduate level. He himself wrote an article for the first issue in 1996 on “Higher Education in India.” See also his article “Engineering Education”, Bulletin of Sciences, ??, 19-23 (1991).

[5] Aside from general history and that of the Indian subcontinent, RN has a keen sense of the history of science and technology. See, for example, his Millennium Essay, “Rocketing from the Galaxy Bazaar”, Nature 400, 123 (1999), in which he contrasts the technology available to the British and Tippu Sultan’s armies of the time, and how and why the disparity changed sign and grew over decades that followed. See also “Sines in terse verse - Coding large numbers in synthetic words made them easier to memorize”, Nature 414, 851 (2001).

[6] See, for example, his article “A metaphysics of living systems: the Yoga-Vasistha view”, J. Biosciences 27, 645-650 (2002).

[7] RN’s publication list contains close to 200 items, including conference proceedings. In addition, he edited more than a dozen books and conference proceedings, including the journal Sadhana for the years 19?? to 19??. He has published energetically even at the peak of “other distractions”. The largest number of papers per year has been about 10 (1996 and 1999).

[8] I count the number of RN's coauthors to be about 75. Not all his collaborators have actually published with him in scientific journals. Thus, the number of people who have actually worked with him is much larger.

[9] His lectures on singular perturbation methods, given in 1967, and integrated in a course on turbulence in 1970, served as a source of inspiration for a number of his students. I was a Master's student in 1970. Without taking anything away from the authors of the following outstanding papers, it could be said that they benefited much from RN's expertise and notes: K.S. Yajnik, "Asymptotic theory of turbulent shear flow", J. Fluid. Mech. 42 , 411-427 (1970); N. Afzal, "A higher order theory for compressible turbulent boundary layers at moderately large Reynolds number", J. Fluid Mech. 57**,** 1-25 (1973); N. Afzal & K.S. Yajnik, "Analysis of turbulent pipe and channel flows at moderately large Reynolds number", J. Fluid Mech. 61, 23-31 (1973). N. Afzal and RN collaborated on another important paper: N. Afzal & R. Narasimha, "Axisymmetric turbulent boundary layer along a circular cylinder at constant pressure", J. Fluid Mech. 74, 113-128 (1976).

[10] For instance, his first paper on transition was: R. Narasimha, "On the distribution of intermittency in the transition region of a boundary layer", J. Aero. Sci. 24, 711-712 (1957); his latest paper on transition, to the extent I am aware, is: R. Govindarajan & R. Narasimha, "Transition delay by surface heating: a zonal analysis for axisymmetric bodies", J. Fluid Mech. 439, 403-412 (2001). The time span covered is about 45 years.

[11] Very few are elected Members of the US National Academy of Sciences and of Engineering, Fellow of the Royal Society in UK, Fellow of the American Academy of Arts and Science, Fellow of the Third World Academy of Sciences---not to mention elections to all the academies within India.

[12] I wrote my thesis in 1974 and graduated in 1975. I started work on the structure of strong shocks, and was making good progress until I was asked, on the side, to look into relaminarization for a "few months". What I began on shock structure saw its fruition much later, although with no connection to my own earlier effort, in R. Narasimha & P. Das, "A spectral solution of the Boltzmann equation for the infinitely strong shocks", Phil. Trans. Roy. Soc. 330A 217-252 (1990). I grew up intimately with that of several others around me. For instance, I took part in the analysis of K. Narahari Rao's "bursting" data, and in making modest extensions of A. Prabhu's thesis work, which was all but completed when I joined RN's group. I was closely aware of the thesis work of V. Ramjee on relaminarization (also completed just about the time I started), that of S. Rajagopalan on the fine structure of turbulence (his stay overlapped with mine), and a host of ME projects on transition (see, for example, the third paper listed in the next footnote); among other things, several of these students took their initiation to hot-wire anemometry and laboratory from me.

[13] The principal papers are: R. Narasimha, "On the distribution of intermittency in the transition region of a boundary layer", J. Aero. Sci. 24, 711-712 (1957); S. Dhawan & R. Narasimha, "Some properties of boundary layer flow during transition from laminar to

turbulent motion”, J. Fluid Mech. 3, 418-437 (1958); R. Narasimha, K.J. Devasia, C. Gururarni & M.A. Badri Narayanan, “Transitional intermittency in boundary layers subjected to pressure gradient”, Experiments in Fluids, 2, 171-176 (1984); R. Narasimha, C.S. Subramanian & M.A. Badri Narayanan, “Turbulent spot growth in favorable pressure gradients”, AIAA J. 2, 837-839 (1984); R. Narasimha, “The laminar-turbulent transition zone in the boundary layer”, Prog. Aero. Sci. 22, 29-80 (1985); R. Narasimha & J. Dey, “Transition-zone models for two-dimensional boundary layers: A review”, Sadhana, 14, 93-120 (1989); J. Dey & R. Narasimha, “Integral method for the calculation of incompressible two-dimensional transitional boundary layers”, J. Aircraft 27, 859-865 (1990); R. Govindarajan & R. Narasimha, “The role of residual nonturbulent disturbances on transition onset in two-dimensional boundary layers”, J. Fluids Engg. 113, 147-149 (1991); J. Dey & R. Narasimha, “Effect of favorable pressure gradient on transitional spot formation rate”, Experimental Thermal and Fluid Sci. 4, 192-197 (1991); R. Narasimha, “A report on the workshop of end-stage transition”, Curr. Sci. 67, 6-9 (1994); R. Govindarajan & R. Narasimha, “Stability of spatially developing boundary layers in pressure gradients”, J. Fluid Mech. 300, 117-147 (1995); M. Jahanmiri, A. Prabhu & R. Narasimha, “Experimental studies of a distorted turbulent spot in a three-dimensional flow”, J. Fluid Mech. 329, 1-24 (1996). R. Govindarajan & R. Narasimha, “Transition delay by surface heating: a zonal analysis for axisymmetric bodies”, J. Fluid Mech. 439, 403-412 (2001).

RN’s attention in recent years has turned into formulating self-consistent equations for the stability of non-parallel flows. See, for example, R. Govindarajan & R. Narasimha, “A low-order theory for stability of non-parallel boundary layer flows”, Proc. Roy. Soc. 543A, 2537-2549 (1997); R. Govindarajan & R. Narasimha, “Low-order parabolic theory for 2D boundary-layer stability”, Phys. Fluids 11, 1449- 1458 (1999); R. Narasimha & R. Govindarajan, “Minimal composite equations and the stability of non-parallel flows”, Curr. Sci. 79, 730-740 (2000); R. Govindarajan & R. Narasimha, “Estimating amplitude ratios in boundary layer stability theory: a comparison between two approaches”, J. Fluid Mech. 439, 403-412 (2001).

There are several significant papers on relaminarization, the process by which turbulent flows are rendered laminar: R. Narasimha & K.R. Sreenivasan, “Relaminarization in highly accelerated turbulent boundary layers”, J. Fluid Mech. 61, 417-447 (1973); R. Narasimha & P.R. Viswanath, “Reverse transition at an expansion corner in supersonic flow”, AIAA J. 13, 693-695 (1975); P.R. Viswanath, R. Narasimha & A. Prabhu, “Visualization of relaminarizing flow”, J. Ind. Inst. Sci. 60, 159-165 (1978); R. Narasimha & K.R. Sreenivasan “Relaminarization of fluid flows”, Adv. Appl. Mech. 19, 221-301 (1979).

[14] The papers on turbulent bursting are: K. Narahari Rao, R. Narasimha & M.A. Badri Narayanan, “The ‘bursting’ phenomenon in a turbulent boundary layer”, J. Fluid Mech. 48, 339-352 (1971); M.A. Badri Narayanan, R. Narasimha & K. Narahari Rao, “Bursts in turbulent shear flow”, Proc. 5th Australsian Conf. Hydraulics and Fluid Mech., Melbourne, pp. 73-78 (1971); M.A. Badri Narayanan, S. Rajagopalan & R. Narasimha, “Experiments on the fine structure of turbulence”, J. Fluid Mech. 80, 237-257 (1977); R.

Narasimha & S.V. Kailas, “Turbulent bursts in the atmosphere”. Atmos. Environ. 24A, 1635-1645 (1990); S.V. Kailas & R. Narasimha, “Similarity in VITA-detected events in a nearly neutral atmospheric boundary layer”, Proc. Roy. Soc. 447, 211-222 (1994).

Other important papers on developed turbulence are: R. Narasimha & A. Prabhu, “Equilibrium and relaxation in turbulent flows”, J. Fluid Mech. 54, 1-17 (1972); A. Prabhu & R. Narasimha, “Turbulent non-equilibrium wakes”, J. Fluid Mech. 54, 19-38 (1972); K.R. Sreenivasan & R. Narasimha, “Rapid distortion of axisymmetric turbulence”, J. Fluid Mech. 84, 497-516 (1978); K.R. Sreenivasan & R. Narasimha, “Equilibrium parameters for two-dimensional turbulent wakes”, J. Fluids Engg. 104, 167-170 (1982); R. Narasimha, “The turbulence problem—a survey”, J. Ind. Inst. Sci. 61A, 1-59 (1983); K.R. Sreenivasan, A. Prabhu & R. Narasimha, “Zero-crossings in turbulent signals”, J. Fluid Mech. 137, 251-272 (1983); G.S. Bhat & R. Narasimha, “A volumetrically heated jet: large-eddy structure and entrainment characteristics”, J. Fluid Mech. 325, 303-330 (1996); A.J. Basu & R. Narasimha, “Direct numerical simulation of turbulent flows with cloud-like off-source heating”, J. Fluid Mech. 385, 199-228 (1999).

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[17] R. Narasimha, “Nonlinear vibration of an elastic string”, J. Sound and Vibration 8, 134-146 (1968).

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