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Book Review

Self-Sustaining Mechanisms of Wall Turbulence

R. L. Panton (Ed.), Computational Mechanics, Inc., Billerica, MA, 1997, 422 pp., $134.00

For many years, boundary-layer turbulence was considered to be a random phenomenon. However, in the past few decades, important progress has been made, and now it is believed that this turbulence is not entirely random. There are orderly turbulence regeneration processes in play, but they are masked by a noisy background. This book is concerned with this line of development and reports the current status. The discovery of the orderliness is significant because it opened the door to a rational approach to turbulence control and the development of structure-based turbulence closure models. In particular, this book is concerned with one of the fundamental questions of turbulence, namely, What is the regeneration mechanism of wall turbulence? The answer would impact practical issues such as better models of wall turbulence closure, the quieting of wall turbulence, and drag reduction. This will improve our understanding of the structure of high-Reynolds-number wall-turbulence and the effects of roughness, which are related issues. In turn, this knowledge will allow a rational bridging of the gap between low-Reynolds-number laboratory testing and high-Reynolds-number, full-scale vehicle application. To emphasize, the aim is that such an understanding will lead to a rational approach to design and turbulence control. This book should be viewed with this technological potential in mind.

Focus on the question of the regeneration mechanism can be traced back to the work of Townsend.[1] Much has been learned since then. Clearly, the editor is seeking to determine the current status of our understanding. However, he has preferred to limit his role largely to the choice of contributors. Their regeneration models are invaluable distillations of knowledge gained over a lifelong devotion to the subject. The papers probably have not gone through an orthodox review process, but the quality is uniformly high. A good part of the materials in the papers, although not all, has appeared in archival journals. The editor recognizes the subject to be wide open and leaves the possibility in the title that there may be more than one mechanism in play. However, because the subject is still open, the editor has allowed the authors to air some of their personal opinions and tentative proposals. Young researchers thus would need to read the book with some caution.

The book is meant for potential and active researchers. It is too advanced for undergraduate students and too "frontier-like" for industry applications. One gets a reasonable assessment of the status of our knowledge. However, there are a few more supplementary and complementary views that are missing. Names like Benney, Black, Brown, Chong, Dinkelacker, Hama, Kronauer, Lumley, Narasimha, Perry, Morrison, and Willmarth come to mind, and there are others. They have views on the self-sustaining mechanism somewhat different from those aired in the book.

The mechanism knowledge base contained in the book is slanted toward low-Reynolds-numbers physics, drawn from either visualization experiments or direct numerical simulations (DNSs). Thus, the structural description presented makes little distinction between a large structure and a small structure. The question arises as to how relevant these mechanisms are as the turbulence spectrum widens at higher Reynolds numbers: Would the wave nature of low-Reynolds-number, near-wall turbulence be relevant when it is excited by outer layer "noise" at higher Reynolds numbers? Morrison et al.[2] warned us about this nearly 30 years ago. It is not comforting that the papers remain silent on their remarks. This probably signifies the fact that the focus of the subject has not moved to high Reynolds numbers, and difficulties remain.

The views aired in the papers are frequently based on structure-identification techniques that are subjective in nature. Examples are flow visualization, conditional sampling techniques of VITA (variable interval time averaging) applied to hot-wire anemometry and VISA (variable interval space averaging) applied to the DNS database, and various vortex identification techniques also applied to the DNS database. They involve interpretation of momentum transfer from mass transfer or user-biased threshold settings. Although the major overviews of the mechanism are primarily based on flow visualization, the *quantification effort is mostly aimed at quantifying the subjectivity*. It is very important for the reader to realize that the methods resorted to in the papers are still far from being objective and user independent. This is because no good stability theory that describes the repetitive breakdown process exists. The rational foundation of the threshold settings can come only from such theories. The reader thus needs to be aware that the subject of the book is a controversial one. Theoretical development of the subject is badly needed.

However, not all structure identification techniques are subjective. If a statistically stationary result is sought, then techniques of correlation and triple moments are available, and they are objective. Odd-powered moments retain the sign of fluctuations, and a combination of variables can be used to accurately determine structures. Yet there is no paper in the book that makes use of these techniques. Townsend's roller eddies, which may have started our interest in coherent structures in turbulent boundary layers, were obtained by the technique of correlation. Head and Bandyopadhyay's[3] description of the turbulent boundary layer as a jungle of hairpin vortices and Brown and Thomas's[4] description of large structures at higher Reynolds numbers were also derived by studying the correlation of signatures of hot-wire rakes. Yet there are notable papers in the book (Chapter 1) that deride this technique, and the reader should treat such comments with reservation. Correlation techniques, when applied in a physically meaningful manner, remain objective and extremely powerful.

Although the book is supposed to cover mechanisms, it dwells mostly on structures that result from the breakdown of the near-wall vorticity. The subject of breakdown of the mean flow vorticity is covered little and relegated to the latter part of the book. Does this mean that, although more important, the instability mechanisms presented in the latter part of the book are relatively soft and must await a more rigorous scrutiny, perhaps experimentally, before they can be deemed well established? The subject of instability clearly emerges from the book as the most important area of future research on regeneration mechanisms.

We will now discuss the individual papers. There is one paper in the book that probably has not appeared in any form before. It is the first chapter and is authored by Kline, who played a key role in establishing that wall turbulence is not a random phenomenon but is partially deterministic. Thus, his firsthand description of the history of the subject has a special significance. This is not a complete account; there are important omissions. For example, Hama's discovery of wall streaks, Head and Bandyopadhyay's demonstration of the hairpin vortices and their Reynolds number effects, Brown and Thomas's discovery of the 18-deg large structures at high Reynolds numbers, and Perry and Chong[5] and Bandyopadhyay and Balasubramanian's[6] structural models are not mentioned. But the paper does give a glimpse of Kline's philosophy of research. He seems to have always built on his own personal laboratory observations. The paper shows how he was wrestling to form a sensible, simple, and yet complete picture of the mechanism based on those observations. This may also have been his last paper and clearly is of historical value.

Smith and Walker, in Chapter 2, have synthesized low-Reynolds-number results from their own visualization experiments and DNS simulations to arrive at a conceptual model of the hairpin vortex regeneration process. Because of the low-Reynolds-number emphasis, the model shows a domination of overturning in the outer layer. The outer layer is seen as a graveyard of vortices, and the dynamics is thought to be inner layer dominated. This contrasts with high-Reynolds-number-based models where the outer layer, or a combination of inner and outer layer, is thought to dominate the regeneration process. For the regeneration process, Smith and Walker assign key roles to vortex deformation and their interaction. The role of mean flow instability is not detailed.

The role of mean flow instability is envisaged clearly by Blackwelder in the next paper (Chapter 3). He gives a near-wall model of the regeneration process. The near-wall region is seen to be populated with counter-rotating longitudinal vortex pairs that reside in a strong mean shear. The velocity profile abounds with inflections in the surface-normal and spanwise directions, and its breakdown leads to turbulence generation.

In Chapter 4, Bernard and Wallace also assign the key role of turbulence regeneration to the omnipresent streamwise near-wall vortices. They do not discuss the role of the mean flow explicitly. Instead they propose that, when the "necessary local conditions prevail," existing vortices cause the generation of new vortices that are of the opposite sign. The key regeneration question in the self-sustaining mechanism of wall turbulence is, What is that necessary condition? The subject badly needs theoretical development.

In the next paper (Chapter 5), Hanratty and Papavassiliou present a somewhat incomplete model where both inner and outer layers are thought to provide relevant scales to the regeneration mechanism. The role of the inner layer is clear. The near-wall longitudinal eddies account for the Reynolds stress. They explain the exchange of momentum between the low-speed inner region and the high-speed outer region. The role of the outer layer, however, is not clarified by the channel flow studies. A lack of clarity of the role of the outer layer can be seen in many of the papers. This is probably not just because most of the knowledge base reported in the book is derived from low-Reynolds-number studies but also because they are conducted in channels. Future high-Reynolds-number studies conducted in turbulent boundary layers are expected to help.

The high-Reynolds-number regeneration process is explicitly studied by Zhou et al. (Chapter 6) and by Klewicki (Chapter 7). The former authors have done so in laboratory flows, whereas the latter has studied particularly atmospheric boundary layers. Zhou et al. have combined PIV (particle image velocimetry) diagnostics with simulation to study the regeneration process. They have confirmed the existence of the 18-deg large structures observed statistically by Brown and Thomas and individually by Head and Bandyopadhyay at higher Reynolds numbers. These structures are the envelopes of arrays of hairpin vortices forming periodically and represent the play of a nonlinear breakdown process of the vorticity-rich sublayer. Because their existence was predicted, the observation of Zhou et al. brings the regeneration theory of Black[7] back into focus. This theory is not discussed by the papers in the book. These large structures are not observed in the low-Reynolds-number experimental and DNS studies. Therefore, they signify an important departure of the regeneration process at higher Reynolds numbers where the outer layer is not dominated by overturning. Furthermore, Zhou et al.'s simulation study shows that there is a critical level of hairpin strength relative to the mean flow, above which it only regenerates itself. If this result guides the development of a theory of the regeneration process, then the subject will become truly objective, and a strong scientific footing will be established.

The fact that low-Reynolds-number structural descriptions should be extrapolated to high Reynolds numbers only very carefully is also borne out by Klewicki's study. At an extremely high Reynolds number (4×10^6, based on momentum thickness and freestream speed), 80% of the near-wall streaks appear in pairs, whereas they generally appear singly in low-Reynolds-number DNS simulations.

There are 16 chapters in the book. The next, which is the eighth chapter and was written by Kline and Portela, again returns the regeneration subject to low-Reynolds-number studies. It also denotes the transition of the book from an experiment-derived knowledge base to a simulation-derived knowledge base. The authors believe that they have "a relatively complete description of the kinematics of the flow." However, they offer no explanation for the large standard of deviation of the elements of the kinematics. Why is there such randomness even though the Reynolds number is so low? The authors' description is based on the low-Reynolds-number DNS simulation study of Robinson. This description contains asymmetric open vortices away from the wall, and no satisfactory explanation is offered as to how this can be valid or whether this a low-Reynolds-number feature. Cantwell et al. and Schoppa and Hussain, in two later chapters, have questioned the objectivity of the vortex identification method of Robinson. The former authors have found new objective variables for vortex identification. However, their physical meaning is unclear. The latter authors, on the other hand, have claimed improved *quantification of the subjectivity* in vortex identification. Interestingly, they claim to identify vortex structures that are different from Robinson's. Note also that, at higher Reynolds numbers, Klewicki has observed 80% of the near-wall vortices to be symmetric. When viewed in conjunction with the other chapters in the book, the low-Reynolds-number, DNS-based kinematic description of Kline and Portela is certainly far from universal.

In Chapter 9, Antonia and Djenidi have looked at the regeneration process by comparing smooth and rough walls. This may be a useful approach because, at very high Reynolds numbers, all practical surfaces on aircraft or submarines are rough. The authors believe that the active motion is nonuniversal. This raises a serious question of the relevance of a low-Reynolds-number, smooth-wall regeneration mechanism to high-Reynolds-number flows.

In the next chapter (Chapter 10), Meng has attempted to distill our understanding of organized structures with a clear motivation to control it. He proposes a Markov chain to link probabilistically the principal events of the regeneration cycle. Because near-wall length and timescales diminish with increasing Reynolds number, such a scheme will be complicated at high Reynolds numbers. A theoretical simulation study of the Markov process needs to be carried out, and this will give a foundation that his approach requires.

Rather than chasing eddies, Sreenivasan and Sahay in Chapter 11 have addressed the core issue, namely, the instability process of the mean velocity profile that self-sustains wall turbulence and leads to the formation of coherent eddies. In pipe and channel flows, where the mean velocity profile is self-similar, they have examined the relationship between the shape of the mean velocity profile and the Reynolds number variation of the location of the peak Reynolds stress. They conclude that a critical layer is located at this position. The value of this work may be that the location and properties of this layer provide a clear target for the design of turbulence control actuators.

Most researchers have taken a direct approach to uncovering the self-sustaining mechanism. They describe the boundary-layer statistics, structures, or dynamics exactly as they exist. However, some have taken a reverse approach in the spirit of "what if" questions. This involves a structural or dynamic system modeling. Herein, either the statistical properties of the turbulent boundary layer are reproduced from model structures or the dynamics are simulated and it is shown that it reproduces the principal unsteady features of the near-wall streaks or the sweep and ejection motions. These reverse approaches tend to verify our understanding gained from the direct approach and can also be a tool for new insight. In the next chapter (Chapter 12), Nadine has looked at the dynamics of the reproduction process from the latter point of view. An important result is that the flow is organized into families of modes. The value of this result is that it provides a rational scheme for closed-loop control.

In the past, several mechanisms have been proposed to explain the repetitive formation of wall streaks. They are a Goertler instability or a nonlinear resonance between Orr–Sommerfeld and Squire modes. Waleffe and Kim (Chapter 13) and Schoppa and Hussain (Chapter 16) have examined the DNS database of a transitional low-Reynolds-number Couette and channel flow to discover the pristine breakdown process. They believe that this is an extremely organized, periodic, Kelvin–Helmholtz-type instability mechanism.

In Chapter 14, Sirovich has reviewed his past computational simulation studies on the dynamics of the self-sustaining process in a channel flow. He has identified two clear phases in the cycle: the appearance of organized streamwise rolls, followed by the emergence of disorganized waves. An important computational check of this result is also mentioned. When a small set of the waves is subjected to an artificial phase randomization, a drag reduction as large as 50% is achieved. Such tantalizing results increase the appeal of mechanism research. But a reality check is in order. In a turbulent boundary layer, when Tani[8] and, later on, Sirovich himself examined the effects of random sand-grain roughness, they observed a riblet-like drag reduction of only about 7%. The question then is, Why does the experimental turbulent-boundary-layer-drag-reduction result fall so far short of the simulated channel flow result?

Finally, we come to Chapter 15, authored by Cantwell et al. (The final chapter, by Schoppa and Hussain, has already been discussed.) These authors have been concerned by the threshold setting involved in Robinson's and others' DNS and experimental works on vortex identification. They have correctly recognized that objectivity is essential for true scientific progress and there is a dire need to find an objective basis for vortex identification that is unambiguous and involves no threshold setting. They use their knowledge of vortex morphology and show that certain scalar measures of the velocity gradient field give us an unambiguous and coordinate-independent tool for vortex identification. The criteria also seem very general, that is, independent of pressure gradients, Reynolds number, boundary conditions, and compressibility. Such theoretical objective criteria now need to be implemented in the experimental diagnostics.

The authors have distilled their many years of passionate research into short papers, and the many lists of references in the various papers in the book will be useful to readers. The reader would also clearly benefit from the individual papers but will also gain by trying to synthesize these seemingly disparate papers. Such a synthesis does not exist in print today, but the qualitative consensus with regard to structures and instability seems to be converging to the analytical theory of Black. A quantitative synthesis will help pave the way for application of the knowledge base.

One of the problems with research on the wall turbulence mechanism has been, What do we do with the knowledge? This is where this book can have the most impact. It perhaps should be used to chart the direction of future research. If we understand the mechanism, then we should be able to compute numbers with it, and we should be able to control the phenomena. Structural modeling of wall turbulence, particularly for roughness at high Reynolds numbers, is an area worth exploring. This might allow us to replace the traditional approach of sand-grain roughness by a more rational approach and would be very valuable to high-Reynolds-number modeling, where all surfaces are actually rough. The other area where this book should be useful is in charting the course of a rational approach to drag reduction and the suppression of wall-pressure fluctuations for quieting of turbulence-induced noise. Closed-loop control is the only approach that is rational and has a high payoff potential. We need to develop drag-reduction schemes that utilize the knowledge base given in the book.

A few words of caution are pertinent if we seek to extrapolate and apply the knowledge to achieve drag reduction. The research on this subject of self-sustaining mechanisms has sometimes been likened to the proverbial drunk looking for the lost coin under the street lamp. Our overwhelming occupation with low Reynolds numbers is clearly analogous. Experimental investigations have repeatedly indicated that low-Reynolds-number flows are notoriously environment dependent. We should not ignore the difficulty that was experienced in extrapolating low-Reynolds-number LEBU (large eddy break-up) drag-reduction schemes to higher Reynolds numbers. We should also remember how laboratory laminar heating schemes of transition delay were rudely exposed in real ocean water, which is dirty, and how laminar flow control over an entire aircraft is still eluding us. Thus, if new researchers are to apply our knowledge of self-sustaining mechanisms to the drag reduction of aircraft or submarines, they need to apply a great deal of filtering. But with increasing concern for oil supplies, nuclear disposal issues, and the environmental impact of population and technology, there is a mounting need to direct future research on the mechanism of turbulence production toward drag reduction at high Reynolds numbers. This book will prove useful in that endeavor.

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