

BOOK REVIEWS

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Thermoacoustics: A Unifying Perspective for Some Engines and Refrigerators

G. W. Swift

Acoustical Society of America, American Institute of Physics Press, New York, 2002.

*xi+300 pp. +CD-ROM: \$70 (softcover), \$50 for ASA members
ISBN: 0-7354-0065-2.*

"I am thrilled by the power density and efficiency recently achieved by thermoacoustic engines and refrigerators, and I am fascinated by some of the latest developments in thermoacoustics."

With that sentence, Dr. G. W. Swift begins a textbook that employs 21st century pedagogical tools to introduce students and researchers to a 21st century technology. In addition to a logical and complete development of this multidisciplinary subject, the 300-page textbook includes a CD-ROM with computerized animations and DELTAE software, with its own 200-page manual in searchable PDF format.

In many ways this textbook represents a milestone in the literature of acoustics. Unlike Swift's excellent 1988 review paper, "Thermoacoustic engines," published in this Journal [84(4), 1145–1180], this textbook is destined to become the gateway by which many trained both inside and outside the acoustics community can enter this fascinating and challenging field. Swift's use of computer animations as an integral part of the text is sure to become more common in this century. These are not just pretty "moving pictures." I consider myself to be quite well-versed in the physics of the oscillatory thermoviscous boundary layer, but I was pleased with the new insights I gained just by watching his "Lagrangian marker" whip through the viscous medium like a limp linguine in a sea of thick minestrone. The more complex animations can be an even richer source of intuitive insights. Certainly, forsaking the wave equation in favor of an approach more closely tied to the fundamental conservation equations, and consistent with the DELTAE software solution of complex quasi-one-dimensional acoustical networks, brings a fresh perspective that should be of interest to all of us who teach classes in acoustics. At the very least, a textbook that is independent of the software, yet consistent with it, provides a new (and welcome!) bridge between concept and computation.

Swift makes his ambitious goals clear from the start: He attempts to interweave the physical, the mathematical, and the intuitive into a coherent picture that supports his claim that thermoacoustics describes "a mental framework, not a class of devices." The thermoacoustic paradigm abandons the 19th century crankshaft-based technology used to enforce control of gas motion in today's engines and refrigerators. Instead, it relies on oscillating pressure gradients to produce oscillatory gas motion, and on the oscillating gas motion to produce oscillatory pressure gradients. This "circularity" is inherently challenging, but it is also both fascinating in concept and elegant in its execution.

Swift's first chapter provides a short historical overview, presents some very basic concepts whose understanding is significantly enhanced by computer animations, and introduces the four examples that are used throughout the text to apply the thermoacoustic principles. He chooses two engines and two refrigerators, produced over the past ten years in his laboratory, to provide physical dimensions and to compare the results of the calculations to *actual measured performance* as the theory is developed.

Most of the audience for this book might have expertise in either the material contained in Chap. 2 or 3, but rarely would a reader new to thermoacoustics begin reading with a mastery of both. Chapter 2 provides background, nomenclature, and useful results from thermodynamics, hydrodynamics, and the transport properties of ideal gases. Chapter 3 introduces the concept of the simple harmonic oscillator and the use of complex numbers to describe oscillatory phenomena. That concept is then applied to a gas spring and one-dimensional wave propagation.

These first 68 pages set the tone for subsequent chapters and provide the first 50 relevant (and clever!) homework problems. These problems serve the goals of the text by providing the dedicated reader with guidance to the derivation of some of the results; they tie concepts to experience (What is the displacement and adiabatic temperature variation caused by ordinary speech?); and they broaden the application of the concepts (How deeply should water pipes be buried where you live?) beyond thermoacoustics.

Chapters 4–7 elucidate the theoretical framework that Swift has developed to establish his unifying perspective. He credits the pioneering work of Nikolaus Rott for development of the correct expressions for the acoustics and time-averaged energy transport within a channel that might also sustain a temperature gradient, but in Chap. 4, Swift eschews the wave equation for a coupled set of first-order differential equations that are represented by his "five-parameter thermoacoustic impedance model."

The coupled first-order approach has two advantages: The first is that it maintains an immediate connection between the five lumped parameters and the fundamental principles of the mass conservation (the continuity equation), momentum conservation (the Navier–Stokes equation), and energy conservation. The second advantage is that this approach is consistent with the operation of the differential equation solver that is the kernel of the DELTAE software and the structure of the complex pressure, complex volume velocity, and temperature boundary conditions between the "segments" that define each DELTAE model.

The lumped elements of that model are displayed on the book's front cover and a phasor representation is used to illustrate the acoustical effects of those elements. The thermoviscous functions, f_ν and f_κ , are introduced to keep track of the important viscous and thermal-relaxation effects and to quantify the behavior of Swift's "fifth element:" the current-controlled current source that is responsible for the production of useful work or refrigeration in thermoacoustic devices.

Chapter 5 addresses the central concept of power in thermoacoustic systems. Swift starts with a careful analysis of the mechanical power transported by the sound field. He then points out that the total power, represented by the enthalpy flux, is the conserved quantity that is of utmost importance in the application of the First Law of thermodynamics to acoustic systems that can exchange heat with external sources and sinks. Overall evaluation of the performance of such complex systems is addressed in Chap. 6 with the introduction of the concepts of lost work and entropy generation. The exergy function is then used to provide the self-consistent accounting scheme for energy production, dissipation, and transport that can take place at a variety of different temperatures within a single device. To this reviewer's best knowledge, this is the first time that such a comprehensive analysis of the energetics has appeared in either the thermoacoustic or the Stirling engine literature.

In earlier drafts of this text, Chap. 7 was entitled "Thermoconfustics." Unlike the previous chapters, Chap. 7, now entitled "Beyond Rott's Thermoacoustics," transcends the formal techniques of hydrodynamics, thermo-

dynamics, and acoustics and attempts to address important issues that arise at high Reynolds number, in tortuous porous media, and when second-order effects like streaming and shock formation are significant. In many ways, this chapter is the most interesting because it provides insight into how a scientist of Swift's caliber can make progress by using dimensionless groups (similitude) and by piecing together knowledge from other disciplines to calculate useful results, even when a fundamental understanding or adequate computational techniques are unavailable.

Under these circumstances, Swift exposes another important component of the philosophy that has made him the world's acknowledged leader in the field: "Given today's imperfect foundation, additional approximations are useful whenever they improve computational ease dramatically while only slightly reducing accuracy." Although he demonstrates that this philosophy can produce substantial progress, he warns his readers that such an approach "will not find a dramatically improved point-of-view, no matter how interesting or important that might potentially be." I would argue that the progress that his "approximate" approach enables has led him to develop many of the "dramatically improved points-of-view" that he provides in this textbook.

The final two chapters deal with the details of thermoacoustic hardware and the strategies for measurement of acoustic and thermal performance of complete devices. The "Hardware" chapter covers ideal gases, stacks and regenerators, heat exchangers, resonators, buffer tubes, and electroacoustic transducers. The high-quality photographs of actual thermoacoustic components are an essential complement to the fairly brief discussion provided in the text. The 170 references allow the reader to fill in many of the missing details and provide an excellent bibliography for most of the important work in this field.

The last chapter on "Measurements" goes well beyond the "mechanics" of building adjustable acoustic loads and making accurate determinations of acoustic pressure, power, and heat flows. He suggests "confidence building experiments" in the early stages of testing your new apparatus. Make the easy measurements and compare them with your expectations to insure that the basic design is correct and that your sensors and signal-conditioning electronics are calibrated and functioning properly.

In this important chapter, Swift addresses how the experimentalist's point-of-view can influence how those measurements are interpreted as well as the experimental design that a particular point-of-view will dictate. His discussion is again philosophical, and is brought to a very practical level by his generous use of concrete examples that illustrate each experimental philosophy based again on the four examples. The final illustration of the "thermoacoustic" point-of-view is a wonderful excursion into the interplay of direct physical measurements and the interpretation and interpolation of those measurements made possible through the intelligent use of the DELTAE software.

Again, the end-of-chapter "homework" problems included in these last two chapters are worthy of special note. They distill two decades of experience with the design and testing of thermoacoustic hardware. They include topics from order-of-magnitude estimates of forces on stacks and the flutter of NiCr heater ribbon, to the energy released by exploding pressure vessels (resonators). The measurement exercises go from mundane, but important, calculations regarding the cutoff frequency of signal conditioning electronics to exercises that include sample experimental data from a device that did not function as designed and requires the reader to provide "analysis and action plan toward diagnosis of this unfortunate situation."

The text closes with two appendices. The first, entitled "Common Pitfalls," is only a page and a half in length, but warns the neophyte of such ubiquitous failings as "computer intoxication," "unrealistic optimism," "multi-vendor gridlock," and the tendency to avoid the real challenges. Among Swift's words of advice: "Attack the hard problems early, whether they are technical or personnel, and address them immediately."

The second appendix includes the DELTAE files for the four examples that are used throughout the text. In conjunction with the software manual contained as a searchable PDF file on the CD-ROM, the DELTAE software has become the "language of thermoacoustics." The software and the software manual are co-authored with William Ward, one of Swift's long-time collaborators at Los Alamos. Anyone who masters this software can look at DELTAE "output" file and appreciate the most intricate details of any device and also gain nearly telepathic access to the mindset of its designer.

Although the DELTAE software and its manual are worthy of a separate review, a few more comments here are justifiable. The software interprets a

sequence of "segments." Each segment represents one component, from a simple straight or conical duct, to a variety of heat exchangers, stacks, and regenerators. All physical properties of the segments are expressed in MKS units. The software is a one-dimensional differential equation "solver" and it is **extremely fast**. My research group's most complicated file contains 37 segments and runs in under one second! The challenge in its application is making the determination of which results should be "targets" that the solver will try to match and which variables are to be used as "guesses" that the solver will be allowed to vary. The solver seeks to minimize the "length" of the error vector that measures the difference between the targets and their targeted values. That important selection of an equal number of "guesses" and "targets" is aided by the "thermoacoustic point-of-view" that is described explicitly in Chap. 9, but which permeates the entire text.

Two particularly interesting "segments" are THERMOPHYSICAL and RPNTARGET. The THERMOPHYSICAL segment provides thermo-physical properties for a range of gases, gas mixtures, and solids used in the models. Each segment uses the output of THERMOPHYSICAL internally, but it is also available as an independent "segment" in the model or as a convenient freestanding electronic "handbook" of thermodynamic and transport properties.

The RPNTARGET is a mathematical segment that lets the user easily calculate any quantity of interest using the "reverse polish notation" made popular by Hewlett-Packard calculators. It can take results from previous segments, manipulate them using trigonometric functions and complex arithmetic, and then make the results of the calculation available for use in other segments and by the solver as a "target." I find the flexibility of the RPNTARGET provides an important tool for letting the software calculate useful performance parameters, but its real value is its ability to let the user introduce new physics into a model that is not a "canned" function already within DELTAE.

The Reference chapter of the manual is essentially a review of the current state-of-the-art in thermoacoustic modeling. It provides algebraic representations of the algorithms used by the program for calculation of heat exchanger performance, thermoviscous functions for various geometries, energy flow through regenerators, as well as the more mundane calculations of the compliance of a volume or the solution of the wave equation in a conical horn.

One caution: the DELTAE software is not particularly "user friendly." I use the version that runs under DOS and has none of the convenience features of contemporary softwares such as pull-down menus, multiple windows, etc. The MAC version has those features. The ability to "scroll" through the window is much nicer than unidirectional output available under DOS. If you think you will ignore the text and manual and just run DELTAE like a video game, you will be instantly disappointed.

On the other hand, DELTAE does provide features that were clearly meant to satisfy the needs of eternally impatient experimentalists that go well beyond just the use of MKS units. For example, the BLOCKDATA segment makes it easy to import experimental results allowing direct comparison between the measurements and the model results. There is a provision to generate tabulations of results as two variables are allowed to step through user selectable limits. No provisions are made for graphical display of the results but the resulting files (header and data) can be exported to the user's favorite plotting software.

The design of DELTAE was motivated by the need to analyze electroacoustic systems with geometrically complicated gas-filled components, all of which might be at different temperatures and made of different materials. In the proper hands, the utility of DELTAE to the acoustics community should go well beyond thermoacoustics. I have used it to analyze the radiated power spectrum of Brüel & Kjaer Type 4295 OmniSource that was designed by Jean-Dominique Polack. Professor Polack wrote a finite-element code containing dozens of segments to tune the modal frequencies of the source to the values necessary to satisfy the standards for omnidirectional sound sources [ISO 140 and ISO 3382]. Using the physical dimensions provided, I made a seven-segment DELTAE file with a VESPEAKER segment representing the electrodynamic speaker at one end, a PISTBRANCH segment to apply the radiation condition at the other end, and an ISOCONE segment between the two. DELTAE quickly produced modal frequencies that agreed with Polack's results in air at room temperature to within $\pm 0.2\%$. I suspect that the use of DELTAE for design of acoustical networks like engine mufflers that sustain significant temperature gradients and contain porous media like catalytic converter ceramic substrates would be equally rewarding.

Much has been learned about thermoacoustics in the 14 years between publication of the 1988 review article and the publication of this textbook. Swift and his co-workers have again generated almost all of that improved understanding through a novel series of clever experiments and the publications generated by those experiments. Although there is still much to be learned, and many clever devices to be built and tested, thermoacoustics has evolved to a level where it now has significant commercial potential in addition to providing intellectual challenges for the rigorous education of acoustics graduate students and faculty, as it has done so well over the past two decades. The complete and systematic exposition of thermoacoustic theory and experimental technique in this new textbook should make Swift's understanding accessible to a far wider group of scientists and engineers who can go on to exploit that understanding and produce practical devices while contributing to the extension of that understanding by bringing their expertise from outside "acoustics" into thermoacoustics.

Only time will tell whether Swift's vision of a future populated by rooftop thermoacoustic heat pumps, thermoacoustic gas liquefiers and separators on offshore oil rigs and behind every hospital, and thermoacoustic refrigerators and air conditioners on sale in the appliance sections of major retail outlets will become a reality. There is no question about whether this highly original textbook and the unlimited availability of the DELTAE software will go a long way toward making that vision a reality. For many of us who had the pleasure of reading the earlier drafts posted on the Los Alamos web site and using earlier versions of DELTAE, it already has.

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Music and Technology in the Twentieth Century

Hans-Joachim Braun (Editor)

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256 pp. Price: \$24.95 (hardcover) ISBN: 0801868858.*

This is a collection of papers originally presented in a two-day session on *Technology and Music*, part of the 23rd Symposium of the International Committee for the History of Technology (ICOHTEC), which took place in Budapest in August 1996. To anyone even distantly interested in the subject, these papers make interesting, sometimes even fascinating, reading.

The very fact that we distinguish various "periods" in the history of Western music indicates that there never was a time when this musical culture was not changing. There is no question, however, that the twentieth century saw a great acceleration of this process, to the point where the duration of what we denote as a "period" is often measured in years, perhaps even months, rather than centuries. This acceleration is closely tied to the rapid technological advances that took place at that time, together with (in the words of editor Hans-Joachim Braun) "the problematic identification of technical change with musical progress."

It seems to me that, in all musical cultures and at all times, the process of composition has had to deal with two opposing needs: the need to be understood, in other words to compose in a language that is known to the listener, and the need to be original, in other words continually to violate the rules of that language. Without the first, a composition is unintelligible; without the second, it is boring. What characterized the twentieth century in particular was an exponential growth of the second need at the expense of the first; that is, of originality at the expense of intelligibility. Although this tendency can sometimes be discerned in contemporary music produced by traditional means, it surely comes into its own in the frantic technological search for new sounds, new tonalities, and new timbres as well as electronic modifications of old ones.

To set an appropriate backdrop, the book contains a number of excellent papers of historical narrative: on the growth of a particular Cleveland recording studio, by Susan Schmidt Horning; on the background of the 45 rpm record, by Alexander B. Magoun; on the history of tape recording, by Andre Millard; on the development of the synthesizer, by Trevor Pinch and Frank Trocco; on the role of the Yamaha Company, by Tatsuya Kobayashi; and on labor relations in the music industry, by James P. Kraft. But having read those, I found the real excitement in the chapters that dealt with the philosophies expressed by the people who themselves populated twentieth-century music, that is, with the thinking that led them to do the things that they did.

In this category is "A Servile Imitation: Disputes about Machines in Music, 1910–1930," by Karin Bijsterveld. Here we are, of course, dealing with the early part of the century, when the quest to "enrich the musical alphabet" by, for example, forming orchestras consisting of assorted noise machines instead of limiting oneself to the "dull" palette of strings and winds, was gathering momentum. At the same time, the technique of recording music was making giant strides, and some people were worrying that mechanically (or, later, electronically) played-back music would lose the live quality (what Walter Benjamin called the "aura") of a real concert. Yet the same techniques, somewhat modified, also made it possible to play music that was otherwise, due (for example) to tempo or unusual pitches, unplayable by a human being.

The paper "Soundsampling: An Aesthetic Challenge," by Helga de la Motte-Haber, addresses the aesthetic development of the whole century, including (toward its end) the accessibility of modern computers. It was, of course, inherent in the exponential growth of the quest for originality at the expense of intelligibility that, sooner or later, a brick wall would be encountered; in this case it was the very dramatic fact that, with a modern computer, *any sound, or combination of sounds, can be produced as easily as any other*. What started out in the beginning of the century as a drive to enrich the palette of available sounds now found itself trapped in the paradox that writing music, in the sense of realizing one's musical ideas, is now infinitely easy—but to have those ideas in the first place is infinitely hard. The challenge, it suddenly seemed, was to find a way, not to increase one's palette but (on the contrary) to diminish it.

One possible, but in my opinion limited, way out of the paradox is treated in the paper "New Technology—New Artistic Genres," by Martha Brech. She describes various ways of making sound in combination with other stimuli, for example sound-producing devices with which the listeners interact, or "sound installations" that have a number of loudspeakers deployed in a specific space of some complexity so that the sensation of the audience extends to the acoustic and visual events interacting with each other. Insofar as these events are unpredictable (for example, because they depend on the actions of other members of the audience), the fact that a modern computer can so easily produce any programmable sound becomes less important since these sounds are not, strictly speaking, programmable. On the other hand, I find it implausible to expect that such an arrangement, which in effect removes the composition of the sound from the hands of its nominal composer, can long satisfy those urges which lead a person to want to compose in the first place.

The book is not, of course, without its shortcomings, but that is mostly unavoidable in a work with such a multiplicity of authors. Naturally, too, some papers are weaker than others, but I hesitate to go into disparaging detail when the book as a whole is so thoroughly worthwhile. One fact that I did find puzzling, however, is that neither Pierre Boulez, nor IRCAM (the very successful institute that he founded in Paris in 1970 for exploring precisely the coordination of technology and music), receives any mention at all.

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