This short article gives a description of DeltaE's original public release in 1994, before mixture separation and superimposed steady flow were included.

Design Environment for Low-amplitude Thermoacoustic Engines

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ABSTRACT

In thermoacoustic engines, and in many simple acoustic systems, a one-dimensional wave equation determines the spatial dependence of the acoustic pressure and velocity. Design Environment for Low-amplitude Thermoacoustic Engines (DELTAE) is a computer program that integrates such wave equations in the acoustic approximation, in gases or liquids, in user-defined geometries. Boundary conditions can include conventional acoustic boundary conditions of geometry and impedance, as well as temperature and thermal power in thermoacoustic systems, and voltage and current in electroacoustic systems. DELTAE can be used easily for apparatus ranging from simple duct networks and resonators to thermoacoustic prime movers, refrigerators, and combinations thereof. It can predict how a given apparatus will perform, or can allow the user to design an apparatus to achieve desired performance. DELTAE is now available to the public.

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DELTAE – Design Environment for Low-amplitude Thermoacoustic Engines – is a computer program for modeling and designing thermoacoustic and other one-dimensional acoustic apparatus. In essence, DELTAE numerically integrates a one-dimensional wave equation in the usual low-amplitude or acoustic approximation. It does so in a gas or liquid, in a geometry defined by the user as a series of segments such as ducts, lumped impedances, transducers, and thermoacoustic stacks and heat exchangers. DELTAE can be used for apparatus ranging from simple duct networks and resonators to thermoacoustic prime movers, refrigerators, and combinations thereof, and even Stirling-cycle systems (including pulse-tube refrigerators) at low pressure amplitudes. It might be useful in teaching as well as in a research setting.

DELTAE views systems as a series of segments; twenty segment types are supported. The purely acoustic segments include ducts and cones, and lumped impedances including compliances, series impedances, and endcaps. All these include the effects of viscous and thermal losses on their surfaces as appropriate. Electroacoustic transducer segments can be defined using either frequency-independent 2-port coefficients or the conventional parameters of electrodynamic drivers: mass, spring constant, *BL* product, etc. Transducers can be current driven, voltage driven, or connected to an electrical load impedance. Thermoacoustic stack geometries include parallel plates, circular and rectangular pores, and pin arrays. Thermoacoustic heat exchangers are assumed to have parallel-plate geometry. Side branches can be defined with fixed impedances, frequency-dependent radiation impedances, or as an auxiliary series of segments of any types.

DELTAE uses continuity of oscillating pressure $p_1(x)$, oscillating volumetric velocity $U_1(x)$, and mean temperature $T_m(x)$ to match the solutions of adjacent segments. Within each segment, it integrates a one-dimensional wave equation appropriate to the geometry of that segment. For example, it uses the lossy Webster horn equation [1] in conical segments, and Rott's [2] wave equation (as extended by Swift [3]) in thermoacoustic stacks, to determine pressure and volumetric velocity. In isothermal segments such as ducts, the wave equation is sufficient to determine the solution; in thermoacoustic stacks, Rott's enthalpy equation [4] must also be used to compute $T_m(x)$. In all cases, the integration is controlled by global variables such as frequency and mean pressure and by local variables such as the geometry of the segment and the enthalpy flow determined by adjacent heat exchangers.

Much of the versatility of DELTAE is due to the range of boundary conditions the user can choose from. The solution $p_1(x)$, $U_1(x)$, $T_m(x)$, with p_1 and U_1 complex, is only determined uniquely if five real boundary conditions are imposed. (This is true whether we consider a single segment or a one-dimensional string of segments with each joined to its neighbors by the continuity conditions discussed above.) If all five boundary conditions are known at one end of the apparatus (i.e., if the initial values of p_1, U_1, and T_m are known), then the integration is utterly straightforward. But generally at least some of the boundary conditions are known at other locations in the apparatus, and the problem must be solved iteratively. The user enjoys considerable freedom in choosing which variables are computed as solutions. For example, in a resonator, DELTAE can compute the input impedance as a function of frequency, or the resonance frequency for a given geometry and gas, or the length required to give a desired resonance frequency, or even the concentration in a binary gas mixture required to give a desired resonance frequency in a given geometry. In addition to such results, in thermoacoustic apparatus DELTAE can compute heat flows for given heat exchanger temperatures, or temperatures for given heat flows, or even geometry required to achieve desired temperatures with given heat flows. The user can select working fluids from among air, helium, neon, argon, hydrogen, deuterium, carbon dioxide, nitrogen, helium-argon mixtures, helium-xenon mixtures, liquid sodium, and eutectic sodium-potassium. For the gases, the ideal-gas equation of state is used, with transport properties from Touloukian. [5] Solids that can be used include stainless steel, copper, kapton, mylar, molybdenum, tungsten, and nickel. Additional fluids and solids can be defined by the user, or the existing fluids can be redefined by the user who requires more accurate equations of state or transport properties.

Geometry and other parameters are defined by the user in an input file created by any text editor. DELTAE processes the input file in a menu-driven environment, allowing the user to view and change variables, change the choices of boundary conditions and solution variables, print results or send them to files, and the like. In plotting mode, DELTAE runs repeatedly, incrementing one or two independent variables and tabulating selected results for use in any spreadsheet or graphics programs. DELTAE is currently supplied for MS-DOS and MacIntosh personal computers and for Sun and Silicon Graphics workstations. It runs comfortably on anything at least as sophisticated as a 286 personal computer with math coprocessor (not required) and 300 kilobytes of free RAM. It may be obtained from the Energy Science and Technology Software Center, US Department of Energy, P.O. Box 1020, Oak Ridge TN 37831-1020; phone 615-576-2606; e-mail ESTSC@ADONIS.OSTI.GOV. Specify the version(s) you require. The Software Center charges a significant distribution cost, which depends on your platform and your organization type (governmental, educational, business, or foreign). You will receive a diskette or tape with executable code and examples, and an instruction and documentation manual some 100 pages long. [Note added April 2010: The discussion of the Oak Ridge Software Center is obsolete. To obtain the most recent beta version at no cost, simply go to www.lanl.gov/thermoacoustics/DeltaEC.html or www.lanl.gov/org/padste/adeps/materials-physics-applications/condensed-matter-magnet-science/thermoacoustics/computer-codes.php]

The manual includes comparisons of DELTAE's results to Hofler's measurements [6] with a thermoacoustic refrigerator, and to Swift's measurements [7] on a thermoacoustic prime mover. DELTAE's results have also been compared to prime-mover measurements by Olson and Swift [8]. The differences between experiment and calculation are typically 10%, and are clearly smallest in the limit of low amplitude, as is to be expected of these computations based entirely on the acoustic approximation. We hope the availability of DELTAE will help free researchers to address the more challenging problems of predicting thermoacoustic behavior at nonnegligible amplitude, where the acoustic approximation is inadequate.

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