JOURNAL OF AIRCRAFT
Vol. 40, No. 1, January–February 2003

Introduction: Exergy

VARIOUS aspects of the first and second laws of thermodynamics are used throughout the design of aerospace vehicles. An aircraft uses fuel as an energy source to do work in some form. The powerplant is the most obvious thermodynamic device on any aircraft designed to produce the maximum work from that energy, and "availability" is common terminology for that aspect.[1] Application to the airframe, however, is ad hoc and frequently implicit. As an example, the Breguet range equation is derived from the work done to overcome vehicle drag. This result, strictly applicable to steady cruise, leads to the classical design objectives of minimizing weight and maximizing lift/drag. Design to weight is a dominant feature today, but we can question how to trade "good weight" against "bad weight." To accomplish this, the designers need to analyze each component and subsystem in terms of a common system-level metric. The papers in this special section are oriented to discuss such a design common currency in the form of exergy, defined as the work available from an energy source.

Exergy and thermoeconomic considerations are reasonably mature for the design of a ground powerplant, as an example. Here, the customer explicitly wants to buy energy, for example, in the form of electricity. The power station purchases fuel, which is the source of exergy, that is, the amount of this fuel energy available for work to produce the form of energy for sale to the customer. There is also an overhead associated with doing this work, plus waste that can be minimized. The problem can now be expressed as maximizing the work output of the fuel into a product that the customer will purchase and to generate profits. The application of these methods to the design of a complete flight vehicle is considerably more complicated. The papers in this special section will present the basic theory to support a thorough foundation for the proposed methodology. Together, they also show the application of exergy methods to all levels of flight vehicle design.

If we look into the future and consider the design of a total aircraft system in terms of an optimum balance of energy, then all of the classical engineering disciplines may need to be reassessed. The first consideration is whether the engineering tasks can all be formulated in a common framework of exergy or thermoeconomic metrics. The answers to this question range from the trivial to the very complex, but they comprise the thesis of this special section of the journal.

The papers in this section attempt to cover the complete range of vehicle design. A definition of mission requirements in terms of the work to be done is shown in the paper by Moorhouse. Then the total vehicle design process can be formulated in similar or consistent terms. Munoz and von Spakovsky discuss the theory of system-level optimization, with a formal decomposition to a rigorous exposition of unit-based optimization procedures to the system level. This general theoretical treatment is then illustrated by the concurrent optimization of an environmental control system and propulsion system using exergy methods. These two energy systems are optimized to system-level metrics of takeoff gross weight, fuel weight, and the component weights. Minimum weight is a common system metric, but, in general, there will always be a variety of constraints. It is not suggested that a simple minimum amount of fuel energy consumed to do the required work will always be an acceptable solution. Paulus and Gaggioli propose a method for creating an overall objective function for any vehicle design. This can and should be used throughout all of the phases from conceptual to detailed design. The authors illustrate their process by showing the flow down through a design to the selection of a component. Roth and Mavris apply exergy principles to the propulsion system by drawing a "boundary" around the engine and airframe. This analysis is stated in the context of the primary function of a jet engine, which is to accelerate the air mass flowing through it, thereby producing thrust to accelerate the vehicle and overcome the drag. The engine and airframe are broken down into components to identify the real sources of waste in the process. In simple terms, this formulates the traditional mission analysis in exergy terms. The authors also show that the gas-turbine engine is responsible for the vast majority of the exergy destroyed in a conventional gas-turbine/airframe configuration. They support the conventional technology development of turbine engines. The methods are completely general, however, and could be applied to any integrated propulsion/airframe system. Similarly, Bejan examines exergy methods relative to aircraft and shows the application down to the very detailed level of optimum geometry for the most efficient way to extract work from a heat source. The author illustrates that exergy methods could apply to a simple heat exchanger, or to the most efficient energy exchange of a propulsion system. Again, the benefits of this new methodology to a conventional gas-turbine engine may be minimal because of the evolutionary knowledge in current engines. A significant payoff should be realized if these methods are applied to new forms of integrated propulsion systems, such as will be necessary for an efficient hypersonic plasma-based flight vehicle. Figliola and Tipton show the application of exergy methods to the design of an integrated aircraft thermal system. The authors show the similarities and the differences between the new (exergy-based) and traditional (energy-based) methods. Their conclusion is that the two approaches "seek answers to somewhat different questions," which could imply that the preferred method depends on the application. Finally, Gurdal uses exergy methods to illustrate the optimum design of an aircraft power distribution system. This also should become more important as technology advances, such as toward an all-electric airplane.

Reference

[1] Clarke, J. M., and Horlock, J. H., "Availability and Propulsion," *Journal of Mechanical Engineering Science*, Vol. 17, No. 4, 1975, pp. 223–232.

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Received 2 September 2002; revision received 23 October 2002; accepted for publication 23 October 2002.

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