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Proposed System-Level Multidisciplinary Analysis Technique Based on Exergy Methods

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It is suggested that it may be time to consider whether we have reached a plateau in terms of the evolutionary nature of flight vehicle design and optimization. For a time, progress was measured in terms of maximum speed, which is a straightforward metric when the next design is evolved from the preceding model. There are times, however, when we need to depart from the evolutionary process and create a breakthrough design. The question to be asked is whether there is any way to define system-level analysis and optimization techniques to facilitate the vehicle design process with a more global measure of effectiveness. This paper presents such a methodology for the design of the complete integrated system of systems. Work that has been done in energy-based methods is briefly reviewed, since energy is an implicit consideration in many aerospace disciplines. In addition, methods such as exergy and thermoeconomics have been applied in the design of ground power stations and they are currently being studied for application to aircraft subsystems. The objective of this paper is to expand exergy methods to the design of a complete flight vehicle by defining mission requirements as an exergy/work problem cascading down to each component in the same framework. This paper also serves to introduce a special section of this journal devoted to the application of exergy methods to all levels of flight vehicle design. Overall, the proposed technique provides a method to facilitate system-level optimization at all levels of the design process.

Nomenclature

D	=	drag, lb
D_p	=	"drag" accountable to the payload, lb
E_w	=	specific energy (kinetic + potential)/weight, ft lb/lb
H	=	energy content of the fuel, ft lb/lb
h	=	altitude, ft
L	=	lift, lb
P	=	payload power requirement, ft lb/s
R	=	range, ft
T	=	thrust, lb
t	=	time, s
U	=	airspeed, ft/s
W	=	aircraft gross weight, less payload, lb
W_p	=	payload weight, lb
w_c	=	customer work, ft lb
w_o	=	overhead work, ft lb
w_i	=	ith component of work, ft lb
η	=	overall propulsive efficiency

Introduction

AIRCRAFT have evolved to a point where they are extremely complex machines posing a very integrated design problem. A military vehicle includes many systems that are all interrelated and dependent on power (or energy) in some form. In some of the systems, by-products are created in the form of heat energy that have to be removed from that equipment. There are obviously methods for the design of all these systems, but they are based on the evolutionary nature of vehicle development. However, the more we depart from the existing databases and experience levels, the less confidence we have that we are close to an optimal design. In addition, many of the classical techniques are based on simplifying assumptions that were used in the original derivation; if these are not considered, then there is no guide to when those classical techniques no longer give an acceptable solution.

The need is for a methodology that can support design of the complete vehicle as a system of systems in a common framework. All aspects in terms of common metrics must be considered in order to conduct fully credible trades. The vision is to develop such a methodology that will support all required levels of design activity in a natural fashion, from conceptual comparisons through to the final configuration, and lead to a true system-level optimized design. In nature, if something is inefficient, then it dies out or it adapts to the environment. It is claimed that this "inefficiency" can be considered in terms of energy used for work done vs energy wasted. We can also consider an aircraft, or any vehicle, as consuming fuel and doing work in some form. Lower specific fuel consumption of the engine is one dominant factor, but when this is considered completely separately from the vehicle application, then the system will probably not be truly optimum. In the aerospace vehicle context, therefore, there is a need for tools and processes enabling the discovery of new and innovative configurations by designing for maximum efficiency and minimum energy waste at the overall optimum system design level, subject, of course, to the appropriate constraints.

Various future missions may stretch the extrapolation of traditional methods. One is the design of a vehicle to orbit high-powered sensors at altitude for extended periods of time. In isolation, the vehicle wants to "optimize" to a very high-aspect ratio wing configuration with large propellers. This vehicle-driven solution would have a relatively slow cruise speed and probable sensor/propeller interference, so requirements may drive another solution. At the same time, the payload consumes power and generates heat energy. This simple example is used in this paper to illustrate the proposed methodology. These considerations will apply even more to the design of revolutionary concepts such as a plasma-based hypersonic vehicle. Here, there is no database to support an evolutionary approach. Also, the traditional analysis techniques would probably violate the applicable range of validity. The mission requirement and all the advanced systems that will be required create a total energy problem. A methodology that can relate every system component to the overall system requirements in a framework of common metrics will be mandatory.

There are many instances of energy consideration throughout traditional vehicle design, but they are implicit and not integrated. The

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classical Breguet range equation is work done to overcome drag, an implicit energy consideration, but only an approximation. The well-known elliptical lift distribution to minimize induced drag could be considered as part of a minimum energy solution. The underlying assumptions, however, show it is not correct when derived as an explicit problem to minimize the generation of entropy. The proposed methods are either consistent with, or correct, traditional methods. At the same time, it will be shown that the correct form for the design methods is in terms of "exergy," which can be defined as the work potential of an energy source. Energy can only be redistributed, not destroyed, whereas exergy can be destroyed by waste or inefficiencies throughout the system. It is derived from consideration of the second law of thermodynamics. This term has also been called availability (see, for example, Ref. 1).

This paper proposes a new system-level multidisciplinary design and analysis technique using exergy-based design methodologies, as discussed above. It also introduces the other papers in this special section of the journal. Together, the papers cover a range of related aspects from the basic scientific principles and system-level optimization down to detailed component design. Some of the basic principles, such as exergy and thermoeconomics, are well known in nonaerospace applications. Many other energy aspects are already implicit considerations. The thrust of this effort is to integrate these into one approach. The design of a flight vehicle is discussed from the perspective of defining the total mission requirement as an energy problem. This is illustrated with very simple examples, and connection is made to traditional analysis methods and typical results to show either an improvement or absolute consistency. The decomposition of the design problem into appropriate subelements is illustrated. It is postulated that the use of exergy-based methods will allow more complete system integration and facilitate the connection of all traditional results into a design framework with a common metric. It will be possible to conduct explicit trades between dissimilar technologies in a system context. The ultimate vision is to facilitate complete system-level analysis and design of an integrated system of energy systems.

Background

Traditional Methods

Energy consideration has already shown the inaccuracies in traditional wellknown techniques. Trajectory optimization is a tradeoff of potential and kinetic energy. The Breguet range equation is pseudoenergy-based, calculating the balance of fuel burned by the engine in order to do work overcoming the drag of the airframe. An explicit energy consideration leads to different results in both cases.[2] Either method, however, leads to the desire to reduce fuel consumed by the engine, reduce vehicle weight, and improve lift/drag. These have often been done in isolation. In a simple one-dimensional view, aerodynamic optimization to reduce drag is already an example of minimizing the use of energy represented by fuel burned. History provides a lesson learned about this one-dimensional approach. The Spitfire originally had a wing with a perfect elliptical planform, theoretically producing minimum induced drag (theory that was based on a gross simplifying assumption[3]). It had excellent cruise performance but deficient roll performance for combat, the airplane's primary mission. The wing was subsequently cropped to satisfy mission requirements. Could those requirements have been defined in terms that would have guided the designer to a better initial solution? This will be addressed in the next section.

The traditional performance analysis has been typically used to calculate the range or radius resulting from a fuel load with specified mission constraints. Even if it included segments to represent combat, this traditional analysis was based on very simple airplane models that were designed through trial and error rather than true integrated procedures. At the subsystem level, the engine also has to supply energy, in different forms, to drive the hydraulic pumps, to power the environmental control system, etc. The power that is required from the engine for these functions is not calculated on a real-time basis and is usually a simple average, so the analysis of a mission that includes combat maneuvering is only an approximation. Further, that environmental control system has probably been designed as an independent subsystem and "integrated" via a definition of the interfaces.

Exergy Methods

A very large theoretical base has been developed in nonaerospace applications for the application of the first and second laws of thermodynamics in design (see Refs. 4 and 5 for examples). It is a logical process to consider static systems, such as power or refrigeration plants, in terms of an energy balance in order to analyze and minimize the losses. The same principle is being applied to aircraft systems. It has also been stated that the appropriate term is "exergy"—in simple terms it is defined as the work potential that can be extracted from an energy source. In particular, this early work is focused primarily on the application of exergy methods to the design of an aircraft environmental control system. In formulating this problem we "draw an imaginary boundary" around the appropriate subsystem components and analyze the exergy exchanges. Similar principles have been applied to the propulsion system.[6,7] Another question that needs to be explored is which parts of an aircraft can and should be considered energy systems, and if there are other parts that should not.

Exergy-Based Design

Mission Requirements

The starting point for any design exercise is some consideration of customer requirements. So we must express the mission requirements in the appropriate exergy terms. The underlying requirement is for a flight vehicle to do work to satisfy a customer. It will be illustrated by means of a simple example using the analogy of the work that the customer wants to purchase, plus minimizing overhead and waste. The transportation of a payload from point A to point B is the simplest example of this premise, by defining the problem as work to be done. We could consider only the cheapest way of doing this work and optimize cost. There will always be constraints, however, such as doing the work in some minimum time rather than by the absolute measure of minimum energy wasted. For some missions, high speed is one of the major design constraints; thus, stating the customer requirements of many military missions is far more complex than a simple one-dimensional mathematical optimization problem. It will now be shown that the appropriate method is to define the total mission energy required.

In order to illustrate the process, let us consider a notional reconnaissance mission, although it will be discussed in the most general terms to apply to any mission. There is the need for a payload, e.g., radar antenna, to be placed into an orbit at a given altitude for a specified period of time. What the customer is buying is composed of the energy or work that has to be accomplished to raise the mass of the antenna to the required altitude w_1; plus the work needed to accelerate that mass to the cruise speed w_2; plus the work done to transport that mass for the required time and distance w_3; plus the energy that is required to power the antenna w_4. The customer desires to purchase w_C where

$$w_C = w_1 + w_2 + w_3 + w_4 \tag{1}$$

To illustrate the process, we can consider a payload weight of 5,000 lb that must be taken to 65,000 ft and orbited for tens of hours. We will assume that these numbers are fixed, whereas other terms may be fixed or allowed some flexibility to vary and support derivation of a constrained optimum solution. The orders of magnitude of terms in Eq. (1) can now be estimated. First assuming only a climb to that altitude, the potential energy term is

$$w_1 = W_p \times h = 5{,}000 \times 65{,}000 = 325.0E6 \text{ ft lb} \tag{2}$$

The second term is the energy used to accelerate the payload to the speed at the top of the climb. This is a term that may be defined by sensor operation, or allowed to fallout subject to constraints. Assume that the customer has no need to go supersonic and also "not too slow," say 500 ft/s. Then

$$w_2 = W_p \times U^2/2\text{g} = 5{,}000 \times 500^2/64.4 = 19.4E6 \text{ ft lb} \tag{3}$$

These two terms represent the energy required to get the payload to the start of cruise. Whatever the mission of the aircraft under consideration, this is consistent with conventional mission analysis, although just for the payload.

It is more convenient to calculate the rate of doing work for the other two terms. First

$$\frac{dw_3}{dt} = D_p U \text{ ft lb/s} \tag{4}$$

where both D_p and U would be functions of time in the general case. Mission profiles should be laid out in the conventional manner to integrate required values of this quantity. For this illustration only, we size a conceptual configuration that achieves a high lift/drag ratio, say a cruise value of 35 assuming some technology input. A system that could be required to achieve such a value is discussed later. This defines the drag force in cruise to be weight/35 lb, i.e., the cruise drag accountable to the weight of the payload is 143 lb. The actual cruise speed may be specified by the mission considerations as a constraint, but for this example again we can assume an average cruise speed of 500 ft/s, then

$$\frac{dw_3}{dt} = 143 \times 500 = 71{,}000 \text{ ft lb/s} \tag{5}$$

The energy consumption required to power the antenna and related equipment, P, will be specified by customer requirements, and could be integrated over a mission if a constant value is not appropriate. Assuming 100 kW for this example gives

$$\frac{dw_4}{dt} = 75{,}000 \text{ ft lb/s} \tag{6}$$

The final customer-required energy work for the mission, i.e., what the customer wants to purchase, is

$$w_c = W_p\left(h + \frac{U^2}{2g}\right) + \int (D_p U + P)\,dt \tag{7}$$

Eq. (7) can be considered as completely generic and exact since the weight of the payload is constant over the mission, which is also true for a transport mission delivering cargo. A fighter or bomber mission could be analyzed in segments if all or part of the payload is expended. Equation (7) could also be completely generalized if we include additional climb segments, and additional acceleration segments such as is commonly done subjectively for combat missions. Any mission can be defined in these terms, as work that a customer will purchase. It is also assumed that climb and acceleration are irreversible processes. In a purely theoretical sense, the payload at altitude could perform work if there were a way to retrieve it. In a different mission, the potential energy could be used to accelerate to a higher speed by diving if that were required. The assumed numbers would indicate that

$$w_c = 344E6 + 146{,}000t \text{ ft lb}$$

and for this example the customer would specify the mission time t may be 24 h (86,400 s!). The orders of magnitude are only presented for illustration. The use of simple average values is not recommended for a real design application, although for this low-speed cruise mission the approximations could be reasonable. We see that the climb energy is equivalent to 39 min of cruise and may become insignificant for this example, but that observation is not a general result.

Vehicle Design Considerations

Equation (7) is a statement of the mission requirements in energy terms. Continue the analogy to a ground power station. In order to accomplish this work, a vehicle is required to carry the mission payload so that there is a "business overhead." This is the work that has to be done carrying the vehicle weight throughout the mission. This weight has to be given potential energy as it is lifted to altitude, and also has to be given kinetic energy as it is accelerated to mission airspeed. There is also the conventional work to be done overcoming drag. A mission could also include descents and climbs, so there may be a continual exchange of potential and kinetic energies. For this example

$$w_o = W\left(h + \frac{U^2}{2g}\right) + \int DU\,dt \tag{8}$$

Again, we consider simple average values for illustration only. We might size an initial vehicle with a weight estimate of approximately 70,000 lb that has to be lifted to the orbit altitude and speed. The average weight of the vehicle without payload over the mission would be approximately 45,000 lb, with an average drag force of 1,285 lb. We see that overhead energy for climb plus the rate of doing work to accomplish this overhead is

$$w_o = 70{,}000 \times 65{,}000 + 70{,}000 \times 500^2/64.4 + 1{,}285 \times 500 \times t = 4{,}822E6 + 640{,}000 \times t \text{ ft lb} \tag{9}$$

which is many times the actual mission value. The customer pays for both the mission plus the overhead work done, which is accomplished using the exergy of the fuel burned. The basis of traditional design, of course, as well as the proposed methods is to minimize this overhead.

The above discussion also addresses a mission dominated by cruise, although for general applications a combat segment could be defined in terms of energy required to accelerate the vehicle plus additional induced drag due to the maneuvering requirements. In the example, we need to consider that an orbit requires frequent turns to reverse direction. The required design load factor capability has an obvious direct effect through the vehicle structural weight. In addition, a 1.2 g turn would increase the drag terms in both Eqs. (4) and (8) on the order of 20 percent (only induced drag is increased by 20 percent but there is also drag due to control). This increase would be for approximately 60–70 s in a 180 deg turn, and it would be easy to calculate the frequency of turn that is required to maintain a specified orbit. A circular orbit would mean that the total values in Eqs. (4) and (8) would need to increase approximately 20 percent, whereas it would be far less significant for, say, a border patrol with few turns. The proposed methodology will account for that effect explicitly and, again, it can be integrated over each event in the mission.

All the preceding equations appear to be consistent with the Breguet range equation. This is the traditional top-level analysis, showing a relationship between lift/drag, fuel weight/vehicle weight (in terms of initial and final weights), and the thrust specific fuel consumption. It is typically used for initial vehicle sizing, before more detailed design development. Then the design partitioning starts and those three things are optimized separately. It is very common to hear of the very stringent weight budget as the design progresses, e.g., "Any change has to buy its way on to the aircraft—with no weight increase!" Of course, so far the preceding discussion of work and energy only proves what is common knowledge, i.e., minimizing the customer's overhead means attempts to reduce weight. However, it is hoped that it is obvious that the one-dimensional approach of only minimizing weight is not a solution, so the question is how to do that in the optimum way.

The next level of analysis needs to consider more details. The gross approximation in Eq. (8) would not be satisfactory in practice. Because of the continually changing vehicle weight, it is convenient to express the integral over time in terms of the total energy of the aircraft. Further, we can then use a "specific energy"

$$E_w = h + U^2/2g \tag{10}$$

which is only a function of altitude and speed, as is the rate of change. At the system level, it is convenient to use the specific energy content of the fuel H together with an overall propulsive efficiency η. The conservation of energy in time interval dt can be shown to be

$$W\,dS + \eta H\,dW + DU\,dt = 0 \tag{11}$$

This is the balance between change in aircraft specific energy, the exergy derived from the fuel, and the exergy destroyed to overcome drag. Of course, the change in aircraft weight is a negative quantity equal to the fuel burned. This is the general energy equation for the system-level performance analyses. It allows optimization of climb performance with speed and altitude as independent variables. For certain vehicles it is possible that a periodic form of climb/descent would be the optimum solution rather than a simple monotonic climb. In addition, it would be straightforward to calculate the effect of descents and climbs back to altitude during parts of the mission. Recognizing that range R is equal to $U\ \mathrm{d}t$ then equation (11) can be rearranged to derive a more accurate range equation:

$$\mathrm{d}R = -\left(\frac{\eta H}{D}\right)\mathrm{d}W - \left(\frac{W}{D}\right)\mathrm{d}E_w \tag{12}$$

Eq. (12) is the most general form, but can be simplified to show consistency with traditional analyses. In level cruise, W/D is the same as L/D, and we get to the Breguet range equation with an additional term accounting for the energy changes due to changing aircraft weight during the cruise. It is suggested that, in addition, Eq. (12) would give far more accurate results for other than straight and level cruise. This will be important for a hypersonic cruise vehicle.

System Design Considerations

Next, we need to consider all the aircraft systems that can be formulated in energy terms. Table 1 is a listing of simple conventional components, although it is pointed out that weight is only one aspect of the work to be done. It is also common practice to encounter design conflicts in terms of bookkeeping who is responsible for adverse effects. The intent of this discussion is to show how all the systems and subsystems can be designed in common terms, from top-level system analyses down to detailed subsystem design.

The fuel supplies the exergy to accomplish all the required work. The weight of the fuel itself is part of the overhead, and the concept of a multiplication factor at the vehicle level for fuel saved is well known. The reverse is that any change in heat content of a fuel must be balanced against possible changes in fuel weight or volume, i.e., aircraft size and weight. This becomes even more of a design consideration if we are using unconventional fuels or mixed cycle operation. In addition, the fuel may be used as a cooling medium and, therefore, a critical part of the aircraft thermal energy distribution and management system.

The propulsion system is an obvious energy system. Detailed considerations will provide the required level of fidelity in the overall propulsive efficiency used earlier. It must be recognized that the engine supplies power for purposes other than to overcome aerodynamic drag, which has already been partitioned into "mission vs overhead." An example of exergy methods applied to the propulsion system for the F-5 aircraft has already been discussed.[7] Here, the aircraft is decomposed into various components of drag, including component weights that produce induced drag, so that the fuel burned can be assigned to the actual causes. This "weight budget," of course, is already one of the most critical aspects of a new aircraft design. In the proposed exergy-based methodology, weight is integrated with all other aspects of the design process.

Table 1 Breakdown of subsystems in terms of energy effects

Overhead	Positives	Negatives*
Actuation	Essential functions	Weight + power used
Structure	Carries payload	Weight
Adaptive structure	Minimize drag	Weight + power used
Controls	Trim/stability/control	Weight + cause drag + power used
Flow control	Reduce drag	Weight + power used + waste
ECS	Essential cooling	Weight + engine bleed + waste
Propulsion	Supplies power + thrust	Weight + waste
Fuel	Supplies exergy + cooling	Weight

*weight now reflects work that needs to be done.

When we consider a plasma-based hypersonic vehicle, then we can expect that it will not be straightforward to separate the airframe and the propulsion system. The integrated system will need to be decomposed into the components that determine how efficiently the fuel is converted into useful work. It may no longer be possible to consider the weight of the engine and the weight of the fuel that must be carried as items chargeable to the propulsion system. Moreover, it applies to those traditional portions of vehicle drag that could be considered as directly chargeable to the propulsion system, such as nacelle drag, inlet drag (spillage, bleed, etc.), and throttle-dependent afterbody drag. In addition, however, the decomposition will show how much exergy is lost because of the irreversibility of the processes (i.e., unavoidable overhead) and how much is wasted by design aspects that should be considered as avoidable overhead and should be changed.

Aerodynamics may not be considered as an aircraft energy system, but it is a critical part of the energy problem, requiring exergy be expended to overcome drag. It was traditional to consider an elliptical lift distribution as providing minimum induced drag, i.e., a starting point for efficient cruise. This well-used result was dependent on an assumption that there was a planar wake extending to infinity. Although this was obviously not correct, the answer was good enough. A new approach, considering the minimization of entropy generation as the basis for minimum drag, showed that the optimum lift distribution is not elliptical but parabolic, with less lift at the tip.[3] This also will produce significantly less roll damping and would have been a better initial solution for the Spitfire discussed earlier. Although that work was based on a different set of assumptions that can be challenged, it shows the possibility of doing the basic aerodynamic design to the same energy principles as everything else in the proposed methodology. In the example shown earlier, a lift/drag of 35 was used. It was stated that a new technology could be required, e.g., laminar flow control. Power is obviously required for such a system and the aerodynamics becomes an exergy balance. Is less exergy destroyed by the reduced drag than is destroyed by the weight and power consumption of the laminar flow control system? This trade-off or conflict is even more true when we consider flow control devices such as will be used on a hypersonic plasma-based configuration. Those devices will obviously be a part of the energy balance in the exergy-based design.

One important design aspect is the vehicle subsystems that operate using power generated by the engine. It has already been said that other papers address design of an aircraft environmental control system (ECS) using exergy methods. For the example, this could mean design of energy-efficient cooling for the mission payload. The customer is buying the energy needed to power the radar for the mission, but the heat that it generates needs to be removed from the electronic components. The first task is to consider the most efficient way to remove this heat and maintain the electronics at an appropriate temperature. On the other hand, the heat is wasted unless it can be used. One possibility for a conventional gas turbine configuration is to use this heat to maintain the fuel at some appropriate temperature. This requires an analysis of whether the heat can be used in an efficient manner, or whether the complete integrated vehicle system requires it to be discharged overboard.

Consideration of the ECS needs to be expanded to other uses of power from the engine, such as for other mission avionics, control devices, landing gear and flaps, etc. Obviously, the power required for landing gear and flaps will occur when the vehicle has an excess capability—the radar is not likely to be needed and the engine thrust is much greater at low altitudes. In this case, the weight of the components will be the primary effect on vehicle energy balance as they must be carried throughout the mission, contributing to exergy consumed to overcome vehicle drag. A secondary effect will be the integration of the power distribution system with the rest of the vehicle, which should be included in the design of the vehicle energy management system. A critical part of the distribution system design will be customer requirements that dictate when and how exergy can be shared or allocated on a priority basis.

Total influence of the control system can also now be designed from exergy principles. There will be an obvious weight component contributing to terms in Eqs. (8) and on. The power to drive the controls, whether hydraulic, electrical, or something else, is part of the integrated subsystem of power generation and distribution, i.e., an exergy subcomponent of the complete vehicle system. Last, it is possible to add a flight control system design requirement in exergy terms, a component that is currently ignored whether it is negligible or not. We should try to minimize exergy use caused by control activity, which will add a contribution to exergy consumed through the drag of the individual devices. It also affects the vehicle drag if it generates high load factors for maneuver, or allows significant deviations from the minimum drag trim condition. When we start to consider control technologies, active flow control could be a candidate. There have been techniques examined that can reduce drag or create control forces, e.g., by manipulating the position of vortices or flow separation points. Such schemes need power, and could be analyzed in terms of the system exergy balance. A very significant part of the design problem is to maximize the efficiency of converting fuel to work; this means decomposing the system-level exercise into an assessment of the vehicle systems to ensure that minimum exergy is wasted. Again, as we consider the possibility of plasma devices and flow control through magnetic fields, the only efficient solution will be realized through the use of the proposed exergy methods. The flight control system design must be integrated with every other exergy aspect of total vehicle design.

Finally, we need to discuss whether the aircraft structure is considered an energy system. Traditionally it was not; it held the aircraft together and absorbed the flight loads. Structural optimization implied minimum weight to accomplish that task, even though the weight is still a component of the exergy destroyed. Also, the historical cost models were correlated in terms of cost/lb of structure, driving the one-dimensional consideration. In recent years, research has expanded to include consideration of air loads and controls. For the future, we need to consider a fully adaptive structure that can be actuated to change shape, e.g., to produce a control effect, to reduce drag, etc. Such a fully adaptive structure will definitely be an exergy system. It will use actuation power in addition to the conventional weight effects, but it may also affect exergy consumption through drag reduction or replacement of traditional control surfaces. The weight of the structure will need to be assessed against system-level criteria. In addition, the proposed methodology of a system framework in exergy terms could avoid the bookkeeping problem of who is responsible for interdisciplinary effects.

Required Research

The basic scientific theories of exergy and thermoeconomics are not new; they have been used in the design of ground power stations. There is a large community of expertise in these theories outside the aerospace design community. A full range of analysis and design techniques required to build a flight vehicle is also well developed. A new vehicle that is not too far from existing databases can be expected to be successful technically, in general. The risks are in terms of time and cost overruns. In the area of integration, the progress that has been made continues. A good example is the development of methods for integrated structures/aerodynamics/controls to address aeroelasticity problems in the early design stages. This is still disconnected from other aspects of the vehicle, which are developed in parallel. It is not possible yet to model and analyze a complete aircraft system with fidelity. In analyzing a particular system or subsystem, compromises are introduced by using simplified models of interacting components. It is suggested that there is a need for a unifying framework and set of metrics to facilitate such a complete design process and, further, that the exergy-based methods discussed in this special section of the journal have tremendous potential as representing the answer.

It is currently in vogue to claim optimization of life cycle cost, which is impossible to calculate with any degree of certainty using the available models. If we consider the potential of using energy-based optimization, then "everything" must be put in thermoeconomic terms, but to do this we must consider energy and cost to be equivalent units. The future of this methodology depends on being able to formulate the individual technical disciplines in this common framework for analysis and optimization, in parallel with the development of the necessary physics-based modeling.

There is further work required to expand some of the underlying theories. One question to be addressed is the possibility that some vehicle components do not fit consideration as energy systems. Then, theoretical methods need to be developed into design codes in a form that industry designers will use. A validation against flight results will be the only real proof of the validity of the methods. This need not be a dedicated flight demonstration; the validation could be a parallel activity on any appropriate flight program.

Conclusions

It will be universally agreed that the time has long passed when the individual technical disciplines could be practiced independently. Optimization of individual disciplines leads to a suboptimum system. This is probably obvious to many when considering design of a flight vehicle, but it is also just as true when considering applied research and technology development. This paper, together with the other papers in this special section, is intended to present the need, and a rigorous basis for, developing new design methodologies based on exergy. We are suggesting the need for developing new methodologies in order to facilitate a fully integrated system optimization. The emerging discipline of thermoeconomics can, perhaps, be developed as a methodology for total-vehicle system optimization in the future. Such an exergy-based design methodology would also be equally applicable to ships and land vehicles as well as aircraft.

It has been shown that aircraft mission requirements can be defined in energy terms. A notional mission of orbiting a reconnaissance sensor at high altitude has been used as an example. The process to expand the design problem into an integrated treatment of all the various subsystems has been defined. Any vehicle design can be expressed in these terms, but the payoff would probably be minimal for very conventional requirements. We would expect significant benefits in using the proposed methodologies for vehicles without a large supporting database, for example a hypersonic plasma-based configuration.

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