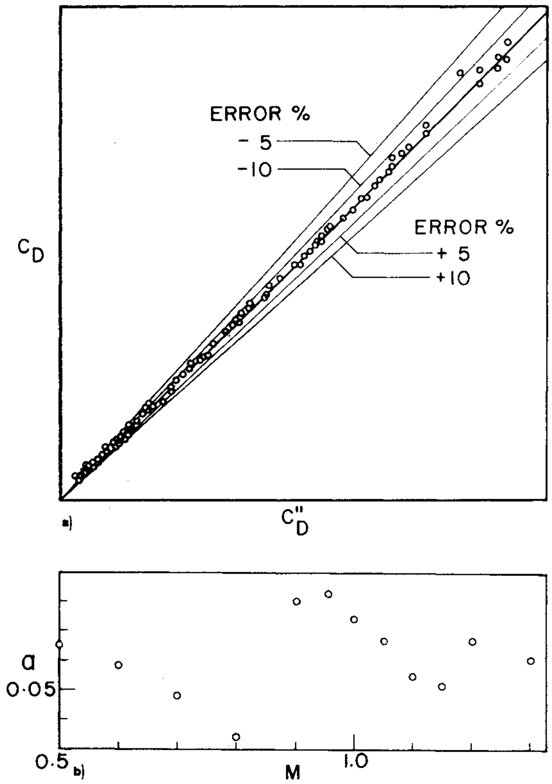

Fig. 3 a) Effectiveness of the representation given by Eq. (2); b) variation of a with Mach number, M.

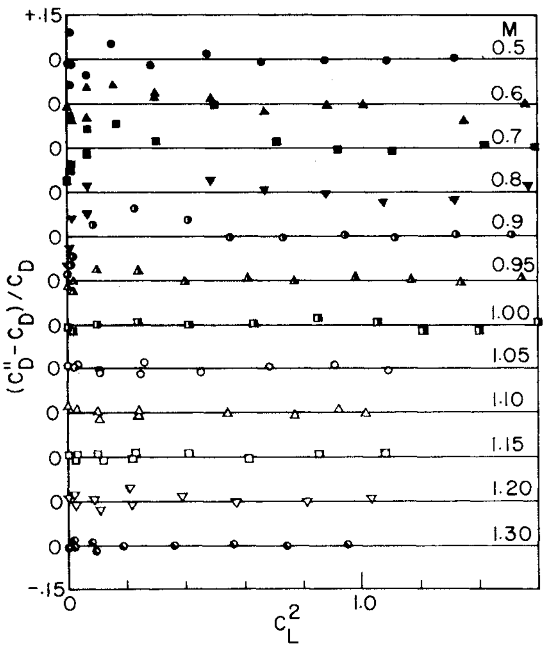

Fig. 4 The distribution of relative error $(C''_D - C_D)/C_D$ in subsonic, transonic and supersonic range.

can well approximate the curve. Hence it is reasonable to take the correction as

$$f=(C_D - C'_D) = aC_L^n \tag{1}$$

where the coefficients a and n have to be chosen for the given drag polar. The histogram of n (Fig. 2) shows that the three-fourth of the sample under study has n ranging from 3.4 to 4.2.

Further examination showed that the values of n were sensitive to the details of the method of determining C'_D. For instance, if a line with a slightly different slope was judged as a tangent, the value of f could significantly change for large C_L. A numerical method was selected to reduce the uncertainties. The classical representation was first fitted as a line of regression of C_D on C_L^2 to the four experimental data points having the smallest values of C_L^2. The index n was then found from the line of regression of log $(C_D - C'_D)$ on log (C_L^2). The values showed an increase in the transonic range. Also, differences between the numerically and the graphically obtained values of n were often significant.

Since n seemed to be rather sensitive to extraneous details, it was felt that a simpler representation, if sufficiently accurate, is to be preferred. With this view, we examined the simpler representation

$$C''_D = C_{D0} + kC_L^2 + aC_L^4 \tag{2}$$

The above expression can be considered as a quadratic curve of regression of C_D on C_L^2. The examination was restricted to two configurations for which we had detailed data.

The calculated values C''_D are compared with the experimental values of C_D in Fig. 3. There is no evidence of a systematic departure. Also, the index of correlation of Eq. (2), which is the ratio of standard deviations of C''_D and C_D, was typically in the range of 0.997 to 0.999. The closeness of this index to 1 is an indication of the effectiveness of the representation equation (2).

Figure 4 shows the relative error in the subsonic, the transonic, and the supersonic range. Evidently, the agreement of C''_D with the experimental values is better than 3% in the transonic and the supersonic range, perhaps due to the reduced relative error in measuring larger forces and the smaller range of C_L. While the relative errors are somewhat larger in the subsonic range, the agreement is still fairly satisfactory.

Conclusion

The present study suggests that the simple analytical approximation (2) can be advantageously used in the turn calculations of a fighter aircraft. The magnitude of a is of the order of k and hence aC_L^4 is comparable to kC_L^2 when C_L is of the order of unity. The variation of a with Mach number is shown in Fig. 3.

Reference

[1]Buckner, J. K., Hill, P. W., and Benope, D., "Aerodynamic Design Evaluation of the YF-16", AIAA Paper 74-935, Los Angeles, Calif., 1974.

Engine Life Cycle Cost: A Laboratory View

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LIFE cycle cost (LCC) is defined by Air Force Regulation 800-11 as "the total cost of an item or system over its full life." As applied to airbreathing engines, it includes the cost to develop and test the engine during the engineering development phase; the cost to produce the engine in quantity during

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the production or acquisition phase; and the cost to operate, maintain, and support the engine during the operational phase. This life cycle cost definition is indeed all-encompassing, having many ramifications. In the broad perspective, *cost* must be related to *effectiveness*, and the connotation of these terms depends upon one's point of view. For example, it can be said that in the Air Force Systems Command, (AFSC) effectiveness is viewed in terms of weapon system performance, and the associated costs are the research and development (R&D) cost, and the acquisition cost. In the Air Force Logistics Command (AFLC), effectiveness might be measured in terms of the availability or readiness of the weapon system, and the cost is the logistics cost to provide this availability. To the using command, effectiveness is the capability inherent in the weapon system to fulfill a mission requirement, and the costs are those associated with operating, maintaining, and supporting the weapon system. Reducing LCC of a weapon system requires tradeoffs with each of the cost and effectivenss categories described above.

The AF laboratories can play a vital part in controlling this total cost/effectiveness situation because their emerging advanced technologies greatly impact life cycle cost. A pictorial representation is shown in Fig. 1 of the decisions which determine the LCC of a weapon system, as a function of when in time those decisions are made during the lift cycle of the weapon system.[1] As shown in Fig. 1, most of the decisions (approximately 85%) which affect the life cycle cost of a weapon system are made by the end of system definition, or before the start of engineering development. It is during these early conceptual and validation phases that the laboratories provide the advanced technologies which form the technology base for the future weapon system. In these early stages, LCC must be a consideration in the technical decisions that are made.

In order to determine the effect of the propulsion system on LCC, the total weapon system and its mission requirements must first be considered. A typical advanced fighter LCC breakdown is shown in Fig. 2. Once the basic weapon system LCC is established, then the cost sensitivities to changes in mission requirements can be made. The propulsion system LCC can then be established, as a subset of the given weapon system LCC (Fig. 2). The cost sensitivites to changes in engine characteristics, as they relate to the given weapon system, can now be made. Figure 3 shows the propulsion system LCC breakdown for different types of weapon systems. The relative size of each circle is proportional to total propulsion system LCC. As is shown in Fig. 3, some elements of the propulsion system LCC are very much a function of the weapon system type. In particular, fuel cost is very dependent on the type of weapon system. This macroscopic (or global) view of the propulsion system LCC highlights the need for obtaining data for the development, production, and operational phases in order to accurately estimate LCC.

Each of these phases will now be examined more closely, with the objective of identifying what can be done in order to reduce the LCC of the weapon system. It is during the feasibility and conceptual phases, looking forward in time, that the greatest impact can be made on LCC.

Development Phase

In the development phase, over 50% of the cost is for hardware and associated testing. History has shown that there exists a relationship between test time, and engine failures (which is proportional to the amount of hardware required) for a given engine development. Data from past programs have indicated that the number of failure events is related to cumulative test hours by the general equation $N=K H^{1/2}$ where N is the number of failure events, H is the number of cumulative test hours, and K is a constant factor for a given engine development.

The objective then, in order to reduce hardware and test time, and hence to reduce the development cost, is to reduce

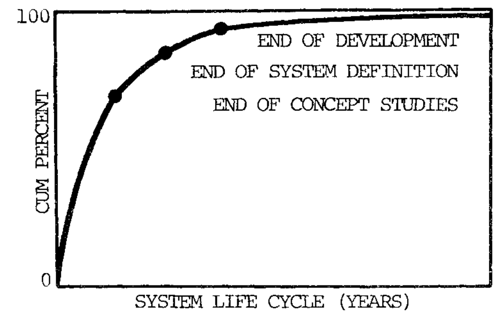

Fig. 1 Time phased decisions defining life cycle cost.

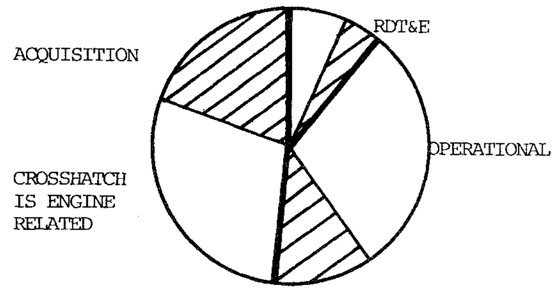

Fig. 2 Advanced fighter weapon system life cycle cost breakdown.

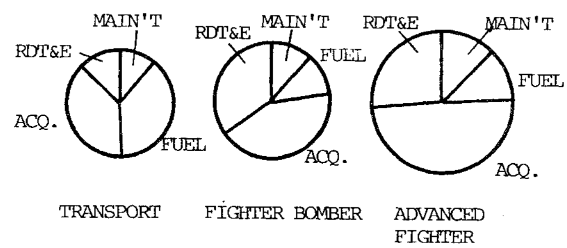

Fig. 3 Propulsion system lift cycle cost comparison.

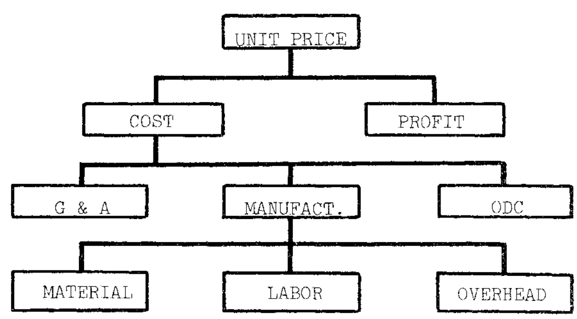

Fig. 4 Production cost elements.

the quantitative value of the factor K. This factor K is a function of two conditions: 1) the degree of advanced technology; and 2) the technological uncertainty of the advanced technology. If we assume that advanced technology is necessary to meet the future weapon system requirements, then a reduced value of the factor K can be achieved only by reducing the technological uncertainty. Therefore, effective exploratory and advanced development programs are necessary to fully characterize the advanced technology, and hence, to reduce the uncertainty, or risk, during the development phase.

Acquisition Phase

The acquisition phase is one of the largest, if not the largest, cost phase. A typical procurement breakdown of these cost elements comprising the engine price is shown in

Fig. 4. The cost elements on which the laboratory can have the greatest impact are the material cost, and the labor cost. These costs can be reduced in basically two ways. First, material and labor costs can be reduced by better manufacturing methods. For engines in operational use, approximately five pounds of raw material weight are required to produce one pound of finished engine weight. New techniques using the "near-net-shape" fabrication concept will reduce this raw material/finished hardware ratio. Second, material and labor costs can be reduced by fewer number of parts. Increased aero/thermal performance will result in fewer parts, as will simplicity in design. Also, improved component areo/thermal efficiency can result in fewer parts. The potential payoff here is not only in the acquisition phase, but also in the operational phase. It should be noted that many tradeoffs between energy output, efficiency, and manufacturing methods can be made in establishing a design configuration, and cost must be considered in making these tradeoffs.

For this phase, better production cost estimating techniques are needed. These techniques must be sensitive to design changes, and material changes. There are two basic approaches to developing these techniques. One approach is known as the industrial engineering method. With this method, the system is broken down into its lower level components, and cost estimates at the component or subassembly level are made. The results are then combined with the cost of integrating the components to arrive at a total system cost. This method is preferred, but is difficult to apply because of the knowledge required of the system characteristics and their effect on the design at the component level. The other approach is the parametric method. This method depends on establishing relationships between physical and performance characteristics of the system, and aggregate cost. The deficiency of the parametric method is that the cost estimating relationships developed, based on previous systems, may not be predictive of new systems.

Operational Phase

Looking forward in time from the feasibility phase to the operational phase poses numerous problems and makes estimating cost associated with the operational phase hard to do. There are several reasons for this difficulty. First, one must project 15 to 20 years into the future. Extrapolating economic conditions and the operational use of the weapon system, is difficult. Second, identifying all the maintenance and support cost elements, and establishing a data base for these cost elements are difficult. However, some "cost-drivers" in this phase are apparent. Fuel cost, which has risen from 10.7¢ per gallon in FY73 to over 37¢ per gallon in FY75, has become a major cost consideration, particularly for transport aircraft. Projections for future fuel costs are even higher. Maintenance cost is also an important cost category. Historical data have shown that maintenance cost is initially high with the introduction of a new engine into the inventory. As maintenance deficiencies are identified, corrected, and incorporated into the inventory, the maintenance cost will drop. In addition, the maintenance cost for a mature engine will fluctuate with time. These facts must be taken into account when using historical data as the basis for the cost estimates. Fuel consumption, and maintainability of the engine, are "cost-drivers" and must be considered from the inception of the engine design.

Conclusion

The need to reduce the LCC of weapon systems is clear, the challenge is great. LCC is a multi-specialty field. It involves the disciplines of several engineering specialties, as well as logistics, operations, management, and finance. Cost has become an integral part of R&D engineering. It must be considered in the laboratory advanced technology programs, when the design can be easily changed to achieve reduced cost payoff. The laboratories can make a vital contribution to reducing LCC.

Reference

[1] Reel, R.E., Totey, C.E., Johnson, W.L., "Weapon Systems Support Cost Reduction Study," June 1972, Report ASD/XR 72-49, Aeronautical Systems Division, Wright-Patterson AFB, Ohio.

Analysis of Circulation Controlled Airfoils

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A CIRCULATION controlled airfoil is an airfoil with a bluff trailing edge with tangential blowing in a downstream direction, from a slot on the upper surface near the trailing edge (Fig. 1). Experiments by Kind,[1-3] Walters et al.,[4] and Englar[5] have shown that such an airfoil can produce high lift coefficients for low blowing rates. Circulation controlled airfoils produce high lift coefficients because the Coanda effect enables the wall jet to follow the contour of the convex curved rear portion of the body. It is possible under the proper blowing conditions to move the rear stagnation point to the underside of the body. The result is a significant increase in circulation and lift.

Theories have previously been advanced for circulation controlled airfoils. The first theoretical investigation was made by Dunham,[6] improved upon by Kind,[1-3] and improved further by Ambrosiani and Ness.[7] The Kind theory required for its application experimental static pressure distribution in the turbulent wall jet region (Fig. 1) while the Ambrosiani and Ness analysis was directed towards a self-contained approach without recourse to any experimental data. The latter work applied only to elliptical airfoils. More recently, Gibbs and Ness[8] have extended the work of Ref. 7 to arbitrary shaped airfoils and have introduced additional refinements.

The required input for the latter analysis are: the airfoil geometry, the angle of attack α, the freestream Reynolds number $Re_\infty = V_\infty c/\nu$ (where V_∞ is the freestream velocity, c the airfoil chord, ν the kinematic viscosity), and the sectional lift coefficient c_ℓ.

With the input prescribed a potential flow analysis is performed. The Theodorsen method[9] is used. The potential flow analysis provides the location of the forward stagnation point, the rear (potential flow) stagnation point, and the velocity and pressure on the airfoil.

A boundary-layer analysis is then performed for the lower surface of the airfoil. The analysis starts at the forward stagnation point and proceeds downstream until separation (laminar or turbulent) occurs. The pressure coefficient at this separation point, designated $c_{p_{sep,\ell}}$, is then known from the potential flow analysis. The Cebeci and Smith finite-difference method[10] is used for the boundary-layer analysis.

A boundary-layer analysis is then performed for the upper surface of the airfoil. The analysis starts at the forward stagnation point, is initially laminar but, because of the prevailing pressure gradient, usually becomes turbulent

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