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.

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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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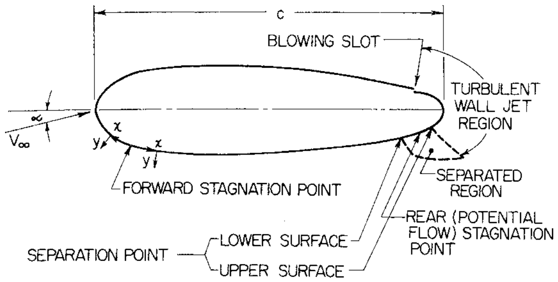

Fig. 1 Main features of a circulation controlled airfoil.

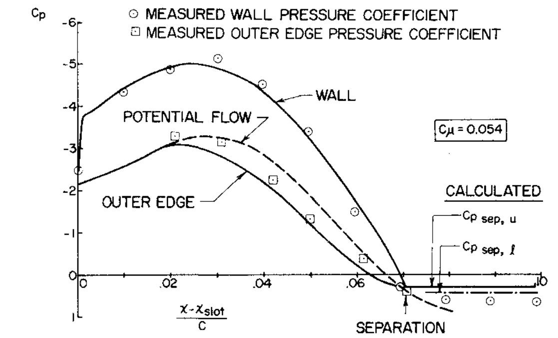

Fig. 2 Comparison of calculated and measured wall jet pressure distribution.

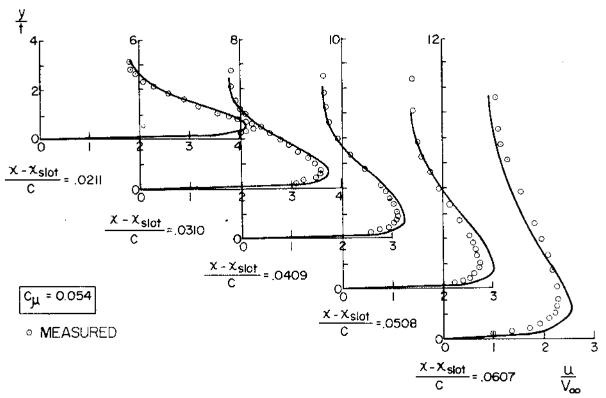

Fig. 3 Comparison of calculated and measured wall jet profiles.

before reaching the blowing slot. If the boundary layer separates upstream of the blowing slot, calculations are terminated. If the boundary layer remains attached at the slot, this analysis provides the boundary layer properties at the slot. For this portion of the analysis, the Cebeci and Smith method[10] is used.

An analysis is then performed for the turbulent wall jet region. A slot blowing momentum coefficient c_μ is assumed where

$$c_\mu = (\rho_j \int_0^t u^2 \mathrm{d}y)/(½)\ (\rho V_\infty^2 c)$$

where t is the slot thickness, c is the chord, ρ_j the slot fluid density, u the slot fluid velocity, and ρ the freestream density. The analysis begins at the blowing slot and proceeds downstream until separation occurs. At separation, the pressure coefficient, designaged $c_{p_{\mathrm{sep},u}}$ for upper surface separation, is determined and is compared to $c_{p_{\mathrm{sep},\ell}}$. The Thwaites condition[11] requires a constant pressure on the body in the separated region and is satisfied in the analysis by an iteration on c_μ. The calculations indicate a high sensitivity between c_μ and $c_{p_{\mathrm{sep},u}}$ which means that the turbulent wall jet region should be analyzed as accurately as possible.

The major effort in Ref. 8 involves the generation of a self-contained analysis for the turbulent wall jet region. This region involves the merging of an upstream boundary-layer profile with a blowing slot profile in a region where the radius of curvature of the body R is of the same order of magnitude as the boundary-layer thickness Δ. Pressure gradients across the flow as well as along the flow result. The turbulent wall jet system of equations are solved by a finite-difference method based on the Keller and Cebeci method.[12]

Calculations were performed to compare the present theory with Kind's test data designated Flow II.[1-3] Kind's airfoil was a 20% thick ellipse with the trailing edge replaced by a circular arc of 9/16 in. radius. The chord length $c = 14\frac{5}{8}$ in. and a blowing slot was located on the upper surface at the junction of the ellipse and the circular arc. Test conditions were: $Re_\infty = 7.5 \times 10^5$, $\alpha = -0.7°$, $c_\ell = 1.82$, $c_\mu = 0.055$. Kind provided experimental velocity profiles both upstream and downstream of the blowing slot and, also, the surface pressure distribution downstream of the slot. The calculations used the Kind test conditions for Re_∞, α, c_ℓ, c_μ as input and compared the resulting theoretical velocity profiles and wall jet pressure distribution with Kind's experimental data.

Figure 2 compares calculated and measured pressure distributions in the wall jet region, and indicates the calculated upper surface separation point. Calculated and measured upper surface separation points are in reasonably good agreement at $[(x - x_{\mathrm{slot}})/c] = 0.0706$ and 0.0711, respectively, as are the separation pressure coefficients. The calculated and measured pressure distributions are in reasonable agreement, although there is some discrepancy in the pressure gradients over the latter portion of the wall jet region.

Figure 3 compares calculated and measured wall jet velocity profiles. The agreement for the outer portion of the flow is good, while the agreement for the inner region is fair. Part of the disagreement is due to discrepancies in the calculated pressure gradients and outer edge velocities over the latter portion of the wall jet region. For $[(x - x_{\mathrm{slot}})/c] > 0.05$, pressure effects are comparable to shear stress effects, and the inner portion of the velocity profile is thus sensitive to the wall pressure gradient. Although there is room for improvement, the results are encouraging considering the complexity of the turbulent wall jet region.

In conclusion, a self-contained analysis for arbitrary shaped circulation controlled airfoils in incompressible flow has been developed. The theoretical model provides reasonable agreement with limited test data.

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