will be taken, equivalent to maximum takeoff wing loading around 6000 Pa.

Let us now apply the former values to two different situations, namely $\beta = 0$ and $\beta = 0.5$. Imposing a flight altitude of $h = 35{,}000$ ft and following Eqs. (6) and (7), the designer in the first case will try to fly at the typical cruise point where

$$M_{cr} = 0.93 \qquad C_{Lcr} = 0.35 \tag{11}$$

On the other hand, for the same long-range condition but $\beta = 0.5$, the second designer will find

$$M_{cr} = 0.80 \qquad C_{Lcr} = 0.47 \tag{12}$$

which are much closer to the common figures for medium haul transport airplanes. In this sense it must be recalled that Torenbeek[12] advises a first approximation of $0.17A^{1/2}$, here providing $C_{Lcr} = 0.48$.

It is reasonable to argue that the first designer will guess that he must shift flight conditions towards more common numbers, for example by increasing the aspect ratio of wing within realistic limits, say up to $A = 9.5$. The new long-range cruise would be at

$$M_{cr} = 0.89 \qquad C_{Lcr} = 0.38 \tag{13}$$

As shown here, the improvement is very poor and, moreover, any attempt to fly above $M = 0.8$ will undoubtedly find compressibility effects, counteracting the gain.

The implications of all these mistakes can be clearly described by means of Fig. 2. After abandoning the unrealistic top point, the first designer (the one assuming $\beta = 0$) believes that the airplane will operate on the dashed area, meanwhile the truth is that his aircraft is doing something worse, by some 7–10%, more or less around the pointed region since the specific fuel consumption is higher than expected.

Final Comments

Consideration of Mach number effects on specific fuel consumption during initial airplane design is important because these effects lead to improved accuracy and possibly to more realistic results; errors involved in the range parameter, through inappropriate values of β, are high enough for concern. On the other hand, these errors do not present an obstacle to the range equation which, as shown, can be treated and integrated analytically.

Two main assumptions have been made in the model: constant polar parameters and constant flight altitude. The first one seems to be an adequate hypothesis when flying in long-range conditions, since the Mach number is then well below the drag divergence value. Such simplification would not hold for high-speed cruise, but this is beyond the scope of the present study. Analogously, although the greatest fuel economy must be made through cyclic cruise and optimum trajectories, each cruise segment, obliged by air traffic control at constant altitude, could be analyzed in the above manner.

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Advanced Pneumatic Impulse Ice Protection System (PIIP) for Aircraft

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Introduction

THE modern pneumatic deicer is designed with a stretchable fabric-reinforced elastomer surface, specially compounded for weathering and erosion resistance. The surface distorts considerably when pressurized, serving to debond the ice under the combined influences of shear and peel, and to break the ice cap into pieces. The removal process is augmented by the scavenging airstream (see Fig. 1).

It is generally conceded that the principal advantages of a conventional pneumatic deicer, as compared to other systems, are its low weight, low cost, and adaptability and retrofitability to many types of aircraft, as well as the fact that it is a known, reliable performer.[1,2]

Despite the wide acceptance and long history of pneumatic deicers, some changes in design requirements have been suggested. For example, ice-sensitive airfoils and applications where engine ice ingestion are a concern generally require thin ice-shedding capability and small ice-particle shed size. In some cases ice as thin as 0.030 in. or as small as 0.25 in. equivalent particle diameter may be required to be shed. Since most mechanical ice removal systems shed thick ice more effectively than thin; the "thinness" of the ice becomes a measure of system performance. Requirements for rain erosion longevity and prolonged resistance to the elements for many applications may dictate a metal or plastic rather than an elastomeric surface. Finally, the fact that the typical pneumatic deicer is a "skin-bonded" article is often objectable; an aerodynamically nonintrusive system that allows the original airfoil design to be maintained is often required.

In 1984, an advanced type of pneumatic deicer was conceived at BF Goodrich. The desired improvements listed above became performance objectives for the new system.

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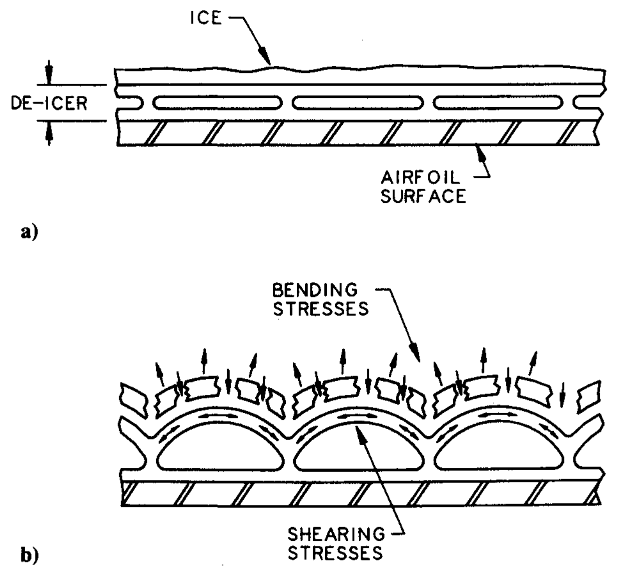

Fig. 1 a) Deflated pneumatic deicer and b) inflated pneumatic deicer.

The new ice protector relies not only on distortion of the surface to debond accreted ice, but also on rapid movement of the surface to "launch" the ice. Surface displacements, typically 0.030–0.050 in., are obtained in as little as 50 μs. The surface itself is a thin material overlying a flexible, thermoset plastic matrix. The matrix contains flat fabric-reinforced "tubes" which, when rapidly pressurized with air, expand slightly, affecting the desired displacement of the surface.

The erosion surface, matrix, and spanwise-running tubes comprise the active, ice-moving portion of the leading edge. This article may either be bonded to a metal leading-edge skin, in a manner similar to conventional pneumatic deicers, or backed with reinforced-epoxy composite structure. The latter construction may be cured in a female tool built to the airfoil design contour, resulting in a lightweight, nonintrusive metal or plastic surfaced, stand-alone composite leading-edge structure with the deicer built in. This stand-alone composite leading edge may then be attached to the afterbody with mechanical fasteners in a manner similar to conventional aluminum leading-edge skins. The system has been labeled pneumatic impulse ice protection (PIIP). A comparison of attributes vs conventional pneumatic deicers is shown in Table 1.

PIIP System Description

A PIIP system schematic is shown in Fig. 2. High-pressure air (400–1500 psig nom.), either generated onboard the aircraft with a small compressor or tapped from an existing high-pressure system on the aircraft, is the source of the impulse. This air is supplied via small-diameter tubing or hose to one or more impulse generation valves, located in the vicinity of the surface to be protected.

The rapid pressurization of the impulse tubes "snaps" the surface outward, introducing chordwise tension and bending. The ice is primarily debonded by the resulting shear stress developed at the ice/surface interface; however, it has been found that simply debonding the ice is not always sufficient to ensure its removal. The experience of numerous icing tunnel tests has shown that for a low deflection system it is necessary to "launch" accreted ice from the surface in addition to debonding. This is achieved by imparting a sufficient amount of momentum to the ice by rapid outward movement of the surface, followed by a sufficiently large deceleration of the surface to allow the inertia of the ice to overcome any residual adhesive forces.

The system will generally be operated on either a fixed time cycle basis, in which the valves are sequentially and symmetrically actuated by the controller at repeated time intervals while the system is "on." Initiation of the system may be by cockpit command or by input to the controller from a remote ice detector.

Table 1 Comparison of PIIP and pneumatic deicers

	PIIP	Standard pneumatic
Surface stain, typical, %	0.1–0.2	30–40
Displacement, in.	0.030–0.050	0.25–0.38
Inflation time, s	0.000050	0.5–6
Source pressure, reg., psi	400–1500	18
Surface material	Metal/plastic	Rubber
Weight, psf	0.37	0.44
Mounting	Integral	Usually skin-bonded

Table 2 Typical PIIP compressor parameters

Drive	Hydraulic
Weight	21 lb
Envelope	12 × 9 × 11 in.
Hydraulic consumption	1.6 gpm @ 3000 psig (Skydrol)
Power	3 hp

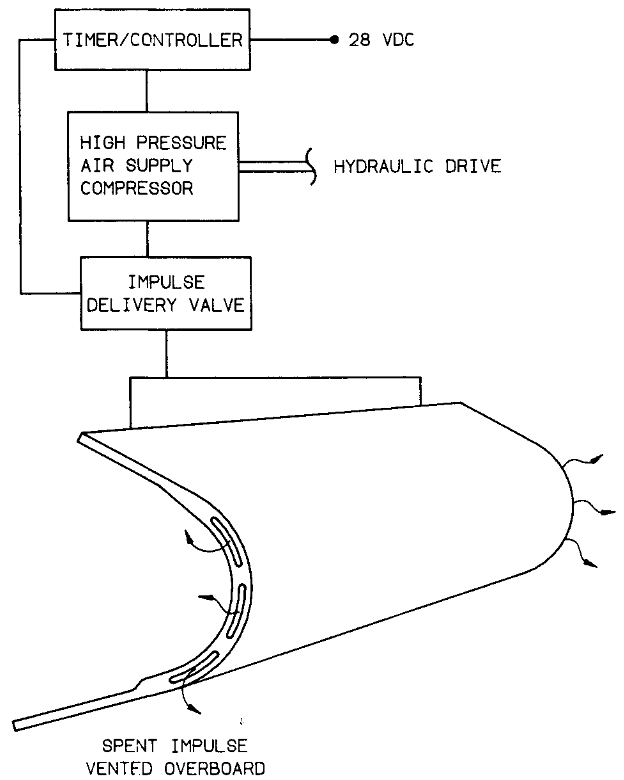

Fig. 2 Pneumatic impulse ice protection system schematic.

For most applications a dedicated onboard compressor or air intensifier is required to provide source air for the system. The compressor may be either electric or hydraulic motor-driven, the hydraulic option being the lower weight approach if the aircraft hydraulic system can support the flow required. Table 2 lists estimated compressor size and power requirements for a typical commuter application.

Icing Test History

The first icing tunnel tests with PIIP were conducted in 1985 in the diffuser section of the NASA Lewis Icing Research Tunnel (IRT) in Cleveland. These tests were with a rubber matrix, polyetheretherketone (PEEK)-surfaced deicer bonded to an aluminum leading edge. Ice removal performance on the order of 0.10 in. was obtained, indicating sufficient promise to warrant further development of the system.

The first natural flight test of the system was conducted in March 1986 on Cessna's 208 Caravan, a single-engine turboprop.[3] Testing was conducted over the northern plains of the midwest, but due to the lateness of the icing season only three test flights were made. For these tests as well as the NASA IRT tests, an early version of the system was configured. PEEK-surfaced, rubber matrix deicers were installed on the right inboard wing (approximately 12.5 ft long) and on the right strut (approximately 8 ft long), in place of the standard pneumatic deicers. The ice protectors were configured with a single leading-edge tube located over the leading-edge centerline, and were bonded to the aircraft's leading edge skin in a manner similar to conventional pneumatic deicers. Thickness of the ice removed was typically 0.25 in. or greater, with some thin ice removal noted in the vicinity of the impulse entry ports. The testing underscored the need to tailor tube size and location to the specific airfoil geometry.

It was desired to make the PIIP system available for commercial aircraft, as a low-power alternative to bleed-air. The PIIP surface, while suitable for many applications, did not possess the rain erosion resistance required for commercial aircraft, and was therefore replaced with titanium in 1986.

A number of tests were conducted in Lockheed's icing tunnel in Burbank in late 1986 and 1987. Articles for these tests were titanium-surfaced, but still contained a rubber matrix and were bonded over metal leading-edge skins. These tests series revealed difficulty with the system in removing "slush" ice.

Since this test series, development of the system has focused on tailoring the surface dynamics in order to be able to remove effectively the difficult thin and wet ice. At the same time we have moved away from an external, skin-bonded construction toward a nonintrusive composite leading-edge embodiment, in which the ice protector and the leading-edge skin are integrally cured into a single leading-edge structure. The rubber matrix of the ice protector was replaced with a tough, flexible thermosetting plastic resin. Rain erosion testing of the new composite leading-edge construction using titanium skin demonstrated over 7 h @ 600 mph, in 1 in. per hour of rain, and 2-mm-diam. drops, with no damage. This far exceeds the rain erosion longevity of conventional aluminum leading-edge skins.

The 1988 activity culminated in a week of testing in the IRT at NASA Lewis Research Center. The system demonstrated 0.040-in. threshold thickness shedding capability in "dry" ice conditions and 0.090-in. shedding capability in wet ice or "slush" conditions.

Subsequent testing at the BF Goodrich Icing Tunnel as well as the NASA IRT of improved versions have demonstrated the low power requirements,[4] ease of intallation, and durability of PIIP. Life cycle tests have demonstrated in excess of 250,000 cycles on the ice protector and 2,000,000 cycles on the impulse valve, equivalent to the life of the aircraft on a commuter application.

Concluding Remarks

Over the last several years, there has been under development a new impulse-type mechanical ice removal system. This system is considerably different from other dynamic systems in that a pneumatic rather than an electrical impulse is imparted to the ice-accreting surface to remove accumulated ice. The system has demonstrated the capability to remove ice accumulations as thin as 0.030 and as small as 0.25 in. equivalent particle diameter,[4] rendering it viable for ice-sensitive airfoils and engine inlets, while retaining the capability to remove thicker ice of over 1 in. Life cycle tests have demonstrated long life capabilities, estimated to be equivalent to the service life of a commuter aircraft and more. Applications being studied for PIIP include: airfoils, tailplanes, and engine inlets for military, commercial, commuter fixed-wing or rotorcraft. PIIP is now being viewed as a replacement for the currently used gas turbine-generated bleed-air ice protection system.

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Minimizing Supersonic Wave Drag with Physical Constraints at Design and Off-Design Mach Numbers

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Introduction

SINCE the concept of supersonic area rule was introduced[1,2] the area-rule method has been the most successful and systematic method for the arrangement of vehicle components and the determination of the vehicle area distribution for minimum wave drag at a particular Mach number.

To date, the most widely used computer program incorporating the area-rule method is the Harris code, written by the Boeing Company and reported in Harris.[3] A useful feature introduced by Sheppard[4] for designing the fuselage area distribution with minimal wave drag was built into the Harris code. However, several drawbacks exist in Sheppard's design procedure.

1) It has no control on the difference between the volume of the baseline and optimum fuselage. This may give the volume of the optimum fuselage to be much less than a required value.

2) The "control points" on the fuselage impose the constraints that no area change at those points is allowed on the optimum fuselage. However, in most design situations, the area at these points may be allowed to change, but within an upper and lower bounds.

3) Sheppard's design procedure only gives the optimum area distribution at design Mach number. Therefore, among all area distribution and Mach number pairs, the designers may have to find a compromised solution by a trial-and-error procedure so that the performance at off-design Mach numbers are not drastically inferior.

4) In many design situations, only a particular section of the fuselage is allowed to be modified for the minimum wave drag. Sheppard's design procedure gives the area distribution along the whole aircraft only.

With the advent of super-speed computers and a general-purposed optimizer,[5] the above drawbacks in the Harris code can be solved by coupling itself with an optimizer and for-

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