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Parametric Optimization of Manufacturing Tolerances at the Aircraft Surface

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Up until now, aircraft surface smoothness requirements have been aerodynamically driven with tighter manufacturing tolerance to minimize drag, that is, the tighter the tolerance, the higher is the assembly cost in the process of manufacture. In the current status of commercial transport aircraft operation, it can be seen that the unit cost contributes to the aircraft direct operating cost considerably more than the contribution made by the cost of block fuel consumed for the mission profile. The need for a customer-driven design strategy to reduce direct operating cost by reducing aircraft cost through manufacturing tolerance relaxation at the wetted surface without unduly penalizing parasite drag is investigated. To investigate this, a preliminary study has been conducted at 11 key manufacturing features on the surface assembly of an isolated nacelle. In spite of differences in parts design and manufacture, the investigated areas associated with the assembly of nacelles are typical of generic patterns in the assembly of other components of aircraft. The study is to be followed up by similar studies extended to lifting surfaces and fuselage. Parametric tradeoff study involving manufacturing cost reduction and parasite drag rise indicates that, in general, there is scope for some tolerance relaxation from the current allocation to an optimum to maximize direct operating cost saving. For a short/medium range mission profile, it was found that tolerance allocation relaxed to an optimum could reduce direct operating cost by 0.421%. The results offer considerable insight to a relatively complex problem in a multidisciplinary environment. The findings lay a foundation for future work on design for manufacture for assembly embracing wider areas of study as a business strategy to lower cost of production.

Nomenclature

C_D	=	drag coefficient (based on wing area)
$C_{D_{p\,\min}}$	=	minimum parasite drag
P	=	profile waviness

Subscripts

n	=	placed normal to flow
p	=	placed parallel to flow

Introduction

FROM the market trend and forecast analysis of the early 1990s, one major concern that emerged in the commercial aircraft industry was to tackle inflation in the free market economy by addressing the issues of aircraft manufacturing cost. Airline operators conveyed to the aircraft manufacturers that unless the aircraft acquisition cost was lowered by a substantial margin, growth in air traffic volume would prove difficult. In addition to this stringent demand, there was a fierce competition amongst aircraft manufactures and their subcontractors. Since the mid-1990s, all major manufacturers started implementing cost cutting measures and translated the same message to their subcontracting industries. As one cost cutting measure, Bombardier Aerospace-Shorts took the initiative in 1996, in collaboration with the Queen's University of Belfast, to undertake a U.K. government- (Engineering and Physical Sciences Research Council) funded project. This paper is the outcome of the project.

Aircraft unit cost is directly related to the manufacturing tolerances, that is, the tighter the tolerance, the higher is the aircraft acquisition cost. The aircraft direct operating cost (DOC), in turn, depends more on the aircraft acquisition cost, that is, unit price, than on the cost of fuel consumed for the mission profile. Aircraft unit cost-dependent DOC components are 1) maintenance, 2) depreciation, 3) interest, and 4) insurance. Today, for the majority of mission profiles, fuel burn constitutes between 10 and 20% of the DOC, whereas aircraft unit price contributes between three and four times as much, depending on the payload range.[1,2] A typical DOC breakdown, using Association of European Airlines (AEA) rules, for a 150 passenger subsonic jet transport aircraft flying over 2800 n mile is given in Fig. 1. Figure 2 shows the effect of range variation on DOC components up to 3000 n mile. This is the typical trend reflected by the bulk of airlines' fleet. The trend is still the same for long-range (6000 n mile) aircraft of the Boeing 747/Airbus A340 class.

The change of scenario from escalating fuel price during the 1970s and the 1980s to inflationary economics accompanied with high work-hour rates during the 1990s demanded new measures, that is, the aircraft manufacturing cost must reduce to achieve lower DOC.[3] This new factor forms the basis for the investigation reported in this paper. Fuel cost is still below that of the 1980s despite recent increases in the cost of crude oil.

The manufacturing tolerance allocations for aerodynamic surfaces at the assembly joints are generated from the specifications laid down by aerodynamicists to minimize aircraft parasite drag, that is, to reduce fuel burn. One of the reasons for parasite drag increase is the degradation of the surface smoothness qualities by, for example, the discrete roughness on the component parts and at their subassembly joints, seen as aerodynamic defects, collectively termed as one of the excrescence effects, typically, 1) mismatches

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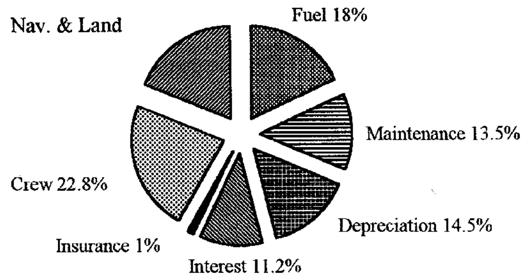

Fig. 1 DOC breakdown.

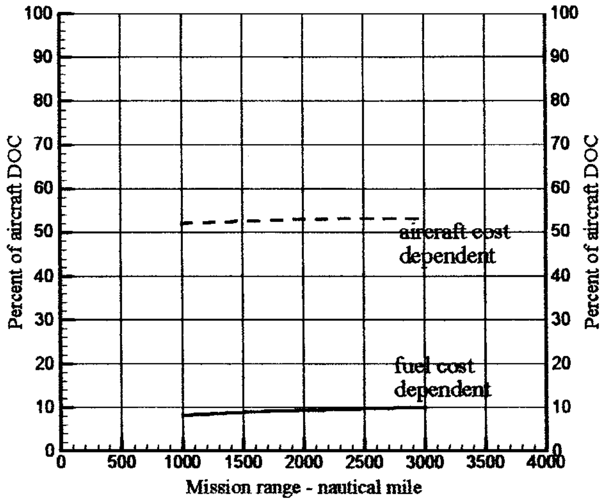

Fig. 2 Effect of range on DOC.

(steps, etc.), 2) gaps, 3) contour deviation, and 4) fasteners (rivets, etc.) flushness on the wetted surfaces. Excrescence drag arising out of these aerodynamic defects is of a considerably lower order of magnitude than the total drag of the aircraft. With today's manufacturing standards, with proper tolerance allocation, the excrescence drag due to surface roughness can be reduced to rather small but significant values of the order of 2–3% (Ref. 4) of the aircraft parasite drag at cruise condition.

There is little information disseminated on cost implication arising out of tighter tolerance specified by aerodynamicists. The tolerance relaxation tradeoff study between aircraft parasite drag increase (loss of quality function) and manufacturing cost reduction (gain) offers scope to lower the aircraft cost, thereby reducing the aircraft DOC from the current level. The tradeoff reported here shows parametric optimization in a multidisciplinary environment, involving fluid mechanics (nacelle flowfield), aircraft aerodynamics (drag estimation), performance analysis (DOC), manufacturing/tooling philosophy, and costing.

This finding stresses the need for a multidisciplinary approach to design, at the conceptual stages of project development in a concurrent engineering environment, to take advantage of possible tolerance relaxation. Also the findings will strengthen the case for industry standardization of aircraft surface smoothness requirements for the generic class of aircraft components, benefiting the customers, who could be subcontracting component manufacturers. Moreover a foundation is laid for future work on design for manufacture for assembly (DFMA) embracing wider areas, for example, material selection, structural detailed design, new manufacturing processes, etc., to accommodate the benefits achieved through the possible revision of aerodynamic surface smoothness requirements as a customer-driven business strategy.

Background

Since the time of the first flight by the Wright brothers, the importance of improving aircraft drag estimation methodology and the quest for drag reduction have been technology drivers. While aircraft drag estimation methodology matured, the importance of excrescence drag estimation methodology trailed behind. The first evidence of experimental investigation of these relatively unattended areas was in 1929,[5] followed by more experiments by Williams and Brown[6] in 1937 and Young et al.[7] in 1939. In Germany, Wieghardt's[8] work in the early 1940s may be considered as the starting point of a systematic investigation on discrete surface roughness. Subsequently, Gaudet and Johnson[9] and Gaudet and Winter[10] carried out experimental work to higher Reynolds numbers. An important discovery by Nash and Bradshaw[11] demonstrated that the effect of pressure gradient has a magnification factor over the results at zero pressure gradient. Hoerner[12] collated all works on drag (including excrescence effects) up to the early 1960s. Bertelrud[13] provided a more recent review on the topics, reinforcing the need to give more attention to minimizing aerodynamic defects.

Haines,[14] in his classical paper of 1968, gave an appreciation of subsonic aircraft drag, comparing postwar progress to prewar technology. To reduce drag, he pointed out that one of the many areas that needed attention was that of surface imperfections. A breakdown of drag sources on a number of transport aircraft reviewed indicate contributions from surface imperfections and other types of excrescence varying from 15 to 24.5% of parasite drag, which probably represents 10–15% of cruise drag. As much as nearly half of this could arise from surface assembly during manufacture. The drag savings by reducing excrescences, though small, are significant enough to offer competitiveness in a customer-driven market.

A detailed analysis of drag effects by Kranczock[15] on the small transport aircraft VFW614 shows 22% of the parasite drag is because of all types of excrescence effects, a magnitude in line with what Haines[14] found. A study by Peterson et al.[4] shows that with proper manufacturing tolerances, the skin roughness drag can be reduced to a rather small but significant value, for example, in the case of Lockheed C5 it is 3.5% of cruise drag. In the 1970s, when fuel price increased suddenly, fuel savings to reduce DOC by drag reduction became an important consideration for commercial aircraft design. This logic prevailed until the 1980s. The Boeing Company's program to control excrescence drag is found in Ref. 16.

Progress in aerodynamics, as a matured technology, showed diminishing returns. As escalating inflation reflected high work-hour rates in the developed countries and as fuel price stabilized, market-driven economics became the dominant factor for aircraft design. Rubbert[3] of The Boeing Company commented on the approach to aircraft design: "The old technology driven strategy is being replaced by one based on being 'market driven' and 'customer driven.'. . .the new measure of goodness is whether or not it adds value as seen from the eyes of a customer" (italics added). In the context, the old technology-driven strategy means aerodynamic drag reduction (seen as a quality function) whereas customer driven suggests looking into reducing aircraft price (cost function) to reduce ownership cost, that is, the DOC.

Experimental results and semi-empirical relationships, to estimate excrescence drag of surface irregularities on flat plates, are incorporated in ESDU[17] datasheets and are not valid where there is separation, a phenomenon which can be quite serious if a local shock is present. Little experimental data are available on three-dimensional excrescence drag in pressure gradient. A comprehensive review of the state of the art on excrescence drag has been compiled by AGARD.[18] To broaden the scope of estimating excrescence drag on aircraft components, Kundu et al.[19] assessed the use of computational fluid dynamic (CFD) methods. Results on elementary defects, such as two-dimensional steps at cruise conditions, show deviation of ±20% from the experimental results. CFD has not proved to be a satisfactory method for estimating excrescence drag.

In cruise, aircraft wetted surfaces generating aerodynamic drag are primarily manufactured from sheet metals/composites. In present day manufacturing philosophy at assembly, the following are the main features contributing to excrescence (parasite) drag in shaping sheet metals/composites: 1) control of leading-edge profile and surface panel profiles (wing/flaps/empennage, etc.), 2) control of profile of bodies of revolution (fuselage/nacelle, etc.), 3) rivets/fastener flushness for skin joints, and 4) component surface geometry, subassembly joints, and access panel fitment mismatches.

Defects normal to freestream airflow are in the majority, and their contribution is dominant over those placed parallel. On swept surfaces, the joints could remain inclined (in general less than 30 deg) to the freestream flow. However, for initial analysis these few inclined joints are considered normal to the airflow. Gaps and alignment deviations between two relative moving components, for example, flaps, ailerons, etc., have not been studied. For the present study, problems arising out of the tolerance chain buildup due to relaxing the limits are not taken into account. It was considered that the sheet metal/composite at the surface would accommodate a certain degree of tolerance relaxation, at the cost of, possibly, losing some cosmetic appeal. Typical aerodynamic defects, as discrete roughness associated with the key features, are steps, gaps, fastener flushness, and contour deviation, placed normal or parallel to the freestream airflow as shown in Fig. 3. About 10% of rivets are expected to be reworked. Those standing high are easy to rework by grinding, practically at no cost.

Analysis

To give an insight to this complex multidisciplinary aircraft design process, the paper limits the study to an isolated long duct nacelle as a single manageable entity without having to consider the effects of interference of other bodies. The importance of the aerodynamic design of aircraft nacelles is second only to that of wing design and represents all of the flowfield characteristics of lifting surfaces (wing, empennage, pylon, etc.) as well as that of an axisymmetric body, for example, fuselage. Although it is true that the structural design philosophy of each of the aircraft components, for example, wing, fuselage, nacelle, etc., differs, making parts manufacturing process also differ, the tooling philosophy for assembly is of a generic nature, conventional in approach. It is for this reason, for a preliminary analysis of this complex multidisciplinary investigation, that the results thus obtained for nacelle assembly are applied to the assembly consideration of all other components of the entire aircraft. Future studies will include the investigation to parts manufacture of wing, fuselage, etc., for an appropriate DFMA study.

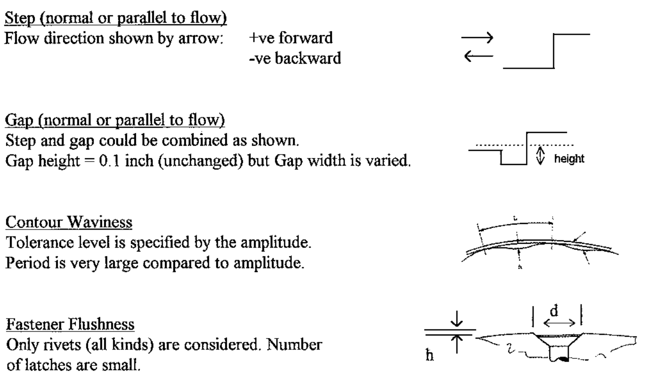

Fig. 3 Surface excrescence at the key manufacturing features.

Tolerance/Key Features

The main components of the nacelle, along with the 11 key features affecting excrescence drag, are shown in Fig. 4. The tolerance allocation at each feature is given in Table 1. The nacelle geometry considered is symmetrical about the vertical plane. All but features 7 and 8 are concerned with steps and/or gaps.

Excrescence Drag

In current industrial practice, the excrescence drag is estimated using semi-empirical ESDU methods derived from experiments done on two-dimensional flat plates in zero pressure gradient and backed up by related theories. The two-dimensional experimental results are semi-empirically corrected to three-dimensional values for the nacelle. The mission profile at long-range cruise (LRC) studied here minimizes shocks and separations, and as a design consideration, the joints are placed away from critical areas for all aircraft components. One of the main difficulties to estimating excrescence drag is the very small excrescence dimension as compared to the component geometry. The physical dimension, for example, step height, is of the order of less than 3% of the boundary-layer thickness (above the viscous sublayer); the degree of variation depends on where it is placed. Feature by feature, the excrescence drag increment is computed as percent of nacelle $C_{D_{p\,\min}}$.

Aerodynamic defects such as steps and gaps are not uniform throughout the entire length of the joint. In practice, almost all features exhibit, on average, half of the specified tolerance range (difference between upper and lower limits). For steps, if both forward and backward facing types are involved, then 90% of the joint length is considered, the rest being considered close to the nominal dimension, as shown in Fig. 5.

Lipskin profile waviness amplitude to length ratio is of the order of 0.03, and the drag rise is estimated from Ref. 18. Only 10% of fasteners are considered to be reworked, out of which half will be

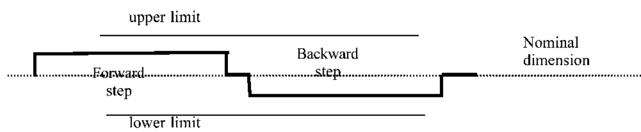

Fig. 5 Forward and backward step along the circumference at feature 1.

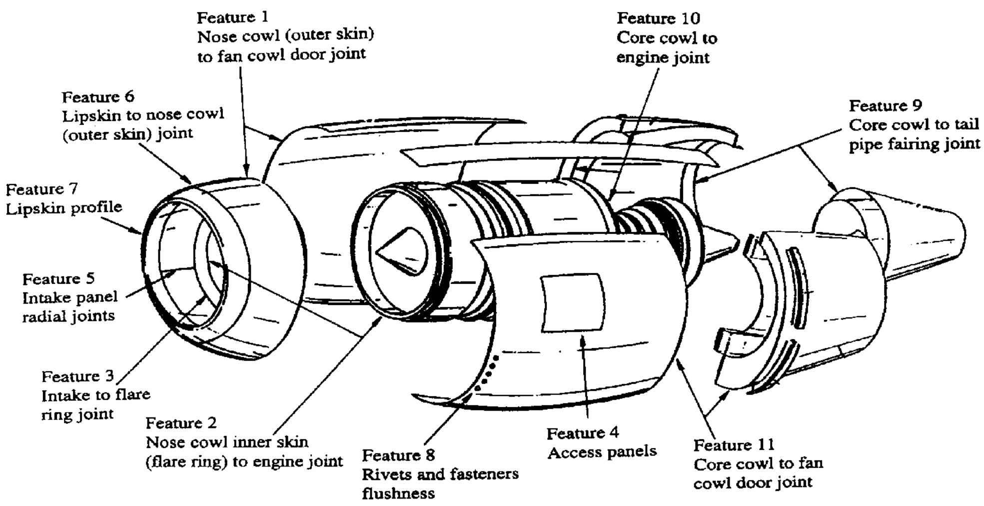

Fig. 4 Nacelle's 11 key features.

Table 1 Tolerance allocation

Feature (tolerance allocation)	Existing limit, in.	Relaxed (optimum) limit, in. (% increase)[a]	Drag increase as percent of $C_{Dp\,\mathrm{nac}}$	Savings as percent of nacelle cost
F1 ($0.04 \le \mathrm{gap}_n \le 0.13$)	0.09	0.109 (21.11)	0.0266	0.1878
F1 ($-0.06 \le \mathrm{step}_n \le 0.03$	0.09	0.1117 (24.1)	0.202	0.09336
F2 ($0.019 \le \mathrm{gap}_n \le 0.029$)	0.01	0.01678 (67.8)	0.01898	0.02433
F2 ($-0.015 \le \mathrm{step}_n \le 0.015$)	0.03	0.0416 (38.67)	0.0254	0.16318
F3 ($-0.03 \le \mathrm{step}_n \le 0.03$)	0.06	0.0753 (25.5)	0.0458	0.04316
F3 gap is sealed				
F4 ($0.025 \le \mathrm{gap}_n \le 0.06$)	0.035	0.0472 (34.86)	0.0091	0.07093
F4 ($0.025 \le \mathrm{gap}_p \le 0.06$)	0.035	0.05474 (56.41)	0.001967	0.077236
F4 ($-0.03 \le \mathrm{step}_n \le 0.01$)	0.04	0.0468 (17)	0.02	0.0396
F4 ($-0.015 \le \mathrm{step}_p \le 0.015$)	0.03	0.03445 (14.83)	0.000172	0.0392
F5 ($0 \le \mathrm{gap}_p \le 0.04$)	0.04	0.0518 (29.5)	0.00025	0.11451
F5 ($-0.03 \le \mathrm{step}_p \le 0.03$)	0.06	0.0723 (20.5)	0.000276	0.0706
F6 ($0.04 \le \mathrm{gap}_n \le 0.1$)	0.06	0.0801 (33.35)	0.038	0.22567
F6[b] ($-0.02 \le \mathrm{step}_n \le 0$)	0.02	0.0287 (43.5)	0.181	0.24161
F7 ($-0.268 \le \mathrm{waviness} \le 0.332$)	0.064	0.1 (56.25)	0.00785	0.1838
F8 ($-0.001 \le \mathrm{rivets} \le 0.003$)	0.004	0.006304 (57.6)	0.00475	0.041
F9 ($0.02 \le \mathrm{gap}_n \le 0.16$)	0.14	0.184 (31.43)	0.0194	0.1027
F9 ($-0.04 \le \mathrm{step}_n \le 0.02$)	0.06	0.0738 (23)	0.0321	0.1616
F10 ($0.02 \le \mathrm{gap}_n \le 0.12$)	0.1	0.1681 (68.1)	0.0434	0.02738
F10 ($-0.04 \le \mathrm{step}_n \le 0.02$)	0.06	0.08115 (35.25)	0.06528	0.09646
F11 ($0.02 \le \mathrm{gap}_n \le 0.18$)	0.16	0.2064 (29)	0.0276	0.12415
F11 ($-0.04 \le \mathrm{step}_n \le 0.02$)	0.06	0.0774 (29)	0.054	0.13235
Total			0.82393%	2.26%

[a]Limits indicate maximum, for example, for feature 1, step = 0.03 + 0.06 = 0.09 and gap = 0.13 − 0.04 = 0.09.
[b]Except at feature 6, all can have both forward and backward steps at the joint, wherever applicable. Feature 6 is allowed to have backward step only.

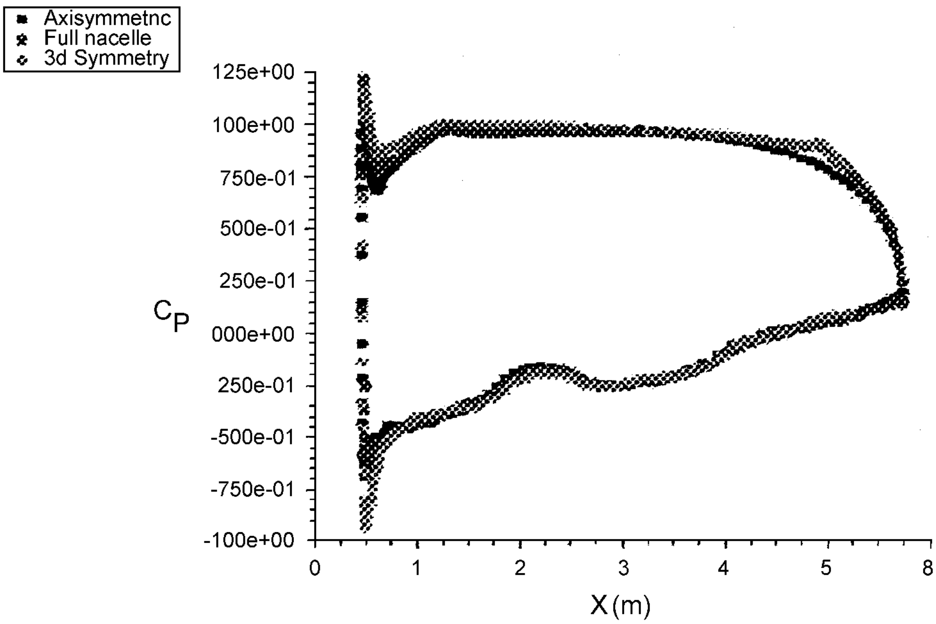

Fig. 6 Nacelle C_p distribution at mean half breadth.

standing out and, therefore, easy to be reworked flush to the skin by grinding.

Nacelle Flowfield

A knowledge of the nacelle flowfield, particularly the pressure gradient, is necessary to apply a magnification factor[11] to the two-dimensional excrescence drag. The nacelle flowfield (Fig. 6) at cruise is taken from the CFD results of Humphries et al.,[20] which is in agreement with Chen et al.[21] and Uanishi et al.[22] Being symmetrical in the vertical plane, the crown cut and keel cut generate local extreme values for the flight profile in the pitch plane. When symmetric in the vertical plane, the flowfield at the side cuts on both sides at the maximum half-breadth (MHB) is nearly identical. The flowfield at MHB represents the average condition blending between flowfield around the crown and keel sections.

Magnification Factor

The location of a feature on the nacelle is important to determine the magnification factor to be applied to the two-dimensional excrescence drag. The nacelle is divided into two zones, as shown in Fig. 7. Zone 1 is in the front end up to the fan face. The outer surface in zone 1 is in a favorable pressure gradient and has high velocities. Here, a magnification factor of 2–3 is used. The inside surface of zone 1 is the diffuser, where lower velocities permit no magnification effect. However, from the point of view of engine performance, care has to be taken not to perturb the engine flow.

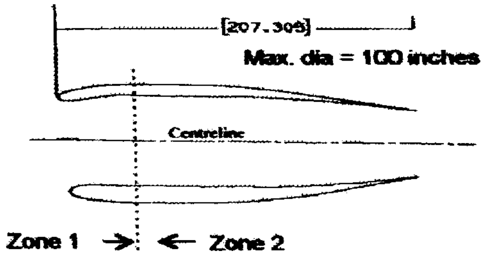

Fig. 7 Nacelle zones.

Zone 2 is at the aft end of the nacelle, where adverse pressure gradient keeps the magnification factor around 1. At LRC of 0.75 Mach, shocks are local (in zone 1 only) and are not close to any feature as stated earlier.

Manufacturing (Assembly) Consideration

The relation to establish manufacturing cost C at the assembly is given by the sum of all of the costs involved as shown next. To avoid part rejection, concession is required when rework to bring surface assemble within the tolerance is not possible: Assembly (manufacture) cost is equal to (basic work time plus rework time) multiplied by work-hour cost plus number of concessions multiplied by cost of concessions plus nonrecurring costs plus cost of support/redeployment/management.

Change in tolerance will affect rework time, number of concessions, and the cost of support. Tolerance relaxation would reduce assembly cost as more components and their assemblies become right-first-time. Soderborg[23] and Dong et al.[24] give methods for modeling cost vs tolerance relationships, but none of the examples are applicable to the components under study. In-house estimation of the cost vs tolerance relationship is worked out by Sanchez et al.[25] from the normal distribution of the defect population at each feature. Industrial data for both single component and the tolerance buildup at the assembly interface of each feature has been used. The results indicate trends comparable to those as shown by Soderborg[23] and Dong et al.[24]

About two-thirds of the aircraft price is considered to be due to the integral aircraft structure unit, that is, the empty shell[2] plus build units such as ducting, plumbing, linkages, undercarriage, etc. The rest are the bought-out items (engines and avionics). The nacelle structure is also with build units similar to the standards of integral aircraft structural unit for cost comparison and extrapolation. This price includes amortization of launch cost.

Component and assembly tolerance data and their relationship with assembly cost of the turbofan engine nacelle have been supplied by Bombardier Aerospace-Shorts. Note that assembly cost data are classified proprietary information and, therefore, are kept commercial in confidence. The paper uses nondimensionalized manufacturing cost data expressed in percent terms.

Aircraft Performance and DOC Estimation

The drag and cost variation with tolerance changes affect aircraft DOC. Aircraft performance and DOC were estimated using PIANO[26] software. Aircraft data representative of the class of the Airbus A320 were used for the analysis. The payload range for the mission profile is kept constant throughout the aircraft performance analysis. Excrescence drag affects only the parasite drag of the aircraft. The effect of changes in maximum takeoff weight (MTOW), operational empty weight (OEW), aircraft price, and DOC with respect to parasite drag changes is estimated. AEA[27] ground rules are adopted to evaluate DOC values. Tradeoff studies at each feature are made by incorporating drag and cost variation with tolerance relaxation. Parametric optimization suggests a new set of specifications for aerodynamic smoothness requirements to minimize DOC.

Results

LRC drag coefficient of the wing mounted twin turbofan aircraft based on the reference wing area of 1200 ft^2 (111.5 m^2) is estimated to be $C_D = 0.0308$ at 0.75 Mach and 36,089 ft (11 km). The aircraft payload range is 150 passengers and 2830 n mile. The C_D breakdown, weights summary, and other pertinent details are given in Table 2 (prices at 1997 level).

Table 2 Aircraft Details

Parameter	Value	Parameter	Value
Minimum parasite drag $C_{D_{p\,\min}}$	0.0211	MTOW	162,040 lb (73,500 kg)
Lift dependent drag C_{D_i}	0.0097	OEW	91,073 lb (41,310 kg)
(nonelliptical effects included)		Fuel	40,874 lb (18,540 kg)
Compressibility drag, C_{D_w}	0.00001	Fuel price	U.S. \$0.60 (1997 level)
Total C_D	0.0308	Aircraft price	U.S. \$47 million

Figure 8 shows the typical changes in nacelle drag, cost save, and cost to drag ratio with respect to tolerance relaxation for features 1, 7, and 8 (the rest of the features have similar trends and are not shown here). The optimum is where cost saving to drag rise ratio is maximum. The results are given in nondimensional form for proprietary reasons. Table 1 totals feature-by-feature percentage changes for one nacelle with a drag coefficient increment of 0.824% and a cost reduction of 2.26%. The contribution to parasite drag of two nacelles is $C_{D_{p\,\mathrm{nac}}} = 0.002$ ($\approx$ 9.5% of $C_{D_{p\,\min}}$).

Changes in drag and cost, as obtained from Table 1, are applied over the entire aircraft, that is, $C_{D_{p\,\min}}$ increases to 0.021274 (1.74 counts increase) and aircraft cost reduces by 1.491% (two-thirds of 2.26%) at the optimum relaxed tolerances at each feature (varying between 17.78 and 65%, typically averaging at 34.1%). Any tolerance relaxation above the limits shown in Table 1 has little or no benefit in manufacturing cost saving. Above this limit, there is a diminishing return of cost benefits as rework/concession work-hours reduces, but on the other hand, drag increases.

Aircraft performance and DOC estimation are carried out at several tolerance relaxation levels. Figure 9 shows how MTOW and aircraft cost are affected by tolerance range relaxation. As tolerance is relaxed, the associated drag rise (top line) results in MTOW growth because 1) additional fuel must be carried to meet the payload range and 2) reinforcement of related structures is required (cascading effect). The aircraft cost would have increased had there been no cost saving because of tolerance relaxation. The DOC variation shows a minimum, that is, an optimum (at 34.1%) tolerance relaxation.

At optimum, the corresponding growth in MTOW is from 162,040 to 162,300 lb, of which 40 lb goes to structural reinforcement and the rest in onboard fuel. The corresponding reduction in aircraft cost brings it down it to U.S. \$46.44 million, that is, a saving of U.S. \$0.56 million. The net saving in DOC is a reduction of 0.421%. Note that the DOC change is rather flat at the optimum, that is, it is not very sensitive to the degree of accuracy needed to revise the current tolerance allocation to an optimum one.

The 0.421% DOC reduction translates into a saving of U.S. \$132 per aircraft per sortie of 7-h block time (at the design range of 2830 n mile). At an annual utilization of 500 sorties (two sorties a day), the DOC saving is U.S. \$66,000. For an airline fleet of 10 aircraft having an operating life span of 14 years, the savings total to U.S. \$9.24 million in the life cycle cost (LCC). The saving increases at lower ranges. Figure 10 show that at shorter ranges the DOC saving is higher as the yearly utilization starts to fall off because of loss of time during turn around; in other words, the percentage DOC contribution by the aircraft cost becomes higher than what is contributed by the cost of block fuel consumed.

The DOC benefits are higher when aircraft cost goes up and lowers when fuel cost goes up. DOC level reflecting inflationary economics is shown in Fig. 11.[28] The fuel price is varied from U.S. \$0.50 to 1.00 per U.S. gallon and aircraft price from U.S. \$27 to 47 million. The best DOC saving is 0.428%, when aircraft cost is high (U.S. \$47 million) and fuel cost is low (U.S. \$0.50), and least DOC saving is just below 0.2%, when aircraft cost is low

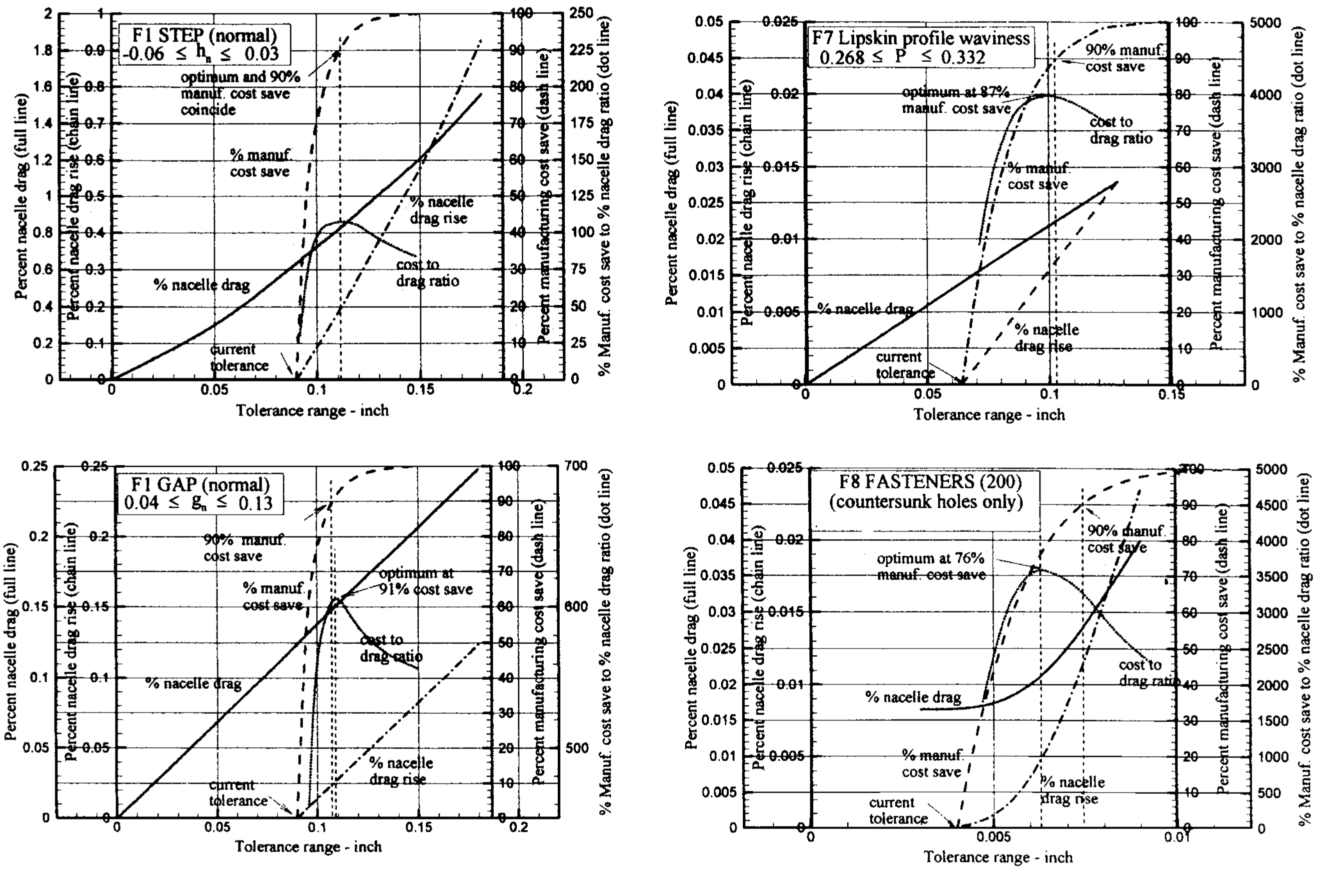

Fig. 8 Nacelle drag and cost variation with tolerance change for features 1, 7, and 8.

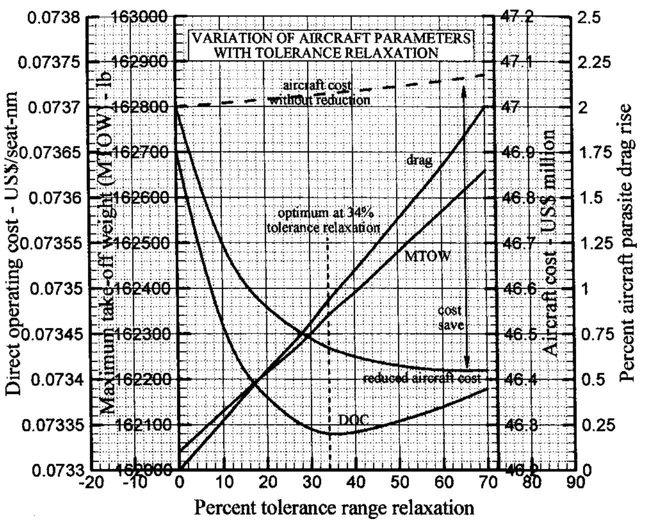

Fig. 9 Variation in MTOW, DOC, aircraft drag, and cost with tolerance relaxation.

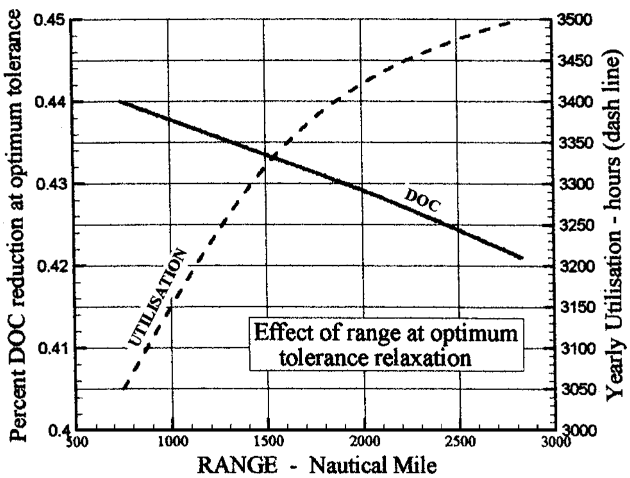

Fig. 10 Effect range at optimum tolerance relaxation on DOC.

(U.S. $27 million) and fuel cost is high (U.S. $1.00). At low aircraft and high fuel costs, tolerance requirements are tighter as compared to high aircraft and low fuel cost, especially for aircraft operating with longer range missions.

Discussion

General

It is clear that aircraft aerodynamics depend on a complex combination of interacting phenomena, and, in particular, the contributions made by skin friction and pressure effects around the aerodynamic defects arising from manufacturing tolerance allocation. Even after more than half a century of work, the interactive phenomena associated with parasite drag buildup are still not fully understood. They are 1) pressure force on the aerodynamic defect itself, 2) changes in the local surface shear force forward and aft of the protuberance, 3) modification in the development of the boundary layer downstream of the defect, and 4) potential separation due to added disturbances (with or without shock).

Drag

Accurate estimation of aircraft drag is of importance in dealing with small changes in drag on account of the excrescence effects, which amount to the order of 3% of the aircraft parasite drag, as confirmed by flight tests. Of this 3%, about two-thirds is considered

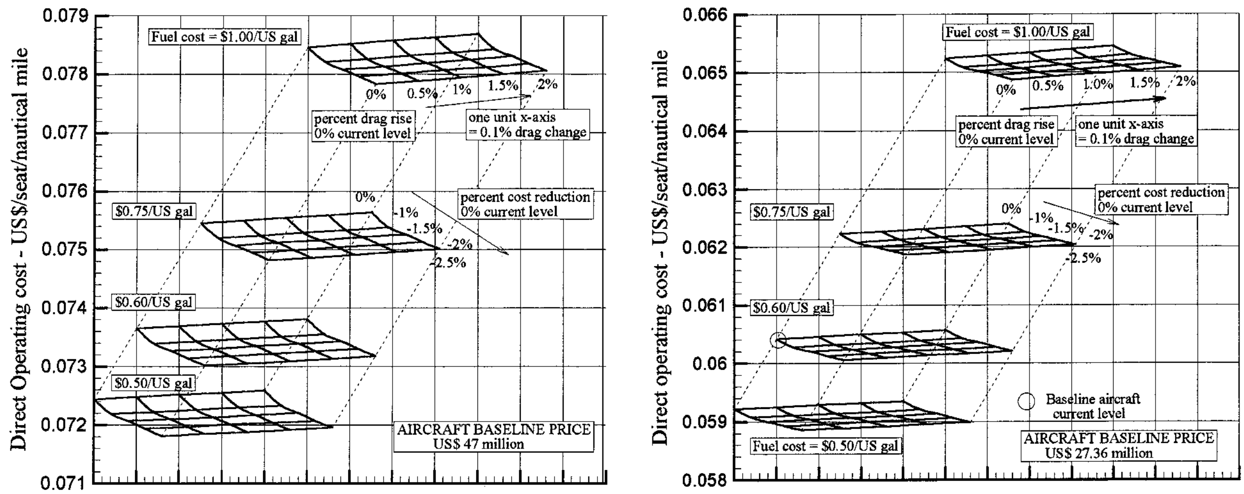

Fig. 11 Inflationary effect on DOC.

to arise from surface roughness effects, primarily originating from manufacturing capabilities. The results of this paper show that the estimated total excrescence drag of the nacelle, at the currently specified tolerances, to be 2.26% of the nacelle parasite drag, which is in line with the flight-tests results.

Excrescence Drag

An accurate estimation of parasite drag of excrescences of very small dimension pose a difficult problem. Currently, semi-empirical methods continue to be the state of art supported by theory and experiments and nowadays supplemented by CFD investigations and validated against flight and wind-tunnel tests. ESDU state that their semi-empirical methodologies are validated against a large amount of experimental data and can be considered to have accuracy of within the stated experimental scatter of $\pm 10\%$.

The physics of flow over steps or gaps placed parallel is simpler than those placed normal to the flow. The interaction between a step and gap occurring together is of low order and is ignored. The methods for correcting the two-dimensional results to three-dimensional surfaces with pressure gradient are based on very scanty experimental results. Experiments show that the excrescence drag in a pressure gradient is considerably higher than the earlier estimates, which assumed an increase by the ratio of local dynamic head to freestream dynamic head. The pressure gradient in the flow downstream of the excrescence magnifies the local excrescence drag increment. The magnification factor for backward facing steps in pressure gradient are nearly 50% higher than forward facing steps. This is possibly because the former have greater influence on the downstream flowfield and, hence, on the skin friction. The magnification effect of a gap in pressure gradient is small because the downstream flowfield is not strongly affected. With the application of CFD,[29] some encouraging progress has been made in understanding this phenomenon.

Excrescence drag due to surface waviness, especially on lip curvature at the leading edges of nacelles, is an outstanding instance where there is a lack of adequate methods of assessment. Some insight to the problem was made as a result of investigation on Boeing 720 fuselage pressurization effects.[30] However, the excrescence drag due to the lipskin profile waviness is very small in magnitude, and hence, the confidence level in accuracy is not of great significance in its estimation.

A considerable amount of experimental data on various kinds of fastener heads, both rising above the surface and sunk below it, are available in Refs. 12, 17, and 19. By far the majority of fasteners are rivets and hilocks (blind rivets). In general, the error band of ESDU estimates should be in line with the stated $\pm 10\%$, validated against experimental data. By far the majority of the nacelle rivets are staggered in two rows, with no influence on each other. The shallow countersink of a rivet is not deep enough to be treated as a hole, and the excrescence drag contribution is low. Raised rived heads are flush ground at practically no cost. The tolerance allocation for fasteners appears to be too tight, possibly because of cosmetic considerations.

Featurewise Contribution

Of the 11 features under consideration, only two key features, features 1 and 6, both placed in zone 1, contribute more than half the total excrescence drag of the nacelle. Feature 1, which has both forward and backward facing steps, is placed at the most critical location in zone 1 at 2.37 ft from the nacelle highlight plane, just behind the local transonic region at LRC. Feature 1 alone contributes more than one-third of the nacelle excrescence drag. The excrescence drag contributions of feature 7 (lipskin waviness) and feature 8 (fasteners) total only about 1% of the nacelle parasite drag, a very small amount. The rest of the features may be considered as average contributors. The thicker boundary layer at the end of the nacelle in zone 2 permits larger tolerances as compared to those in zone 1.

Assembly Cost Data (at Manufacture)

The literature survey indicates no other source of such data, possibly because of the commercial sensitivity in a competitive market. The stochastic method used to obtain the cost vs manufacturing tolerance relationship needs no presupposition regarding a mathematical model to represent the curve. A complete and exact set of assembly cost data from the industry is used to establish the cost vs tolerance relationship. Although some features showed off-center distributions, it was considered by the manufacturer that, by suitably adjusting the manufacturing process at assembly, the distribution could be normalized. Also note that there are concessions made for exceeding the specified tolerances at some features, and these have not led to any adverse effects in operation.

Aircraft Performance and DOC

The use of the term LCC, popular in the context of commercial administrative considerations, is not suitable in the context of this paper. LCC becomes more meaningful for combat aircraft design and manufacture, which invariably are associated with specific one-off-type nonflying supporting accessories that are paid by the government with no return in revenue. A more appropriate costing parameter would be the aircraft DOC, which includes all of the components of design and manufacturing costs. To capture changes of the order of 0.5% in aircraft drag and cost and to reflect the effects in DOC changes of 100th of a cent (10,000th part of a U.S. dollar) is a daunting task.

Confidence Level

The aircraft drag computed in this paper is validated against known data for several aircraft and also is in conformity with the industry standard drag data, which came with the PIANO software for the Airbus A320 class of aircraft. In summary, the aircraft drag estimation for this work may be considered to have a error band of ±3% and excrescence drag error band within ±10%. A high degree of accuracy is maintained in the cost data as they are based on the actual cost incurred by the manufacturer. The cost figure can only increase, for example, if any aspect got overlooked, which would reinforce the findings of this work. The accuracy of the results for aircraft performance and DOC estimation is of a high order because of the use of proven industry standard software that is used by all major aircraft manufacturers on both sides of the Atlantic.

Drag and Cost vs Tolerance

As tolerance is increased, it is associated with a nonlinear drag rise. On the other hand, the cost reduction initially shows a rapid decrease, with diminishing returns. No cost benefit is realized beyond a certain tolerance level as the assembly becomes right-first-time, that is, no rework/concession involved.

The net effect of the initial tolerance relaxation is a rapid decrease in DOC due to rapid reduction in manufacturing cost and in spite of the drag-rise penalty. However, as the tolerance is further relaxed, the saving exhibits diminishing returns as the cost of fuel burn increases rapidly because of the nonlinear drag rise, and the DOC starts to increase gradually after reaching a minimum value at the optimum tolerance range variation. The minimum DOC can be demonstrated in Fig. 9 to occur with a 34.1% tolerance range relaxation from the current level for all of the features representing the average condition. In actuality, at the optimum, each defect at each feature has its own percent tolerance range change varying from 14 to 68%.

Mere DOC saving is not the only outcome of the paper. It also indicates that industry must pay attention to how the surface smoothness requirements are specified at the conceptual/project stages of the design cycle. It needs a change of culture to develope specifications in a concurrent engineering environment through a design build team (DBT), where production engineers could exercise their judgment to reduce the cost of production. The DBT should be able to explore the benefits from alternative design and manufacturing processes that could possibly make use of alternative materials, tooling, etc., to further reduce the cost of manufacturing.

It is possible that the internal tolerance could be tighter to satisfy the six-sigma philosophy.[31] A front-loaded expenditure on tool design with tighter internal tolerances could benefit costing with low rework and concessions. This raises the question of tolerance chain buildup and would require investigating cost reduction through changes in internal tolerances. It does not stop there. The low cost components (without sacrificing the structural integrity and maintainability) would invariably result in lower cost of inventory and maintenance. It will not be easy to find all of the answers to the questions raised in this paper.

When all of the benefits are added up, the total saving could be several times higher than that claimed in this paper. In fact, this paper is conservative with regard to drag estimation, and the cost figures are real and cannot be less than what actually occur. The extent of DOC savings would depend on the inflation level and on the aircraft mission profile.

Whereas the industry is looking for ways and means to reduce cost of production, any change from continuing practice exhibits resistance to change. It has to face the difficult task of convincing the customer to accept some loss of cosmetic appeal, an important consideration. Surely the aircraft customers/operators need to be briefed on the financial benefits to help them to overcome the lost cosmetic appeal of surface finish. After all beauty is only skin deep.

Conclusions

The principle conclusion of this paper is that there is scope for relaxation of manufacturing tolerance allocation to minimize aircraft DOC, seen as a customer requirement. The strength of the paper lies in the credibility of the real life actual shop floor data obtained from industry and the use of industry-standard methodologies and tools for the analysis. The following conclusions are of interest to the aircraft industries and associated establishments (government, academia, research and development organizations, operators, commercial establishments, etc.).

1) A methodology has been proposed that offers a credible way to specify an optimized manufacturing tolerance allocation for the technology level adopted.

2) With the advent of modern manufacturing/tooling philosophy, including computer-based tools in virtual reality and advanced statistical process control methods along with advanced analysis for aerodynamic considerations, it should now be possible to specify jointly the optimized tolerance allocation at each key manufacturing feature affecting drag to minimize DOC. The joint approach necessarily has to take place at the initial phase of the project, possibly at the conceptual stage, in a concurrent engineering environment of a DBT comprising primarily experienced engineers from multidisciplinary areas.

3) The results stress the need for multidisciplinary investigation at all levels, to stay abreast of current needs and to recommend means for future improvements.

4) Presently, the tolerance specifications differ, to some extent, from manufacturer to manufacturer, for the same generic class of aircraft components. Therefore, the varying smoothness specifications for a generic aircraft component could be standardized, or at least brought closer together.

Evidently, the conclusions and recommendations given represent far-reaching consequences in the national aircraft manufacturing infrastructure, and the changes, if adopted, would be painful and slow. Further research work is planned to extend the study to wing and fuselage in a true DFMA study.

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