PARASITIC DRAG AND REQUIREMENTS FOR AIRCRAFT EXTERNAL SURFACE FINISH

Gennady A. Fedorenko*

Abstract

Statistical data are presented on the number and frontal areas for principal types of manufacturing and constructive imperfections characterizing the condition of aircraft external surface and the level of parasitic drag. Basic laws of varying drag coefficients for various types of surface excrescences as functions of Mach and Reynolds numbers are analyzed. The methodology is considered for evaluating requirements for aircraft surface finish based on the specified level of parasitic drag.

Introduction

Aircraft aerodynamic characteristics, primarily aerodynamic drag, obtained by testing models in wind tunnels need some corrections taking into account the difference between test and flight conditions, as well as between aircraft and model geometries.

One of such corrections is that for parasitic drag caused by the presence of a number of fabrication-produced nonsmoothness of aircraft external surface: roughness of covers, waviness of surface, gaps around doors, windows, and control surfaces, small protuberances and various parts protruding into the flow on an aircraft surface.

All the above-named surface imperfections deteriorate the hydraulic smoothness of an external surface and can (depending on external surface condition and flight regime) be responsible for substantially increasing the zero-lift drag coefficient. The range of change of values of parasitic drag for aircrafts of various purpose changes over a wide range from 3 up to 25 % from drag coefficient of aircraft at zero-lift force.

The problem of reducing drag penalties caused by manufacturing imperfections received the buck of attention over the course of the aviation history. The peculiarity of such investigations consists in the fact that the direct duplication of surface imperfections on models is hampered or even impossible due to the model scale being small. Besides, the roughness and excrescence drag value obtained in such an experiment would not be corresponding to the full-scale value, since boundary-layer parameters on the model and in full-scale conditions are different.

Because of this special investigations of roughness/excrescence drag are required under conditions maximally closed to those observed in flight. One of such experimental techniques in near-full-scale conditions (with thick boundary layer) is the test using strain gage balance with a floating platform mounted flush with the tunnel wall surface. Specimens of excrescences and protuberances are installed on this platform.

The methodology of calculations aircraft parasitic drag elements is developed on the basis of results obtained in such experiments at TsAGI and on the systematized experimental data obtained by many other authors [1]. For verification of this technique a tenfold tests of full scale fighter aircraft with both original and smooth external surface had been carried out in TsAGI low speed wind tunnel that validated the one. The technique may be used for Mach number range M = 0.5-5 and flight altitudes from sea level up to H = 30000 m.

Figure1 illustrates the results of calculating the parasitic drag elements for maneuverable aircraft with computer program [1].

The value of additional drag can achieve significant magnitudes, therefore, first, corrections for parasitic drag should be introduced in aircraft design process at its early stage using statistical data on aircraft external surface condition, second, joint efforts of aerodynamicists, de-

Deputy Head of the Aerodynamics Department, Central Aerohidrodynamic Institute name after Prof. N.E. Zhukovsky (TsAGI), Zhukovsky, Moscow reg., 140180, Russia, Email : aerobig@mail.ru

signers, stress men, and manufacturing engineers are required aimed at reducing the value of parasitic drag.

Calculations have shown that an increase in C_{D0} by 1 percent lead to trip fuel over consumption by ~40 and ~90 tons for one year for short/medium and long-range trunk-route airplanes, respectively. Costs of this fuel are ~40 - 90 thousand dollars.

The same increase in the drag of a supersonic civil aircraft type "Concord" on a typical transatlantic route results in a degradation of a pay load approximately on ~1ton.

The methodology for evaluating requirements for aircraft surface finish based on the specified level of parasitic drag is considered in this article.

Requirements for Aircraft External Surface Finish

The basic dependences : According to statistical data on external surface condition for aircraft of various types, the frontal area of manufacturing imperfections and excrescences references to $1m^2$ of an exposed wetted surface is widely varied from aircraft to aircraft:

$S_{Mimp}\backslash Swet = 0.0005 \div 0.00265$

$S_{Mp}\backslash Swet = 0.00018 \div 0.0018$

$S_{M\Sigma}\backslash Swet = 0.00075 \div 0.005$

The range itself of varying the indicated parameters points to the potentialities of improving the aircraft surface finish quality at the current state of the art in manufacturing engineering.

Statistical data processing has shown that in the average (without taking into account the purpose of aircrafts) the external surface finish quality is characterized by the number of excrescences per unit of exposed wetted surface and the height of protrusions or recesses of principal manufacturing imperfections presented in the following Table 1.

Aircraft parasitic drag (referenced to C_{D0}) can be represented as a sum of its principal elements :

$$\Delta C_D = \Delta C_{Dr} + \Delta C_{Dwave} + \Delta C_{Dimp} + \Delta C_{Dp} + \Delta C_{Dsl}\,, \tag{1}$$

where ΔC_{Dr} is an additional roughness drag, ΔC_{Dwave} is an additional of surface aircraft waviness drag, ΔC_{Dimp} is an additional drag of manufacturing imperfections (items 2 ÷ 6 in the Table-1), ΔC_{Dp} is an additional drag of small parts, ΔC_{Dsl} is an additional drag associated with unpressurized slots along the edges of control surfaces and high-lift devices.

Table-1

Type of Surface Imperfection		Quantity		h_0, mm
		number/m^2	m/m^2	
1	Roughness	Entire Surface		0.011
2	Waviness : a) 2-dimensional b) 3-dimensional	Entire Surface 20% of Surface		3 (h/1 = 0.003)* 0.25 (h/1 = 0.01)*
3	Rivet heads	420	-	0.1
4	Screw heads	70	-	± 0.4**
5	Panel joint steps	-	1.1	± 0.4**
6	Steps around hatches, windows, doors	-	0.34	± 1.1**

* wave height-to-length ratio

**(+) screw head protrusion; forward-facing step

(-) screw head recess; backward-facing step

The basic laws of change of drag coefficients of the listed imperfections are resulted in works [2, 4].

The surface roughness does not increase the turbulent skin friction drag if heights of its excrescences are no greater than some allowable value which depends on flight speed and altitude. The allowable value may be design from the equation: $C_F/C_{Fo} = 1, 0$.

Here :

$$\log \frac{C_F}{C_{Fo}} = 0.1 \cdot \log^2 \mathrm{Re}^* h \qquad (at\ 0 \le \log \mathrm{Re}_h \le 1)$$

C_F - friction drag of a rough surface,

C_{Fo} - turbulent friction drag of aerodynamically smooth furface

$$\mathrm{Re}_h^* = U_\infty \sqrt{(C_F/2)}\, h/v$$

For subsonic regime (M = 0.8 ÷ 0.9 and H = 11000 ÷ 12000 m) the allowable roughness height is as high as 5 ÷ 6 mkm, for supersonic regime (M = 2.0 and H = 17000 ÷ 18000 m) it increases up to 12 ÷ 14 mkm.

As modern paint and varnish coverings have a level of roughness Rz < 5mkm, $\Delta C_{Dr} = 0$.

Slots around the edges of control surfaces and high-lift devices. For cruise flight all slots being pressurized, then $\Delta C_{Dsl} = 0$, but if their existence is indispensable their additional drag cannot be eliminated.

Waviness of surface aircraft cause the additional drag, proportional to { $h^{1\backslash 3}$ $(h\backslash l)^2$ }. For modern aircrafts the waviness of an external surface of a covering causes insignificant increase in drag especially on subsonic speeds.

Manufacturing imperfections. The drag of manufacturing imperfections $C_{Dimp\ i}$ (item 3 ÷ 6, Table-1) change proportionally ~ $(Reh^*)^{1\backslash 3}$, that is ~$h^{1\backslash 3}$ and the additional drag of manufacturing imperfections:

$$\Delta C_{Dimp} = C_{Dimp} * S_{M\,imp} \backslash S \sim h^{4/3}$$

are proportional to $h^{4/3}$.

Total additional drag of all imperfections ΔC_{Dimp} (items 1 ÷ 6 Table- 1) approximately also changes proportionally $h^{4/3}$ and can be concern rather average level presented by following dependence:

$$\Delta C_{Dimp} = \Delta C'_{D\,imp} (h \backslash h_0)^{4\backslash 3} \tag{2}$$

where : $\Delta C'_{D\,imp}$ - the additional drag corresponding average quantity and height of manufacturing imperfections - h_0 (Table-1) for H = 11km Π $S_{wet}/S = 4$.

Dependence (2) can be applied at values h\h0 ≤ 2. In the vicinity of average value h0 the Eqn. (2) can be represented for arbitrary flight altitude by the following formula (3):

$$\Delta \bar{C}_{Dimp} = \frac{\Delta C_{Dimp}}{C_{D0}} = \Delta C'_{D\,imp} \left(h = ho\, ;\, H = 11KM\, ;\, \frac{S_{wet}}{S} = 4 \right)$$

$$(h/h_0)^{4/3}\ \frac{S_{wet}/S}{4\, C_{D0}}\ (\,1.4 - 0.4\, H/11) \tag{3}$$

Protuberances (small protruding into the external flow details) cause the additional drag which depends on their number, size, geometry and location on the aircraft surface [3]. Some of them are necessary for normal operations of aircraft equipment and according to their purpose are to be exposed into the external flow (pressure and temperature probes, antennas, lights, and so on), others are associated with structural imperfections (fairings, pivoting joints, and so on) and are not necessary elements of the aircraft external surface.

According to statistical data, the total frontal area of protuberances for a non-maneuverable airplane S_{Mp} = 0.00022 S_{wet}, with instrument equipment protuberances being about half the total one, that is S_{Mp} = 0.00012 S_{wet}.

The quantity and the sizes of protruding parts is usual are known already on an early design stage of an aircraft, and their additional drag can be defined approximately, using the average value of a coefficient of their drag - C_{Dp} and the total frontal area - S_{Mp}.

$$CD_p = \frac{\sum (C_{Dpi} \cdot S_{Mpi})}{\sum S_{Mpi}} \tag{4}$$

The additional drag of protruding parts can be represented in the form:

$$\Delta \bar{CD}_p = CD_p \cdot \frac{S_{Mp}}{S_{wet}} \cdot \frac{S_{wet}}{CD_0 \cdot S} \qquad (5)$$

where C_{Dp} is an average drag coefficient of the all parts referenced to their total frontal area (4): C_{Dp} = 0.3 at M = 0.9 and C_{Dp} = 0.35 at M = 2.0.

Taking into account Eqs.(2), (5) and $\Delta C_{Dsl} = \Delta C_{Dr}$ = 0, formula (1) can be brought to the form:

$$\Delta\bar{CD} = \Delta CD'_{imp} \left(h/h_o\right)^{4/3} \cdot \frac{S_{wet}/S}{4CD_o} \left(1.4 - 0.4\, H/11 \right)$$

$$+ CD_p \frac{S_{Mp}}{S_{wet}} \left(\frac{S_{WET}/S}{CD_o}\right) \qquad (6)$$

From Eq. (6) we can determine the tolerance values $h \backslash h_0$:

$$h/h_o = \left[\frac{CD_o}{S_{WET}/S} \cdot \frac{4}{\Delta CD'_{imp}(1.4 - 0.4\, H/11)}\right]^{3/4} \cdot$$

$$\left[\Delta\bar{CD} - CD_p \frac{S_{Mp}}{S_{wet}} \left(\frac{S_{WET}/S}{CD_o}\right)\right]^{3/4} \qquad (7)$$

Formula (6) is to be used under the assumption that the change of external surface condition is accomplished by simultaneously changing all manufacturing tolerances, while in practice the specified level of parasitic drag can be obtained through the redistribution of tolerances among various surface imperfections, and also depending on an arrangement of imperfections on an external surface of aircraft [5].

It follows from (7) that for the specified flight regime (H, M) and the specified level of parasitic drag $\Delta \bar{C}_D$ the tolerance values h\h0 are determined by:

- the value of C_{D0} S/S_{wet}, which characterizes a degree of aircraft aerodynamic perfection in terms of its zero-lift drag;

- the value of additional drags of protuberances the number and the frontal area of which characterize the structural perfection of the external surface.

Than the aircraft is more perfect in the aerodynamic relation (less value of parameter C_{D0} (S/S_{wet}) and more frontal area of protruding parts S_{Mp}, more rigid requirements are shown to technological perfection of an external surface (to admissions on manufacturing imperfections) for maintenance of the set level of parasitic drag.

Analysis requirements for aircraft surface finish. Below the preliminary analysis of requirements to quality of an external surface of supersonic passenger aircraft of type Tu-144 or "Concord" is executed. Initial data for calculation are resulted in Table-2.

Substituting in the formula (7) values $\Delta C_D{}'_{imp}$ and CD0 (S/Swet), we shall receive :

$h \backslash h_0 = 7.4\, (\Delta \bar{C}_D - \Delta \bar{C}_{Dp})^{3/4}$ for M= 0.9; H= 11 ÷ 12 km

$8.2\, (\Delta \bar{C}_D - \Delta \bar{C}_{Dp})^{3/4}$ for M= 02.0; H= 17 ÷ 18 km

(8)

The results of calculations under formulas (7) for subsonic and supersonic flight regime aircraft are presented in Fig.2, 3.

From results of calculations follows:

- More rigid requirements to a condition of an external surface of supersonic civil aircraft are determined by a subsonic regime flight;
- At the set level of additional drag equal 3% from C_{D0} aerodynamically smooth aircraft and at minimally necessary quantity of protruding parts (S_{Mp}/S_{wet} = 0,00012), average values of tolerances on manufacturing imperfections should be approximately three times less in comparison with average (Table-1), that is h_{av}/h_0 = 0,35.
- As the total area $S_{Mp} \backslash S_{wet}$ of aircraft Tu -144 has value S_{Mp}/S_{wet} = 0.00026 his additional drag is ~1.5 time more and has value ~ 4 ÷ 4.5 % of C_{D0}.
- If the condition of an external surface of aircraft Tu-144 corresponded to an average level ($h \backslash h_0$=1) and

Table-2

Flight Regime		C_{D0} $(S \backslash S_{wet})$	$C_D{}'_{imp}$ ($h \backslash h_0$ = 1.0 H = 11 km, $S_{wet} \backslash S$ = 4)
M	H, km		
0.9	11÷ 12	0.0027	0.00078
2.0	17 ÷ 18	0.0034	0.00104

S_{Mp}/S_{wet} = 0.00026 his additional drag would make ~9-10 % C_{D0}.

By the manufacture of aircrafts as tolerance values it is set not average values of heights of manufacturing imperfections, and their maximal values. According to the normal law of distribution of random variables, the value h_{av} is accepted as a average of distribution. If we accept that the bottom border of a field of dispersion (-3σ) coincides with zero value (h = 0) the top border of a field of dispersion ($+3\sigma$) will correspond $h_{max} = 2h_{av}$. In the Table-3 these maximal values are compared to tolerances to manufacturing imperfections of supersonic passenger aircrafts "Concorde" and Ty-144 which as a whole confirm results of the analysis.

The received requirements to quality of an external surface are identical to all wetted surface of the aircraft. These requirements can be specified in view of conditions of a flow of various sites of an external surface of the aircraft [6].

At the analysis of requirements it is necessary to mean, that on the real aircraft except the considered basic types of manufacturing imperfections, as a rule, there are additional sources of the drag, not submitting to statistical regularities which must be considered after detailed study of a design of the concrete aircraft; it - slots which for any reasons cannot be pressurized, gaps on a surface of the engine gondolas, necessary for indemnification of temperature deformations, welded seams, etc.

Opportunities of Reduction of Parasitic Drag

Screw heads : On thick panels screw heads can be deepening and hollows are putted.

Steps on joints of a covering sheets and panel : At subsonic speeds essential reduction of forward-facing and backward-facing steps drag (approximately twice) can be reached by performing of a chamfers with corners of 20 - 30° (Fig.4). For the same effect at supersonic speeds corners of chamfers should be 6-8° which is difficult to provide. In this case gaps between joints panels with enough a width are carried out which is filled by special hermetic or paste that allows to form chamfers with corners 5-6°.

The gaps which are not a subject filling on conditions of operation (for example, on gondolas of engines), have smaller drag if the width to depth ratio does not exceed b/h = 2 ÷ 3 (Fig.5).

Table-3

Type of roughness	The average level	The admissible level $h_{av} = 0.35\ h_0$; $h_{max} = 2\ h_{av}$		Requirements in manufacture h_{max}, mm	
	h_0, MM	h_{av}, MM	h_{max}, MM	«Concord»	Ty-144
Roughness	0,011	0.005	0,01	<0.005	<0.005
Waviness : a) 2-dimensional b) 3-dimensional	 0,003 0,01	 0,001 0,0035	 0,002 0,007	 0,001÷0,003 0.005	 0,001÷0,003 -**)
Heads of rivets	0,1	0,035	0,07	-	+(0,01÷0,13)
Heads of screws	±0,4	±0,14	±0,28	-	-(0,05÷0,25)
Panel joint steps	±0,4 (±0,65)*	±0,14 (±0,23)*	±0,28 (±0,46)*	±0,25 -	+(0,05÷0,4) -(0,1÷0,5) -
Steps around hatches, windows, doors	±01,1	±0,38	±0,76	-	±(0,5÷1,5)
Small details, $S_{Mp}\backslash S_{wet}$	0,00022	0,00012		-	0.00026

* In view of steps on mechanization of a wing

** there are no data

At different height of a forward and back step it is desirable, that the height of a forward step exceeded height back (Fig.6).

Protruding parts (Small details) : On an external surface of the aircrafts it is expedient to have only those details which on the purpose should act in an external stream. It is desirable, that all aerials of radio equipment were internal accommodation if weight of their design less than equivalent weight, in view of aerodynamic drag, of the aerial with external accommodation.

Reduction of small details drag can be reached by reduction of their number and dimensions. Details of type of auxiliary air inlets are expedient for placing in root parts a wing and tail or to carry out drowned. The details used only on the ground or not in all flights, it is necessary to carry out demountable or removed.

Decrease in a drag of aerials and probes of air pressure, probes of temperature of braking, probes of temperature of external air is promoted by reduction of relative thickness of aerials and racks of probes on which they fasten, and the various kind fairings - by increasing of their lengthening (Fig.7 and 8).

Results of the present researches have been used in developing the requirements to quality of an external surface of subsonic and supersonic aircrafts.

The fulfillment of the requirements in manufacturing subsonic aircraft IL-96-300 has allowed its parasitic drag to be reduced by about 8%, in comparison with the last aircraft of same class IL-76 (Fig.9).

References

1. Fedorenko, G. A and Bashkirov, I. G., "Parasitic Drag Prediction", Fundamentals and Computer Code, TsAGI, Russia.

2. Fedorenko, G. A., "Resistance of Manufacture Imperfections in a Turbulent Boundary Layer", Works of TsAGI, Release 2100, 1981.

3. Fedorenko, G.A and Pavlenko. I.V., "The Protuberances of an External Surface Aircrafts" (Coefficients of Aerodynamic Drag), Album, TsAGI, 1989.

4. Fedorenko. G.A., "Parasitic Drag Prediction", Proceeding of Aerospace Technologies Development and Strategies, International Seminar, 05 - 08 February 2003. Bangalore, India.

5. Fedorenko. G. A., "The Sizes of Technological Zones with Increased Requirements to Quality of Furnish of an External Surface of Wings with Usual and Supercritical Profiles", Technique of Air Fleet, 1991, 3.

6. Barinov, V. A and Fedorenko. G. A., "Approximate Estimation of the Effect of the Wing and Tail Geometry Deviations from Design Parameters on the Drag Coefficient of Subsonic Airplanes", ISSN 0321 - 3439, Scientists of Note TsAGI, Volume XXII, 2, 1991.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig.7

Fig.8

Fig.9