



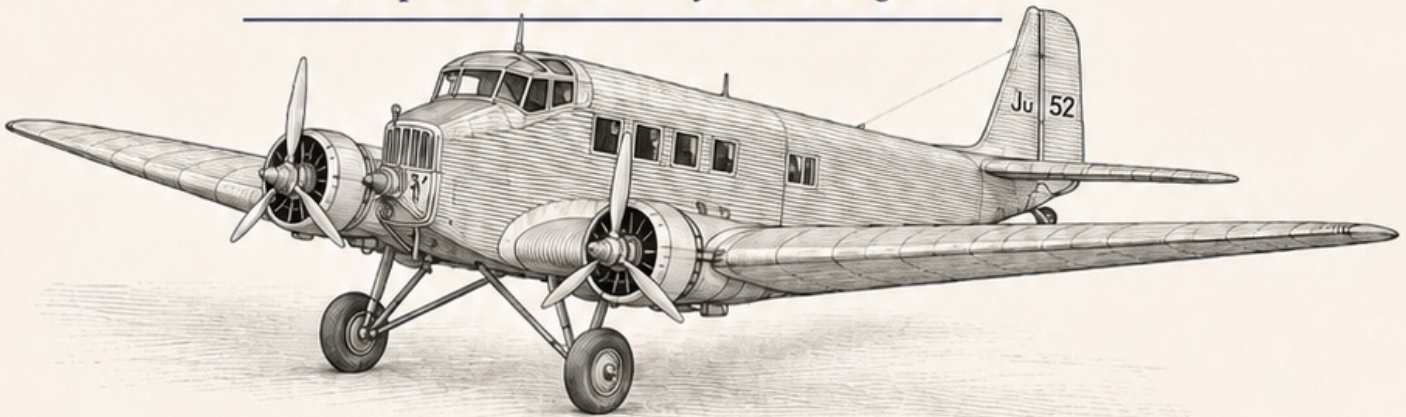
KING ETHELRED'S COLLEGE OF ENGINEERING

Established in 978 (ish)

DEPARTMENT OF AERONAUTICAL ENGINEERING
AND APPLIED FLUID MECHANICS

THE AERODYNAMIC EFFECTS OF CORRUGATED SURFACES ON THE JUNKERS JU 52 WING

An experimental and analytical investigation



*A dissertation submitted in partial fulfilment of
the requirements for the degree of*
Bachelor of Engineering (Honours)
in Aeronautical Engineering

BY

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UPPER PIDDLINGTON

MAY, 2024

*Fortitudine.
Ingenio.
Tea and biscuits.*





DECLARATION AND ACKNOWLEDGEMENTS

I declare that this dissertation is my own work, except where the laws of aerodynamics, the NACA, Professor Junkers, the Smithsonian Institution and several generations of competent engineers had the matter substantially worked out before I arrived.

I am grateful to the staff of the Department of Aeronautical Engineering and Applied Fluid Mechanics for access to the library, the wind tunnel and the cupboard containing the good biscuits. Particular thanks are due to Professor C. P. Wainscot for repeatedly asking whether an increase in wetted area might, in fact, increase drag; to Mr. T. Arbuthnot for locating NACA Report 336; and to Estates for eventually confirming that the humming noise from Tunnel No. 2 is “probably normal”.

The technical portions of this dissertation distinguish historical measurements from analytical estimates. The fictional departmental experiment in Appendix C is parody only and is not used as evidence.

Fortitudine. Ingenio. Tea and biscuits.



ABSTRACT

Corrugated duralumin skin is one of the defining features of the Junkers Ju 52. The construction provided useful local panel stiffness and formed part of a mature Junkers all-metal structural system, but its external geometry necessarily departed from an aerodynamically smooth wing. This dissertation examines the resulting aerodynamic penalty using historical experimental evidence and an aircraft-level analytical sensitivity model.

NACA Report 336 tested smooth and corrugated Clark Y airfoils at Reynolds numbers up to approximately 1.94 million and found increased drag at small flying angles together with a flattening of the lift curve near stall. Hoerner later tabulated minimum section drag coefficients of approximately 0.0086 for the smooth surface and 0.0104-0.0118 for two corrugated forms, corresponding to section minimum-drag increases of roughly 21-37%. These values are not transferred directly to the Ju 52 because representative full-scale cruise Reynolds number is approximately 14-17 million and because geometry and corrugation arrangement differ.

A representative Ju 52 model using span 29.25 m, wing area 110.5 m², mass 10,500 kg and 235 km/h cruise at 2,000 m gives C_L about 0.43 and induced C_D about 0.0103. An assumed corrugation drag increment $\Delta C_D = 0.0020$ -0.0035 increases the illustrative whole-aircraft cruise drag by approximately 4-8%. The central $\Delta C_D = 0.0025$ case requires about 52 kW additional engine shaft power with propeller efficiency 0.75.

The study concludes that the corrugations imposed a real and operationally meaningful drag penalty, but one substantially smaller at aircraft level than the percentage increase in wing-section minimum drag alone. The design remained rational because corrugation bought structural panel stiffness, production maturity and serviceability in a period when smooth semi-monocoque practice was still developing. The Ju 52 therefore represents an engineering compromise rather than an aerodynamic mystery.

Keywords: Junkers Ju 52; corrugated duralumin; profile drag; boundary layer; NACA Report 336; Doppelflügel; Reynolds number; aircraft structures.



EXECUTIVE SUMMARY

The central finding of this dissertation can be stated plainly: **corrugating the Ju 52 wing was aerodynamically worse than making the same external shape smooth, but the penalty was not so large that it invalidated the aircraft.** Historical wind-tunnel tests on corrugated metal wings measured higher profile drag, while contemporary Junkers practice used corrugation because it provided useful stiffness to thin light-alloy skin and fitted a robust manufacturing system.

The strongest quantitative historical reference is NACA Report 336. Its corrugated Clark Y models produced minimum drag coefficients around 0.0104 and 0.0118 versus about 0.0086 for the smooth reference. The difference is large when quoted as a percentage of *section minimum drag*, but an aircraft is not a bare two-dimensional wing section. The Ju 52 also had induced drag, fixed landing gear, three radial-engine installations, fuselage drag and interference losses.

Using a transparent aircraft-level budget, this thesis estimates that a reasonable corrugation increment would add roughly 4-8% to total cruise drag at a representative operating point. The central estimate corresponds to about 593 N of drag and approximately 52 kW of extra engine shaft power at 235 km/h and 2,000 m. These values are sensitivity estimates, not factory flight-test results.

The Ju 52's excellent low-speed utility should also not be credited to corrugation. The aircraft employed the separate Junkers Doppelflügel trailing-edge surface, whose inner sections acted as flaps and outer sections as ailerons. Contemporary NACA work on external auxiliary flaps confirms the high-lift logic of such a device.

The technically defensible conclusion is therefore nuanced. Corrugation increased drag and was ultimately superseded by smoother structural systems. Yet in 1930 it could still be a rational trade for stiffness, known manufacturing methods and repairability. The design was not aerodynamically optimal; it was *systemically practical*.



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NOMENCLATURE AND CONVENTIONS

Symbol	Meaning	Units
AR	wing aspect ratio	-
b	wing span	m
c	representative chord	m
C _D	drag coefficient	-
C _{D0}	zero-lift / parasite drag coefficient	-
C _{Di}	induced drag coefficient	-
C _L	lift coefficient	-
D	drag	N
e	span efficiency factor	-
L	lift or developed surface length (by context)	N or m
mu	dynamic viscosity	Pa s
P	power	W
q	dynamic pressure	Pa
Re	Reynolds number	-
rho	air density	kg/m ³
S	wing reference area	m ²
V	true airspeed	m/s
eta _p	propeller efficiency	-

Convention: all aircraft-level drag coefficients are referenced to wing area S. Values labelled “representative”, “illustrative”, “working range” or “assumed” are engineering-model inputs rather than measured Ju 52 coefficients. Historical measured values are identified by source.

1 INTRODUCTION

Why an aeroplane famous for corrugations is a useful drag problem

1.1 Background and research question

The Junkers Ju 52 is visually inseparable from its corrugated metal skin. That surface was not an ornamental flourish: it was part of a broader Junkers philosophy of robust all-metal construction developed when light-alloy aircraft structures were still comparatively young. Corrugation raised the local bending stiffness and buckling resistance of thin sheet and could simplify the problem of supporting large panels. The price was aerodynamic. A surface that is no longer geometrically smooth presents more wetted area, more opportunities for local pressure losses and a stronger disturbance to the boundary layer.

The engineering question is therefore not whether a corrugated wing produces more drag than a properly smooth wing. Historical wind-tunnel work already answers that in the affirmative. The useful question is *how large the penalty was in the operating regime of an aircraft such as the Ju 52, what physical mechanisms produced it, and why the design remained rational in the early 1930s.*

1.2 Scope

This dissertation combines three forms of evidence. First, it reviews contemporary and near-contemporary aerodynamic experiments, particularly NACA Report 336 on smooth and corrugated Clark Y sections and NACA Technical Memorandum 428 on profile-drag measurements on a Junkers wing. Second, it applies conventional boundary-layer, wetted-area, induced-drag and power calculations at representative Ju 52 conditions. Third, it examines the structural and manufacturing role of corrugated light-alloy skin and the separate contribution of the Junkers offset trailing-edge control surface, commonly known as the *Doppelflügel* or double wing.

No claim is made that the Clark Y test section was the Ju 52 aerofoil, nor that a low-Reynolds-number historical tunnel test can be transferred directly to the full aircraft. The historical results are used as a physically grounded bracket, while the aircraft-level calculations are explicitly sensitivity estimates.



Figure 1.1 - The Ju 52/3m: corrugated external skin, fixed undercarriage, three radial engines and offset trailing-edge surfaces made aerodynamic cleanliness only one of several competing design priorities.

1.3 Objectives

The principal objectives are: (1) to identify the aerodynamic mechanisms associated with the corrugated surface; (2) to quantify the scale difference between historical test Reynolds numbers and Ju 52 flight; (3) to estimate the wing-profile and whole-aircraft drag sensitivity attributable to corrugation; (4) to separate the corrugation question from the high-lift benefits of the *Doppelflügel*; and (5) to judge the design as an engineering compromise rather than by the standards of a later smooth semi-monocoque transport.

Research hypothesis. Corrugation imposed a measurable and operationally significant profile-drag penalty, but the penalty was smaller at aircraft level than the percentage increase of wing-section drag alone suggests. For a slow, rugged transport with fixed landing gear and three uncowed or partially cowed radial installations, the corrugated wing was one contributor among several to a comparatively high parasite-drag budget.



2 THE JU 52 WING IN HISTORICAL CONTEXT

Metal, corrugation and the Junkers construction system

2.1 From fabric-covered trusses to all-metal aeroplanes

Hugo Junkers was among the earliest designers to pursue practical all-metal aircraft. Period NACA translations describe Junkers practice in which corrugated duralumin sheet formed a supporting outer covering over a metal framework, reducing dependence on the dense rib-and-fabric construction familiar from earlier aircraft. The same family of structural ideas continued into the inter-war period and is strongly associated with the Ju 52.

It is important not to convert this historical shorthand into the modern claim that the Ju 52 was a pure stressed-skin shell. The wing retained substantial internal structural members. A Deutsches Museum technical history notes that the corrugated skin of the Ju 52 could take only limited torsional moment and that the tubular structure remained important for torsional stiffness. Corrugation therefore increased panel stiffness and participated in load carrying, but it did not make spars and internal bracing superfluous.

2.2 Representative geometry

Ju 52 dimensions vary between variants and sources. A representative Ju 52/3m configuration is commonly quoted with a span of approximately 29.25 m and a wing area of 110.5 m². These values give an aspect ratio of 7.74 and a simple area/span mean-chord proxy of 3.78 m. The Smithsonian example has a span close to 29 m and a gross weight of 9,200 kg, while later and military variants are quoted at higher allowable masses. The calculations below therefore use 10,500 kg only as a representative upper operating mass, not as a universal Ju 52 figure.

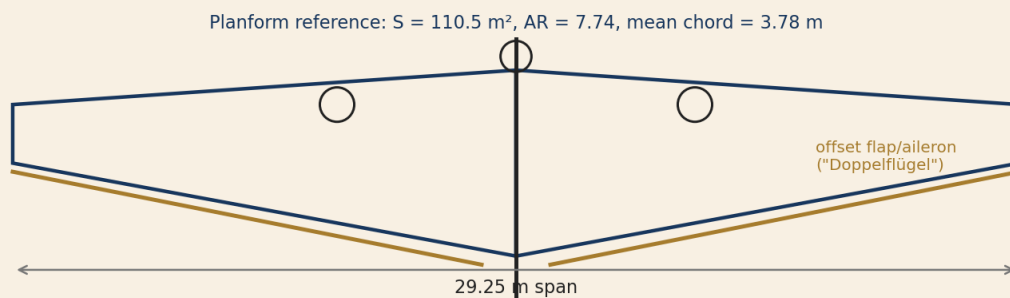


Figure 2.1 - Simplified planform and dimensional reference used in this study. Geometry is deliberately schematic; values are representative rather than a manufacturing drawing.

The aircraft was a low-wing cantilever monoplane. Its most distinctive aerodynamic feature after the surface itself was the separated full-span trailing-edge system: inner sections acted as flaps and outer sections as ailerons, with the auxiliary surface positioned below and aft of the main wing. This arrangement reduced landing speed and improved low-speed controllability without requiring the auxiliary surface to blend into the main wing contour.

2.3 Why corrugate the skin?

Thin flat sheet is efficient in membrane tension but prone to local buckling when asked to sustain compression or bending between supports. Corrugation increases the second moment of area of the sheet about one direction with a small amount of material. In structural terms, the geometry trades isotropy for directional stiffness. Contemporary Junkers practice oriented the corrugations approximately parallel to the airflow; this was aerodynamically less objectionable than forcing the external flow repeatedly over transverse ridges and was structurally compatible with the intended panel load paths.

The cost of this choice was an increase in developed surface area and the creation of grooves in which viscous shear and secondary cross-flow could develop. The metal skin was consequently more resistant to local deformation and relatively practical to repair, but never aerodynamically equivalent to a smooth sheet of the same projected area.

2.4 The design environment of 1930



The appropriate comparison is not between a Ju 52 wing and a modern bonded composite transport wing. It is between competing technologies that could be manufactured, inspected and repaired reliably in the late 1920s and early 1930s. Flush-riveted smooth semi-monocoque structures would soon dominate high-performance aeroplanes, but corrugated Junkers construction was already understood, rugged and production-proven. A modest cruise-speed penalty could therefore be rational if it purchased lower structural risk, known tooling, durable panels and good serviceability.

The eventual migration of transport aircraft toward smooth stressed skins does not show that corrugation was foolish; it shows that the balance shifted as metallurgy, riveting, analysis and manufacturing improved. Once a smooth skin could provide the required strength and stability economically, there was little aerodynamic reason to keep the external ridges.

2.5 Orientation of the corrugations

The direction of the ridges matters. Junkers practice generally arranged the external corrugations approximately parallel to the local airflow rather than transverse to it. This avoided forcing the boundary layer to climb and descend a succession of ridge faces at every pitch. It did not make the surface aerodynamically smooth: the flow still encountered a larger developed area, groove-scale secondary motion, joints and local pressure gradients. It did, however, make the chosen corrugated construction substantially less objectionable than an otherwise identical sheet with the ridges turned across the stream.

This orientation also illustrates the structural compromise. Corrugated sheet is strongly anisotropic: it is stiff in some deformation modes and comparatively compliant in others. The direction selected by the designer therefore reflected both aerodynamic and structural load paths. The outside appearance is simple, but the engineering choice was not.

2.6 Surface finish, joints and service condition

A service aircraft was not an ideal mathematical corrugation. The aerodynamic surface also contained panel joints, fastener heads, inspection openings, paint layers, dents, repairs and contamination. NACA investigations of practical-construction wings showed that joints, waviness and surface roughness could increase profile drag even when the nominal aerofoil geometry was unchanged. The drag measured on a real Ju 52 was therefore the consequence of the complete manufactured surface, not of corrugation amplitude alone.

That distinction matters when assigning blame to the ridges. A modern smooth flush-riveted wing offers both lower geometrical waviness and better control of joints and fasteners. The historical comparison consequently bundles together several advances in manufacturing quality. This dissertation isolates corrugation only to the extent allowed by the controlled NACA smooth-versus-corrugated experiments and treats the remaining aircraft-level result as a sensitivity estimate.

Design feature	Likely aerodynamic consequence	Engineering purpose
Longitudinal corrugation	More wetted area; groove-scale mixing	Panel stiffness and buckling resistance
Panel joints / fasteners	Local roughness and pressure loss	Assembly, inspection and repair
Internal tube structure	No direct skin-drag benefit	Primary load path and torsional stiffness
Offset flap/aileron	Additional gap and interference drag	High lift and roll control

Table 2.1 - The visible corrugated wing embodied several separate structural and aerodynamic compromises.



3 AERODYNAMIC THEORY

How corrugation changes the boundary layer and profile drag

3.1 Reynolds number and similarity

The chord Reynolds number is the first scaling parameter for the viscous flow over the wing:

$$Re = \rho V c / \mu$$

where ρ is air density, V is true airspeed, c is a representative chord and μ is dynamic viscosity. Reynolds number governs the relative importance of inertia and viscosity and strongly influences transition, separation and skin friction. The 2 ft chord models in NACA Report 336 were tested up to Re approximately 1.94 million. By contrast, the representative Ju 52 calculation in Chapter 5 produces Reynolds numbers of order 14-17 million in cruise. A direct percentage transfer from model to aircraft is therefore not justified.

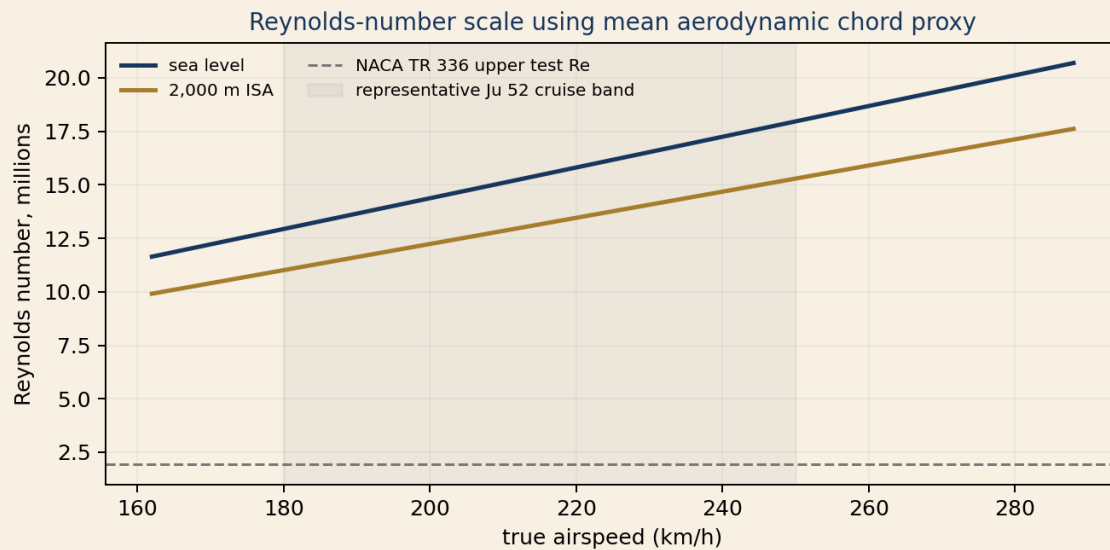


Figure 3.1 - Reynolds-number scale for a 3.78 m mean-chord proxy. The historical NACA corrugated-wing tests occupy a much lower Reynolds-number regime than full-scale Ju 52 cruise.

3.2 Profile drag: friction plus pressure

For a two-dimensional wing section, profile drag can be thought of as the sum of viscous shear and pressure (form) contributions. A smooth surface minimises unnecessary contour length and avoids repeated local pressure gradients. Corrugation affects both terms. Even when the corrugation ridges run approximately with the external flow, the developed surface length is greater than the projected chordwise or spanwise distance. The grooves also support local cross-stream velocity, weak recirculation and additional mixing.

If a sinusoidal corrugation of pitch p and amplitude A is represented by $y = A \sin(2\pi x/p)$, the developed length of one pitch is

$$L = \int_0^p \sqrt{1 + (dy/dx)^2} dx$$

and the ratio L/p is greater than one. For the illustrative geometry used in Figure 3.2 - chosen to reproduce the approximate 20% developed-area increase discussed by Hoerner for historical corrugated sheet - the surface-length ratio is about 1.19. That does *not* mean wing drag must rise by exactly 19%, because pressure drag, transition, lift coefficient and the state of the boundary layer also change.

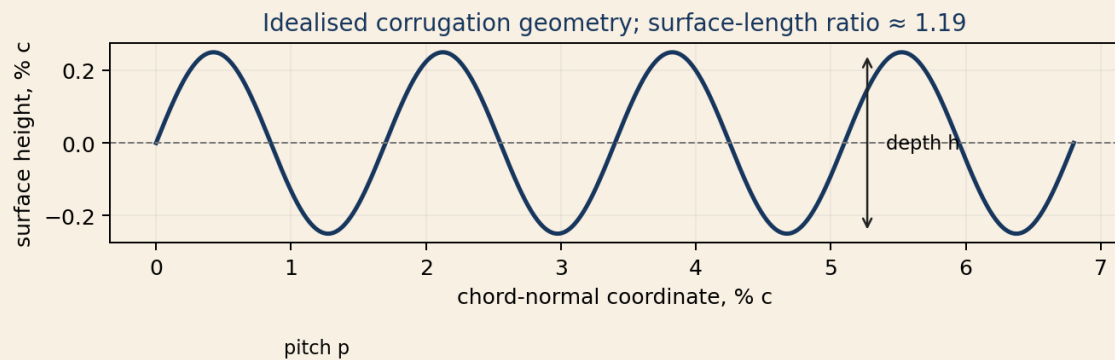


Figure 3.2 - Idealised corrugation geometry. The displayed dimensions are a normalised analytical example, not a measured Ju 52 panel.

3.3 Roughness, transition and local flow

At sufficiently high Reynolds number a large portion of an ordinary transport-aircraft wing boundary layer will be turbulent, particularly on a practical 1930s airframe with joints, fasteners, contamination and engine slipstream. Corrugation nevertheless increases local shear area and modifies the near-wall velocity field. A groove that is small relative to boundary-layer thickness may behave mainly as roughness; a larger groove may support a persistent recirculating cell and act as a geometric change to the section.

Modern studies of highly corrugated low-Reynolds-number wings sometimes report beneficial vortex trapping or delayed separation. Those results are not contradictory. At Reynolds numbers of a few thousand, the flow physics of a thin corrugated micro-air-vehicle wing can be dominated by laminar separation and coherent vortices. A Ju 52 cruise wing operates orders of magnitude higher in Reynolds number. The historically relevant evidence for large aircraft is therefore the NACA full-scale-oriented work, not insect-wing analogies.

3.4 Lift and stall

NACA Report 336 states that corrugation increased drag at small flying angles and flattened the lift curve near the burble or stall point. That wording matters. The primary aerodynamic penalty was not a catastrophic loss of lift throughout the usable range. Corrugation could leave the pre-stall lift slope broadly recognisable while changing the drag polar and the shape of the maximum-lift region.

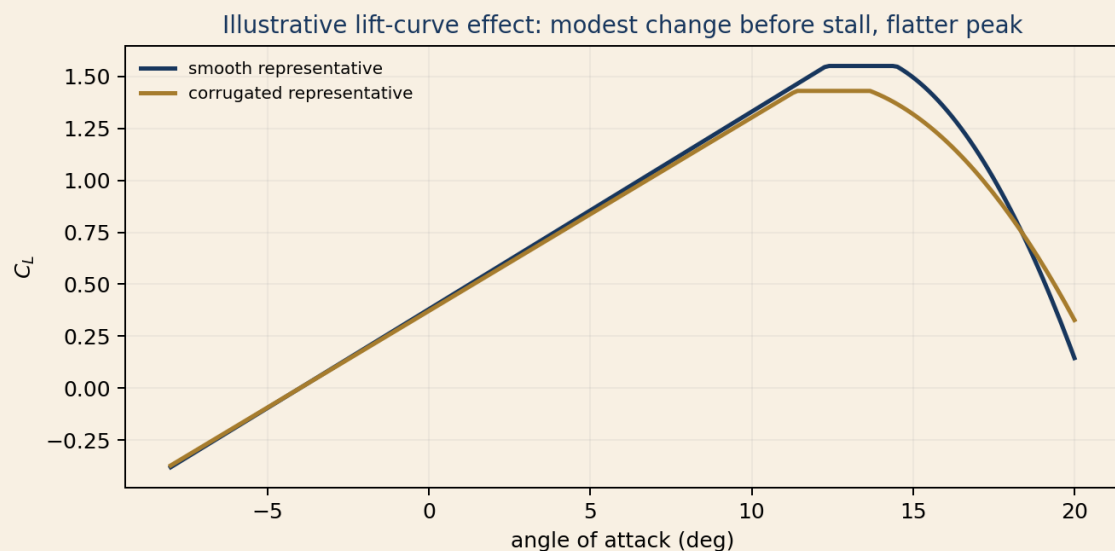


Figure 3.3 - Illustrative lift curves showing the qualitative NACA finding: limited change in the ordinary linear region with a flatter maximum-lift region. Curves are schematic, not digitised NACA data.

3.5 Finite-wing drag

Aircraft drag includes induced drag as well as profile and other parasite drag. A conventional estimate is

$$C_{D} = C_{D0} + C_{L}^2 / (\pi e AR)$$



where C_{D0} collects non-lifting drag, AR is aspect ratio and e is an efficiency factor. Corrugation primarily changes the profile/parasite term. Therefore a 25% increase in *wing-section minimum drag* does not imply a 25% increase in *whole-aircraft drag*. The engine installations, fuselage, fixed landing gear, tail and induced drag remain. This distinction is central to the aircraft-level interpretation in Chapter 6.

3.6 Relative roughness and full-scale similarity

A corrugation is a deterministic geometric feature, not ordinary sand-grain roughness, but roughness concepts are still useful for scaling. Relevant non-dimensional measures include corrugation height relative to chord and relative to the local boundary-layer thickness. At full scale the absolute boundary layer is thicker than on the tunnel model, while Reynolds number is much higher. These competing changes are one reason a single correction factor cannot be extrapolated directly from the NACA model to the Ju 52.

The grooves also differ from isolated roughness because they extend for long distances. With the ridges aligned to the flow, an individual fluid element need not cross every ridge, yet the local velocity field remains three-dimensional and the true wall area remains greater than its projected area. The most defensible interpretation is therefore a combination of additional skin-friction area and a geometry-dependent pressure and mixing loss.

3.7 Skin-friction sanity check

A conventional turbulent flat-plate correlation provides a useful order-of-magnitude check. One commonly used incompressible form is

$$C_f \text{ approximately } 0.455 / (\log_{10} Re)^{2.58}$$

which gives a mean skin-friction coefficient of order three thousandths at Reynolds numbers around 10 to 20 million. If developed metal area is increased by roughly one fifth, surface area alone can therefore add drag of order several ten-thousandths to about one thousandth when referred back to planform area, before allowing for groove pressure losses, transition effects, joints or three-dimensional flow. That sanity check is consistent with, rather than proof of, the few-thousandths drag-coefficient bracket used later.

3.8 Why the historical data are a bracket, not a transfer function

The corrugated Clark Y models in NACA Report 336 were valuable controlled experiments, but they were not miniature Ju 52 wings. Aerofoil pressure distribution, corrugation geometry, ridge orientation, Reynolds number and surface workmanship all influence the result. The historical measurements therefore establish sign and scale: corrugation raised low-angle profile drag and altered the lift curve near stall. They do not supply a unique multiplier that can be applied to every point on the Ju 52 drag polar.

The calculation in Chapters 5 and 6 accordingly uses a bounded increment and reports sensitivity. This is less dramatic than quoting a single “true” drag penalty, but it is more technically honest.



4 HISTORICAL EXPERIMENTAL EVIDENCE

What the wind tunnels actually showed

4.1 NACA Report 336

Donald H. Wood's NACA Report 336, published in 1930, tested large 2 ft by 12 ft airfoils in the Propeller Research Tunnel at Reynolds numbers up to approximately 2 million. The programme included smooth Clark Y models and two corrugated metal-covered Clark Y configurations. The report explicitly concluded that corrugating the surface increased drag at small flying angles and flattened the lift curve near the burble point.

The corrugated models were not casual pieces of roofing sheet. The report states that their dimensions were obtained by scaling the average of several standard corrugated wings. The sheet was aluminium approximately 1/32 inch thick, formed on a grooved wooden form and attached to the model. Leading-edge and trailing-edge details necessarily departed slightly from the ideal Clark Y contour.

4.2 Minimum-drag values and a useful bracket

Hoerner later summarised the NACA results in *Fluid-Dynamic Drag*. For the low-lift region he tabulated section drag coefficients of approximately 0.0086 for the smooth airfoil, 0.0104 for one corrugated configuration and 0.0118 for the other. Relative to the smooth value these correspond to increases of about 21% and 37%. Hoerner observed that the lower increment was of the same order as the increase in wetted area, while the geometry that effectively placed the corrugation outside the original contour produced a larger penalty.

These numbers are valuable because they are measured historical data, but they should be used as a bracket rather than a Ju 52 correction factor. The tested section, corrugation orientation/details and Reynolds number differ from the full-scale aircraft. The plot in Figure 4.1 therefore reconstructs plausible drag-polar shapes constrained only by the published minimum-drag values; it is deliberately labelled a reconstruction rather than a digitisation.

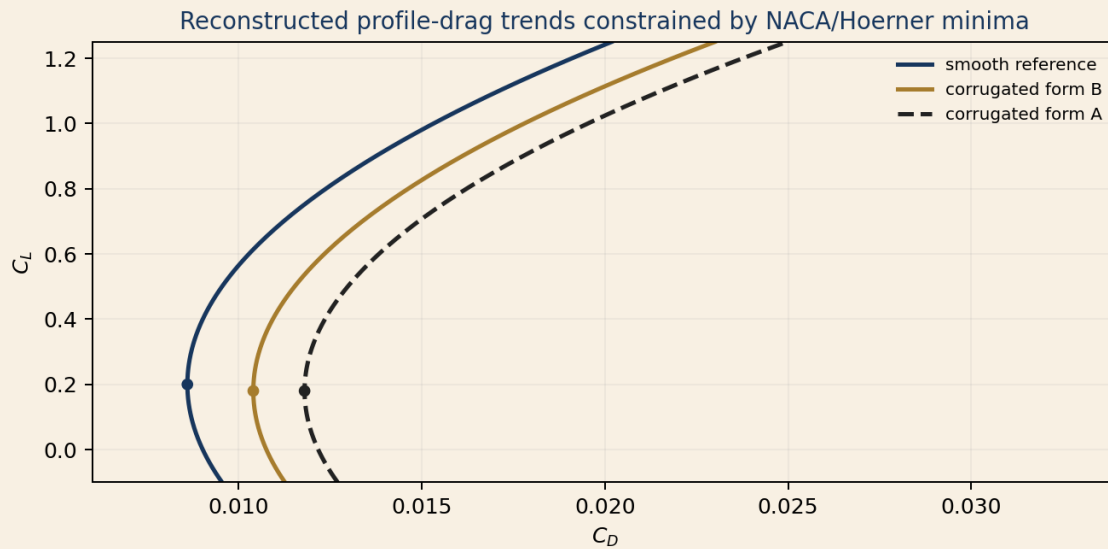


Figure 4.1 - Reconstructed profile-drag trends. Minimum values are anchored to the Hoerner tabulation of NACA Report 336; curvature away from the minima is illustrative.

4.3 NACA Technical Memorandum 428: an actual Junkers wing

A separate and especially relevant source is NACA Technical Memorandum 428, a 1927 translation of Hanns Weidinger's profile-drag work on a Junkers wing section. The study applied the Betz wake-survey method to comparative model and flight measurements on a Junkers A 20 wing. Its importance here is methodological: Junkers engineers were already quantifying the profile drag of their actual corrugated wing system, and the report treats profile drag as a measurable engineering limitation rather than an unknown curiosity.

The A 20 was not a Ju 52 and the results cannot be substituted directly into a Ju 52 drag polar. Nevertheless, the report demonstrates that full-scale/flight profile-drag comparison of Junkers wings existed before the Ju 52. The common claim that



nobody appreciated the aerodynamic cost of corrugation until smooth-skinned aircraft appeared is therefore historically implausible.

4.4 Surface irregularities in the broader NACA programme

Later NACA work on rivets, joints, roughness and practical-construction wings reinforced the same general lesson: small departures from an aerodynamically smooth contour can impose performance penalties that matter at aircraft scale. NACA Technical Note 695 found that rivet heads, joints and surface roughness could increase drag enough to affect high-speed performance and economy. Report 910 subsequently reviewed the drag characteristics of practical-construction wing sections including roughness and waviness effects.

Corrugation is more systematic than random roughness, but the underlying point is the same. The boundary layer responds to the surface actually manufactured, not to the ideal aerofoil drawn on the designer's board.

4.5 What the experiments do - and do not - establish

Established: large-scale historical tests show a clear low-angle profile-drag penalty from corrugated wing surfaces; the penalty can readily be of order tens of percent of the section minimum-drag coefficient; and the stall-region lift curve can be modified.

Not established: that the Ju 52 suffered exactly a 21%, 37% or any other fixed percentage increase in total aircraft drag. Whole-aircraft performance requires scaling to full Reynolds number and inclusion of induced drag, engine/nacelle drag, fixed undercarriage, fuselage, tail and interference effects.

5 ANALYTICAL METHOD

From section drag to a full-aircraft order-of-magnitude estimate

5.1 Reference condition

A representative cruise point is defined at a true airspeed of 235 km/h (65.3 m/s), altitude 2,000 m in standard atmosphere, wing area 110.5 m², span 29.25 m and mass 10,500 kg. The mass is intentionally conservative and corresponds to a later high gross-weight condition rather than every Ju 52 variant. At 2,000 m the analysis uses $\rho = 1.006 \text{ kg/m}^3$ and $\mu = 1.726 \times 10^{-5} \text{ Pa s}$.

With mean-chord proxy $c = S/b = 3.78 \text{ m}$, this gives Re approximately 14.4 million. Sea-level Reynolds number at the same speed is approximately 16.9 million. The lift coefficient required to support 10,500 kg at 2,000 m is approximately 0.43.

5.2 Reference aircraft drag model

The purpose of the drag model is sensitivity, not reverse-engineering an exact factory polar. A simple breakdown is therefore adopted at the reference condition:

Term	Adopted coefficient	Comment
Wing profile, smooth hypothetical baseline	0.0090	Representative turbulent metal-wing value; not claimed as Ju 52 test data
Fuselage, three engine installations, gear and miscellaneous parasite drag	0.0260	Lumped aircraft-level term chosen to represent a draggy fixed-gear trimotor
Induced drag	0.01035	Computed from $CL = 0.434$, $AR = 7.74$ and $e = 0.75$
Total smooth-wing hypothetical baseline	0.04535	Reference for sensitivity only

Table 5.1 - Illustrative drag budget. The absolute coefficients are modelling assumptions; the sensitivity to corrugation is the result of interest.

5.3 Corrugation increment

The NACA/Hoerner section data indicate a minimum-drag increment of 0.0018 to 0.0032 relative to the smooth Clark Y reference. Because the Ju 52 corrugations were arranged to reduce aerodynamic penalty and the full-scale Reynolds number is much higher, the aircraft calculation adopts a working range $\Delta C_D = 0.0020$ to 0.0035 , with 0.0025 as a central value. This range is not presented as a measured Ju 52 coefficient; it is a deliberately transparent engineering bracket.

At the reference condition, $\Delta C_D = 0.0025$ corresponds to about 593 N of additional aerodynamic drag. At 65.3 m/s this requires approximately 38.7 kW of additional propulsive power; with a representative propeller efficiency of 0.75 the corresponding shaft-power increment is approximately 51.6 kW.

5.4 Sensitivity rather than false precision

A single value for “the drag of the corrugations” would imply knowledge that the surviving public data do not support. The wing includes varying local chord, engine slipstream, surface joints and different pressure gradients from root to tip. The aircraft also existed in numerous variants and states of finish. Consequently, the analysis reports ranges and relative effects. The central estimate is useful because it shows scale: tens of kilowatts of cruise power, not hundreds of kilowatts, and a whole-aircraft drag penalty of several percent rather than the full 20-40% section-drag increment.

5.5 Caveats

The model omits compressibility, which is negligible at Ju 52 cruise Mach number; detailed three-dimensional interference; engine cooling drag; propeller slipstream effects; wing twist; flap-gap drag at specific settings; and changes to propulsive efficiency with power. These omissions would be unacceptable in a certification analysis but are appropriate for a transparent first-order comparison.

6 RESULTS

What the calculations imply for the Ju 52

6.1 Reynolds number

The first result is simply scale. The representative Ju 52 cruise Reynolds number is approximately seven times the upper Reynolds number of the NACA Report 336 tests. Corrugation remains geometrically large enough to matter, but the tunnel data cannot be treated as a universal percentage correction. This supports the use of a bracket rather than direct scaling.

6.2 Whole-aircraft drag contribution

At the reference point the hypothetical smooth-wing aircraft has C_D approximately 0.04535, of which induced drag is about 0.01035. Adding the central corrugation increment of 0.0025 raises total C_D to approximately 0.04785, an increase of 5.5%. The adopted low and high increments correspond to approximately 4.4% and 7.7% increases in total drag.

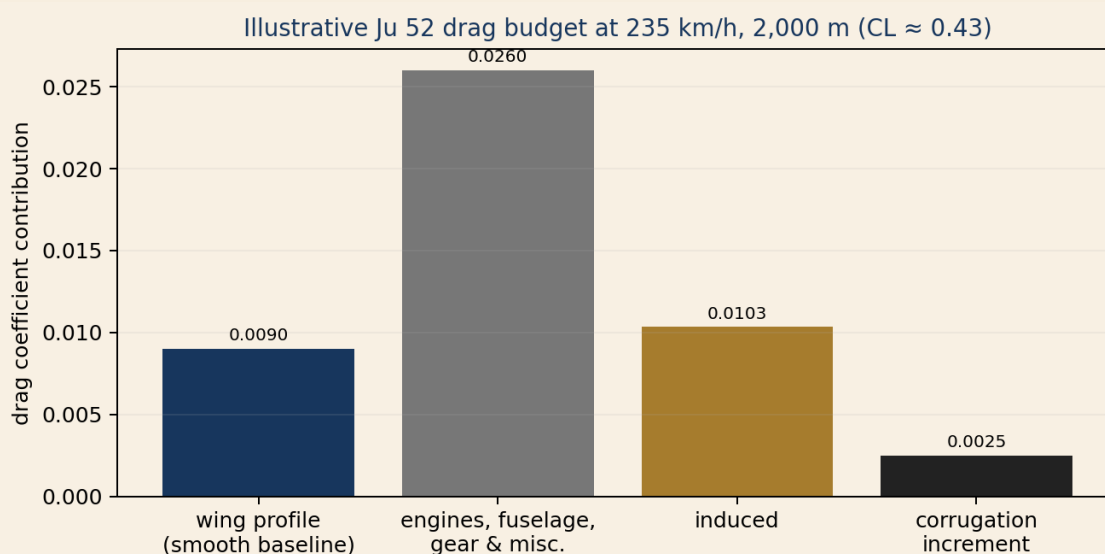


Figure 6.1 - Illustrative aircraft drag budget. Corrugation is significant, but it is only one part of the Ju 52 drag picture.

The result demonstrates why quoting only the NACA section-drag percentage is misleading. A 21-37% increase in the minimum profile drag of one wing section is diluted when incorporated into an aircraft that also carries induced drag, a blunt fuselage, three radial-engine installations and fixed landing gear.

6.3 Power penalty

The additional shaft power rises approximately with the cube of airspeed when ΔC_D is held constant, because drag varies with V squared and power is drag times V . In the central estimate the corrugation requires roughly 52 kW additional shaft power at 235 km/h and 2,000 m. Across the working ΔC_D range the estimate is approximately 41-72 kW.

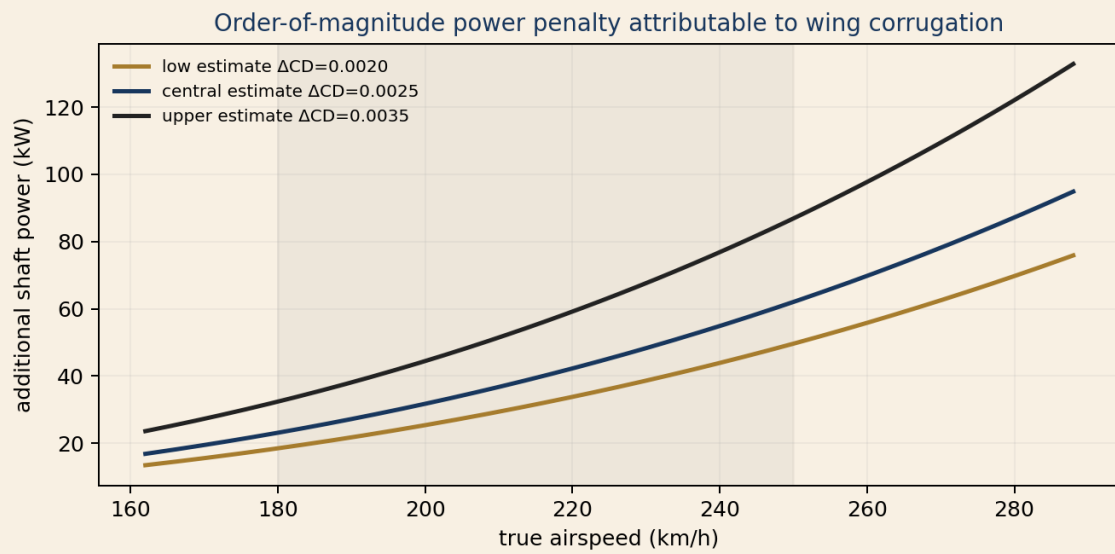


Figure 6.2 - Additional shaft power required to overcome the assumed corrugation drag increment, using propeller efficiency $\eta = 0.75$.

6.4 Lift-to-drag ratio and range implication

At $CL = 0.434$, the illustrative smooth-wing baseline gives L/D about 9.58. Adding $\Delta C_D = 0.0025$ reduces this to about 9.08. If all other conditions and propulsive efficiencies were fixed, a propeller-aircraft range relation would therefore suggest a range penalty of the same general order as the L/D reduction - several percent. It would be unjustified to turn that into an exact number of kilometres because the real aircraft would re-trim, operate at different speed and power, and carry varying payload and fuel.

6.5 Sensitivity

Figure 6.3 shows the central practical conclusion. Even a relatively large increment in wing profile drag does not dominate total drag. Over the working range, corrugation raises estimated total cruise drag by roughly four to eight percent. This is enough to matter to fuel economy and maximum speed, but small enough that a designer might accept it in exchange for structural and production advantages.

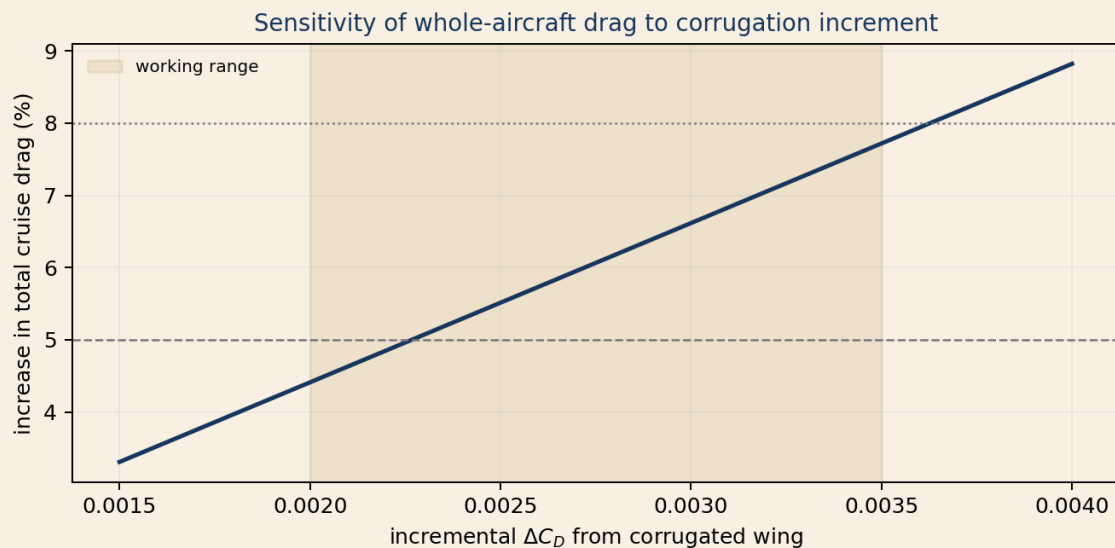


Figure 6.3 - Sensitivity of whole-aircraft cruise drag to the assumed corrugation increment.

6.6 Maximum speed

Maximum level speed for a propeller aircraft is found where available propulsive power equals required power. In the parasite-drag-dominated high-speed region, a fractional drag-area increase produces a smaller fractional speed decrease because required power grows approximately with V cubed. A 5-8% increase in total drag coefficient at a fixed lift condition

therefore does not imply a 5-8% reduction in maximum speed.

As a deliberately crude high-speed sensitivity, if available power is held fixed and the affected drag term is treated as proportional to V squared, speed scales approximately with the inverse cube root of drag coefficient. The low, central and high total-drag increases used here would then imply speed changes of about -1.4%, -1.8% and -2.4% respectively. This is not a reconstructed Ju 52 maximum-speed test; it simply demonstrates the weak cube-root response.

6.7 Fuel and range sensitivity

For a propeller aeroplane the classical Breguet range expression makes range proportional, among other terms, to aerodynamic efficiency L/D . The central illustrative case reduces L/D from about 9.58 to 9.08, a decrease of approximately 5.2%. If propeller efficiency, specific fuel consumption and the logarithmic weight ratio were unchanged, one would expect a range change of similar order.

Actual mission range would not fall by precisely that percentage. The crew could select a different cruise speed, engine specific fuel consumption varies with power and altitude, and aircraft mass decreases as fuel is consumed. The value is therefore best read as an energetic consequence: a persistent corrugation drag increment costs fuel throughout cruise.

6.8 Uncertainty budget

Input / assumption	Range or status	Influence on conclusion
Corrugation drag increment	Delta $C_D = 0.0020$ to 0.0035	High - dominant uncertainty
Oswald efficiency factor	Representative value 0.75	Moderate for total drag
Aircraft mass / altitude	Representative operating point	Moderate for CL and induced drag
Propeller efficiency	0.75 for power conversion	Moderate for shaft-power result
Variant geometry / surface state	Not uniquely reconstructed	Moderate to high for exact aircraft value
Engine / gear / interference drag	Grouped in baseline parasite term	High for absolute C_D ; smaller for relative trend

Table 6.1 - Principal uncertainties in the aircraft-level sensitivity calculation.

6.9 Result interpretation

The numerical model is strongest when used comparatively. Across deliberately broad assumptions, the conclusion does not flip: corrugation is aerodynamically costly, but it does not dominate the whole-aircraft drag budget. The exact penalty for a particular Ju 52 variant, surface condition and operating point would require full-scale flight-test or validated CFD data that are not available in the sources used here.

Principal numerical finding. A defensible first-order estimate places the corrugated-wing penalty at roughly 4-8% of total cruise drag for the representative condition used here, corresponding to approximately 40-70 kW of additional shaft power. These are analytical sensitivity results, not measured Ju 52 flight-test coefficients.

7 THE DOPPELFLÜGEL AND LOW-SPEED BEHAVIOUR

Corrugation was not the only unusual feature of the wing

7.1 The offset auxiliary surface

The Ju 52 used a narrow secondary surface positioned below and aft of the main wing. The inner portion acted as a flap while the outer portion functioned as an aileron. Because the surface remained separated from the main wing, the arrangement resembles an early slotted or auxiliary-airfoil high-lift device rather than a modern plain flap faired into the trailing edge.

Schematic of the Junkers offset trailing-edge “double wing” concept

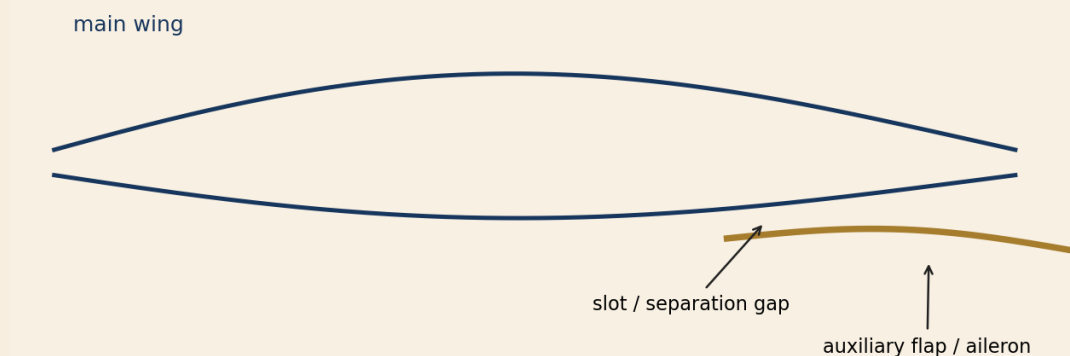


Figure 7.1 - Schematic of the Junkers double-wing arrangement. Geometry is illustrative; the purpose is to show the separated auxiliary surface and slot-like flow path.

7.2 Contemporary NACA interest

NACA Technical Note 524 specifically investigated a wing with a trailing-edge auxiliary airfoil used as a flap and noted that this type of external auxiliary surface had been used on certain Junkers aircraft. In the NACA test, the auxiliary airfoil could increase maximum lift substantially depending on position and deflection. The general mechanism is familiar: the gap permits energetic flow to reach the upper surface of the auxiliary element and delays separation at high lift.

7.3 Why this matters to the corrugation argument

It is tempting to treat the Ju 52 wing as a single feature - “the corrugated wing” - and attribute every low-speed characteristic to the corrugations. That is incorrect. Corrugation primarily altered profile drag and local boundary-layer behaviour. The Doppelflügel was the intentional high-lift/control system. Any assessment of take-off and landing performance must therefore keep those two effects separate.

The historical NACA finding that corrugation flattened the lift curve near stall does not imply that the aircraft had poor low-speed capability. The auxiliary flap system could increase maximum lift and lower the required approach speed. In other words, Junkers accepted a cruise-drag penalty from one part of the wing design while gaining low-speed lift from another.

7.4 Interaction and practical operation

On the real aeroplane the flow was further complicated by propeller slipstream from the two wing engines, local changes in dynamic pressure, flap and aileron deflection and surface contamination. The resulting three-dimensional flow cannot be reconstructed accurately from the public historical data used here. The correct technical conclusion is therefore qualitative: the offset auxiliary surface was a genuine high-lift device and should not be conflated with any supposed “beneficial corrugation” effect.

This distinction also explains why modern claims that the corrugations themselves gave the Ju 52 its short-field behaviour are unsatisfactory. The structural skin may have influenced stall details, but the dedicated trailing-edge system did the deliberate aerodynamic work.



8 STRUCTURAL AND MANUFACTURING TRADE-OFF

Why the aerodynamically inferior surface could still be the better engineering decision

8.1 Local panel stiffness

Corrugation is a geometric stiffener. Relative to a flat sheet of the same thickness, the folded or waved cross-section increases bending stiffness in the direction normal to the corrugation. This allows a thin skin panel to bridge greater distances between supports before buckling or oil-canning. In early metal aircraft this was a valuable way of obtaining stable panels without a dense forest of separate stringers.

8.2 Anisotropy and load path

The same geometry that increases stiffness in one direction makes the sheet mechanically anisotropic. Loads parallel and perpendicular to the corrugation are carried differently, and the panel is not a magic substitute for a complete wing box. Junkers designs therefore combined corrugated skin with tubular spars, frames and bracing. The engineering virtue was not “no internal structure”; it was a known and robust division of work between skin and framework.

8.3 Manufacturing and field repair

A corrugated panel can be formed repeatedly with simple tooling, provides obvious local stiffness and tolerates a certain amount of denting without the entire panel becoming an unstable flat membrane. Contemporary descriptions of Junkers practice emphasised ease of construction, maintenance and repair. Those advantages mattered in commercial and military service where aircraft operated from imperfect fields and maintenance infrastructure varied.

A smooth stressed-skin wing eventually won because flush riveting, better alloys, improved buckling analysis and efficient internal stiffeners produced lower drag at competitive weight and cost. That later superiority should not be projected backwards without considering the production system available to the original designer.

8.4 Engineering trade matrix

Criterion	Corrugated Junkers-style skin	Smooth semi-monocoque skin
Aerodynamic surface	Inferior: larger developed area and local groove losses	Superior when accurately manufactured
Panel buckling resistance	High local geometric stiffness for thin sheet	Requires curvature, stringers or thicker/stiffer panel
Production maturity c.1930	Well established within Junkers system	Rapidly improving but more demanding of flush joints and stiffener design
Field repair	Relatively tolerant and visually inspectable	Can require more careful restoration of smooth contour and load path
Long-term design trajectory	Declining as speed/economy became more important	Dominant solution for later transports

Table 8.1 - Qualitative trade matrix. “Better” depends on the technology, mission and production environment.

The Ju 52 therefore illustrates a recurring aerospace lesson: optimisation is multi-disciplinary. A surface can be aerodynamically sub-optimal and still belong to a rational aircraft if it improves the combined structural, manufacturing, maintenance and cost objective.



9 DISCUSSION

What can legitimately be claimed about the Ju 52 corrugations?

9.1 Claim: “the corrugations were aerodynamically beneficial”

Verdict: generally false for the Ju 52 cruise problem. Historical large-airfoil tests show increased drag from corrugated metal surfaces at small flying angles. Modern low-Reynolds-number studies that find vortex benefits apply to very different scales and flow regimes. The Ju 52 corrugations were principally a structural/manufacturing solution arranged so as to minimise, not reverse, their aerodynamic penalty.

9.2 Claim: “corrugation made the wing much stronger, so the drag did not matter”

Verdict: oversimplified. Corrugation increased local panel stiffness and helped stabilise thin light-alloy sheet. It did not eliminate the wing's internal load-carrying structure, and the drag certainly mattered: contemporary engineers measured profile drag and later aircraft moved toward smooth skins. The design judgement was that the penalty was acceptable, not nonexistent.

9.3 Claim: “a smooth Ju 52 would have been dramatically faster”

Verdict: exaggerated. Replacing the corrugated wing with an aerodynamically equivalent smooth wing while changing nothing else is a useful thought experiment but not a realistic redesign. The fixed landing gear, three radial installations, fuselage form and numerous interference sources would remain. The present sensitivity estimate suggests a few-percent change in high-speed capability rather than a transformation into a DC-3-class clean airframe.

9.4 Claim: “the wing was obsolete before the aircraft entered service”

Verdict: historically simplistic. Smooth semi-monocoque construction was clearly the future and competing transports soon demonstrated its advantages. But an engineering design is judged against available production capability, cost, reliability and mission. The enormous practical success of the Ju 52 as an airliner and utility transport does not prove its aerodynamics were advanced; it does prove that aerodynamic efficiency was not the only axis on which the aircraft delivered value.

9.5 The more interesting conclusion

The real story is not that corrugation was secretly efficient. It is that the design team knowingly lived with an inefficient surface because the rest of the engineering system made that choice workable. The Ju 52 is therefore an unusually visible example of a trade that modern aircraft hide inside smooth skins: every kilogram, joint, stiffener and maintenance task has an aerodynamic, structural and economic price.

A technically honest summary is therefore less dramatic than either myth. The corrugations cost performance. They also bought useful structural characteristics. In the operating environment and manufacturing system of the early 1930s, the bargain was defensible.



10 CONCLUSIONS

The corrugated wing as an engineering compromise

This dissertation examined the aerodynamic consequences of corrugated wing surfaces using historical NACA experiments, a full-scale Reynolds-number comparison and a transparent aircraft-level sensitivity model. The main conclusions are as follows:

- 1. Corrugated metal wing surfaces measurably increase profile drag. NACA Report 336 found increased drag at small flying angles and a flattened lift curve near stall. Hoerner's later tabulation gives minimum section drag coefficients of approximately 0.0086 smooth, 0.0104 corrugated and 0.0118 for a more penalising corrugated form.
- 2. Those historical section results cannot be transferred directly to the Ju 52. The NACA tests reached Re about 1.94 million, whereas representative Ju 52 cruise is of order 14-17 million.
- 3. The principal mechanisms are increased developed surface area, higher viscous shear, local groove/secondary-flow losses and boundary-layer disturbance. For an illustrative sinusoidal geometry consistent with the historical wetted-area discussion, developed surface length is about 19% greater than projected length.
- 4. A 20-40% increase in wing-section minimum drag does not mean a 20-40% increase in whole-aircraft drag. The Ju 52 also carried induced drag, three engine installations, fixed undercarriage, fuselage and tail drag.
- 5. For the representative aircraft model used here, a plausible corrugation increment of $\Delta C_D = 0.0020-0.0035$ increases total cruise drag by roughly 4-8% and requires approximately 40-70 kW of additional shaft power at 235 km/h and 2,000 m.
- 6. The Ju 52's low-speed capability should not be attributed primarily to corrugation. The separated Junkers Doppelflügel was a dedicated auxiliary high-lift/control system.
- 7. Corrugation was structurally useful but not a substitute for the internal wing framework. Its engineering value lay in local sheet stiffness, buckling resistance, mature production practice and repairability.

Final conclusion. The aerodynamic penalty of the Ju 52 corrugated wing was real, understood and ultimately one reason aircraft construction moved toward smoother skins. It was nevertheless not absurd. At Ju 52 speeds, in a drag budget already dominated by several other practical features, the penalty was modest enough to be traded against a mature, rugged structural system.

The proper historical judgement is therefore neither “the corrugations were aerodynamically clever” nor “the designers did not understand drag.” They understood the compromise. Later technology simply offered a better one.

Recommendation for further work: repeat the comparison using laser-scanned Ju 52 panel geometry and a transitional RANS or scale-resolving CFD model at $Re = 15$ million, preferably after the Department has located the workstation power lead last seen beneath the tea trolley.

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- [14] Junkers Ju 52 archival technical compilations. Representative Ju 52/3m values of span approximately 29.25 m and wing area approximately 110.5 m² are used in this dissertation; individual variants differ.

Source discipline. Numerical aerodynamic values quoted as historical measurements are tied to the NACA/Hoerner sources above. Numerical Ju 52 drag coefficients introduced in Chapters 5-6 are explicitly modelling assumptions or derived sensitivity values, not factory test data.

APPENDIX A WORKED CALCULATIONS

Representative reference condition

A.1 Geometry

$$AR = b^2 / S = 29.25^2 / 110.5 = 7.74$$

$$c_{\text{mean}} = S / b = 110.5 / 29.25 = 3.78 \text{ m}$$

A.2 Reynolds number at 2,000 m

$$Re = \rho V c / \mu = (1.006)(65.3)(3.78)/(1.726e-5) = 1.44e7$$

At sea level with $\rho = 1.225 \text{ kg/m}^3$ and $\mu = 1.789e-5 \text{ Pa s}$, the same speed and chord give Re approximately $1.69e7$.

A.3 Lift coefficient

$$q = 0.5 \rho V^2 = 2145 \text{ Pa}$$

$$C_L = W/(q S) = (10500 \times 9.80665)/(2145 \times 110.5) = 0.434$$

A.4 Induced drag

$$C_{Di} = C_L^2 / (\pi e AR) = 0.434^2 / (\pi \times 0.75 \times 7.74) = 0.01035$$

A.5 Central corrugation power estimate

$$\Delta D = q S \Delta C_D = 2145 \times 110.5 \times 0.0025 = 593 \text{ N}$$

$$\Delta P_{\text{aero}} = \Delta D V = 593 \times 65.3 = 38.7 \text{ kW}$$

$$\Delta P_{\text{shaft}} = \Delta P_{\text{aero}} / \eta_p = 38.7/0.75 = 51.6 \text{ kW}$$

These calculations are intentionally simple enough to audit with a pocket calculator. The main uncertainty lies in ΔC_D , not in the arithmetic applied once that coefficient is chosen.

A.6 Developed surface length of an idealised corrugation

For $y = A \sin(2 \pi x/p)$, $dy/dx = (2 \pi A/p) \cos(2 \pi x/p)$. Numerical integration for $A/c = 0.0025$ and $p/c = 0.017$ gives L/p approximately 1.188, i.e. about 18.8% greater developed length than projected length. This is an illustrative geometry selected to be consistent with the order of wetted-area increase discussed by Hoerner; it is not a measured Ju 52 corrugation profile.

APPENDIX B HISTORICAL-DATA RECONSTRUCTION

How Figure 4.1 was produced

Figure 4.1 is deliberately a reconstruction rather than a digitised copy of NACA Report 336. The purpose is to illustrate the magnitude of the minimum-drag shift while avoiding false precision in values not transcribed directly from the original tables.

Configuration	Minimum C_D used	Increase vs smooth	Status
Smooth reference	0.0086	-	Historical value tabulated by Hoerner from NACA TR 336
Corrugated form B	0.0104	20.9%	Historical value tabulated by Hoerner
Corrugated form A	0.0118	37.2%	Historical value tabulated by Hoerner

Table B.1 - Historical minima used to constrain the reconstructed curves.

The plotted off-design curvature is generated by a simple quadratic drag-polar form $C_D = C_{D,min} + k(C_L - C_{L,opt})^2$ with k of order 0.01. The exact k values are not claimed to reproduce the NACA table. They merely provide smooth curves through the historically grounded minima.

B.1 Why not digitise the original plots?

For this thesis the stronger technical choice is to separate hard evidence from illustrative modelling. Digitising a scan would produce many apparently precise numbers whose uncertainty would depend on scan distortion, line thickness and interpretation. The key historical evidence needed here - a significant minimum-drag increase and altered stall region - is already explicit in the published report and Hoerner summary.

B.2 Transfer to Ju 52

No direct scaling law is applied from the Clark Y corrugated test to the Ju 52. The historical values motivate the Delta C_D working range used in the sensitivity analysis, but the Ju 52 calculation is explicitly treated as a bracket. This is particularly important because Junkers oriented corrugations to reduce aerodynamic penalty and because full-scale cruise Reynolds number is much higher than the NACA test value.

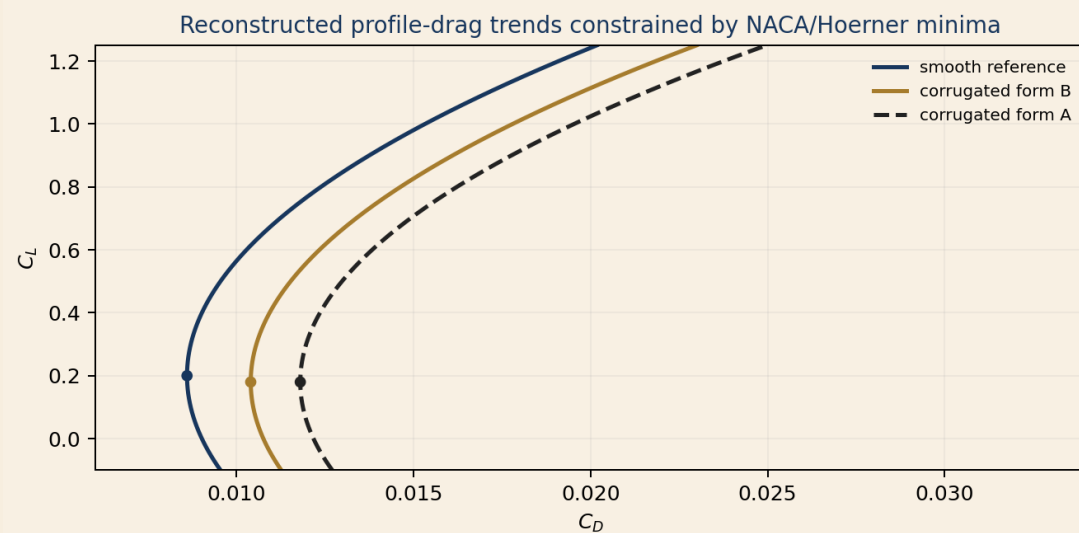


Figure B.1 - Repeated for convenient audit: reconstructed drag polars anchored only at historical minimum-drag values.

APPENDIX C DEPARTMENTAL EXPERIMENTAL NOTES

Extracts from the King Ethelred Low-Speed Tunnel ledger

Purpose of this appendix. The following is an in-universe parody laboratory record. It is not presented as historical evidence and none of its “measurements” are used in the numerical conclusions of the thesis. It exists because a respectable engineering department apparently requires a ledger, a clipboard and at least one instrument whose calibration certificate predates the investigator.

C.1 Apparatus

Tunnel: King Ethelred Low-Speed Facility No. 2, nominal working section 0.9 m x 0.9 m. Balance: three-component departmental balance, zero checked before each run. Airspeed reference: pitot-static head read on digital transducer after the original inclined manometer was removed from service following the Incident of Michaelmas Term. Model: generic cambered section with removable surface panels. The model was not intended to reproduce the Ju 52 aerofoil.

C.2 Procedure

Smooth and corrugated surrogate panels were compared at the same nominal dynamic pressure. Because the facility Reynolds number was far below full-scale Ju 52 flight, the run was treated only as a qualitative demonstration. Tufts showed visibly stronger small-scale disturbance over the corrugated panel and a broader separated region near high angle of attack. No quantitative result from this demonstration is used elsewhere in the thesis.

C.3 Ledger extracts

Time	Entry
09:05	Fan started. Balance zero satisfactory. Tea started independently.
09:17	Smooth panel run. Tufts attached. Two tufts detached and subsequently recovered from downstream screen.
09:42	Corrugated panel fitted. Senior technician remarked that it “looks exactly like a roof”. Remark retained for completeness.
10:03	Repeat run after securing panel edge. Qualitative drag increase unambiguous; no attempt made to infer full-scale coefficient.
10:26	High-angle run stopped when one tuft entered balance fairing. No damage. Biscuit loss: one.
11:10	Facility returned to Mechanical Engineering, who denied having booked it.

Table C.1 - Selected laboratory ledger entries. Scientific value: limited. Departmental authenticity: considerable.

C.4 Safety note

The departmental risk assessment states that the tunnel is safe provided nobody touches the fan, the fan guard, the extension lead, the emergency stop or “the bit that rattles”. This wording has been referred back to the Safety Committee for clarification since 1987.

C.5 Conclusion

The demonstration was consistent with the physical expectation that corrugation increases drag and alters separation, but the Reynolds-number mismatch makes it unsuitable for aircraft-level quantification. The dissertation therefore relies on published NACA evidence and analytical scaling for its technical conclusions.

APPENDIX D CLAIM AUDIT

What is fact, estimate and parody?

Statement in thesis	Classification
Ju 52 used corrugated light-alloy external skin	Historical fact; Smithsonian and technical histories
Representative span 29.25 m and wing area 110.5 m ²	Published representative variant data; variants differ
NACA TR 336 tested corrugated Clark Y models to Re about 1.94 million	Historical experimental fact
C _{D,min} 0.0086 smooth, 0.0104 and 0.0118 corrugated	Historical values as tabulated by Hoerner from NACA TR 336
Representative Ju 52 cruise Re 14-17 million	Derived calculation using stated assumptions
Delta C _D = 0.0020-0.0035 for Ju 52 corrugation	Engineering sensitivity assumption, not measured factory data
4-8% total cruise-drag penalty	Derived from the stated illustrative aircraft drag model
King Ethelred's College, Upper Piddlington and its wind tunnel	Parody; entirely fictional
Departmental tea consumption	Insufficiently instrumented for peer review

Table D.1 - Claim classification. The parody is fictional; the cited aerodynamics are not.

Colophon. King Ethelred's College of Engineering is fictional. This document is a parody thesis constructed around real historical aerospace sources and explicitly identified engineering estimates. No invented King Ethelred laboratory result is used as evidence for the technical conclusions.

