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9.1 Possible Applications Of Soaring Technology To Drag Reduction In Powered General Aviation Aircraft

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Introduction

The term "General Aviation" usually brings to mind the range of powered aircraft encompassing the Piper Cub through executive jet transport aircraft. Depending on one's definitions and biases, however, a case can be made for inclusion of other types of aerodynamically supported vehicles such as the sailplane and their powered derivatives (self-launched sailplanes or motor gliders) and perhaps even the lowly hang glider. While participation in soaring in this country is rather limited and the economic impact of sailplane manufacture is miniscule, the current level of technology in this branch of light aviation is extraordinary - particularly in the areas of aerodynamic efficiency and utilization of advanced materials and fabrication techniques. The purpose of this brief discussion is to outline the present state-of-the-art in soaring performance and review some of the techniques (particularly in the area of drag reduction) used to achieve this performance. It can legitimately be objected that the performance requirements of sailplanes and light powered aircraft are quite different and that sailplane manufactures are not bound by the same economic constraints as their counter parts in powered flight. However, to ignore the aerodynamic lessons learned in sailplane development would be, in our view, a serious oversight. In view of the fact that sailplane technical literature is infrequently consulted by many aeronautical engineers, particularly those at universities, this brief review is considered appropriate.

State-of-the-Art

Most modern soaring aircraft are pure sporting devices, the most elegant and advanced of which are optimized for competition - which today implies racing. The classic design problem is one of optimizing an aircraft for two design points: (1) low speed (minimum sink rate) flight in a rectilinear or banked turning attitude to maximize rate of climb and (2) minimum glide angle (or maximum lift-drag ratio) in high speed rectilinear cruise. In racing performance, however, absolute maximum L/D is less important than maintaining a "low" sink rate (e.g. 2m/sec) at the highest possible speed.*

At present two major types of competition sailplanes are in wide spread use: Standard Class, with spans limited to 15m (49.2 ft) with water balast (to increase wing loading in strong lift conditions) and only simple hinged flaps not connected to the ailerons permitted, and Open Class where anything is permitted. Under pressure mainly from European designers, the Standard Class will be divided into two classes for international competition after 1976, with one branch becoming an "unlimited" class keeping only the 15m span limit and the other basically retaining the present Standard Class rules.

The other category of soaring device of interest in this discussion, the "motor glider", is slowly becoming more popular in Europe and the United States. It is basically a moderate performance sailplane fitted with an engine providing it with a self-launch and out-landing retrieval capability.

Some typical modern sailplanes and motor gliders are shown in Figure 1. Performance and geometric data for several typical types are listed in Table 1. Performance capabilities are further clarified in Figure 2. Also shown for comparison in Figure 2 are glide polars for several other types of low speed flying device from (1). There are few standard handbook type references available on sailplanes and soaring technology. Probably the best sources of information are Soaring magazine, Technical Soaring (12) and the publications of the Organization Scientifique et Technique Internationale du Vol-a-Voile (OSTIV) available from the Soaring Society of America (SSA). Important recent material is available in (5.6).

The basic configuration of the high performance sailplane was well established prior to WWII. Performance increases since that time have been very large, however, due mainly to three factors:

1. A greater appreciation of the importance of the quality of the aerodynamic surfaces and the necessity of sealing gaps and flow leakage in reducing drag.

2. Advanced airfoil designs with greatly improved (compared with Göttingen and NACA 4 and 5 digit airfoils) characteristic in the Reynolds number range characteristic of sailplane operation.

* The ideal sailplane glide polar would be as "flat" as possible over the widest possible speed range. Sailplanes, as in the case of most other aircraft types, seldom "cruise" at the speed for L/D_{max}.

3. The introduction of fiberglass construction.

These factors will be discussed in more detail later. Some comparison, based on data from Table 1, for typical sailplanes of good pre-war technical vintage and modern technology are presented in Table 2.

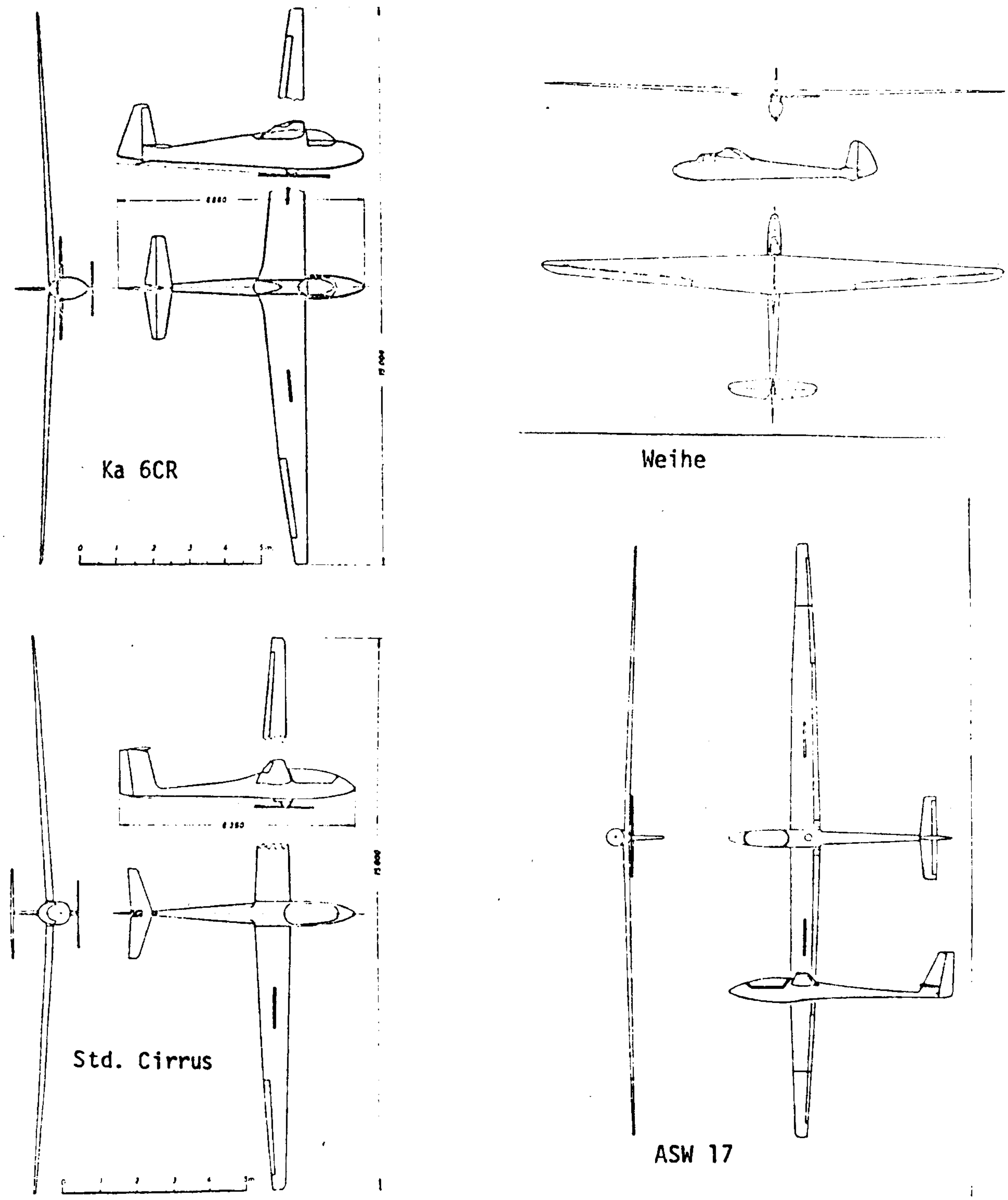
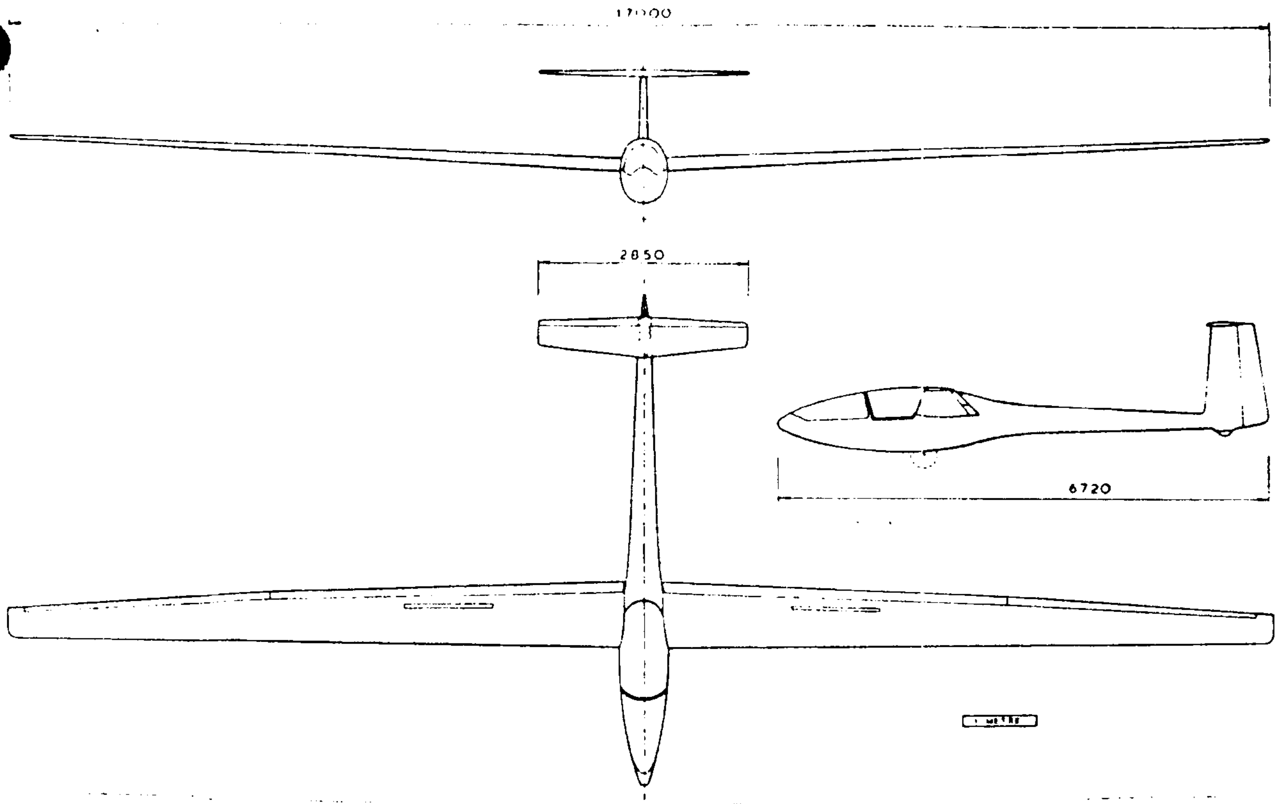


Figure 1. Sailplanes and Motor Gliders

GLASFLUGEL KESTREL



SIGMA.

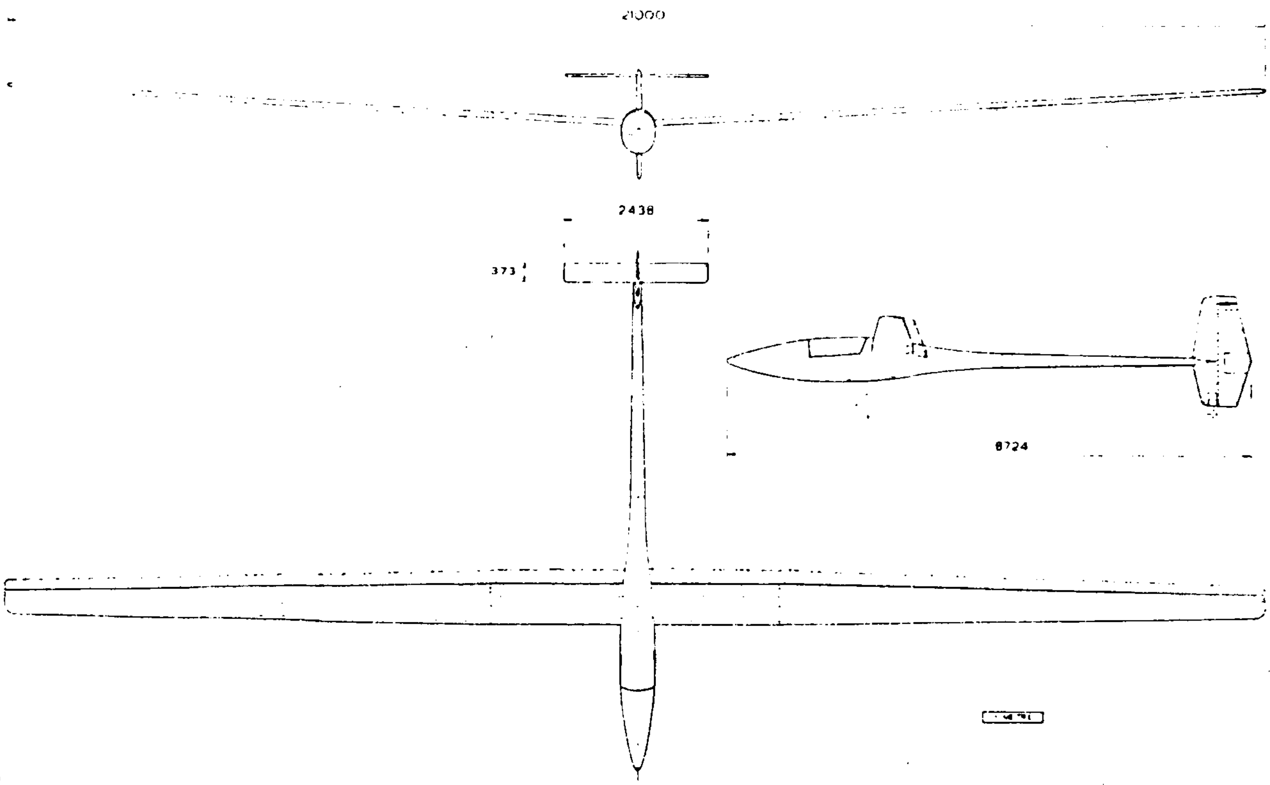
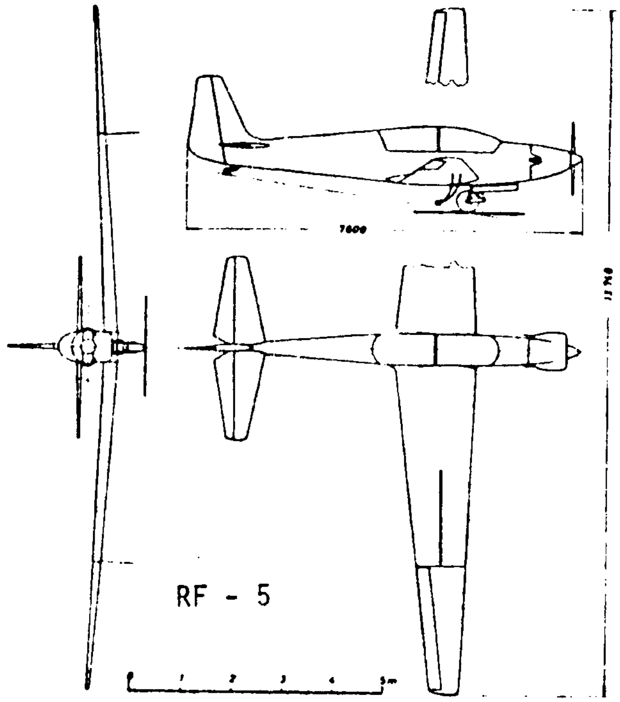


Figure 1. (continued) Sailplanes and Motor Gliders



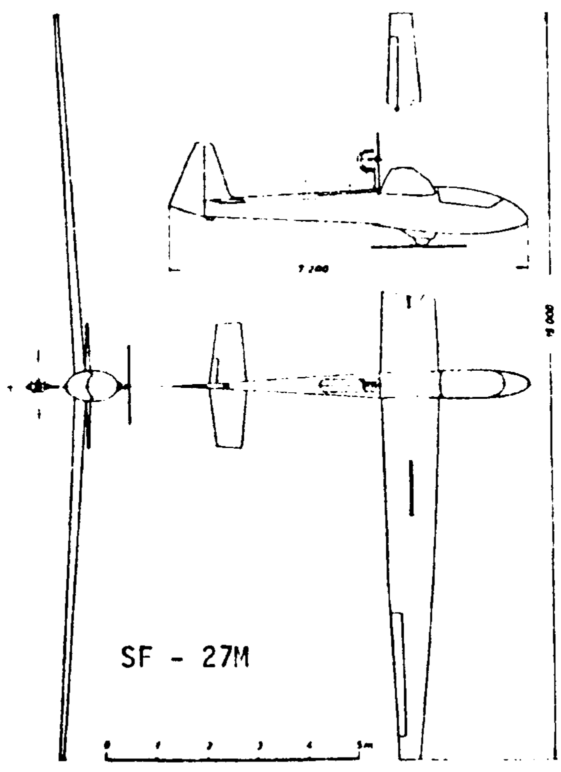


Figure 1. (continued) Sailplanes and Motor Gliders

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Table 1. Sailplane & Motor Glider Characteristics

Type	First Flt.	Wing Span (ft)	Wing Area (ft^2)	Aspect Ratio	Weights (lb) Empty	Weights (lb) Loaded	Wing Load (lb/ft^2)	Airfoil	$\dot{Z}$ (fpm) at (V - kt)	L/D_{max} at (V - kt)	V (kt) at Z = 2 m/s	Power (BHP)	Ref.
Schleicher													
Ka 6 CR	1955	49.2	134	18.1	408	610	4.55	NACA63-618	134 (36)	29 (42)	70		3
ASW 12	1964	60	140	26	680	909	6.5	FX62-K-131	109 (43)	43.3 (48)	91		2
ASW 17	1972	65.6	159.7	27	893	1257	6.7 - 7.9	FX62-K-131 mod.	97	48 (54)			4
Schempp-Hirth													
Std. Cirrus	1969	49.2	107.5	22.5	466	734	6.82	FX66-S-196	134 (42.5)	35.2 (51)	85.5		2
Nimbus 2	1971	66.6	154.9	28.6	760	954	6.16	FX67-K-150	102 (43)	46 (51)	92		3
Glassflugel													
Libelle H-201	1964	49.2	102.3	23.6	397	633	6.18	Hütter	134 (43)	34.5 (50)	82.5		2
Kestrel H-401	1968	55.7	123.7	25.1	638	803	6.5	FX 67-K-170	124 (45)	38 (52)	92		2
Laister													
Nugget	1973	49.2	109	22.2	425	900	5.7 - 8.25	FX67-K-170	128 (42.5)	36 (50.5)	~88		4
Sigma	1973	68.9	131.2 (177.2)	36.2 (26.8)	1000	1300	9.9 (7.33)	FX67-VC-170/136	108 (37.5)	~50 (55.5)			
Jacobs "Weihe"	1938	59.1	198	17.6	508	738	3.7	Gö 549	120 (35)	31.5 (41)	~60		4
Schweizer 1-26	1954	40	160	10	433	593	3.7	NACA 43012A	165 (32.5)	21.5 (42)	54		2
Fornier RF-5	1968	45.0	162	12.5	1035	1430	8.85	NACA 23015	300 (51.5)	18 (57)	67.5	68	
Scheibe SF27M	1968	49.2	130	18.6	617	815	6.25	FX 61-184	152 (45)	31 (51.5)	82.5	26	
Schleicher ASK-14	1967	46.8	137.6	16.2	507	793	5.85	NACA 63-618	148 (39)	28 (45)		26	

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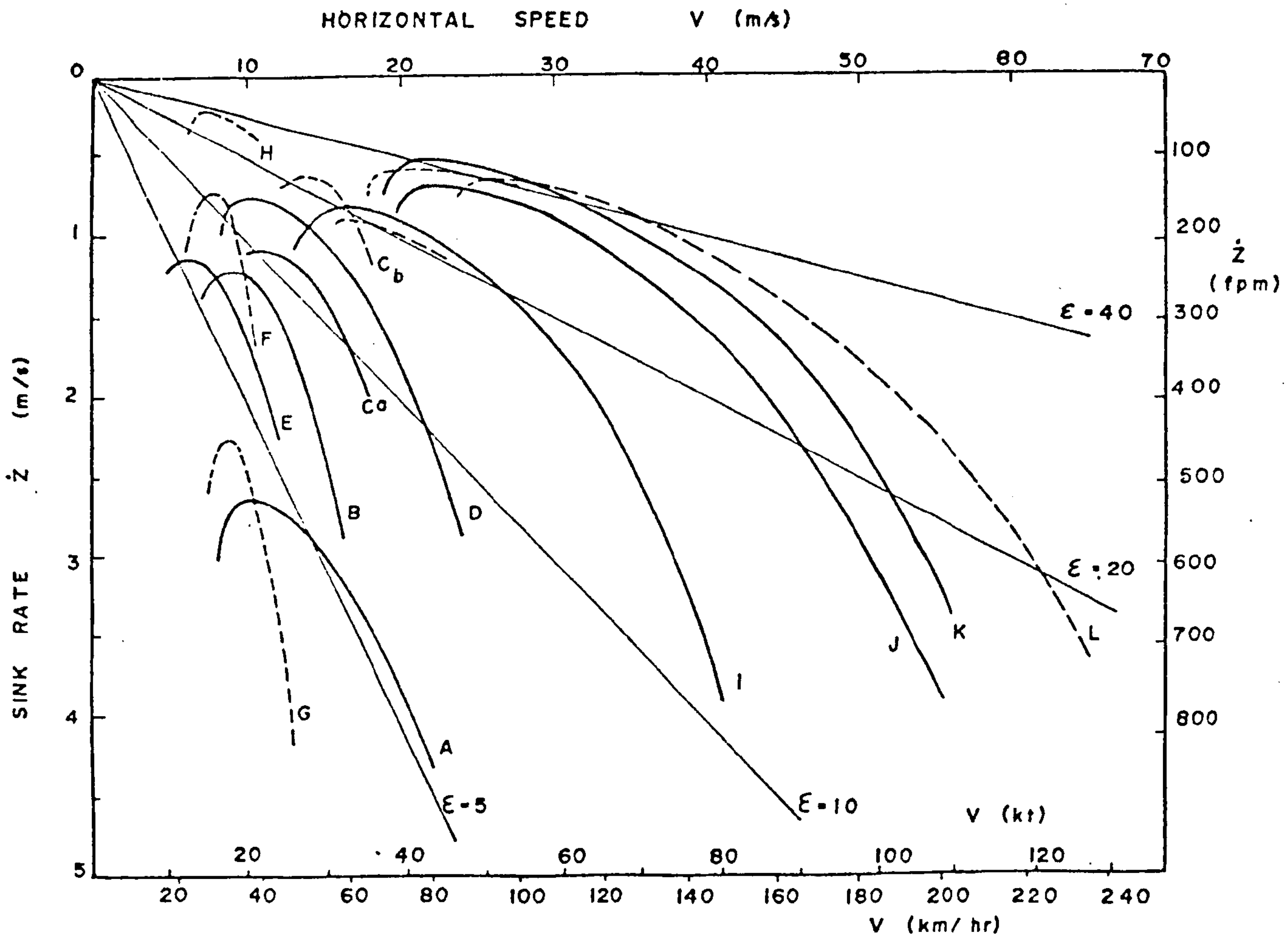


A. PIGEON (5)

B. FULMAR (6)

C. BLACK VULTURE (7)
(a. Parrot, b. Raspet)

D. WHITE-BACKED VULT. (8)

E. DOG-FACED BAT (11)

F. PTERANODON (12 b)

G. ROGALLO HANG GLD. (14)

H. PUFFIN II MPA (18)
(outside grd. effect)

I. I-26 SAILPLANE (22)

J. STD. CIRRUS (23)

K. ASW-12 SAILPLANE (24)

L. VVG SAILPLANE (25)

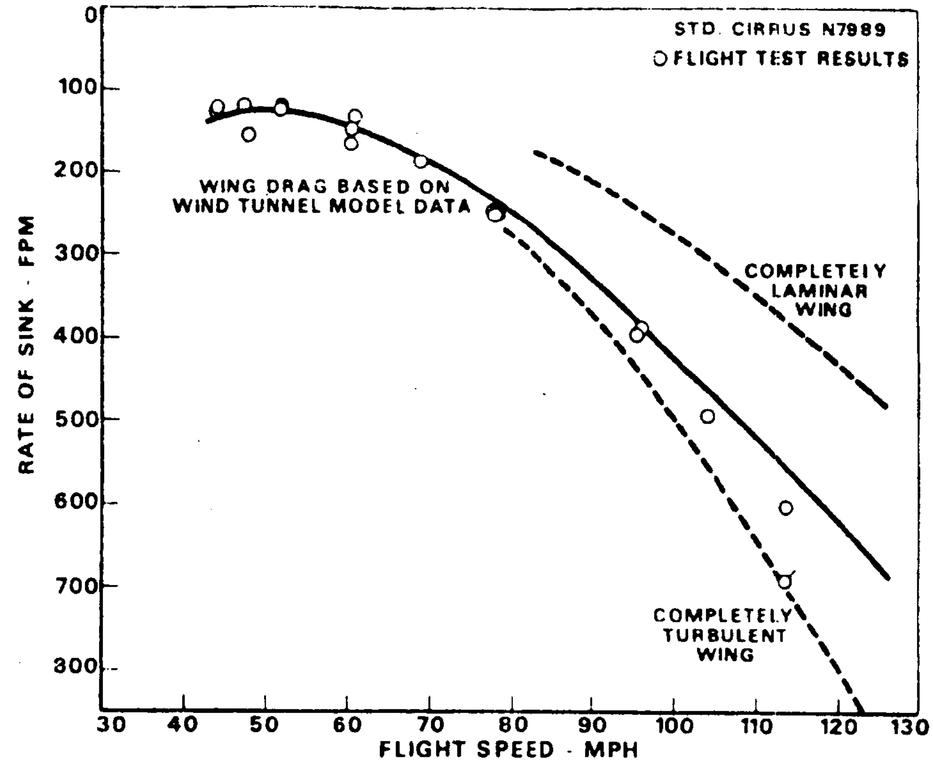
Numbers in ( ) refer to entries in Table I, Ref. I

Dashed curves are estimated.

$\mathcal{E} = L/D$,

Figure 2. Still Air Sea Level Glide Polars For Several Natural And Man-Made Flying Devices

COMPARISON OF FLIGHT TEST RESULTS WITH THEORY



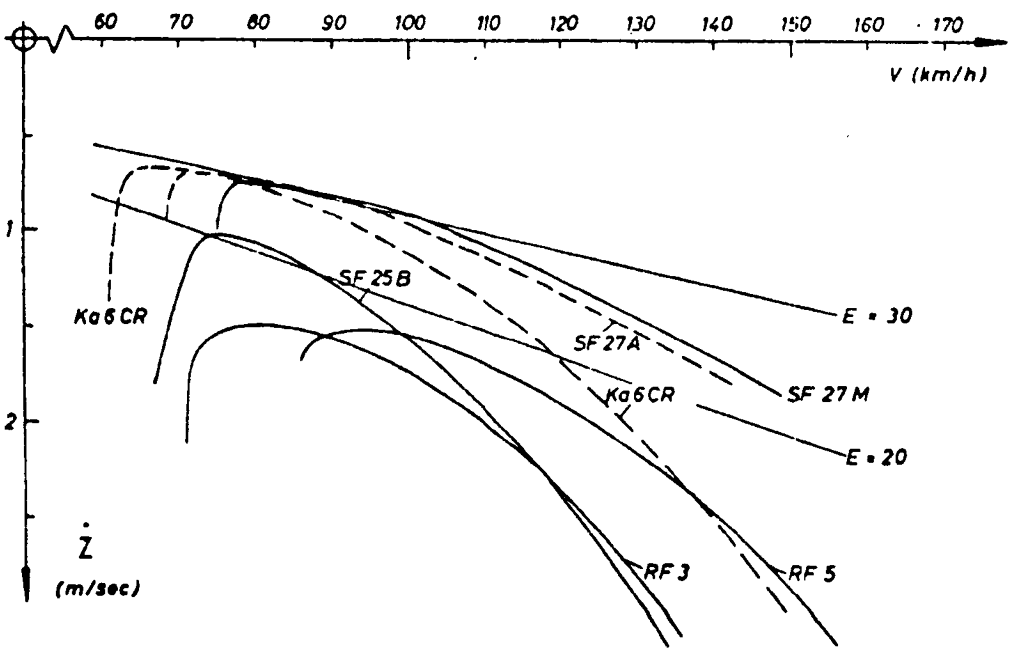


Figure 2. (continued) Still Air Sea Level Glide Polars for Several Natural And Man-Made Flying Devices

Table 2. Performance Improvement Comparison

	Weihe (1938)	ASW-12 (1964)	% Improv.
Min. $\dot{Z}$	120 fpm	109 fpm	+ 9%
V at $\dot{Z}_{min}$	35 kt	43 kt	-23%
L/D_{max}	31.5	43.3	+38%
V at L/D_{max}	41 kt	48 kt	+17%
V at $\dot{Z}$ = 6 fps	62.5 kt	88 kt	+41%
L/D at $\dot{Z}$ = 6 fps	17.6	24.7	

	Ka 6 CR (1955)	Std. Cirrus (1969)	% Improve.
Min. $\dot{Z}$	134 fpm	134 fpm	0%
V at $\dot{Z}_{min}$	36 kt	42.5 kt	-18%
L/D_{max}	29	35.2	+21%
V at L/D_{max}	42 kt	51 kt	+21%
V at $\dot{Z}$ = 2m/s	70 kt	85.5 kt	+22%
L/D at $\dot{Z}$ = 2m/s	18	21.9	

It should be noted that these gains in aerodynamic efficiency have not been accompanied by serious deterioration in stability, control or safety.

Technical Considerations

A number of practical factors make the sailplane design problem difficult, not all of which are directly related to the absence of an engine. For good climb performance (low sink rate) a low wing loading, low weight and excellent aerodynamic efficiency are desired. Further, if climbing is to be done predominantly in thermals, trim drag in moderately steep turns must be low and the speed for minimum sink rate (maximum climb rate) should be low to minimize turn radius (which, for a given bank angle, varies directly with speed squared). On the other hand, for high speed cruise the main concern is aerodynamic efficiency (high L/D). In a first order analysis (i.e. neglecting Reynolds number effects), L/D is independent of weight and thus for a given wing area, a "high" wing loading is desired. The obvious solution of use of variable geometry (e.g. Fowler flaps) to ameliorate the wing loading conflict is limited by several factors (e.g. class rules, economic and/or drag considerations, manufacturing difficulties) some of which will be discussed later. The demands of high aerodynamic efficiency in both climb and cruise require that great care be taken to minimize both parasite and induced drag. The latter is "easily" accomplished by use of high aspect ratio wings of near ideal planform. Given presently achievable values of parasite drag coefficient (about 0.010 based on wing area), the optimum compromise aspect ratios for Standard Class (span limited) sailplanes are between 18 and 22. Corresponding values for Open Class machines are between 25 and 30. *

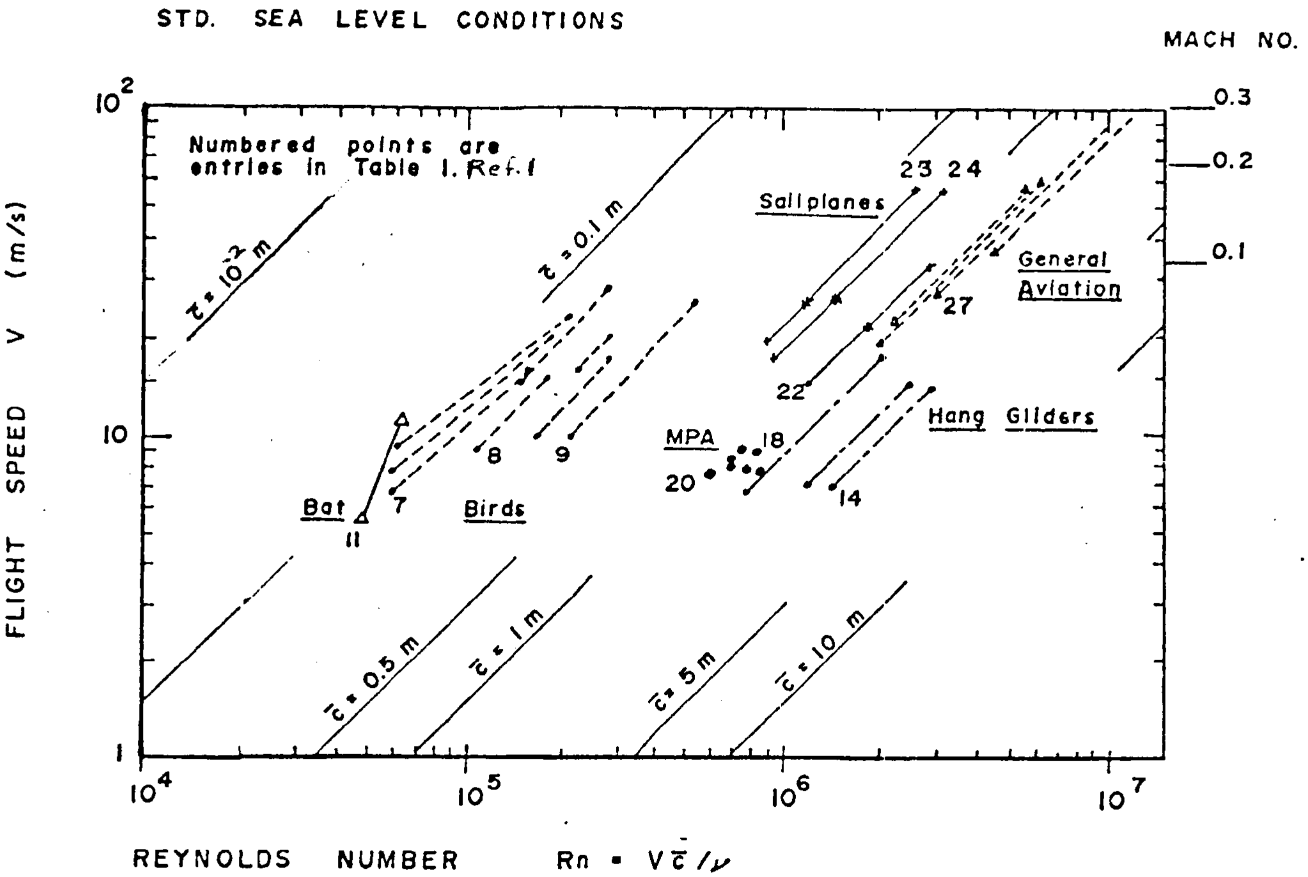
The use of high aspect ratio wings of moderate area at typical sailplane speeds, means that the wing operates in a Reynolds number range well below that of conventional GA aircraft. For example, assuming a machine with an aspect ratio of 22 and wing area of 110 ft^2, with a useful speed range of 40 to 100 kt, the corresponding Reynolds number range (based on average wing chord) is 1.0 to 2.4×10^6 at sea level. If the machine weighed 700 lbs. loaded, the corresponding lift coefficient range at sea level would be $C_L = 1.18$ to 0.19. The general speed/Rn ranges for several types of low speed flying machines are shown in Figure 3. Sailplane experience indicates that with a little care, GA aircraft designers need not be overly concerned about the adverse influence of lowered Reynolds numbers on wing drag when large reductions in wing chord are contemplated.

Parasite Drag Reduction

Post-war advances in sailplane performance began when Raspet (7) demonstrated the startling performance gains achievable by systematically cleaning up a machine of initially good aerodynamic layout. The machine used was Dick Johnson's one-of-a-kind RJ-5 Open Class sailplane which was of conventional layout and construction (largely wood) employing an NACA 6-series laminar flow airfoil. The results of the successive improvements resulting from careful sealing of gaps and leaks, and reduction of wing waviness and roughness are shown in the now classic Figure 4. The total cleanup resulted

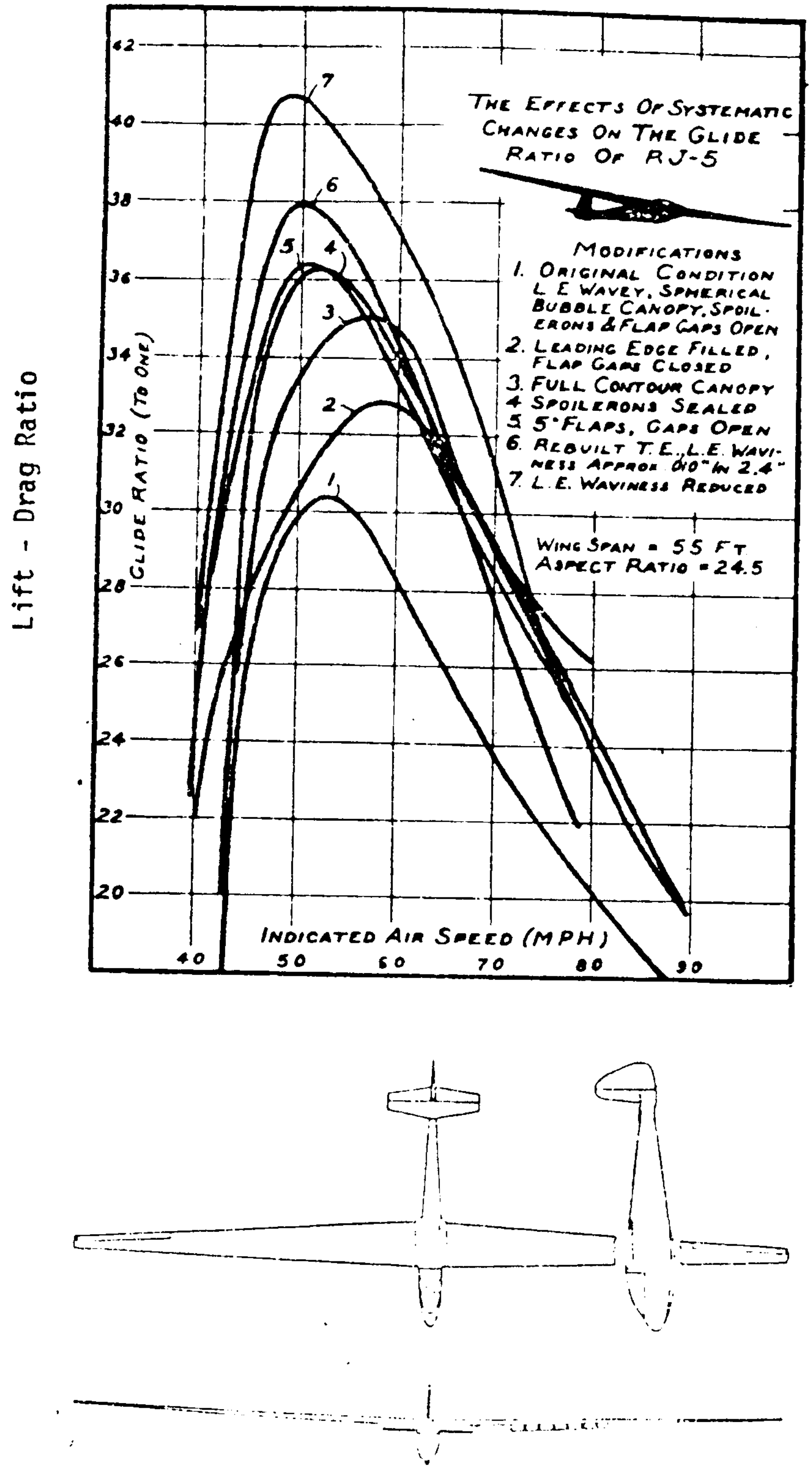
* The "optimum" in this case is not really clear, although practice indicates that machines with span greater than about 22 meters encounter serious flight and ground handling problems. Required wing area depends on the extent to which variable geometry can be achieved and desired wing loading. Thus overall operational consideration defining span and area limit optimum aspect ratios based on achievement of pure maximum L/D in both Standard and Open Class machines.

in a 25% reduction in parasite drag at L/D_{max}, about 40% of which was achieved by simple sealing and smoothing. A slightly more modern discussion of these effects has been presented by Wortmann (8). The impressive results obtained by Wil Schuemann in a general cleanup of an H-301 Libelle are discussed in (9).



Note: Reynolds number based on average wing chord

Figure 3. Flight Speed/Reynolds Number Range for Various Low-Speed Flying Devices



RJ-5

Figure 4. Results of Drag Clean-up on the RJ-5 Sailplane

Low-Speed Airfoils

The requirements of low drag over a reasonably wide lift coefficient range and the generally low values of operating Reynolds number make airfoil selection for sailplanes somewhat difficult. Pre-war sailplane designers relied primarily on Göttingen and NACA 4 and 5 digit airfoil, some of the former type (e.g. Gö 549) being specifically tested for sailplane applications. The advent of the NACA 6-series airfoils held promise of substantial drag reduction over at least the C_L range of the "laminar bucket" and, provided care was taken in manufacture, there appeared hope of obtaining the "bucket" in practice. A number of very successful designs were thus produced in the late 1940's and 1950's using various NACA 6x - 4xx and 6x - 6xx airfoils; the moderate camber of these sections representing a reasonable compromise for centering the "bucket" between the high and low speed extremes in required C_L.

The theoretical work of R. Eppler and F.X. Wortmann in Germany, beginning in the 1950's, showed that by careful contouring of the airfoil envelope and camber line, the transition point on low-to-moderate speed laminar airfoils could be controlled with some precision. This work lead to a family of Wortmann airfoils (the FX or Franz Xavier series) which have been almost universally adopted in sailplanes designed during the last decade. Wortmann's work is well summarized in his paper in (5) and his airfoils have produced something of a revolution in modern sailplane performance.

Wortmann has shown that by carefully contouring the upper surface of a fairly highly cambered airfoil, the upper end of the laminar flow range can be extended to section C_L values required for low sink rate.

When a highly cambered airfoil is operated at low C_L values, however, the airfoil is frequently flying at a negative geometric angle of attack, and thus the lower surface of the airfoil is the one on which transition (and/or separation) is of primary concern in maintaining low profile drag. Thus, by careful contouring of both the upper and lower surfaces, the low drag "bucket" can be significantly extended (in operating C_L range) compared to NACA 6-series sections of similar thickness and minimum drag. The extent of the bucket can often be further increased by adjusting the camber line with a small chord (10 - 20%) simple hinged flap at the trailing edge. Examples of the possible improvement are shown in Figure 5. Several typical sailplane and related airfoils are shown in Figure 6, and the general trend in maximum section lift-drag ratio with Reynolds number for several Wortmann and NACA Sections are shown in Figure 7.

While Wortmann's results are impressive the limited data available on the new Liebeck (10) sections appears spectacular. Whether such airfoils, which appear to approach some sort of theoretical limit in single element airfoil lift-drag ratio, can perform in practice when built into a practical wing remains at present an open question. Wortmann's investigations of the same type airfoils is reported in his paper in (6).

High Lift Devices

In the modern gospel of sailplanes airfoil design according to Dr. Wortmann the wing contour must be absolutely smooth and unbroken as far aft as possible. Thus, leading edge high lift devices, wide chord flaps or ailerons and particularly conventional Fowler flaps of significant chord are out of the question in sailplane design. Thus the designers choice of high lift devices is severely limited. As one example of a way to circumvent this problem, and provide the performance benefits theoretically available from use of area changing flaps *, Wortmann tailored a unique airfoil/flap system specifically for the very advanced British "Sigma" sailplane project (see Figure 1). The FX 67-VC-170/136 section for "Sigma" is fully described in (11) and the combined polar at $Rn=3x10^6$ is shown in Figure 5. The flap of this airfoil is "hidden" inside the basic FX 67-VC-170 airfoil when retracted, thus avoiding flow disruption at high speed. When extended, it produces a 36% increase in chord. An even more exotic scheme has been proposed and tested by Wortmann (11) which involves deploying a large sheet of sailcloth (e.g. dacron) allowing chord extensions of greater than 50% in the high C_L range.

Structures

The third component in the post-war revolution in sailplane performance has been the introduction of fiberglass as the main construction material; as pioneered by Nägele, Eppler, Stender and Hänle in Germany. The use of fiberglass wing skins allows fabrication of relatively wave free surfaces of unexcelled smoothness. A further consequence of the use of relatively low modulus of elasticity fiberglass is that in order to maintain desired levels of torsional and bending stiffness, wing skins must be quite thick and correspondingly stronger than required by existing sailplane airworthiness standards. One thus finds fiberglass sailplanes with load factors approaching those of modern fighter aircraft with little weight penalty (due to the low specific gravity of the fiberglass). Considerable room for further improvements in structures exists by use of advanced composites and materials such as DuPont Kevlar (PRD-49) with nearly three times the modulus of elasticity of existing E-glass systems.

* Partial span Fowler flap systems have been extensively tested on the South African BJ-series of sailplanes with generally poor results.

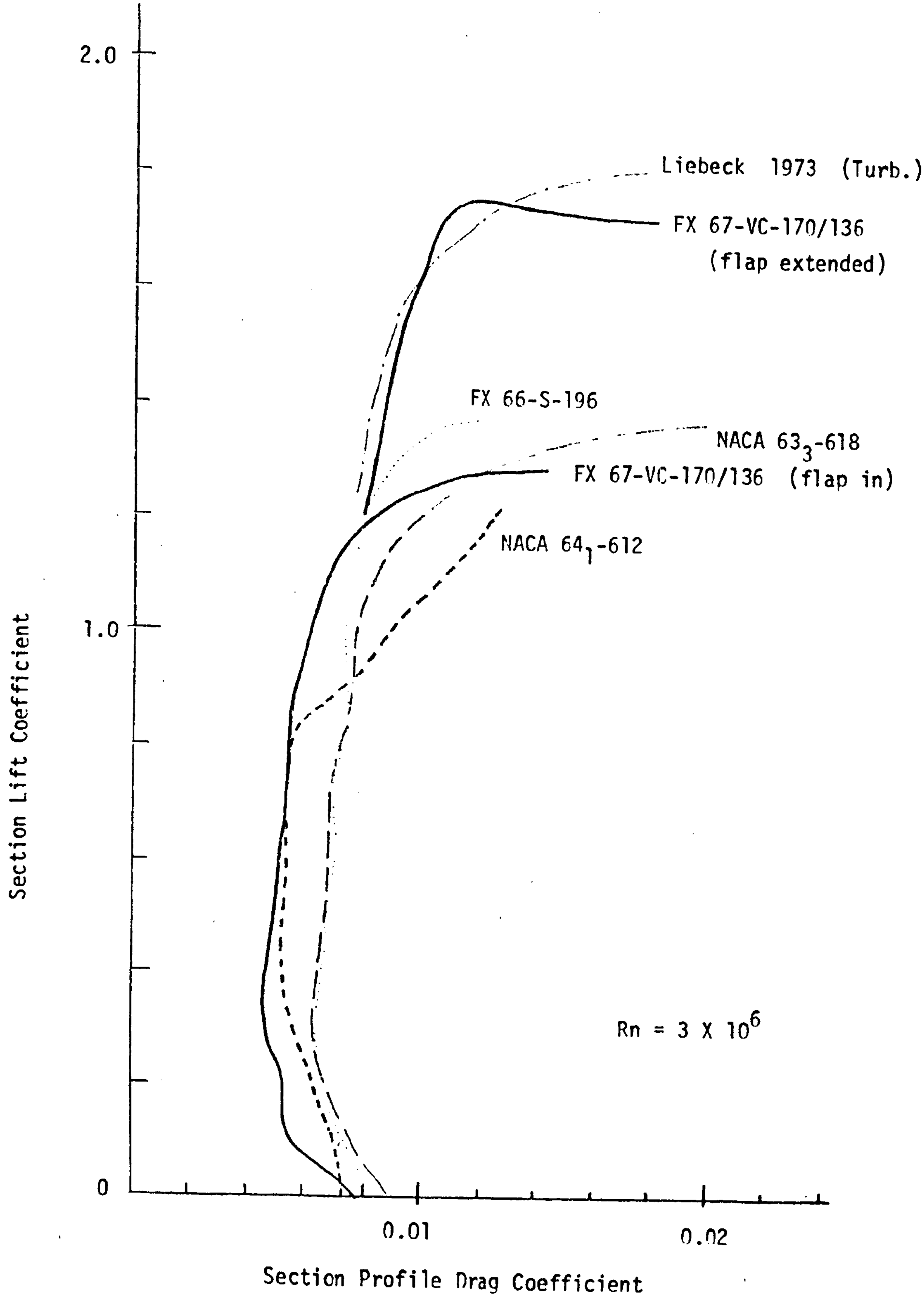


Figure 5. Several Airfoil Drag Polars at a Reynolds Number of 3 X 10^6

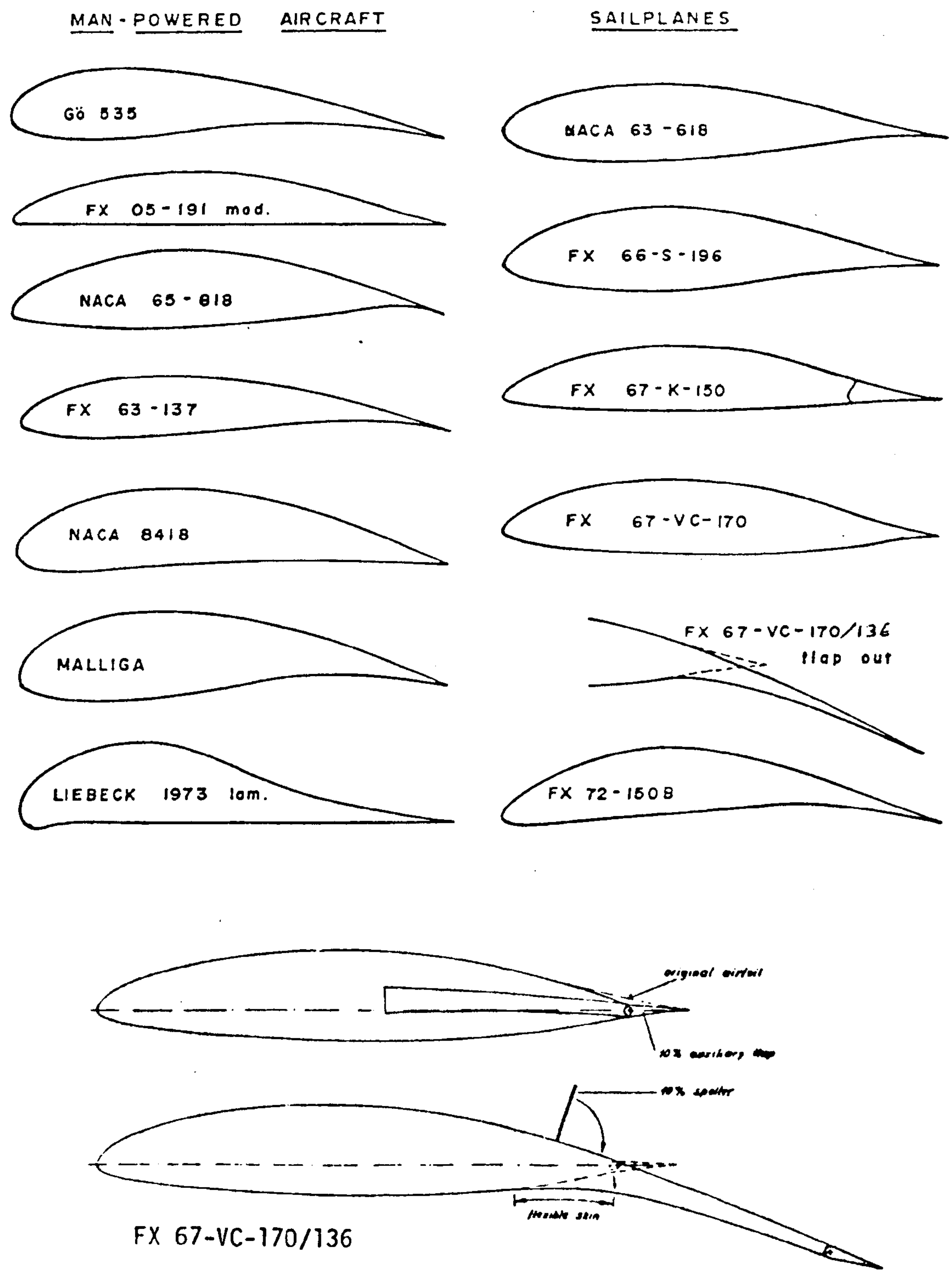


Figure 6. Typical Sailplane and Related Airfoils

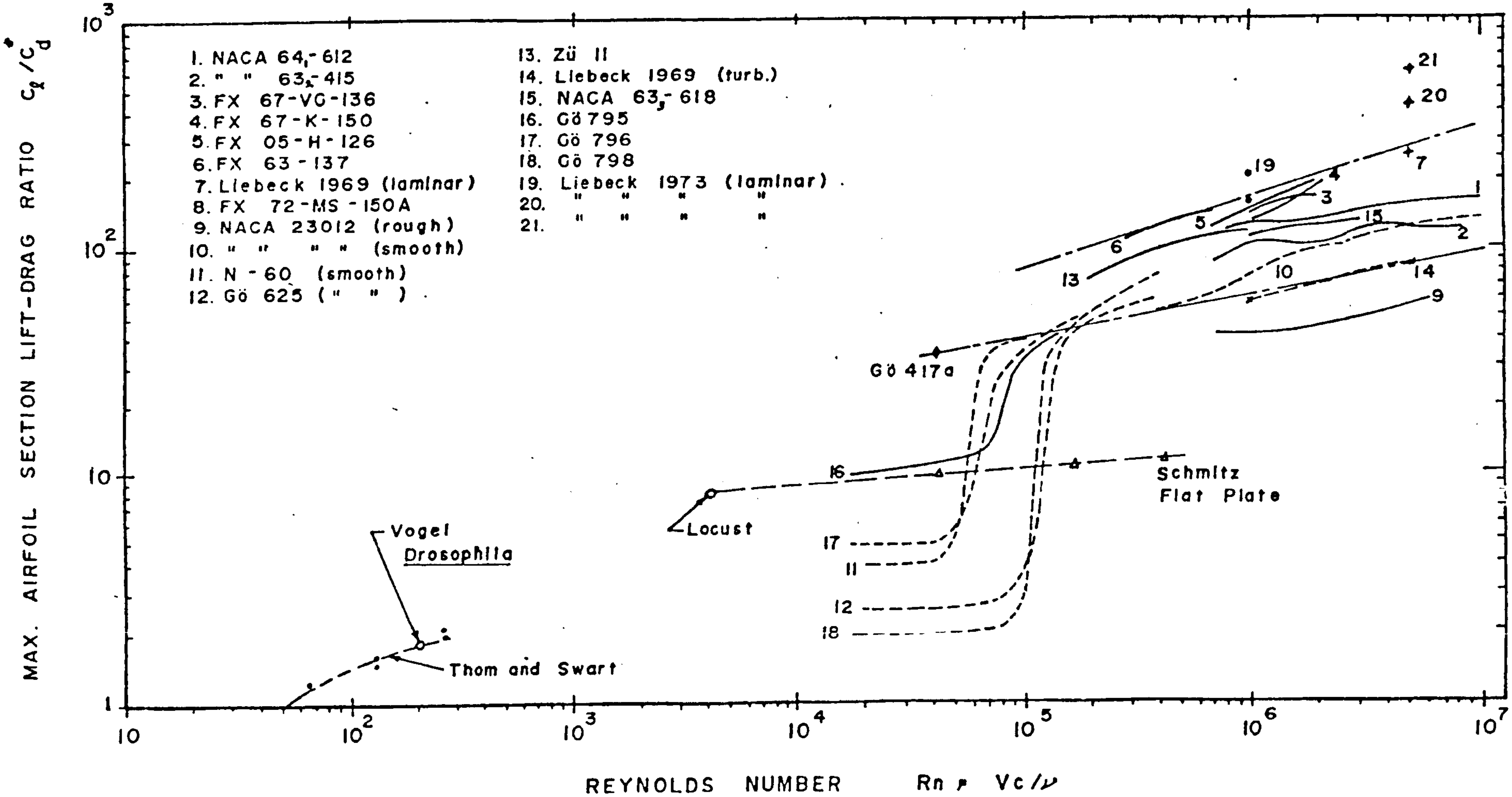


Figure 7. Variation in Maximum Airfoil Section Lift-Drag Ratio with Reynolds Number

Existing fiberglass systems have several disadvantages, however. Since most high performance sailplanes are produced in limited quantities, most fabrication is done by hand lay-up resulting in high cost and major quality control problems. Inspection for structural integrity remains a major difficulty. Questions also remain about the aging characteristics of existing fiberglass systems, and the problem of ultra-violet degradation of the structure carries the commerical disadvantage of offering the customer a choice of the basic color scheme of his aircraft. Thus, alternative fabrication schemes to preserve the beneficial aerodynamic qualities of fiberglass construction, while reducing cost, etc. continue to be explored. Notable among these schemes are the use of bonding (e.g. the Liaster "Nugget") (4), the use of "plastic" coatings over conventional aluminum structure (e.g. Schweizer 1-35) (4) and the extrusion of major structural assemblies as described by Morelli (5).

Concluding Comments

The design of modern high performance sailplanes is an enormously challenging task. The absence of an engine means that the designer cannot indulge in the "luxury" of simply fitting the machine with a larger powerplant to obscure deficiencies in aerodynamic design, weight overruns or to provide the basic design with "growth potential". Further, the machine must have very low drag values over a relatively wide lift coefficient range and these values must be achieved in a relatively low Reynolds number range. It is for these reasons that a careful study of the remarkably successful methods sailplane builders have used to achieve these goals may well repay the designers of powered General Aviation aircraft. It has not been the intention of the authors of this brief discussion to advocate or imply that all sailplane technology is applicable to General Aviation aircraft in general or that the operational and economic constraints faced by the GA designer make incorporation of applicable features feasible. However, even a brief examination of the performance figures achieved by modern soaring machines and a little reflection as the often huge disparity in L/D values between sailplanes and GA aircraft indicates that careful attention to the lessons learned in sailplane design and manufacture hold realistic promise for substantial gains in the aerodynamic efficiency of several GA types. The fuel crisis, whether transient or permanent, may force a redirection in GA design with greatly increased emphasis on operation "economy", perhaps even at the expense of speed (or productivity) and initial vehicle cost. Modern soaring technology indicates one path along which future development might progress.

Research Needs

1. Performance of Wortmann type sail plane airfoils in wings with roughness, waviness and Reynolds numbers typical of light powered general aviation aircraft need to be further investigated.

2. Simple, economical methods of construction need to be found which lead to improved surface finish and manufacturing tolerance to approach the performance of sailplane types for powered general aviation aircraft. Possible examples are:
   - "Plastic" coatings over conventional structures. (e.g. Schweizer I-35 sailplane)
   - Metal bonding techniques (e.g. the Laister "Nugget")
   - Major assembly extrusions from metal and plastic

3. The optimum configuration design implications of the use of sailplane technology in powered general aviation aircraft needs to be investigated. Specifically:
   - optimum wing geometry
   - engine/thrust producing device location
   - requirements for high lift devices
   - wing/body integration (i.e. wing position and body shape) to minimize adverse interference

4. The economic and configuration implications, in light of the fuel crisis and sailplane technology, of optimizing the design of a given general aviation aircraft toward maximum "transport economy" even at the possible expense of "productivity" needs to be evaluated.

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