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Development, Qualification and Fligth Testing of a WINGGRID on a jetpowered testbed

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Abstract

The WINGGRID consists of a grid of identical and parallel winglets mounted to the tip of an aircraft wing for reduction of induced drag. At the ICAS Conference Sorrento 1996 [1] the fundamentals of such an aerodynamic device had been presented. With the conclusive results of the windtunnel tests reportet, full-scale fligth tests of the WINGGRID using an existing aircraft as testbed were conducted. The expected performance figures of the Sorrento 1996 [1] paper were reproducibly confirmed full scale. The question, how storcks use their fingerfeathers for achieving high glide_numbers with low aspect ratio, worked on since Otto Lilienthal, has found an answer. The tests revealed good handling and safety features of the device.
The actual tests were performed in 97.
They comprised the formal airworthiness tests for qualification followed by performance testing. The available results point to an important breakthrough, not the least because applications open a new design-philosophy for wings. The paper analyses the validity of the experimental evidence obtained and identifies major conclusions for applications.

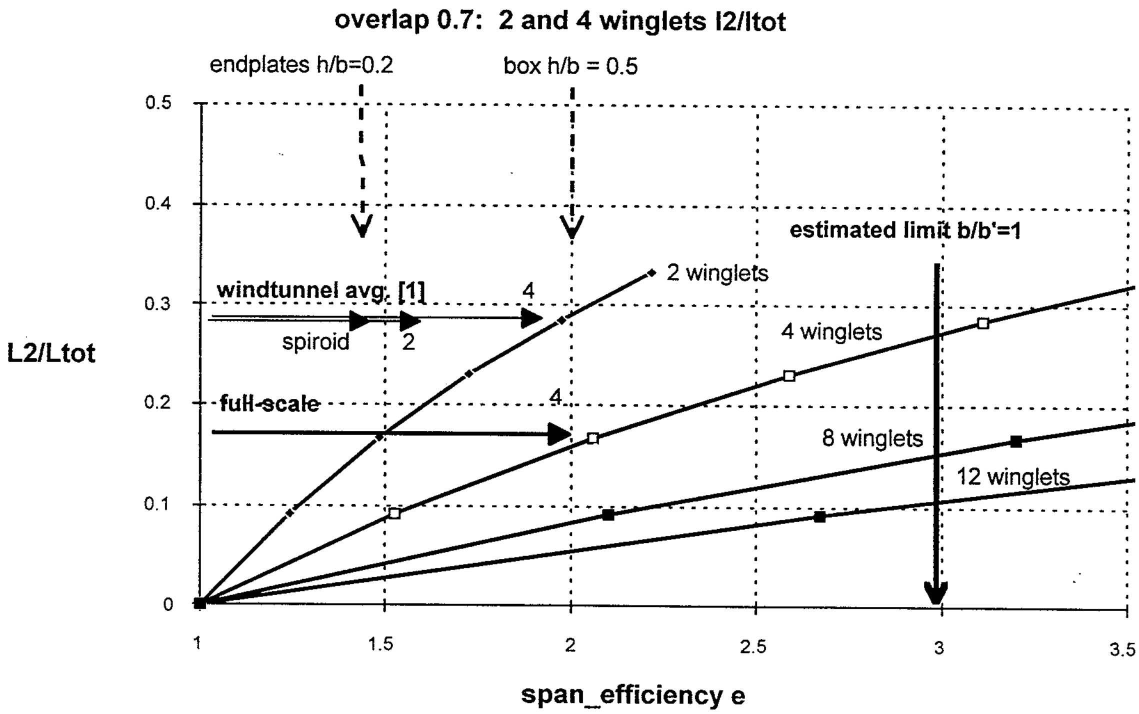


Fig. 1 Span_efficiency e as a function of WINGGRID design parameters L2/L (in Fig. l2/ltot) and nb number of grid winglets. Comparison of windtunnel results [1] and fullscale result with 4 winglets. The estimated limit for b/b'=1 is a practical limit [1] for exploiting the effect.

Introduction

The work reported is based on the windtunnel tests of the WINGGRID device [1]. A key result of this work was the diagram Fig. 1 above showing the span_efficiency as a function of the design parameters L2/L and nb. A main result of the windtunnel investigation was, that in a first order approximation a WINGGRID will increase the apparent aspect ratio of a rectangular wing by adding the aspect ratio of a grid winglet:

aspect ratio combination = aspect ratio of main wing + aspect ratio of grid winglet

Aspect ratio's are calculated for half-wings.
This was explained by stating, that the effect of increasing the farfield vortex-spacing is achieved by transfer of the wings vorticity to the tip of the WINGGRID. By evenly distributing the lift on a number nb of grid winglets the farfield vortex core will be thickened. Since the effect is proportional to L2, the span of the WINGGRID and proportional to the number nb of grid winglets, we arrive at Fig. 1. The lines nb = const. are slightly curved if we calculate them not linearized, as was done in [1], but with the full formula below:

$$e = 1 + \frac{L2}{L - L2} \bullet \{(nb - 1) \bullet overlap + 1\}$$

In the windtunnel tests cited above 50% of the postulated effect was verified resulting in reductions of up to 50% of induced drag for nb = 4. At the time it was realized, that several influences limited the effect possible. One of them beeing low Re numbers working with limited size models, causing laminar separation on the grid winglets. But as a whole, the device was as a result of the windtunnel tests sufficiently well understood to draw Fig. 1 and specify how exactly to design a full scale WINGGRID and what performance to expect from it. A key item of the understanding was that in order to distribute lift on several parallel grid winglets it is not sufficient to have them simply separated by slits. You will have to separate them just far enough to get individual lift producing grid winglets. It is the same separation successful sailing vessels with multiple rigs are using and is condensed by the prescription, that for a WINGGRID overlap should be less than 1. Since the WINGGRID is aerodynamically a grid, design rules are taken from turbomachinery textbooks rather than from classical wing theory.
For comparison with more familiar devices we have added on the e-axis values for endplates and box-configurations.

<u>Nomenclature</u>

GN	glide number from flight trajectory equivalent lift/drag ratio
q	stagnation pressure
q0	reference stagnation pressure
e	span_efficiency
M	aircraft weigth
b	span
f	friction drag as multiple of induced drag
f_calc	friction drag factor calculated for IAS with maximum glide number
L	total half-span of wing configuration considered
L2	partial span of wingtip-device
c	chord winglets
t	grid-interval
overlap	c/t
IAS	indicated air-speed
nb	number of winglets in WINGRID or Spiroid
Re	Reynoldsnumber
Clmax	maximum lift coefficient before stall
Cf	average friction coefficient for testbed
AS	ratio of angle of attack to stagger angle with verified critical value of 0.5
other	to be found in the literature cited or locally explained in the text

<u>Theory - how to assess the effects of WINGGRID ?</u>
The problem we had to solve was how to reproducibly measure the effect of a WINGGRID on a flying testbed. For ordinary airplanes and their wingtips with span_efficiency e up to 1.2 it is well known, that only comparing airplanes practically flying parallel will show measurable differences. The reason for this is that both friction drag and induced drag are involved. As the denominator in the formula for the glide number further down shows, the expression containing friction drag:

$$(f \bullet e \bullet (q/q_0)^2 + 1)$$

defines the speed for maximum GN. If the span_efficiency e has values around 1, then it will be solely friction drag, that defines the location of the glide number polars maximum. Differences in e-value will then only be recognizable by direct differences of glide numbers. Pilot errors and not directly perceptible vertical air movements give both appreciable errors in measured glide-numbers making a separation of the influences of friction drag and induced drag difficult on an absolute basis.

With the test configuration implemented we expected however span_efficiencies of around e = 2, which is a quite different case to test, because now we can use the displacement of the polars maximum for separation of the influence of friction drag and induced drag as first order influences. For instance the testbed used would with a span_efficiency e = 1 and the same friction drag have a calculated glide number of 18 at an optimum IAS 42 m/s. If we set again e = 1 and check for a reduction in friction drag to get us glide numbers of 25+ then f = 0.5 would do the job. However now the optimum IAS will be 51 m/s, see Fig. 2. With the WINGGRID measured glidenumbers are consistently around 23 to 25+ at optimum stagnation pressure equivalent to IAS 43 m/s. The (different) optimum IAS can be easely checked by smoothing the measured values of GN with the calculated values using the measured values of stagnant pressure. The measured displacement of the optimum is only consistent with e = 2 at f = 0.9. Also the exemple shows, that the cases with e > 1.5 if caused by differences of friction drag only would require an improbable reduction of total friction drag to around 50% for e = 1 to e = 2. For the calculations below the used Cf value for the testbed implies already smooth surfaces on the wings for e = 1. Leeway for further reduction of total friction drag in this case would be found in reduction of the 40% drag of total the fuselage represents only. (obviously not sufficient leeway !)

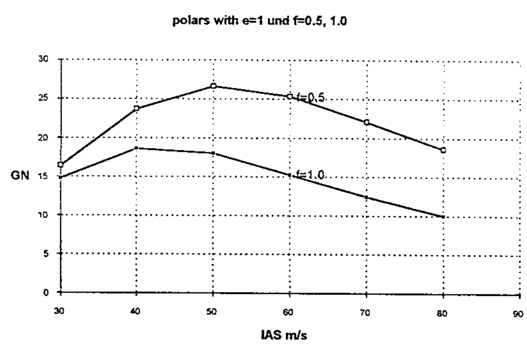


Fig. 2 effect explained with friction drag variation only

The method for evaluation of e requires the value of the friction factor f because the location of the polars optimum is defined by the product e * f.

The friction drag is a basic parameter for correct evaluation. We used the following procedure to evaluate it:
First we did a careful drag analysis [2] of the testbed configuration, resulting in a friction drag factor f_calc vs IAS, see Fig. 3

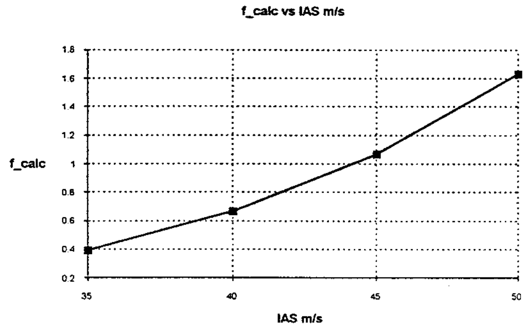


Fig. 3 Friction drag factor vs IAS m/s

Meaningful assessment of results measured would exploit two independent relationships:
a) comparison of calculated and measured glide number and smoothing for definition of polar with best fit.
b) comparison of measured glide number with lift measured on the winglets.
These two checks allow separation of the effects of friction drag and induced drag as explained and are used for filtering the measured data for consistency.
Then by crosschecking calculated polars with different friction factors and measured glidenumbers the matching friction factor for identical IAS values at glide number maximum was found. This friction factor is defined as the ratio of friction drag to induced drag at the IAS reference considered giving glide number maximum.
The next step was calculating the reference polar with its e_value to be compared with the measured glidenumbers for averaging and smoothing. For the testbed used the matching IAS reference speed and friction factor values consistent with each other are evaluated as:

IAS theoretical optimum: 43 m/s
Friction factor at optimum: 0.9

For any given value of L2/L and the number of winglets nb, assuming (the actually) used overlap of e.g. 0.7 we will get the corresponding span_efficiency e assuming fully rectangular lift distribution and an even lift distribution on the winglets. From [1] it is known, that the effect of the WINGGRID is proportional to the lift load, which lends itself for crosschecking the measured value compared to the calculated value of the glide number assuming a span_efficieny of e.g. e = 2 for 100% winglet lift.

Our tests were intended to give a first order verification of this diagram Fig. 1, which was established in [1] and represents our condensed present understanding of the device.
As a consequence we decided to run the test program reported with a single testbed and absolute measurement of (an important increase in) glidenumbers. The calculations for filtering the measured values on absolute glide number values by comparing measured values with calculated values is based on the measured stagnation pressure and the basic formula for glide number as:

$$GN = q_0 \bullet b^2 \bullet e \bullet \Pi / M \bullet \frac{\frac{q}{q_0}}{(f \bullet e \bullet (\frac{q}{q_0})^2 + 1)}$$

This expression (for subsonic velocities) is developed by writing down the definition of the glide number (equivalent to lift to drag ratio) and replacing the friction drag by a factor of induced drag at a suitably chosen reference stagnation pressure (see left side in denominator).
Comparison to the calulated polar given by the friction drag f, the span_eficiciency e, the weigth M , the stagnation pressure q and the span b was then used to find additional effects of the WINGGRIDS operation. q0 used is the reference stagnation pressure , for which the friction-drag factor is evaluated as a ratio to the induced drag. For verification the parameters for the testbed used are given below:

Table of testbed parameters

symbol	item	value	unit
M	weigth	10000	Newton
b	total span	12	meter
L	half total span	6	meter
L2	WINGGRID span	1	meter
aspect ratio		12	[-]
nb	number of grid winglets	4	[-]
overlap	c/t	0.7	[-]
stagger angle		15	degree
e_th	theoretical e	2.08	[-]
ks/l	surface roughness fuselage	0.001	[-]
f0 at optimum	friction drag factor	0.9	[-]
IAS optimum	IAS at polar maximum	43	m/s
Cf_avg	Cf average testbed	0.005	[-]

Design of WINGGRID for the testbed

The aerodynamic design is oriented on rectangular lift distribution at a design speed. This allows to calculate angles of attack as if for 2-D profiles.
In order to get the WINGGRID operating as expected, there are five conditions (logical AND see comments to US patent in publication process at time of writing) to be met:

• the devices span should not exceed a certain part of total span, say L2 <50% of L.

• the device has to have a stagger_angle of at least the maximum angle of attack (corresponding to lowest speed without stall) considered for the main wing. Definition see [1].

• the devices grid winglets should be parallel

• the device should have essentially the same lift per span as the main wing profile in 2-D flow would have at the attachment point.

• overlap of the grid winglets should be less than 1.

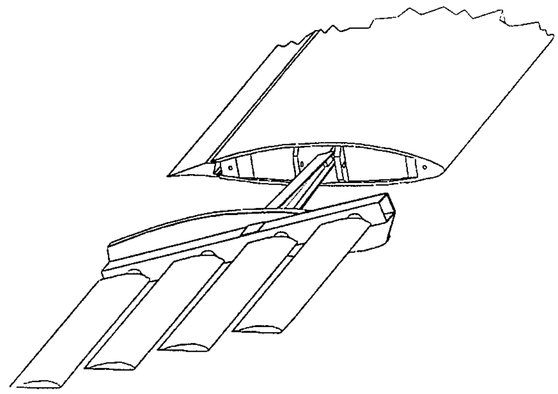
The structure of the Winggrid was designed, tested and qualified for flight on the basis of a prototype project with the inclusion of students at ETH Zürich. Since the structural design has to absorb the rather important lift load produced by the Winggrid, the grid winglets are mainly made out of an aluminum spar reinforced with unidirectional carbon fibers and a carbon skin. The stress level of a single grid winglet can roughly be approximated by the following expression:

$$1 / overlap \bullet (e - 1)^2 \bullet \sigma$$

Where σ is the root stress level of the main wing having identical profile. The smaller than 1 overlap increases the stress for smaller chord grid winglets and a higher e_value requires grid winglets with higher aspect ratio.

Therefore the ultimate design performance of each grid winglet was 1000N uniformly distributed along its length. The acceptance test verified that the WINGGRID tolerates this ultimate load by loading any or all grid winglets simultaneously in the rack for more than 6 sec. For aeroelastic reasons the deflection under this load was limited to 5 cm. The permissible inflight root bending moment corresponded to $^2/_3$ of the ultimate load. This tests and the strength verification documents were accepted by the Swiss authorities for this experimental programme.
Strain gauges at the root of every grid winglet of the right WINGGRID allowed an inflight monitoring, which was also important due to safety reasons for the pilots control.

The drawing illustrates the design for our testplatform. Grid winglets are adjustable individually.



Airworthiness tests

Required were verification of:
- -stability pitch, roll and yaw
- -approach to stall
- -rollrate

for all planned test configurations.

Prometheus is equipped with the 23 m wing of the motorglider "Stemme S10". For the winggrid flight tests, the outer wings with a span of 6.5 m each were replaced with the 1 m winggrid, resulting in a wing with rectangular 12 m span and aspect ratio of 12.
The only modification necessary was to reduce efficiency of the airbrakes.
For taxitests the aircraft was accelerated to 100 km/h to figure out the performance of the full span ailerons. Since these tests were fully satisfying the aircraft was ready for first airworthiness testflights.
These tests showed the configurations with Winggrid to have generally stable and well damped characteristics allowing for easy handling. Specifically, it was noted, that in approach to stall it was nearly impossible to provoke wingtip stall and connected roll instabilities. This was confirmed also with actuation of the airbrakes. As a conclusion we took note, that the WINGGRID is resistant to stall, a feature that confirmed our expectations. For aerodynamic grids the stall C_{Lmax} is up to 2.5+ compared to C_{Lmax} of 1.5+ on single wing profiles. Later experimental evidence confirmed again the resistance to wingtip stall, when a testflight encountered heavy rain, an occasion that was exploited to test approach to stall in heavy wet conditions.

For starting the performance flight tests and the adjustments of the Winggrid, the range of the center of gravity was extended to 42 % MAC alowing to operate with a second crew in the cockpit, handling all measuring equippement.

Measurement Routine

To eliminate wind influence on glideperformance two different methods were tried:
A : Fly one leg with as little crosswind as possible upwind , make 180-turn, fly same measurement downwind.
B: Fly the measurement in a circle with 2-5 degrees bank.

Method "A" was later used.

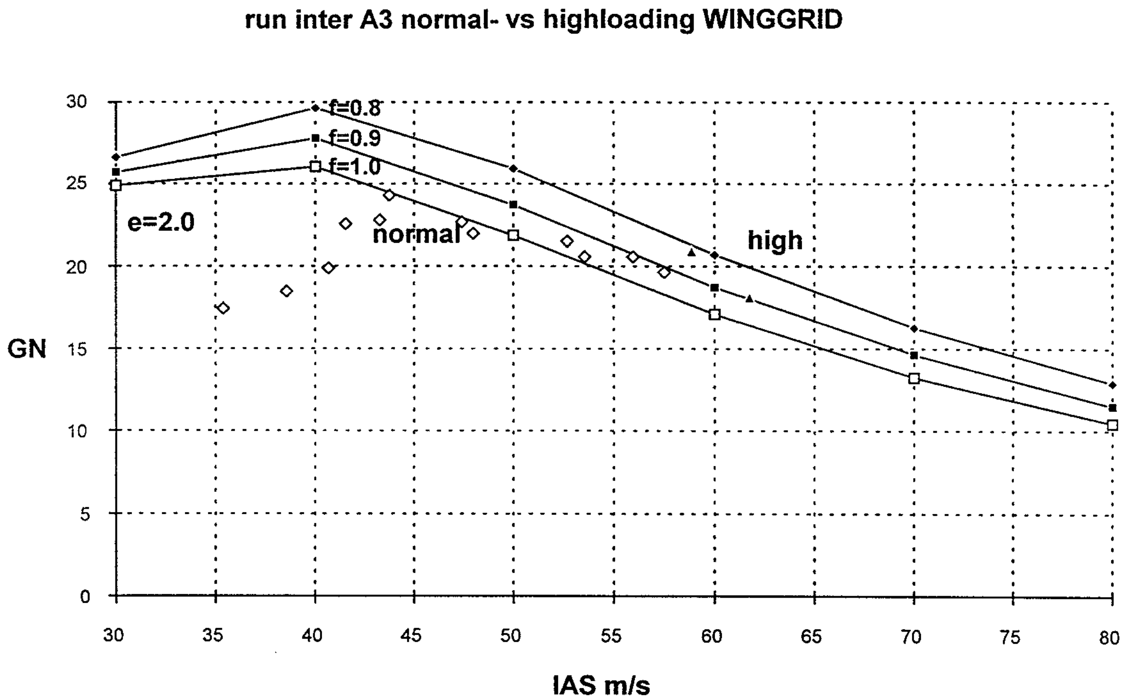


Fig. 4 An optimized configuration "inter A3" showing the three regimes typically encountered:
a) below IAS 45 m/s the WINGGRID's AS=angle of attack/stagger angle exceeds the critical value of 0.5: reduced effect on induced drag, but still marked resistance to wingtipstall
b) above IAS 45 m/s designed WINGGRID angles of attack result in near theoretical performance
c) above IAS 55 m/s increased WINGGRID angle of attack caused by negative flap positions results in a marked increase of the lift load over design values and the measured span_efficiency.

18 Flights with an overall duration of 15 hours were made. Weatherwise we were very lucky as there was allways morning-fog followed by a very stable beautiful "indiansummer" day.

The flights followed identical patterns:
• take off, clean up
• climb with different flap positions for check on lift distributions of winglets (see next chapter)
• engines shutdown, glide with given parameters according method "A" over the most stable terrain (plains of the Lindt and upper lake of Zurich)
• (repeat climb and glide)
• glide home

Load control on grid winglets

In order to validate the basis for transfer of results to other aircraft, systematic variation of the flapperons position in the measurements was used to vary the relative angle of attack between main wing and the grid winglets of the WINGGRID.
For each testrun the WINGGRID was fix during flight. But the pilot had the possibility to move the flapperon from +15 degrees to minus 10 degrees.
An example:
Measurements were asked for at 2 or 3g flight for the WINGGRID qualification.

Anybody familiar with flighttesting knows that it is very difficult to constantly hold a flightpath in a 2 or 3g turn. This gave us the idea:
Instead of flying at 2g, we would lower the flapssetting so as to overload the WINGGRID 200 % and so fly it "at 2g" in normal horizontal flight.
In every climbout we moved the flaps stepwise at different predefined speeds. Loading of every grid winglet was seen online on the laptop,and stored for record and analysis.
Before each flight the system was calibrated. This then also allowed us to optimize angles of attack of each grid winglet in order to have equal liftdistribution from foreward to aft over the speed range used.
E.g. the WINGGRID was mounted with a theoretical optimum corresponding to "Flaps = + 9" degrees
Moving the flaplever to positions lower than 9 degrees will load the WINGGRID over 100 %. Maximum loading was obtained with airbrakes extended on such a setting in diving at speed, see Fig 7 also.

Theoretical 2-D calculations showed overloadings up to 300 % with too much angle of attack!
An important byresult of the full-scale validation was, that we learned new things about the WINGGRID's behaviour:

If at speeds well below critical AS value, a limited overloading of the WINGGRID is possible (not as sharp as calculated 2-D), but sufficiently clear to get a marked improvement of the glide number. Consequently an underloading would always reduce the glide number, see Fig. 4 and 5

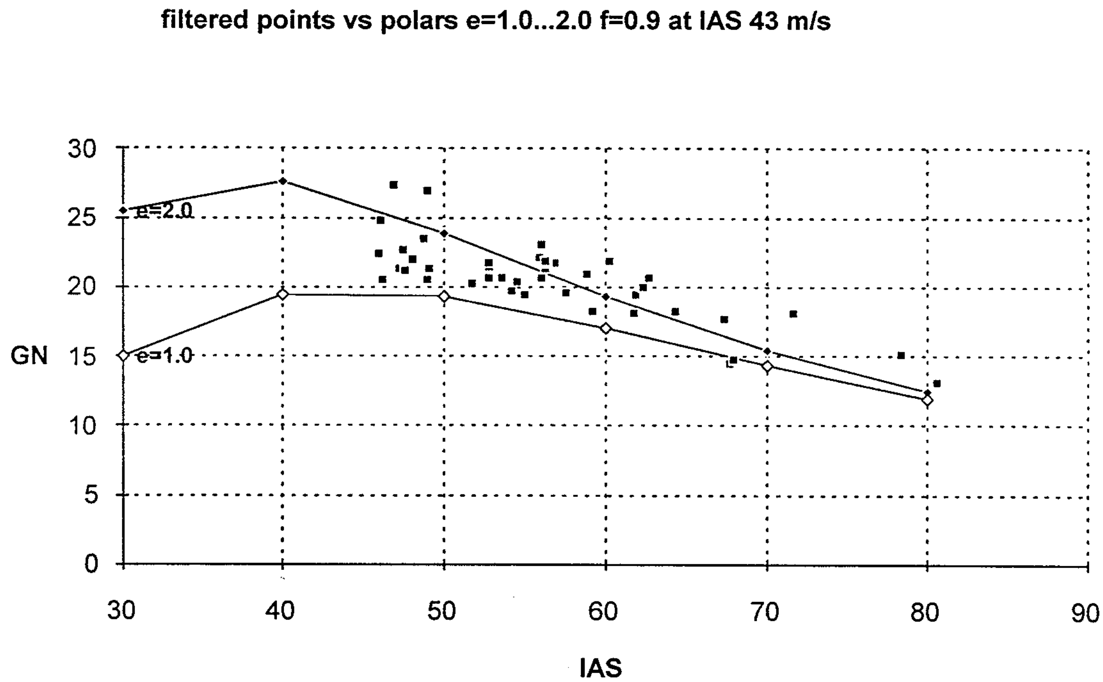


Fig. 4 selected measurements for100% lift loading and below AS=0.5. The friction parameter f=0.9 is deduced from calculated friction drag and verified by reverse calculations of the polar. Comparison is made with polars calculated for e = 1 and e = 2. For IAS above 70 m/s the grid winglets load was set above 100% by appropriate negative position of the flaps.

Results overview

•low-speed breakdown of WINGGRID Fig. 8.

The full scale measurements did not confirm the expected critical AS value of 0.67, but showed this value to be AS=0.5. So in our low speed testruns this results in reduced effect of the WINGGRID on induced drag, since with AS above the ritical value the increasing winglets mutual interference prevents the individual lift production per winglet required. An important result of the full scale tests was therefore verifying this limit. Based on [1] we designed the stagger angle to be 15 degrees or 1.5 times angle of attack at IAS 37 m/s in order to have it work at the low speed range envisaged. The full-scale measurements however revealed a critical limit for the ratio AS (angle of attack to stagger angle) of 0.5 instead of o.67 reached at IAS 45 m/s. Future design will have to take this full scale value into consideration.

With speed above this breakdown, e = 2 is consistently a lower limit of measured values. As is borne out the limiting factor is not the WINGGRID, but the maximum angle of attack consistent with the criterion of maximum AS value of the WINGGRID arrangement.

Even with speeds above the critical AS = 0.5 however the stall inhibiting feature of the WINGGRID works down to the stall limit of the plane, since Clmax of the device is of the order of 2.5+.

•Tests revealed two-way exchange of circulation as should be expected with alleviating consequences for the loads to be handled, this was specifically noted in activating the brakes in different flying conditions and measuring again lift of the winglets.

WINGGRID_Vortex_System

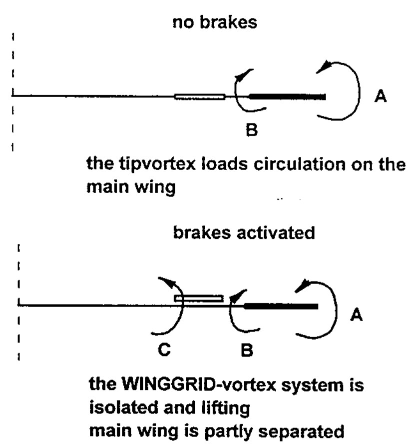


Fig. 7 The WINGGRID's different operatings

•Individual corrections of winglets attack-angles gives solid improvement for configurations without endplate, this was the standard setting used. A comparison of WINGGRID without or with endplate points to no influence for grid winglets adjusted. Grid winglets strictly at identical settings with endplates will result in practically the same performance as the adjusted grid without endplate. Equal lift distribution does moderately improve the effect. The main consideration controlling lift distribution will be limiting structural loads.

Instrumentation

Verification of operation of the WINGGRID was based on two independent measurements:

a) Glide_number measurements with absolute glide_path measurement. 8-parallel channel GPS for groundspeed and barometric vertical speed. These data were sampled at 1 second interval on the GPS data logger

b) Load on WINGGRID by rootmoment with individual straingauge measurement. These data were online displayed and stored with a laptop connected to the straingauge measurement system.

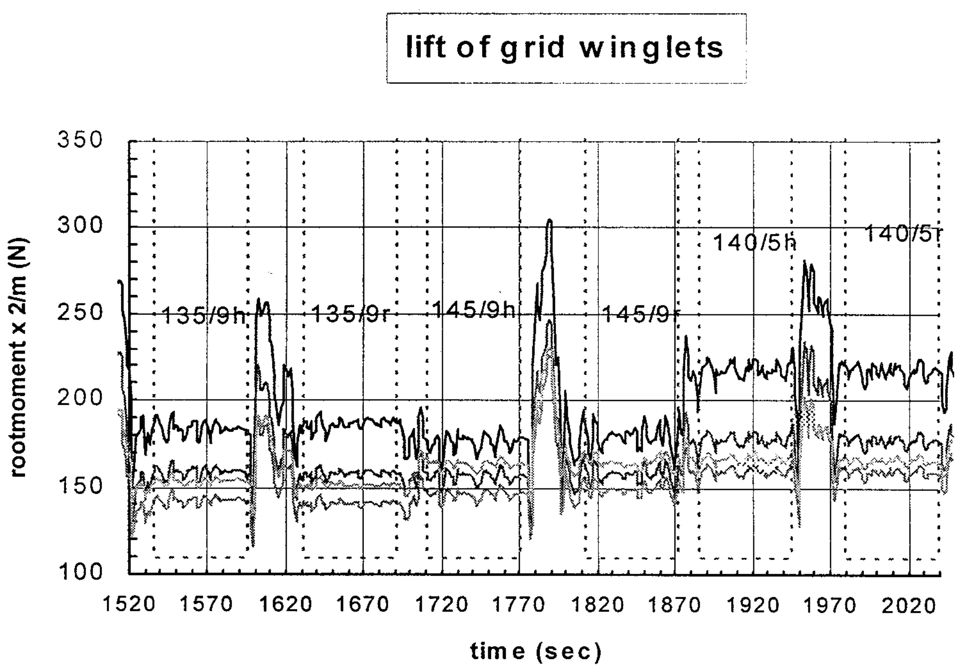


Fig. 7 winglets load during fligth. The rootmoment multplied by 2 gives the equivalent lift load in N. 135/9h and 135/9r is a typical glide number measurement back and forth at nominal speed 135 kmh and flap position +9 degrees. Time in seconds of fligth time. Grid winglets loads from front to rear (in the exemple also from top to bottom in rootmoments).

•For definition of the glide_number measured we used the following input data :
-averaged groundspeed (back and forth)
-corrected barometric vertical speed
-fligth levels
-aircraft weigth
-flap-positions
-individual root-moments of the winglets

•Configurations tested

The testbed is equipped with full-span-flaps. Testruns were made for different flappositions as reference conditions for different settings of angle of attack of the Winggrid's winglet settings.

Within a certain setting based on the rootmoment measurements individual corrections on the winglets attack-angle were made in order to get the lift distribution (equal) as required. The stagger angle between WINGGRID and main profile chord was fixed for all the testruns.

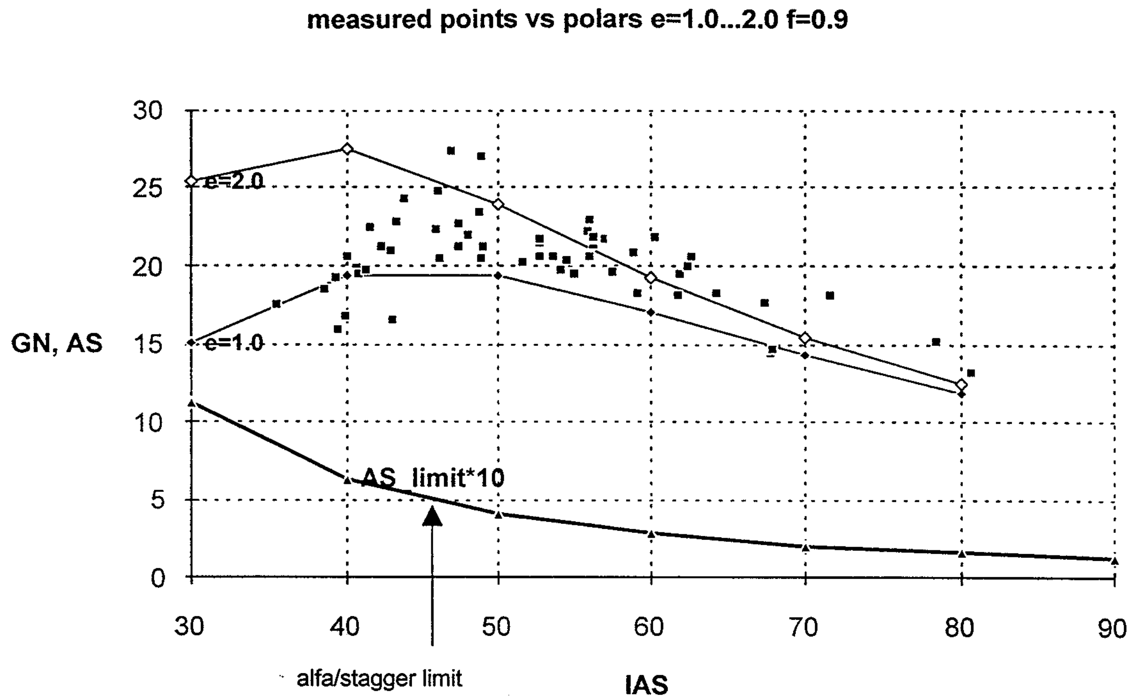


Fig. 8 The ensemble of all the measured points does not represent a mean polar, as the filtering showed, but confirms the onset of breakdown of WINGGRID as a device for induced drag reduction below IAS 45 m/s at an AS of 0.5 instead of the expected value of 0.67 from [1]. Increase of Re number for friction is included in calculated comparison.

Data reduction

Data reduction is performed using the basic glide_number formula together with the concurrent measurements of the winglets lift to filter data-runs for consistency.

The result of the filtering applied is that all the cases, where the glide_numbers measured and calculated and the winglets lift and lift distribution are not consistent within measurements accuracy, are easely identified and if not explainable quantitatively (e.g. weight differences, WINGGRID-lift or flap settings) are taken out of the averaging and polar defining process. From a total of 71 glide number measurements 6 were discarded as not explainable, another 16 beeing identified by deviation from a 100% grid winglet load due to flap settings positive (less loading) or negative (more loading).

The filtered data are used with classical averaging techniques to verify the measured polars, giving the value of span_efficiency as follows:
Define mean polar with adjusting the used value e so as to minimize mean deviation between measured glide_number and glide_number of mean polar at the point in question.

Discussion

With the reported full scale tests certainly not all questions for design and application are answered. The measurements themselves were aimed at clarification of the first order magnitude of the effects a properly designed WINGGRID would have. As a result there are a few key answers found and key questions remaining.
Answers found:
•critical AS
•proper design rules WINGGRID
•performance prediction and analysis using glide number formula
The state of knowledge reached does allow for direct design work for prototypes.
Questions remaining:
•critical AS as function of overlap
•endplates performance and winglet angle of attack corrections
•behaviour in subsonic compressible flow
•behaviour in trans- and supersonic flow
The missing information will make it possible to extend applications to higher speeds and possibly simpler structural designs.

Conclusion

The overall result confirms, that independent of the used configurations for presetting angles of attack of the winglets the optimum speed is around a fixed value given by the airplanes friction drag to induced

drag ratio. The effect of the different settings of the flaps is felt by different lift loading of the WINGGRID for different flap positions. At the optimum speed and with even and full lift load on the WINGGRID the glide_numbers attained are around 25. This amounts to a span_efficiency of the WINGGRID tested of sligthly over 2.0.
As can be seen in the summary of all measurements, near a critical AS value the effect of the WINGGRID breaks down as explained.

If you get a device which will increase the span_efficiency to 2.0 and beyond, applications needs some analysis of airplanes considered [5].
In order to have maximum effect with a rectangular lift distribution along span, the wing should for obvious reasons have no taper and no twist. Because it is a device for massive reduction of induced drag without increasing span, its main effect will be realised in speed regimes where friction to induced drag ratio is not hopelessly high. Such is generally the case in climbing phase of fligth and is usually also the case with airplanes with optimum drag in cruising condition.
Compared to the alternative of simply increasing span for attaining a higher glide number, a WINGGRID will have a comparable effect on glide_number but without increasing span and less friction drag. Equivalence means a e.g. span_efficiency of 2.5 is roughly equivalent to an increase of span of 2.5^0.5 e.g. 1.6.
For high speeds the wing with WINGGRID does have distinctly less friction drag than the wing with the same low-speed glide-number.
Application of a WINGGRID with a given (shortened) span wing will give therefore the combination of low speed high glide_numbers with high speed reduced friction drag, see Fig. 10. A noteworthy feature is the marked resistance of the WINGGRID to (wingtip) stall , which greatly simplifies handling in stall approach with an airplane of short span, even above the critical AS with uneven lift loading on the winglets, as experienced with our testbed below IAS 45 m/s.

By application of the verified design diagram Fig. 1 it is seen, that either we use a small number nb of winglets with a relatively high relative span L2 or a high number of winglets with very much smaller chord c and less relative span L2. Due to the parallel development of an oblique grooves surface texture permitting to avoid successfully laminar separation in positive pressure gradients, reportet at this conference as reserve paper [3], the classic Re number limit for smaller chords [4] can be overcome.

Overloading of the device below the critical AS value of 0.5, e.g. producing higher lift per spanwidth on the WINGGRID than on the main wing results in an additional reduction of induced drag by increasing the farfield vortex-separation, see Fig. 4, 5 and 8.

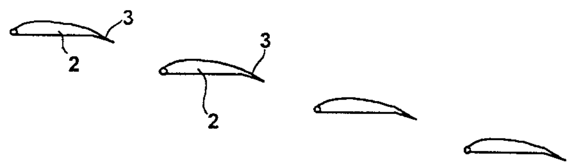


Fig. 9 WINGGRID with individual flaps for infligth lift adjustement

For infligth control of the load on the winglets a refined version therefore would make use of flaps (3) on selected winglets of the WINGGRID.

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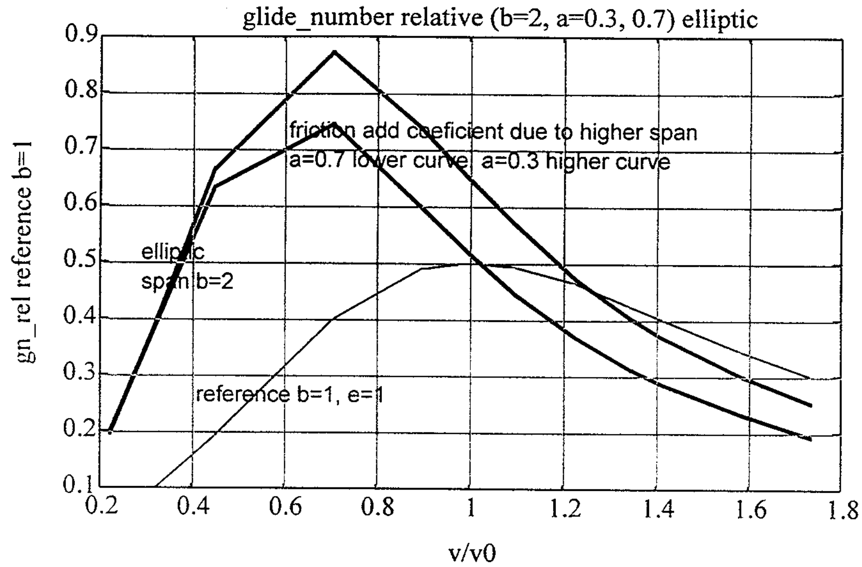
the updated webpage for design, application and source information on the WINGGRID device

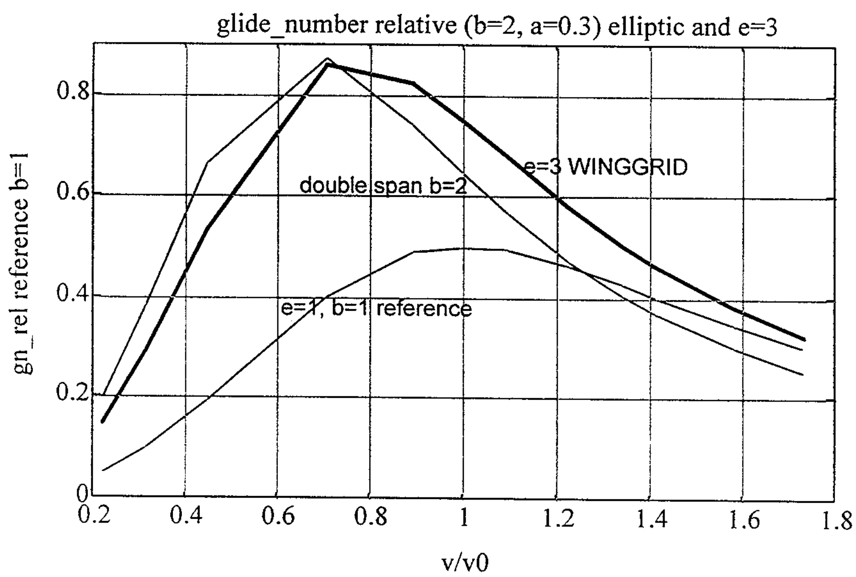
Acknowledgement

It is for all participants of the project a great pleasure to acknowledge the instrumental role that EFF, Entwicklungsgemeinschaft für Flugzeugbau and its representative Mr. Thomas Bircher, BITANX has played in planning and execution of the full-scale tests reported with the contribution of testbed, pilots and fligth program management.
First flights were made by Walter Spychiger , retired professional military flight-test-pilot GR.
Last but not least it was the initiative of Prof. Dr. H. R. Meyer-Piening, dept. ILS Swiss Federal Institute of Technology that took the WINGGRID from imagination to flying reality. And it was due to Ivo Stengele from the same department that structural design and data collection systems worked to professional standards.

Some sample polars calculated



polar with increased span goes below reference at high speed



WINGGRID polar is always above reference at high speed due to very much less
wing area exposed. optimum speed WINGGRID is somewhat higher than with increased s|

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Fig. 10 Comparison of using span vs WINGGRID for increasing glidenumbers. Coefficient a defines friction drag with extended span as f(b>1) = f(b=1)*(1+(b-1)*a), e.g. with low drag wing extensions a will be < 0.5.