DEVELOPMENT AND INTEGRATION OF A NEW HIGH PERFORMANCE WINGTIP DEVICE FOR TRANSONIC AIRCRAFT

G. Heller, P. Kreuzer, S. Dirmeier
Fairchild Dornier GmbH, 82230 Wessling, Germany

Keywords: *wingtip, drag reduction, root bending moment*

Abstract

A significant improvement in overall aerodynamic performance is necessary to fulfil the mission requirements of a business jet that is derived from the basis of a regional transport aircraft. This can be achieved using add-on high performance wing tip extensions to reduce drag. The actual design of the wingtip devices has to provide the required performance gain with minimal integration effects.

A comparative study of various variants of wingtip devices has shown that a new wingtip topology offers the best compromise to satisfy the complex requirements. The design concept of this new Shark wingtip family is introduced. Its aerodynamic performance improvement potential is detailed in results of numerical and experimental studies. Integration effects in particular structural design considerations and aspects of aircraft controllability are discussed showing the benefits of the Shark family.

1 Introduction

Converting a regional transport as Fairchild Dornier’s *728* into the corporate variant *Envoy 7* requests a marked improvement in range capability. Besides increasing the available fuel volume and consequently the takeoff mass a significant reduction of overall aircraft drag is required in the case of *Envoy 7*. Starting point for the aerodynamic performance improvement is the configuration of the baseline aircraft which is optimised for its mission requirements. As with all derivative developments, the design solution giving the necessary overall drag reduction falls under the requirement of minimal changes in aircraft systems and structure relative to the baseline aircraft. Out of these considerations an *add-on* design with minimal integration effects offers the best solution.

Breguet's range equation clearly shows that an improvement of the lift-to-drag ratio is favourable for the aerodynamic performance especially in the extended cruise segment. This is achievable by means of wingtip extensions, i.e. reducing induced drag by increasing the wing aspect ratio.

The actual design of wingtip devices has to pay close attention to minimising the negative effects of the integration of wingtip extensions. The most important of these are structural considerations – structural reinforcements stipulated by the assembly of the *add-on* devices and by the increase in loads – static as well as dynamic – being the consequence of the changed aerodynamic forces along span. Furthermore, aspects of aircraft controllability and aeroelastics need to be addressed.

2 Concept Development and Verification

As described above, the design task for the *add-on* wingtip extension requires a multidisciplinary approach, carried out in two phases. Phase 1 - the concept development and verification - is described in detail in [1]. This section summarises the main results and conclusions.

Phase 1 was started off with a systematic parameter analysis of the different drag components and their underlying physical mechanisms. It became apparent that the given 5% overall cruise drag reduction target is achievable only by an improvement in induced drag going along with a reduction in wave drag which at least needs to compensate for the friction drag and additional trim drag caused by the wingtip extension.

On the basis of a detailed analysis of the dependencies between geometrical parameters and their effects on drag [6,8] a new topology for wingtip extensions was derived applying the following design principle:

> *The geometric parameters of the outer wing at the tip should smoothly and monotonously turn into the intended values along the whole span of the wingtip extension without any discontinuities.*

For concept verification, the resulting new wingtip topology has been investigated in comparison to the tip of the basic wing and a classical winglet. Overall three variants of the new wingtip design were studied. As the look of the

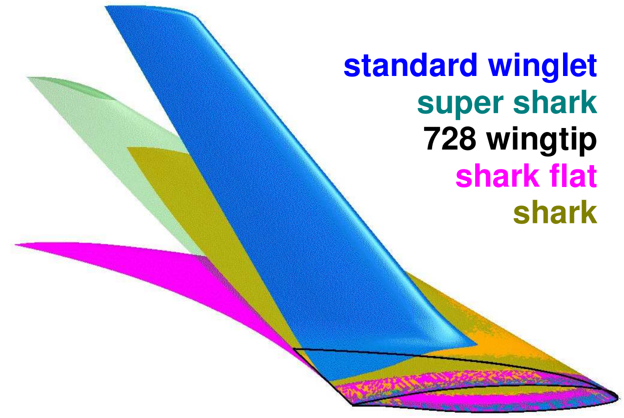

Fig. 1 **perspective view of the baseline wingtip, the standard winglet and the Shark family**

new wingtip family reminds one of the shape of a shark fin they are called the Shark family with the planar variant named Shark Flat, the non-planar Shark and its extended non-planar variant, the SuperShark™, see figure 1 and 2. Whether the Shark family lives up to the expectations, both calculations and, measurements as well as, had to give an exhaustive answer about the aerodynamic performance improvement and the structural impact and thus structural reinforcement requirements. In a first step the designs had to undergo a theoretical treatment starting with simple methods to assess the drag reduction potential and finishing with the

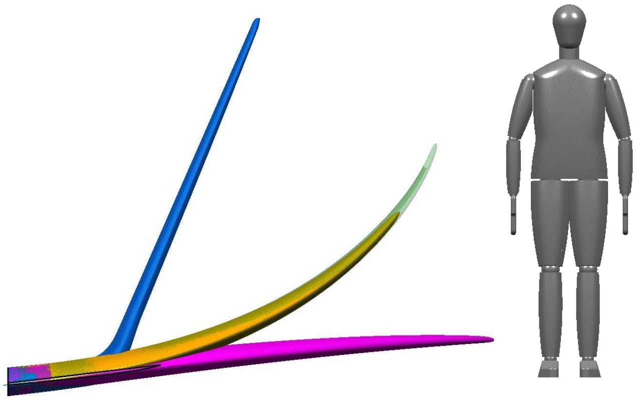

Fig. 2 **front view of the devices under consideration including a true size comparison**

FLOWER Navier-Stokes code [3] for getting insight into the physical flow phenomena and optimizing the designs.

Figure 3 comes up with two extreme results. Looking at the pressure distribution, the SuperShark™ shows well stringed together isobars, only gradually changing along span. The flow is almost 2D and consequently the losses are small.

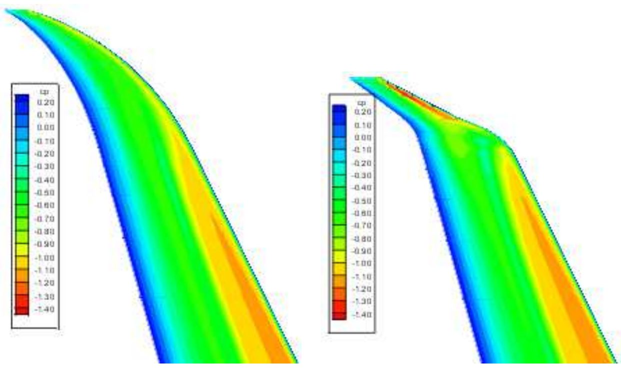

Fig. 3 **isobars on the topview of the SuperShark™ and the standard winglet M = 0.77, Re = 18 Mio, Navier Stokes**

However the standard winglet shows distinct deswept isobars approaching the tip (end plate effect), equivalent to less sweep, effecting in higher wave drag. The complex corner flow refers to an increased interference drag level.

The experimental comparison of the different configurations has been carried out in the most modern transonic wind tunnel, the ETW in Cologne.

For minimized wall interference effects on the tip side the fuselage was only partially re-

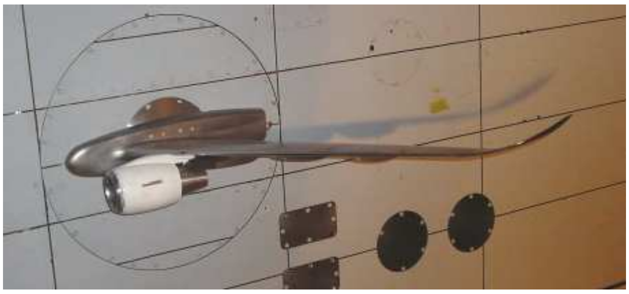

Fig. 4 fully equipped halfmodel in the wind tunnel

presented, figure 4. All devices under consideration have been measured and evaluated under the same conditions, table 1 and figure 5.

Fig. 5 comparison of the model devices for the test

The test results confirmed the aerodynamic improvement potentials of the wingtip devices determined in the preceding numerical studies. Figure 6 shows that SuperShark™ and Shark Flat both meet the challenging 5 % drag reduction target at the cruise point.

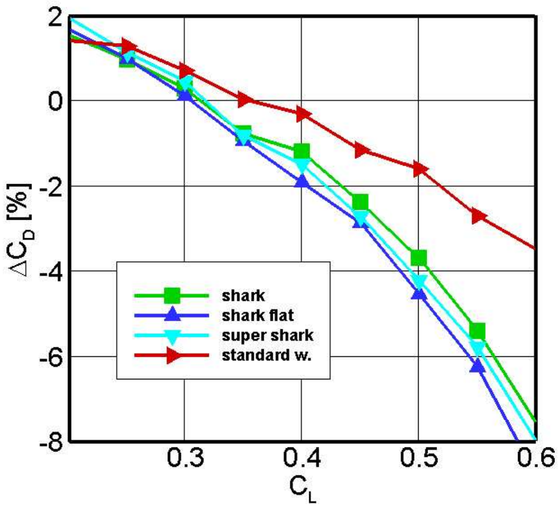

Fig. 6 resulting drag improvement ΔC_D over lift C_L

The most important result of this test campaign is a figure of merit *FM* – drag reduction ΔC_D over increase in rolling moment (as an almost equivalent measure for the wing bending moment) – which allows a first combined assessment of aerodynamic improvement and structural impact of the wingtip devices , fig.7.

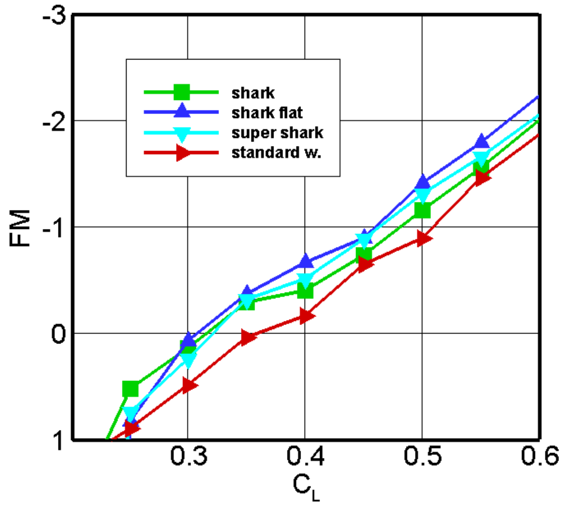

Fig. 7 Figure of merrit FM for the selection

Shark Flat and SuperShark™ turn out to be the best performing wingtip devices providing the best aerodynamic improvement potential at the relatively smallest wing bending moment increase. For the further more detailed investigations into the integration effects it was therefore decided to continue Phase 2 with Shark Flat and SuperShark™ only.

3 Full Model Windtunnel Tests

For the evaluation of longitudinal and lateral properties dependent on a variety of primary and secondary controls settings different models have been built and tested in adequate tunnels, fig. 8 and 9 and table 1 below.

Fig. 8 high speed model – scale 1:20

Model	full	half	full
scale	1 : 13	1 : 9,2	1 : 20
speed	low	high	high
Tunnel	F1, GST, NWB	ETW	HST
Mach	0,3	0,5-0,85	0,5-0,85
Reynolds	4 Mio	7 Mio	4 Mio

Tab. 1 Model overview and flow properties

Some characteristic results out of those measurements are chosen to be subsequently presented without taking Reynolds scaling into account. Note that if there is not a significant difference looking at the results, either the Shark Flat or SuperShark™ will be compared to the base.

Fig. 9 low speed model – scale 1:13

3.1 Maximum Lift

The lifting components of the device contribute to the total lift. Even if there is a pure vertical device only, the endplate effect will lead to a more ample lift distribution at the very end of the wing. The wing sweep shifts the tips and its extra lift clearly behind the center of gravity an therefore a pitch down occurs. The opposite effect comes with a tip stall.

Since the objective with mounting wing tip extensions not centrally is to improve high lift capabilities, however there is a small benefit of about 3% for the clean configuration and a gain of 2% for the flaps/slats fully extended. The main reason for that is the enlarged wing area by the extension. For the high lift case, the percentage of the enlargement is smaller due to the additional flapped area, figure 10.

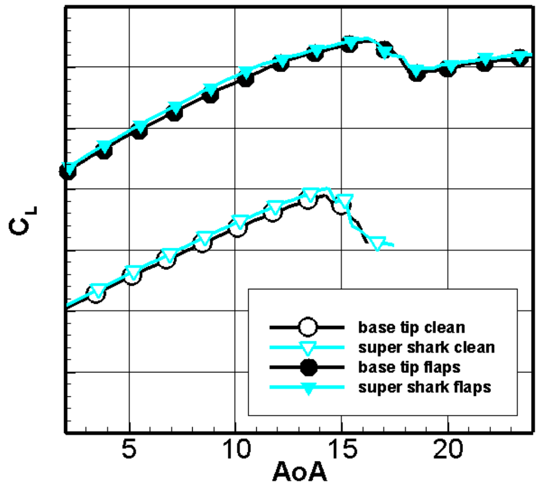

Fig. 10 lift C_L incl. maximum lift C_{Lmax} for clean and full flaps over α - SuperShark™ and base tip

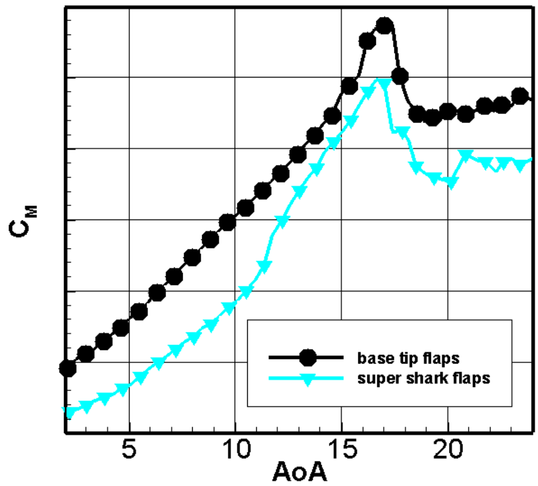

Fig. 11 pitching moment C_M over angle of attack α coresponding to the lift C_L, fig 10.

The accompanying pitching moment, i.e. flaps down, turns out to be more nose down. This is in line with the known mechanism of additional lift at the wing tips, see above. Figure 11 brings that almost constant effect to light over the whole range of angle of attack, even beyond the maximum lift. This indicates a tip free of separation.

3.2 Aileron Efficiency – low speed

An important aspect within handling qualities is controllability. Attaching a tip extension leads to a local lift increase not only on the tip itself but on the outer wing, too. Hence the aileron is faced with increased local lift coefficients for zero deflection already. Deflecting the aileron down leads locally to a lift increase.

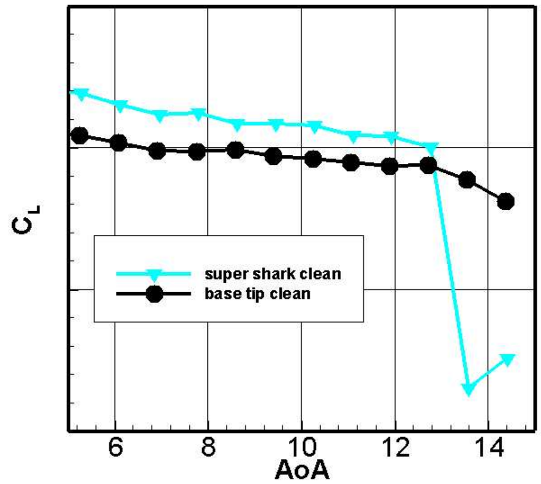

Fig. 12 aileron efficiency – Rolling moment C_L over angle of attack α – SuperShark™ , base tip

Local maximum lift is reached more early at smaller angles - either angle of attack or aileron deflection angles. The roll control capabilities by ailerons will be suddenly cut back, see figure 12, where at high angles of attack at constant aileron of 20° this cut could be seen clearly.

On the other hand for smaller angles of attack the roll power increases compared to the baseline. There is more lift in the vicinity of the aileron, particularly at the tip of the aileron – aileron deflection is more effective.

The harming part of this double-edged effect needs to be observed carefully.

3.3 Drag Rise

Perceiving already the governing role of the induced drag, but for higher Mach numbers the gain in wave drag is no longer negligible. Figure 13 shows an advantage for the extended wingtip, that has at M=0.8 already a magnitude of 5 counts. This is more than the expected compensation for the increased profile drag. Going in line with the findings out of the calculations there is a distinct high speed advantage.

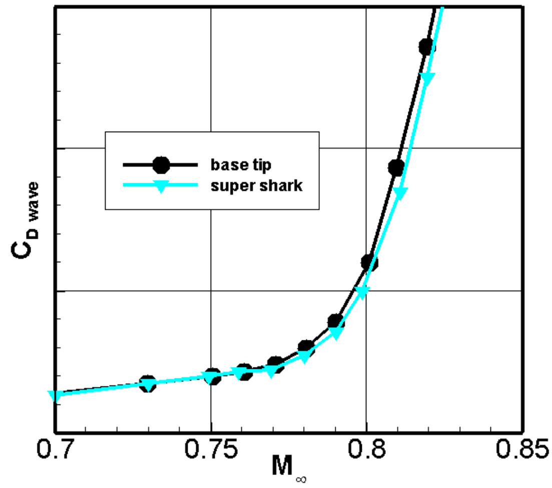

Fig. 13 drag rise – wave drag C_{Dwave} over Mach number for constant lift coefficient

Figure 14 shows the calculated spanwise distribution of local wave drag for cruise conditions, [5]. As a consequence of the built-in sweep, the wingtip extension itself doesn't contribute at all. Again the extra lift on the tip extensions relieves the wing, local lift coefficients on the wing are reduced, the dependent wave drag as well.

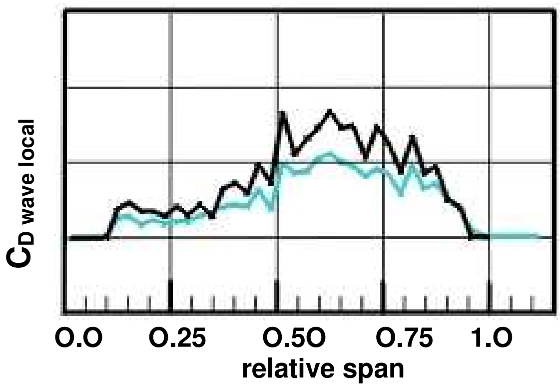

Fig. 14 wave drag $C_{D\ wave\ local}$ along relative wing span with and without SuperShark™

3.4 Lateral Motion - Roll due to Yaw

Dependent on the shape (dihedral, sweep) and size of the device some of the lateral derivatives become sensitive. First of all the rolling moment due to yaw will be influenced. Roll damping typically increases, too. The positive effect of dihedral on drag for non planar solutions [2,4] could cause a harmful change in that derivative in return [7].

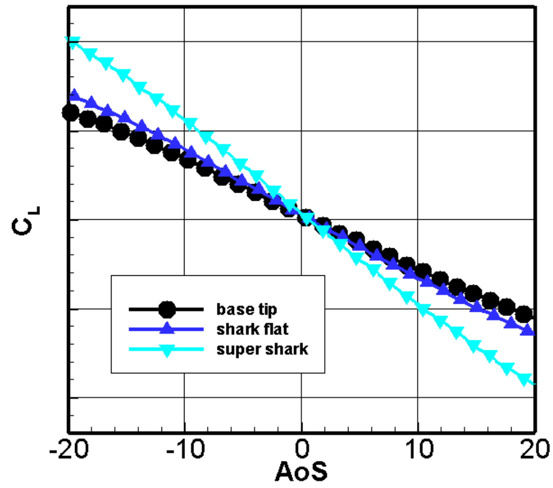

Fig. 15 roll due to yaw – Rolling moment C_L over angle of sideslip β for clean aircraft – Shark Flat, SuperShark™ and base tip

The $C_{L\beta}$ derivative, gradient of the rolling moment over the angle of sideslip, shown in figure 15, rises significantly with dihedral. Even if the dihedral is just continued, like with the Shark Flat, the increase will be already as big as 15%. As the $C_{L\beta}$ is one of the governing parameters of the dutch roll motion, it will be an excellent means to tune it, if the extra drag effect could be accepted as of secondary order.
Finally it becomes an outstanding balancing exercise to find an optimum set of geometric parameters.

4 Structural Integration

Keeping the design simple, harmonic and less complex helps avoiding heavy machined parts, driving weight and cost.

For a typical *add-on* scenario, three things are to be done. Design the tip device, find a proper attachment and beef up the basic wing structure where necessary. The latter might be painful within a retrofit process but not in case of prerequisites in the basic wing structure.

In particular the first task will be carried out more easily if the design process follows a multidisciplinary approach. Taking care about enough volume and local height for the spars as well as harmonic topologies without any pronounced edges or corners smoothes the way for a highly optimized composite design, fig.16. With respect to weight complexity and cost, the thickness of the structure helps easily avoiding heavy machined parts in the tip. The structure could even be a single part, dependent on the manufacturing process.

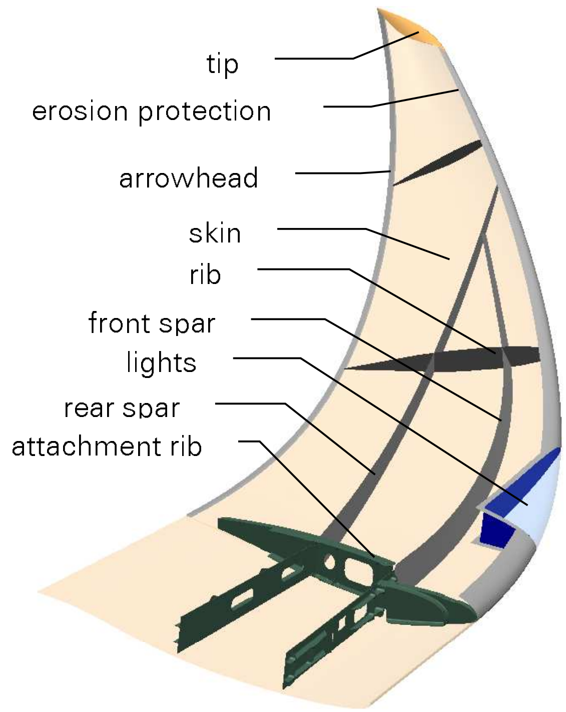

Fig. 16 structural layout of the SuperShark™

With the exception of the tip lights no system need to be incorporated. The sweep allows a positioning of the light under a transparent cover in a leading edge pocket near the tip root. Protection against erosion and lightning are not to be forgotten.

The wingtip device gets married to the wing by means of an attachment rib belonging to the wing. In case of tip damage – during ground handling there is a certain likelihood – an easy exchangeability should be possible.

5 Conclusion

The main objective of the presented family of wingtip extensions is to make cruise flight for a converted jet transport more economic.

The way how such devices could be developed and optimized has been shown. Additionally some characteristic results out of numerous calculations and extensive windtunnel tests were thought to point out some specific problems.

Fig. 17 corporate jet including a wingtip extension out of the new Shark family

However, since the basic parameters of the Shark topology has been varied only up to a certain extend, there is still a potential for further activities. Nevertheless the basic designs are ready to be flown, see figure 17.

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