Low- Speed Aerodynamic Characteristics of a Slender Wing with Vertical Fins

A. Brümmer, D. Hummel

Institute for Fluid Mechanics
Technical University of Braunschweig
Bienroder Weg 3, D - 3300 Braunschweig, Germany

Abstract

At the Institut für Strömungsmechanik of the Technische Universität Braunschweig experimental investigations on wing-fin interference were carried out on a basic configuration which consisted of a sharp-edged cropped delta wing (aspect ratio Λ = 0.93, taper ratio λ = 0.33) as the vortex generator and half-wing-shaped vertical fins of different size. These fins were located at various spanwise positions: Single fins in the symmetry plane of the configuration as well as double fins at mid halfspan and at the tip of the wing were investigated. Six-component balance measurements and flowfield studies by means of the laser lightsheet method were performed in the institute's 1.3 m low-speed windtunnel.

The results of the comprehensive six-component measurements show the effects of the various fins on the lateral stability of the configuration. The results show that a central fin is less effective than double fins of the same area at the wing tips. Concerning unsymmetrical flight conditions, a configuration with twin fins at mid halfspan position shows lateral instability. For a central fin configuration, sudden and considerable changes of the aerodynamic coefficients occur for certain combinations of the angle of attack and the angle of sideslip. An overview of the flow status for the various fin configurations is given on the basis of flow visualizations.

1. Introduction

Generic hypersonic transport aircraft as well as space vehicles will be designed as slender wing-body combinations which are stabilized throughout the whole Machnumber range by means of fin configurations. In the landing situation at low speed and large angles of attack the flowfield is governed by a pair of vortices which is generated at sharp or rounded leading-edges of the wing. In this case the fins act in a vortical flowfield and in general vortex formation occurs as well at the leading edges of the fins. This means that interference between two vortex systems takes place over the upper surface of the configuration, which determines the pressure distribution and the aerodynamic coefficients.

Concerning the basic flow around slender configurations, a large number of investigations is available, see e. g. [1] to [3]. The arrangement of fins is very close to practical applications and therefore systematic investigations are very rare. Recently, a single configuration [4] has been studied in steady and unsteady flow. During the last two international conferences on slender wings [5], [6] many control concepts have been discussed. In particular the papers [7] and [8] present aerodynamic coefficients for double-fin configurations, although the corresponding flow phenomena are not yet understood.

At the Institut für Strömungsmechanik of the Technische Universität Braunschweig basic experimental and theoretical investigations on the wing-fin interference at low speed are being carried out. Three different concepts of vertical fin arrangements are considered:

(i) Central fin, representing configurations similar to the "Space shuttle orbiter".
(ii) Twin vertical fins in about mid-halfspan position, representing modern fighter aircraft as well as the "Sänger"-configuration.
(iii) Twin vertical fins at the wing tips, representing the "Sänger" upper stage "Horus" as well as the "ELAC"-configuration.

Within the research program the capabilities of these three concepts are compared and the aerodynamic characteristics are analyzed by detailed investigations of the vortex formation on these configurations. This work is an extension of the institute's hitherto existing comprehensive studies [1], [9], [10] on the aerodynamics of slender wings.

2. Description of the Tests

The measurements were carried out in the 1.3 m Low-speed Windtunnel of the Institut für Strömungsmechanik at the TU Braunschweig.

The windtunnel model is shown in Fig. 1. A cropped delta wing with an aspect ratio $A = b^2/S_W = 0.93$ and a taper ratio of $c_{tW}/c_{iW} = 1/3$ has been used as the basic wing. Its leading-edge sweep $\varphi_W = 65°$ is the same as in the configuration of the International Vortex Flow Experiment [3] and its taper ratio provides a certain size for wing tip mounted vertical fins. Half-wing shaped fins of three different sizes (small (S), medium (M) and large (L)) have been used and were positioned at the trailing-edge of the wing in three spanwise positions (central (C), mid halfspan (H) and tip (T)). All combinations of size and position were tested with the exception that in the wing-tip position only the small sized fins were possible. Cross sections through wing and fins show very thin flat plates with sharp leading-edges slanted from below at the wing and from both sides at the fins. The basic wing as well as all fins were equipped with a tube system underneath the surface and with pressure holes in order to measure the surface pressure distribution.

For all 7 wing-fin-configurations six-component balance measurements were carried out for angles of attack $-5° \leq \alpha \leq +40°$ and for angles of sideslip $-7.5° \leq \beta \leq +26.0°$. On each wing-fin configuration, the flow on the upper surface was analyzed for 12 different combinations of the angle of attack α and the angle of sideslip β by means of pressure distribution measurements and through visualizations of the surface flow by oilflow patterns and of the 3D flowfield by the Laser-lightsheet method. The free stream velocity was $U_\infty = 34$ m/s, corresponding to a Reynoldsnumber (based on the wing root chord $c_{iW} = 600$ mm) of $Re_\infty = 1.4 \cdot 10^6$.

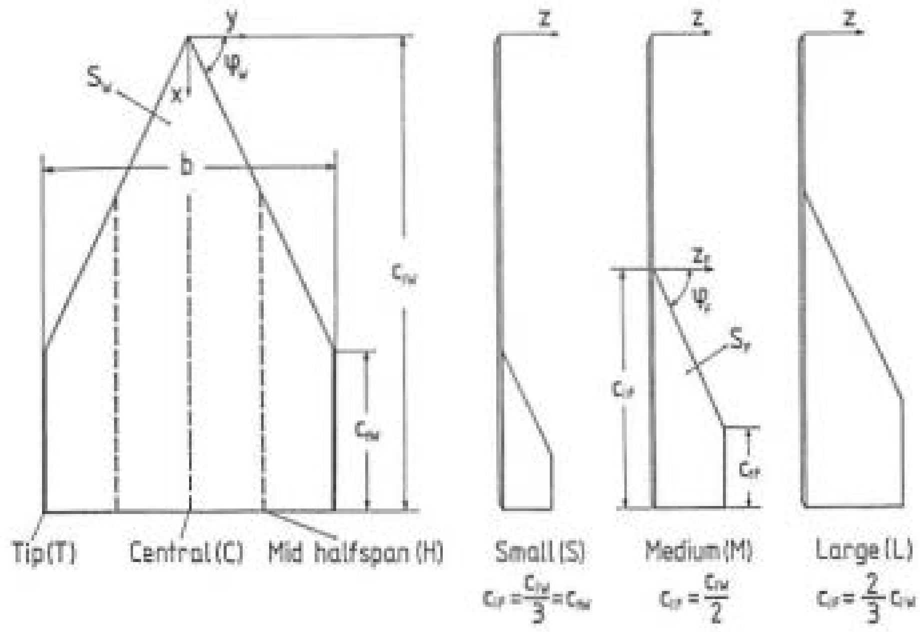

Fig. 1: A Cropped delta wing ($A = b^2/S_W = 0.93$, $\lambda = c_{tW}/c_{iW} = 1/3$, $\varphi_W = 65°$, flat plate) with half-wing-shaped vertical fins of different size (S, M, L) in various spanwise positions (C, H, T).

3. Results

In the following, the aerodynamic characteristics of the three typical configurations are chosen and shown in some detail, namely:

- (i) One medium-sized fin in central position (MC). Area ratio $S_F/S_W = 1/4$.
- (ii) Two small-sized fins at mid-halfspan position (SH). Area ratio $2S_F/S_W = 2/9 = 1/4.5$.
- (iii) Two small-sized fins at tip position (ST). Area ratio $2S_F/S_W = 2/9 = 1/4.5$.

These three configurations are comparable since in unsymmetrical flow the ratio of the total fin area (S_F or $2S_F$) exposed to the lateral flow, to the wing area S_W is about the same for all of them.

3.1. Symmetrical Flow

Results of the three-component measurements are shown in Fig. 2 for all three configurations. The characteristics for the wing alone W are identical with those for the central fin configuration MC. In all cases the well known nonlinear dependence of the aerodynamic coefficients on the angle of attack appears for small and medium angles of attack. At $\alpha = 20°$ a vortex breakdown takes place over the wing. The lift and nose-down pitching moment coefficients are reduced as indicated in Fig. 2 by hatching.

On the configurations SH and ST the vertical fins cause a disturbance of the wing vortices which leads to increased vortex breakdown. The earlier onset of vortex breakdown over the wing at $\alpha = 16°$ as well as the reduction of the aerodynamic coefficients are distinctly marked for the configuration SH with twin fins in mid-halfspan position, since in this case the fins are located close to the wing vortex centre and the effects are very large. Flow visualizations have shown that for $\alpha > 15°$ the fins operate in crossflows which are directed outwards and which lead to the formation of vertices over the outer surfaces of the fins. A very sensitive interference between the fin vortices and the wing vortices takes place, since one must consider that vortex breakdown is already present within the wing vertices in the region of the fins. With increasing angle of attack, vortex breakdown takes place also within the fin vortices, and this leads to a sudden collapse of vortical flow and to a deadwater-type flow structure over the wing outside the fins. Suction is considerably reduced at this position and it is this effect which causes the very low maximum lift coefficient $c_{L\max}$ on the configuration SH.

For the configuration ST with twin tip fins only a slightly earlier onset of vortex breakdown has been found in comparison with the wing alone and therefore the corresponding reductions in the aerodynamic coefficients should be in the same order of magnitude as for the wing alone and configuration MC. The additional reduction of lift and especially of nose-down pitching moment on configuration ST marked in Fig. 2 is a peculiarity of this wing-fin combination. At the wing tips, the wing vortex shedding is continued along the leading-edges of the fins and the axes of the wing vortices are raised in the vicinity of the tip fins. This leads to a reduction of lift and especially of nose-down pitching moment. The effect starts with the onset of the vortex formation at the leading-edges of the configuration at very low angles of attack and is present up to very large angles of attack.

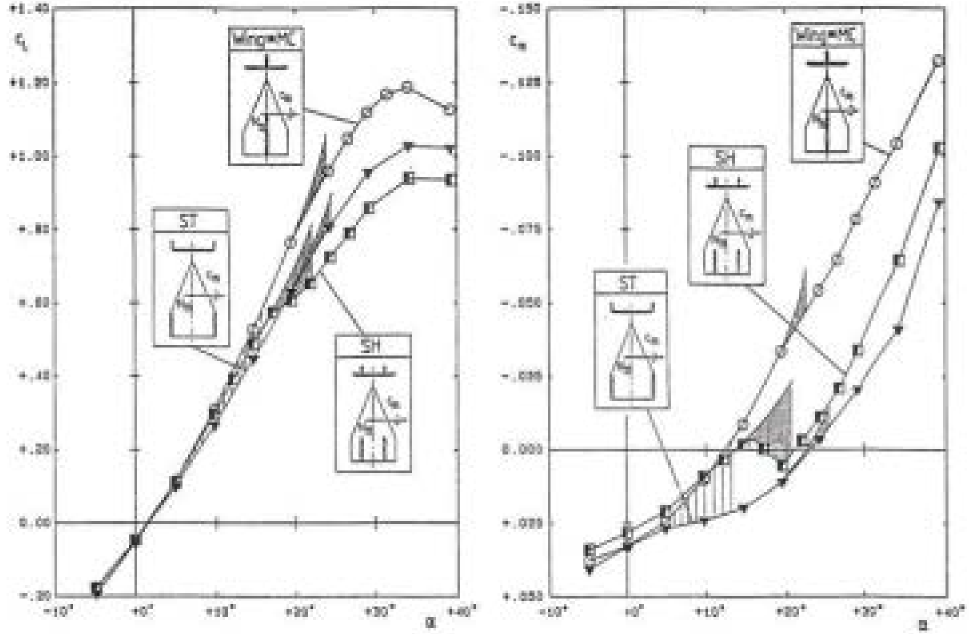

Fig. 2: Lift and pitching moment characteristics for the cropped delta wing with vertical fins in different positions (Indications: see text).

3.2. Unsymmetrical Flow

The purpose of vertical fins is to increase the rolling and yawing moment stability in the unsymmetrical free stream. Stable means that for an angle of sideslip the lift on the windward side is larger than on the leeward side and that a yawing moment is present which acts in the sense of a reduction of the angle of sideslip. In the following, the results are analyzed for the vicinity of the symmetrical flow state $\beta = 0$ and for large angles of sideslip $\beta \neq 0$ separately for all three configurations MC, SH and ST.

3.2.1. Behaviour at Small Angles of Sideslip

The stability derivatives of the lateral motion

$$c_{l\beta} = \left[\frac{dc_l}{d\beta}\right]_{\beta=0} ; \; c_{n\beta} = \left[\frac{dc_n}{d\beta}\right]_{\beta=0} ; \; c_{Y\beta} = \left[\frac{dc_Y}{d\beta}\right]_{\beta=0}$$

are shown in Fig. 3 as functions of the angle of attack α for the wing alone W, as well as for the wing-fin-configurations MC, SH and ST.

For low angles of attack there is not much difference between the wing alone W and the central fin configuration MC concerning the rolling moment derivative $c_{l\beta}$, whereas the sideforce and the yawing moment derivatives $c_{Y\beta}$ and $c_{n\beta}$ are shifted parallel. In unsymmetrical flow, the wing vortex system moves leewards. At low and medium angles of attack $\alpha < 20°$, the vortex on the windward side is stronger than the one on the leeward side and a stable contribution to the rolling moment results from this behaviour. Due to the leeward crossflow, a sideforce occurs on the fin and this corresponds to a positive yawing moment, see Fig. 3 b,c, and to a stable rolling moment contribution. This latter effect, however, is completely compensated by interference effects. Both sides of the fin produce in their vicinity a pressure distribution on the wing which leads to an unstable rolling moment contribution. Therefore, the central fin effects only sideforce and yawing moment but it has no stabilizing influence on the rolling moment. At larger angles of attack, vortex breakdown takes place over the wing for $\alpha > 20°$ in symmetrical flow. If a lateral free stream component is added, vortex breakdown is increased on the windward side and reduced on the leeward side of the configuration. The loss of suction on the windward side and the corresponding gain on the leeward side lead to a sudden destabilizing rolling moment contributions. At very large angles of attack, the attachment lines of the two wing vortices meet on the wing centre line in symmetrical flow. If a lateral free stream component is present, the leeward movement of the whole wing vortex system leads to a crossflow at the central fin which is directed towards the windward side. The corresponding contributions to the sideforce may be taken from Fig. 3c. The sideforce on the fin leads to a destabilizing yawing moment contribution which acts in the same sense as the yawing moment contribution from the wing which results from the difference in induced drag from both sides, caused by unsymmetrical vortex breakdown.

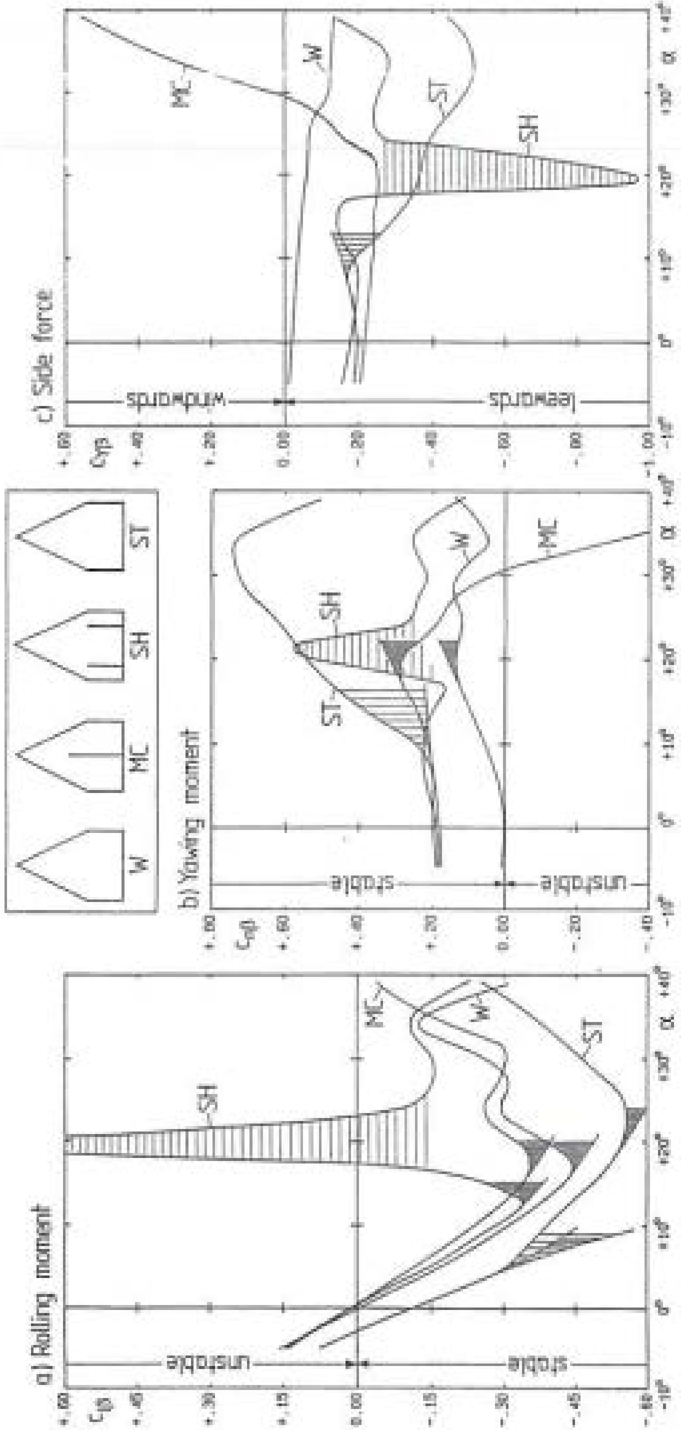

Fig. 3: Stability derivatives of the lateral motion for the cropped delta wing with vertical fins in different positions (Indications see text).

The configuration SH with two small-sized fins at mid-halfspan position shows an outstanding behaviour with extremely unstable rolling moment and stable sideforce and yawing moment derivatives in the vicinity of an angle of attack of $\alpha = 20°$. On this configuration, vortex breakdown occurs over the wing in symmetrical flow for $\alpha > 16°$. In slightly unsymmetrical flow unsymmetrical vortex breakdown causes destablizing rolling momnts as in configuration MC. In the vicinity of $\alpha = 20°$, the flow in the region between the wing and the outer surfaces of the fins is very sensitive to disturbances. A slight increase of the angle of attack in symmetrical flow leads to a collapse of the vortical flow in the wing tip region as already described in section 3.1. In unsymmetrical flow, this collapse takes place on the windward side first. This leads to increased destabilizing rolling moments from the wing and to an additional sideforce in the leeward direction on the windward fin which causes stable yawing moment contributions. At slightly larger angles of attack, the vortical flow in the wing tip region collapses on the leeward side of the configuration, too. Therefore, the previously described sudden changes of the aerodynamic coefficients are reversed and the stability derivatives return to their original values. In slightly unsymmetrical flow at angles of attack $\alpha < 16°$, a vortical flow is present in the outer region between the wing tips and the fins on both sides and for $\alpha > 24°$, a collapsed flow with a deadwater-type flow structure occurs in this region on both sides. In the angle of attack range $16° \leq \alpha \leq 24°$, the transition between these two flow states takes place and an unsymmetrical intermediate flow situation is present: The collapse occurs first on the windward side at $16° \leq \alpha \leq 20°$ and then on the leeward side at $20° \leq \alpha \leq 24°$. This unsymmetrical intermediate flow state causes a large amount of lateral instability.

For the configuration ST with two wing-tip-mounted fins at low angles of attack, the sideforce and yawing moment derivatives generated by the fins are in the same order of magnitude as for the other fin configurations. The rolling moment derivative, however, is shifted towards more stable values. This is an effect of the fins which is not present in the other configurations. In the case of tip mounted fins, the stable rolling moment contribution from the fins is not compensated by a counter-acting contribution from the wing, since outside of the fins there is no wing. The interference between the fins and the inner portions of the wing leads also to a stable contribution from the wing. Flow visualizations at an angle of attack of $\alpha = 10°$ have shown that in unsymmetrical flow a vortex is formed in the lower part of the leeward fin, which leads to an additional sideforce at this fin in leeward direction. The corresponding stable rolling moment and yawing moment contributions are marked in Fig. 3 and this effect increases for larger angles of attack. The raise of the wing vortices in the region of the fins has a consequence in unsymmetrical flow also. The rolling moments are reduced and this effect compensates the stabilizing contribution from the fins as indicated in Fig. 3a. Sideforce and yawing moments are not significantly influenced by this effect. At angles of attack $\alpha > 20°$, unsymmetrical vortex breakdown leads to the well-known loss of stability concerning the rolling moment, whereas sideforce and yawing moment experience only minor contributions from this flow situation.

3.2.2. Behaviour at Large Angles of Sideslip

An analysis of the complete six-component measurements for all configurations shows some irregularities in the aerodynamic coefficients for high angles of attack and unsymmetrical flow $\beta \neq 0°$. In Fig. 4 lift and yawing moment coefficients are given for all configurations as functions of the angle of sideslip and for an angle of attack $\alpha = 25°$. The wing alone W and the configurations SH and ST show a smooth behaviour of the aerodynamic coefficients which would be acceptable for practical flight at high angles of attack and at some sideslip β. For the central fin configuration MC, however, certain deviations can be detected. At a distinct angle of sideslip, the value of which decreases with increasing angle of attack, the central fin passes the attachment line of the windward wing vortex. For larger angles of sideslip, the fin suddenly experiences a crossflow towards the windward side and this causes a sideforce in the same direction and a destabilizing yawing moment contribution. The fin effect on the wing vortices produces additional vortex breakdown on the windward side which leads to a corresponding loss of lift and to destabilizing rolling moment contributions.

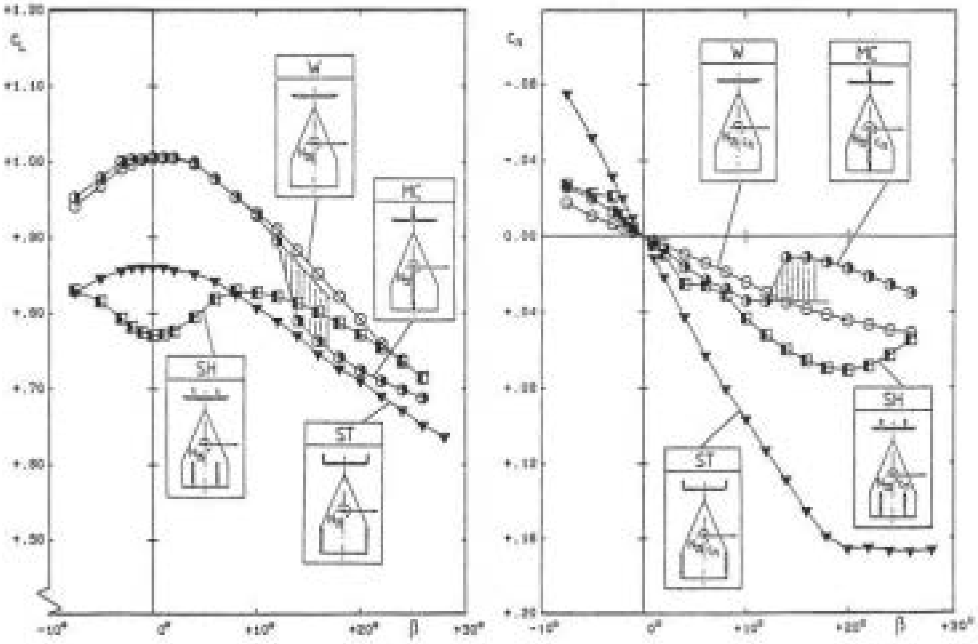

Fig. 4: Lift and yawing moment characteristics for the cropped delta wing with vertical fins in different positions at an angle of attack $\alpha = 25°$ (Indications see text).

4. Conclusions

A comparison of the three concepts for vertical fins on the basis of the present investigations leads to the following conclusions:

1) A central fin configuration reaches high lift coefficients and a stable behaviour in the vicinity of the symmetrical flow state, but for sideslip flight at high angles of attack, problems may arise from sudden changes of the aerodynamic derivatives.
2) Configurations with twin fins in a mid-halfspan position are unstable in a certain angle of attack range and the maximum lift coefficient is relatively low.
3) Configurations with twin fins at the wing tips are stable without problems in sideslip conditions. Their only disadvantage is a certain loss of lift in comparison with the wing alone.

Concerning the physical flow phenomena the following principles have been found:

4) Wing-fin interference takes place when the fins are located on the vortex side of the attachment line on the wing. In this case:
5) Fins cause increased wing vortex breakdown as well as a certain rise of the wing vortices in the case of tip mounted fins and
6) Fins experience wing vortex induced crossflows. This leads to a fin vortex system which interferes with the wing vortices.

5. References

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