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Aerodynamic Interference Effects of Airships

Thorsten LUTZ* and Peter FUNK**

* Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Pfaffenwaldring 21, 70550 Stuttgart, Germany, lutz@iag.uni-stuttgart.de
** Voith Siemens Hydro Power Generation GmbH & Co, Alexanderstrasse 11, 89522 Heidenheim, Germany, pe.fu@freenet.de

Introduction

The aerodynamics of airships is dominated by significant interference effects between the flow about the different components of the vehicle. The complex interaction causes nonlinear aerodynamic behaviour of the airship and represents a challenge for theoretical prediction methods. At angle of attack or sideslip free shear layers are separating from the airship hull. The induction of the wake alters the pressure distribution on the hull surface. Due to this interference effect, an aerodynamic lifting force along with induced drag results even for the inclined bare hull without lifting surfaces. A second interference effect stems from the interaction of the empennage with the hull flow. The flow about the stabilizers has a significant impact on the hull loading, increases the aerodynamic lift acting on the fuselage. This increase of the hull lift is known as Lift-Carry-Over. Also the propulsion can change the aerodynamic behaviour of the airship and vice versa. Depending on the position of the thruster, the propulsive efficiency can be increased or decreased by the interaction. Finally, severe ground interference effects appear for small clearances during landing or when the airship is masted.

Fig. 1 The remotely-controlled airship LOTTE

The present paper describes the most important interference effects being relevant for airships in some more detail. To illustrate the effects, experimental and theoretical results will be presented for the LOTTE configuration (Fig. 1), a remotely-controlled solar-powered airship of 16m length which is operated at University of Stuttgart. Detailed wind- and water-tunnel tests, CFD analyses and finally in-flight tests were conducted for this reference configuration during the activities of the airship research group “FOGL” which was funded by the German Research Foundation DFG during 1997 till 2002.

Wake-Hull Interference

Lighter-Than-Air vehicles are characterised by the fact that the required lift is obtained by the buoyancy of the gas inside the hull. The generation of static lift enables to hover or to fly at low speeds. During manoeuvres or in gusty situations, high angles of attack or sideslip can occur which yields a three-dimensional boundary-layer developing along the hull. Due to the inherent crosswise pressure gradient, the flow direction varies inside of a 3D boundary layer. To illustrate the flow situation, the surface flow pattern for the inclined, bare LOTTE hull were visualised in water-tunnel tests. As can be seen from see Fig. 2 the limiting streamlines converge into an envelope, which represents the 3D separation line (white line below the dark region of high skin friction). Form this separation line a vortex sheet detaches that rapidly rolls up into a distinct vortex comparable to the tip vortex of a lifting wing. Fig. 3 shows the swirling velocity field along with the pressure distribution in a plane at the LOTTE tail.

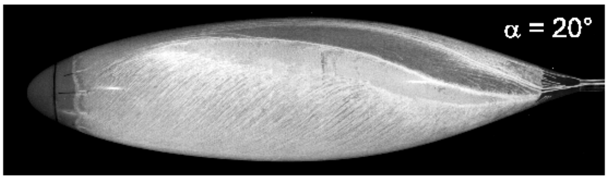

Fig. 2 Limiting streamlines of the inclined bare LOTTE hull [3] (α=20°, Re_V=3.9×10^5, fully turbulent flow)

Due to the induction effect of the separated vortex sheet, the pressure distribution on the hull is strongly affected. On the leeward side of the separation the pressure level is decreased which finally causes an aerodynamic lifting force and, as a consequence, induced drag even for the bare hull. The resulting aerodynamic forces are therefore directly related to a strong interaction between wake and hull flow. Because the extension of the flow separation varies with angle of attack, a non-linear behaviour of the forces and moments vs. incidence results, as can be seen from Fig. 8.

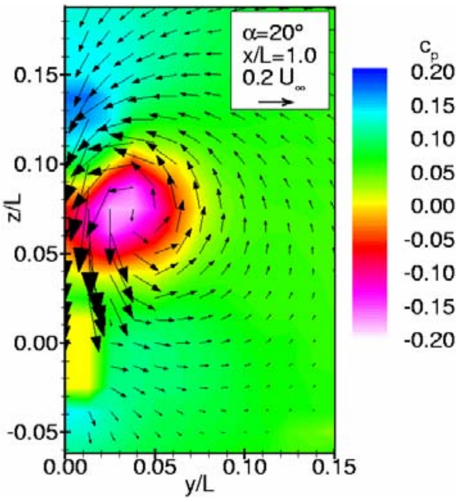

Fig. 3 Measured velocity vectors and pressure distribution in a plane perpendicular to the freestream vector for the inclined bare LOTTE hull [1]
(α=20°, Re_V=3.9×10^5, fully turbulent flow)

Hull-Fin Interference

To stabilize and control the airship, tail fins are added which significantly influence the flow about the hull. Viscous and inviscid interference effects can be distinguished. As an effect dominated by viscosity, the hull and the fin boundary-layers interact in the junction region causing secondary flow effects. Due to the stagnation effect of the fins the hull boundary layer decelerates and can separate. As a consequence one or more corner vortices detach from the hull.

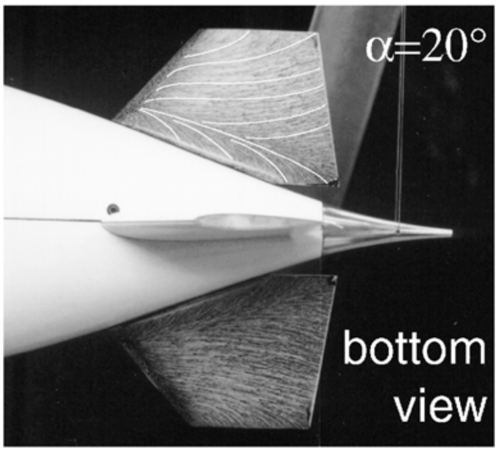

Fig. 4 Limiting streamlines in the tail region of LOTTE [2]
(α=20°, Re_V=3.9×10^5, fully turbulent flow)

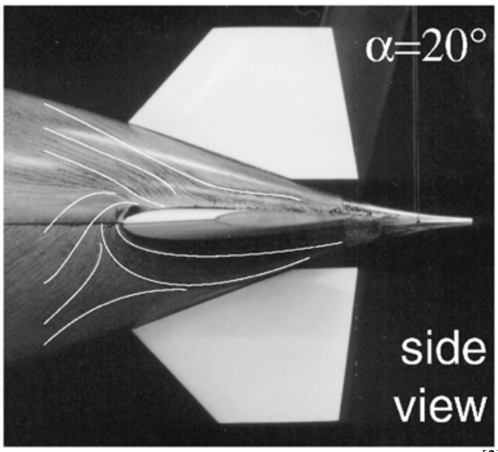

Fig. 5 Limiting streamlines in the tail region [2]
(α=20°, Re_V=3.9×10^5, fully turbulent flow, side view)

The situation is illustrated by flow visulisations for the LOTTE hull-fin combination at α=20° in Figs. 4 and 5. On the pressure side of the horizontal fin, see Fig. 4, the region of viscous interaction near the hull-fin junction is clearly visible. To clarify the flow pattern some limiting streamlines are highlighted by hand. The light streak located directly at the junction corresponds to a secondary flow effect in terms of a corner vortex. Assuming a vortex induced low pressure level, it is plausible that the fluid in the vicinity of the vortex tends towards the hull, whereas the outer region is dominated by the 3D flow about the fin. Fig. 5 shows the limiting streamlines on the hull. The turbulent boundary layer on the hull is not able to overcome the high adverse pressure gradient in the stagnation region of the fin and separates from the surface. Near the junction to the pressure side of the fin two vortices develop which are indicated by the marked limiting streamlines.

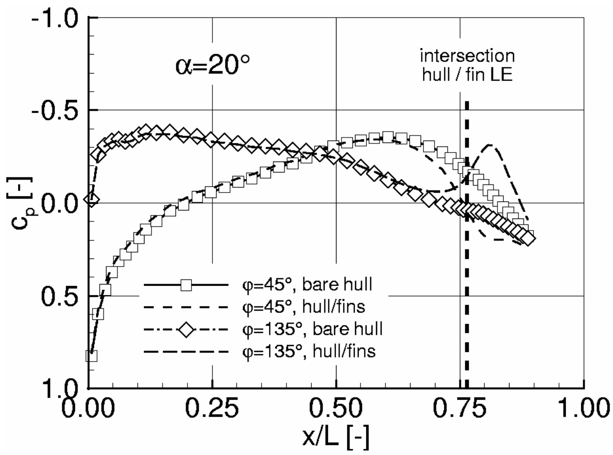

Fig. 6 Measured pressure distribution along meridians φ=45° (between lower vertical and horizontal fin) and φ=135° (between horizontal and upper vertical fin) [2]
(α=20°, Re_V=3.9×10^5, fully turbulent flow)

The inviscid interference effects were examined by measurements of the hull pressure distribution for the configuration with and without fins added [2]. Fig. 6 depicts the c_p-distribution along two selected meridians. Adding the stabilizers mainly affects the pressure distribution in the vicinity of the tail starting at x/L≈0.6, i.e. approximately 15% upstream of the hull-fin junction. Due to the influence of the fins the flow along the meridian φ=45° is decelerated whereas an acceleration results for the meridian φ=135°. Therefore, the hull loading is increased in the tail region by adding the fins. In other words. the bound fin circulation is continued across the hull. This additional lift acting on the hull is called "Lift Carry Over" (LCO).

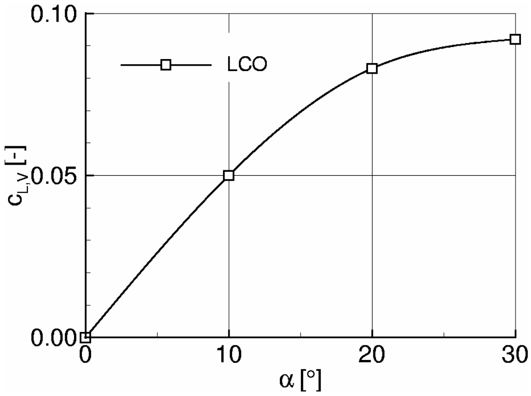

Fig. 7 Measured lift carry over for the LOTTE configuration [2] (α=20°, $Re_V=3.9\times10^5$, fully turbulent flow)

The LCO was quantified for the present configuration by integrating the measured pressure distributions over the hull surface for the configuration with and without fins. The difference between the resulting pressure forces is given in Fig. 7 as a function of the angle of attack. As can be seen from a comparison to the force measurements for both configurations (see Fig. 8), the LCO significantly contributes to the lift increase of the hull-fin combination.

Supplementary to the wind-tunnel tests, CFD analyses utilising a structured RANS solver were conducted. A 31-block mesh with a total of 3.35 × 10^6 cells for the half model of the LOTTE configuration was used. Fig. 9 shows the simulation result for the same onset flow conditions as discussed so far. The depicted flow patterns show the separating hull shear layer along with the roll-up and the fin tip vortex. Moreover, it can be observed that some fluid is sucted beneath the separated hull vortex towards the fin tip and finally merges with the fin tip vortex. This demonstrates the complexity of the interference effects for inclined airship configurations.

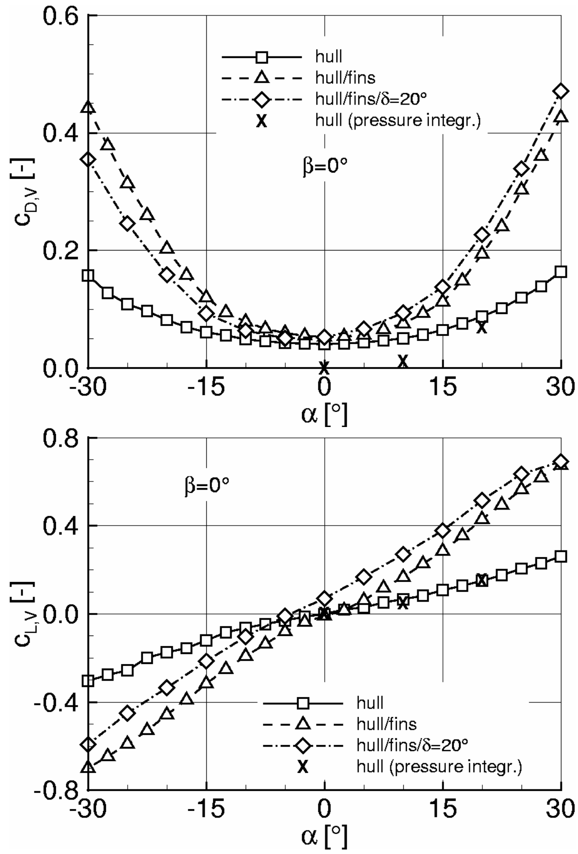

Fig. 8 Measured volumentric lift and drag coefficients for the LOTTE configuration [2]
(α=20°, $Re_V=3.9\times10^5$, fully turbulent flow)

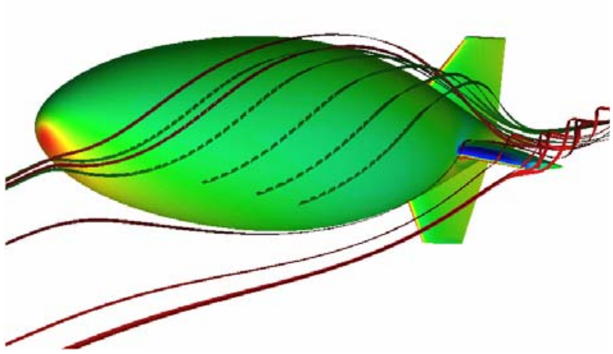

Fig. 9 CFD simulation of the flowfield about the LOTTE hull-fin combination; SPALART-ALLMARAS turbulence model (α=20°, $Re_V=3.9\times10^5$, fully turbulent flow)

Propeller-Hull Interference

The hull of an airship significantly influences the velocity field in the proximity of the hull due to inviscid displacement and viscous boundary-layer effects. This has important consequences for the efficiency of a propeller mounted in the vicinity of the hull. In general, the power to produce a certain thrust decreases if the propeller is located in an area with reduced velocity compared to the freestream. Therefore, the propeller efficiency, based on the undisturbed onset flow velocity, increases accordingly and may be well above 100%. A reduction in propulsive efficiency results if the propellers are mounted near the location of the maximum hull diameter where the local velocity is higher than the airspeed.

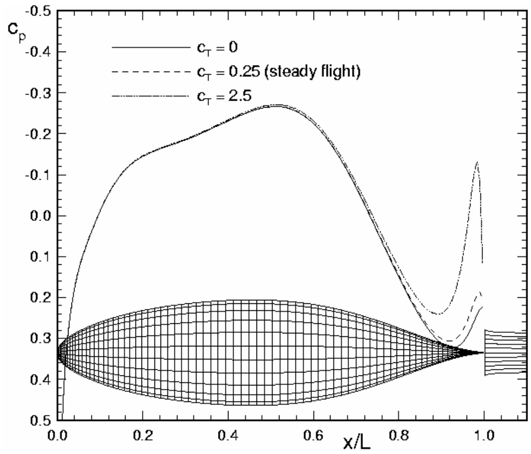

Fig. 10 Calculated pressure distribution of the bare "LOTTE" hull with stern propeller [5] ($Re_L=16\times10^6$)

A stern-mounted propeller operates in the retarded viscous wake of the hull and positive interference is eminent. However, the suction effect of the propeller slipstream accelerates the flow in the tail region of the airship hull which yields an increase of the pressure drag. For obvious reasons, the propeller-induced hull drag as well as the efficiency of the stern-thruster is higher for hull shapes with a blunt tail. The impact of a stern-thruster on the pressure distribution of the LOTTE hull at zero incidence is depicted in Fig. 10. For these investigations the viscous flow about the displacement body was determined by a panel method in combination with an integral boundary-layer procedure. A vortex sheet model was used to calculate the time-averaged influence of the propeller with a fully-relaxed slip-stream[4], [5].

Altogether the increase of the propeller efficiency predominates compared to the additional propeller-induced body drag. Therefore, a reduction in power required to propel the airship can be obtained with the stern-mounted propeller compared to conventional installations, i.e. the propulsive efficiency of the configuration is increased by the interference effect [4].

Detailed experimental investigations on aerodynamic effects of airships with stern-propulsion are hardly reported. An exception represent the wind-tunnel tests performed by McLemore [6]. McLemore examined a 1:20 scale model (L≈6m) of a complete airship configuration with two different stern-mounted propellers. In his experiments, the larger propeller turned out to be very efficient and shows a maximum efficiency of η≈140% (based on the undisturbed freestream velocity). In a second test the characteristics were measured when the propeller produced enough thrust to propel the airship, i.e. for the condition that the thrust is equal to the total airship drag including propeller-induced drag. The maximum efficiency decreased to η≈122% which indicates that the design point of the propeller does not exactly match the steady-state flight conditions.

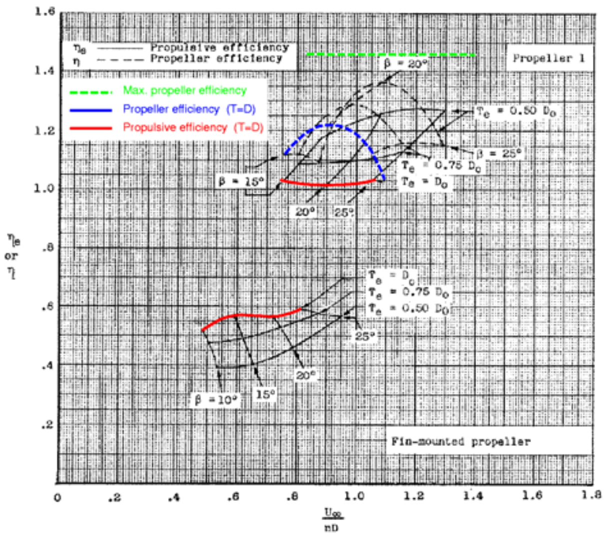

Fig. 11 Measured efficiency characteristics of a stern-mounted propeller [6] ($Re_L=11.9\times10^6$)

In a last evaluation the *propulsive* efficiency η_e was determined which accounts for the propeller-induced additional hull drag. For steady-state flight conditions the measured propulsive efficiency was about 103% compared to a value of only 59% resulting for a fin-mounted propeller, see Fig. 11.

Ground Interference

Important interference effects occur when an airship is hovering near ground during landing or passenger exchange or when it is masted. First of all, at zero incidence and small clearance the flow between the airship hull and the ground is accelerated due to the VENTURI effect. This reduces the pressure level along the bottom of the hull and therefore causes a downforce. On the other side, within the atmospheric ground boundary-layer, the velocity level reduces with decreasing ground distance. This diminishes the under-pressure due to the hull displacement along the bottom.

For circulatory flow at incidence, additional ground interference effects occur. The shape of the wake development is influenced by the presence of the ground in such a way that the induced downwash is reduced which increases the lift. Dramatic ground interference effects were observed at sideslip. The impact of the ground yields an asymmetric shedding of the shear layers from the hull which significantly affects the induction on the hull and can cause considerable lifting forces even for zero angle of attack. The results of some historic wind-tunnel tests for the Akron airship [7] are depicted in Figs. 12 and 13. Noteworthy, the maximum lift at 60° sideslip and α=0° exceeds typical values for the maximum lift coefficient at angle of attack without ground effect.

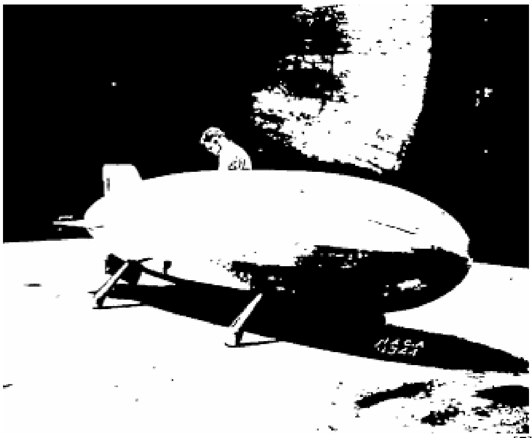

Fig. 12 Wind-tunnel model of the Akron airship [7]

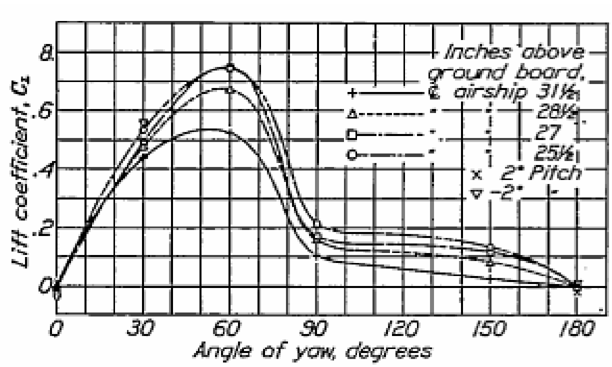

Fig. 13 Measured volumetric lift coefficient for the Akron airship in ground proximity [7]

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