Vortical Flows in Technical Applications[1]

by
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ABSTRACT

Two examples of flows dominated by vortical structures are discussed: In the first interaction and decay of vortex structures in in-cylinder flows of automotive engines are described. Numerical studies revealed clearly identifiable vortex rings, generated during the intake stroke. The influence of compressibility on the vortex formation was studied by using Mach-Zehnder interferometry in a specially designed test stand of a towed one-cylinder engine, and with numerical solutions of the Navier-Stokes equations. In an industrial application a stable vortex ring could be generated by direct high-pressure liquid fuel injection, issuing a conical flow of evaporating droplets and stratifying the evaporated fuel to an ignitable air-fuel mixture. This concept led to a substantial reduction of fuel consumption. In the second example the state of the art of investigations aimed at finding means to destabilize tip vortices of aircraft wakes is briefly reviewed. Enforcing a more rapid decay compared to the natural one and reducing the downwash of large aircraft during take-off and landing are presently pursued in several studies. Discussed are the influence of the spanwise position of the engines, of winglets, of preset and oscillating ailerons on the vorticity distribution in the tip vortices and on their destabilization. The results are preliminary in nature. Further investigations in more detail are needed to substantiate previous findings.

Introduction

The author first met Professor Kunio Kuwahara in Aachen 1982, at the 8th International Conference on Numerical Methods in Fluid Dynamics, organized by the staff of the Aerodynamisches Institut of the RWTH Aachen. The title of the paper K. Kuwahara and K. Horiuti presented was "Study of Incompressible Turbulent Channel Flow by Large-Eddy Simulation". The main concern of the authors at that time was to improve the solution technique for solving the Navier-Stokes equations and increase the accuracy of the prediction without increasing the computational effort. In the eighties, this goal was one of the essentials, since storage capacities were rather limited compared to presently available systems.

To keep the solution technique simple and yet not loose the major aspects of the flows to be analyzed was one of the criteria that led Prof. Kuwahara in computing complex flows in the years to come. This was also the reason why a long-term cooperation was initiated and maintained over many years between Prof. Kuwahara´s group and members of the Aerodynamisches Institut in Aachen.

The joint studies that followed were mainly focussed on studies of flows dominated by vortical structures, as wake flows of blunt bodies and in-cylinder flows of automotive engines. In many cases the numerical simulations were supplemented by experimental investigations carried out at the Aerodynamisches Institut for boundary conditions compatible with those of the computations to enable comparison of results and validation of the numerical approach. Soon after the conference in Aachen joint publications appeared. In these Prof. Kuwahara and the author were co-authored by members of both groups, so in 1985 by B. Binninger, H. Henke, W. Limberg, and H, Weiss; in 1988 by B. Binninger, M. Jeschke, and W. Limberg; in 1989 by K. Ishii, K. Naitoh, S. Shirayama, Y. Takagi, and T. Tamura; in 1990 by K. Ishii, M. Jeschke, J. Klöker, W. Limberg, K. Naitoh, and Y. Takagi; in 1992 by M. Jeschke, J. Klöker, and K. Naitoh; in 1993 by H. Fechner, M. Jeschke, J. Klöker, W. Limberg, and S. Rotteveel; in 1996 by A. Abdelfattah. H. Fechner, W Limberg, M. Meinke, R. Ortmann, S. Rotteveel, and A. Wunderlich; in 1998 by M. Meinke, and in 2003 by K. Naitoh.

Some of the investigations found recognition in Japan and Germany: In 1992 B. Barthmann, R. Neikes, W. Limberg, and the author were honored with an award of the Visualization Society of Japan, Tokyo, for experimental flow visualization studies of "Vortex Formation in a T-junction", as described in Ref. [1]. One year later, in 1993 K. Naitoh, K. Kuwahara, M. Jeschke, and the author were awarded a medal of the Japan Society of Mechanical Engineering for their publication entitled "Numerical Simulation of the Small Vortices in the Intake and Compression Process of an Engine" [2]. In the same year the Alexander von Humboldt-Foundation and Max-Planck-Society in Bonn, Germany, elected K. Kuwahara, R. Peyret and the author for the Max-Planck-Research Award for outstanding international research performances.

Since many of the flows jointly investigated were strongly dominated by large vortex structures, this topic was chosen for this article, and two examples of flow studies are described in the following. After the introduction joint numerical and experimental investigations of in-cylinder flows of automotive engines are briefly reviewed in the first section. These studies demonstrated, that vortex rings are generated, move and interact with each other during the suction stroke. In the course of time a concept emerged, which led to "design" a vortex ring, with the aim of which the fuel-air mixing process can be enhanced and fuel consumption can substantially be reduced, even in realistic production engines.

In the second section results of investigations of aircraft wake flows are described. These studies are presently being carried out in search for technical means for enhancing short or even long-wavelength (Crow) instabilities of the tip vortices of aircraft, to enforce a more rapid than their natural decay, and to reduce the downwash, particularly of large aircraft during take-off and landing. In the wake, the velocity defect of the wing, the tip-, fuselage,- and flap-edge vortices, and the engine jets interact in a complex manner in the roll-up process, which can be affected by the spanwise position of the engines, winglets, and by vortex generators, as, for example, preset or oscillating ailerons. Some of the results obtained so far are described in the following. They are still preliminary in nature and have to be substantiated by further studies. The answer to the question, as to whether or not effective alleviation of the strength of the tip-vortices is eventually possible, needs further investigation in more detail.

2. Vortical Flows in Cylinders of Automotive Engines

A profound understanding of the unsteady three-dimensional, compressible flow generated in piston engines during the intake and compression stroke is crucial for future development and improvement of piston engines with high performance and low emission rates. The main reason for this require-

[1] To Kunio Kuwahara on his retirement.

ment is that the flow at the end of the compression stroke determines the flame propagation speed in homogeneous charge spark-ignition engines and the fuel-air mixing and burning rates in Diesel engines. The flow has a major impact on the emission values and on the breathing capacity of the engine and therefore also on the maximum available power.
During the suction stroke the flow in the cylinder is strongly influenced by the formation of vortex rings and their mutual interaction. The rings can, for example, be generated by flow separation at the valve seat and head, and the strength of the vortices generated depends on seat angle, the rounding of the seat comers, the seat width, and the swirl of the flow in the intake ports. Of outmost importance is that the characteristic flow times are of the order of a few milli-seconds. Rapid transient changes occur in the flow.
At the Aerodynamisches Institut first results of studies of flows in cylinders of piston engines were obtained by H. Henke in 1986 in his dissertation [3]. He numerically integrated the Euler equations for axially symmetric compressible non-reactive air flow for a compression ratio $\varepsilon = 3.5$, and rpm $= 3000\ \mathrm{min}^{-1}$. Lagrangian particles paths and lines of constant vorticity determined from the computed velocity distributions clearly revealed the formation of two vortex rings during the suction stroke. Since the resolution of the computation was relatively crude, experimental verification of the numerical results was urgently asked for. This problem was taken up in the dissertation of H. Weiss in 1988, who constructed a test stand with a transparent cylinder into which water could be sucked by the motion of a cylinder [4]. Fluorescent dye was injected in the open valve slot, and the light-sheet technique was employed to visualize the flow entering the cylinder. The experiment confirmed the numerical results in principle, as the flow was incompressible, but the existence of the two vortex rings, previously observed in the numerical simulation of [3], could clearly be confirmed.
In order to explore the influence of the compressibility on the formation of the vortex rings during the suction and their behavior during the compression stroke, another test stand was constructed: Cylinder and piston were designed with a rectangular cross-section to enable measurements of density contours with the Mach-Zehnder interferometry combined with high-speed photography. The motion of the piston was facilitated by towing it with an electric motor. The details of the measurements were described by B. Binninger in [5] and M. Jeschke in [6] in their dissertations. The following Fig. 1 summarizes the results.

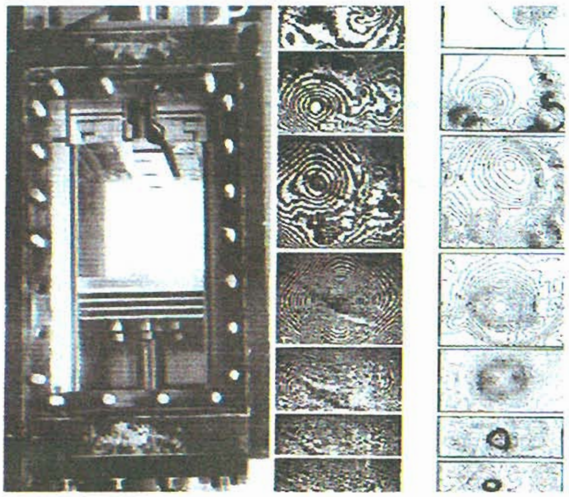

Fig. 1: Mach-Zehnder interferograms (middle), obtained in a towed engine with rectangular cross-section (left) for detecting the influence of compressibility on vortex formation during suction and compression stroke, in the dissertations of B. Binninger [5], M. Jeschke [6], and computations (right) by K. Naitoh [7].

The numerical investigations accompanying the experimental studies were carried out by K. Naitoh [7] and J. Klöker [8] in 1992. Both authors solved the Navier-Stokes equations for time-dependent, compressible three-dimensional, laminar flow, without introducing any closure assumption for the description of the Reynolds stresses and turbulent heat transfer, expected to occur during the compression stroke. These investigations proved, that the vortex structures seen in the experimental visualizations were also recovered with good accuracy in the computations. The large vortex structure generated during the intake stroke was found to resist most of the compression stroke, and only very close to the upper dead center did it decay into small vortices, resembling those observed in turbulent flow.
When more computational power became available with the advent of supercomputers in the late eighties, realistic four-valves cylinder configurations could be considered. In passing it is mentioned that Professor Kuwahara gave a series of lectures in various institutions and universities in Germany during this time and demonstrated very successfully that supercomputers and numerical solutions were to become an indispensable tool in future analyses of complex flows.
An accurate description of the flow required the resolution of all important details of the intake and cylinder head geometry. In the numerical solution developed in Aachen a boundary-fitted block-structured moving grid system was implemented in the algorithm. The grid was refined during the opening and closing of the valve and during the up- and downward motion of the piston, such that the resolution of the flow could approximately be kept constant. Fig. 2 depicts a grid arrangement with about two million grid points [9].

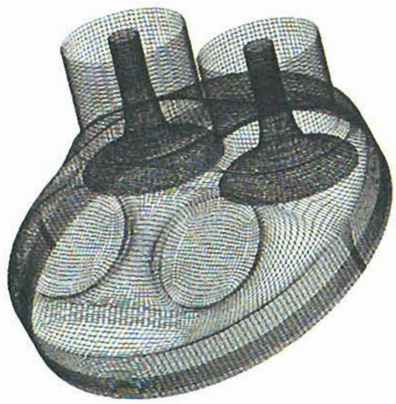

Fig. 2: Grid arrangement for flow computation in four-valves automotive engine [9].

The solution constructed by A. Abdelfattah in [9] was based on an explicit finite-volume discretization method of second-order accuracy in time and space. An example of flow computations obtained with this solution is shown in the following two Figs. 3 and 4, where the two vortex loops, generated during the intake stroke in a four-valves engine are visualized near the upper dead center (Fig. 3), and after interaction with each other, near the lower dead center (Fig. 4).

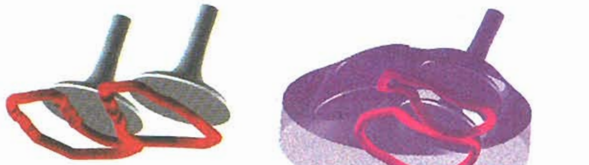

Fig. 3: Vortex loops, generated during the early intake stroke in a four-valves automotive engine near the upper dead center, computed with a solution of the Navier-Stokes equations, described in [9].

Fig. 4. Vortex loops, generated during the intake stroke in a four-valves engine near the lower dead center, after interaction with each other; computed with the solution described in [9]

The accuracy of the solution was tested by comparing the numerical data to those of experiments carried out for the same geometric configuration, with particle-laden water as working fluid, see Fig. 5. Details were documented by R. Ortmann in his dissertation [10].

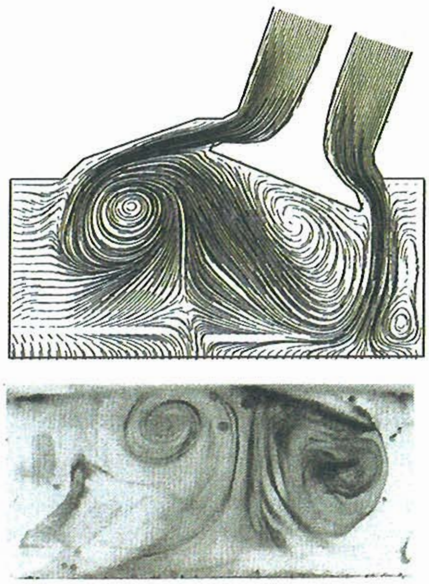

Fig. 5: Comparison of numerical results (top), obtained in [9] with an experimental visualization (bottom) of [10].

The results of these studies raised the question, whether vortex structures could be designed in such a way that they could be used to enhance the fuel-air mixing in the cylinder and reduce the fuel consumption. This goal was achieved a few years later by A. Abdelfattah et al. in an industrial application at BMW in Munich [11]. In this investigation a vortex ring was generated by directly injecting liquid fuel through a conical nozzle with high pressure. The fuel breaks up into small droplets which begin to evaporate. Downstream from the nozzle the flow of the injected fuel retains its conical shape and generates a vortex ring in a plain normal to the axis of the cone. Fig. 6 compares an experimental visualization (left), with that of an accompanying numerical simulation, described in [11].

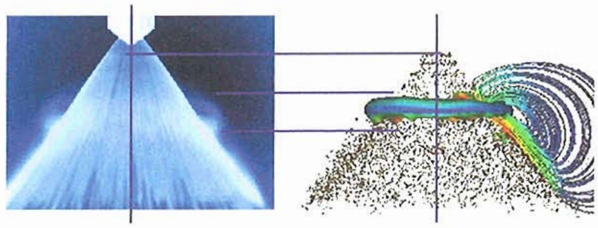

Fig. 6: Injection of liquid fuel through a conical nozzle under high pressure into the cylinder and formation of a vortex ring, after [11]. The fuel breaks up into small droplets, which begin to evaporate. The vortex ring contains an ignitable fuel-air mixture.

Ignition can be facilitated by positioning a spark plug close to the vortex ring, as shown in Fig. 7. The red colored areas show those parts in the cross-section of the vortex ring, in which the mixture is rich, the blue-shaded areas indicate the region where the mixture is lean [11].

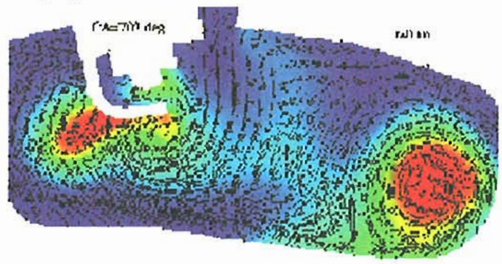

Fig. 7: Numerical simulation of vortex ring generated by direct injection of liquid fuel through a conical nozzle. Shown is a cut through the spark plug and the vortex ring close to the upper dead center [11].

In the meantime a BMW prototype engine named BMG 13ig was constructed, built, and tested. The results of various test series show that the fuel consumption can substantially be reduced with the direct fuel-injection technique proposed. In Fig. 8 of [12] the fuel consumption of the BMW 13ig prototype engine is compared with that of other automotive engines. It is seen that even the consumption of the Diesel engine (VALVETRONIC) is surpassed.

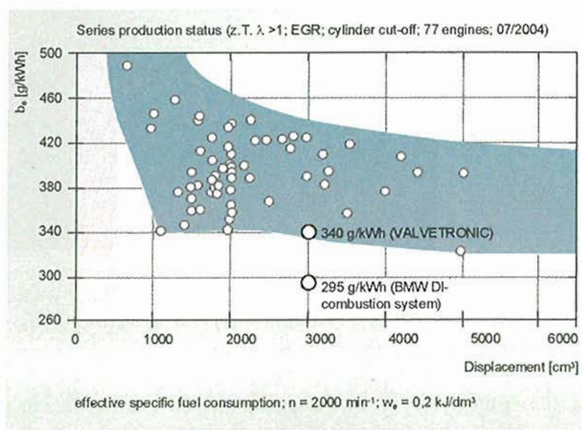

Fig. 8: Fuel consumption of automotive prototype engine BMW 13ig: Direct injection of liquid fuel and formation of a vortex ring leads to an enhanced spreading of fuel droplets and to a substantial reduction of fuel consumption [12].

These results show that vortices can be designed to serve a purpose and be incorporated in a technical system, even if the characteristic flow times are extremely short and the flow is three-dimensional in nature.

3. Vortex Structures in Aircraft Wakes

In the second part of this article some preliminary results of investigations of aircraft wake flows are reported. These studies are undertaken at the RWTH Aachen in search for technical means, by which a more rapid decay of the tip vortices can be enforced in comparison to the natural decay. In particular, the downwash generated by large aircraft during take-off and landing should be reduced, as it may endanger smaller aircraft that followed too closely.

In the near wake, the unstable shear layer downstream from the wing rolls up into the tip vortices, influenced by the fuselage and flap-edge vortices and the jet streams of the engines. The velocity defect of the wing interacts with the vortices and the engine jets in a complex manner, depicted in the following Figs. 9 and 10.

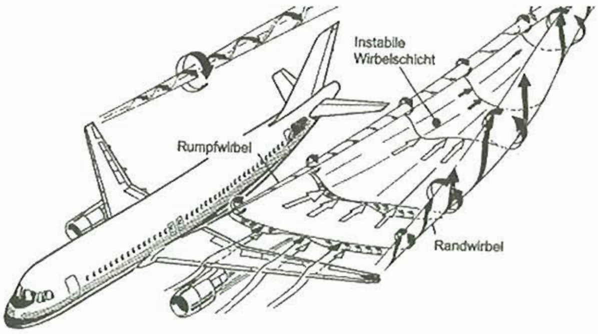

Fig. 9: Schematic of roll-up process in aircraft wake, (Courtesy of EADS).

The roll-up process is affected by the spanwise position of the engines, and by the spanwise position and size of the flaps. It can also be influenced by winglets, which belong to the most interesting changes of basic planform configurations of the last fifty years. Furthermore by vortex generators, as, for example, preset or oscillating ailerons. The photograph in Fig. 10 shows, that the near wake is completely dominated by longitudinal vortex structures.

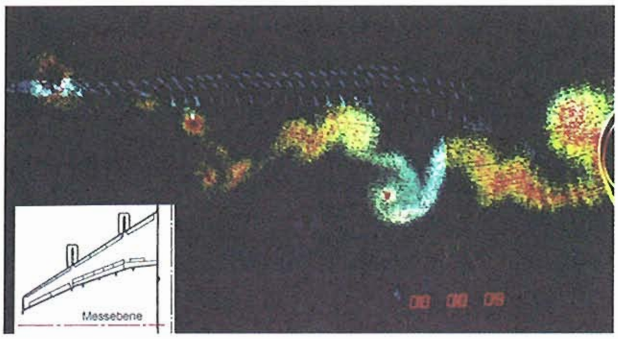

Fig. 10: In flight visualized vortex structures in the near wake of the aircraft A340 in landing configuration; the measuring plane is 1.5 m downstream from the wing tip, (Courtesy of EADS).

Research is underway to investigate possibilities of reducing the strength of the tip vortices by destabilizing them. The long-wavelength or Crow instability was investigated by Leweke et al. in [13]. Some of the experimental visualizations reported therein are depicted on Fig. 11, together with a photograph of a pair of tip vortices, destabilized in free flight (on the right). The initially straight and parallel vortices develop a waviness, which is amplified until the vortex cores touch, break up, and reconnect to form periodic vortex rings. The rings are inclined to the axes of the initial tip vortices.

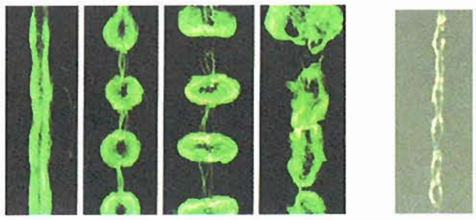

Fig. 11: Experimental long-wavelength destabilization of tip vortices (left), described in [13], compared to free-flight destabilization (right, own observation).

In addition to the long-wavelength also short-wavelength destabilization, depicted schematically in Fig. 12, of [14], is presently being investigated.

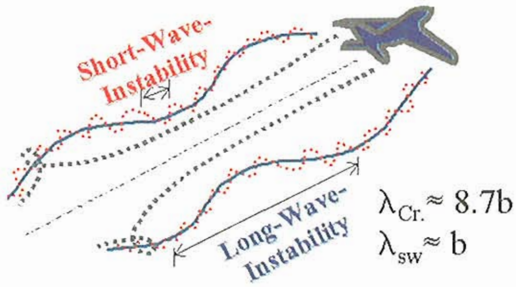

Fig. 12: Comparison of long- and short-wavelength instabilities of tip vortices; schematic sketch, taken from [14].

The short-wavelength instability as observed in free flight is shown in the photograph of Fig. 13, [14].

Fig. 13: Short-wavelength instability of tip vortices, as observed in free flight, [14].

G. Huppertz et al. investigated in [14] the possibility to enhance the short-wavelength instability by changing the spanwise position of the engine. Velocity distributions in the wake of a model of a swept flapped wing, on which a cold-blowing engine model was mounted, were measured with the particle-image velocimetry at low-speeds at a Reynolds number Re = 2.8 x 10^5. The experimental arrangement is contained in Fig. 14.

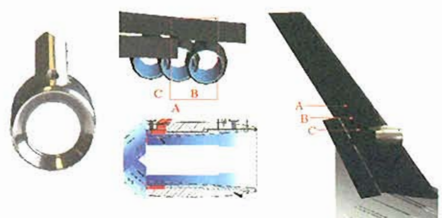

Fig. 14: Experimental arrangement for investigating the influence of engine position on destabilization of tip vortices, [14].

The measurements of [14] led to the conclusion, that an inboard change of the engine position caused a slight increase of the wandering amplitudes of the tip vortex, while an outboard change increased the defect of the axial velocity in the tip vortex and the distance between the tip and the flap-edge vortex. Because of the relatively short extent of the test section of the wind tunnel in the main flow direction, the influence of the engine position on the far field of the tip vortex could not be investigated [14].

Winglets certainly have an influence on the development of the tip vortices; but the actual effectiveness is not really understood. For example, it is reported in the literature, that an increase of span can have a similar effect as winglets, as a comparison of the aerodynamic characteristics - in particular the drag coefficient - of the Boeing 777 and the A330 demonstrates. However, winglets do redistribute the spanwise vorticity component in the tip vortices in the near wake; but whether they also lead to a faster decay of the tip vortices by either short- or long-wavelength destabilization is unknown.

In order to gain some insight into this problem the flow field downstream from the tip of a rectangular wing was studied with triple hot-wire and particle image velocimetry for three winglet configurations, reported in [15]. The following Fig. 15 shows the winglet configurations, used in the experiments: The first had a winglet attached to the upper side of the model of the wing, the second had a winglet on upper and lower side with different spans, and the third with the same span.

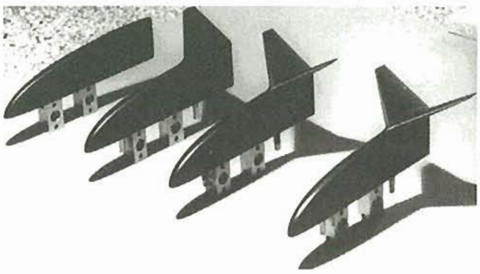

Fig. 15: Winglet configurations used in the experiments of [15]; wing tip without winglet (far left), with winglet on upper side, with winglet of different spans on upper and lower side, and with winglet with the same span on upper and lower side.

The experimental set up is sketched in Fig. 16. The half model of a rectangular wing with a Clark-Y profile was mounted on a flat plate.

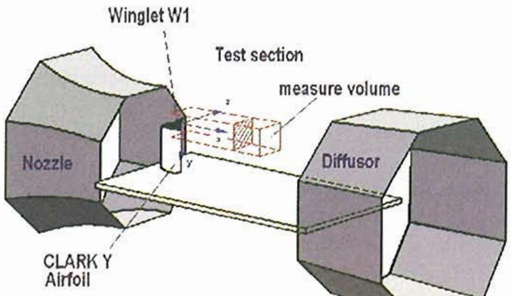

Fig. 16: Experimental set up for wind-tunnel testing of the effect of winglets on tip vortices, [15].

The velocity was measured in a rectangular volume downstream from the tip of the wing. The measurements revealed, that the changes in the velocity distribution decayed over the rather short distance in the main flow direction of about 4 chord lengths. Flow visualizations carried out in these studies showed, that the wing, when equipped with a winglet each on the upper and lower side develops three tip vortices, which interact with each other, as can be seen in Fig. 17.

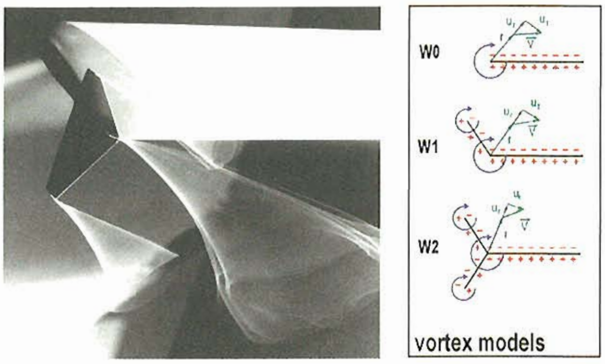

Fig. 17: Flow visualization studies (left) with wool threads, fastened to the tips, show formation of the main vortex at the wing tip and smaller vortices at tips of winglets, (white and grey triangular shaped areas), suggest vortex models for one and two winglet configurations (right), [15].

Fig. 18 summarizes results of measurements with the particle image velocimetry in a plain normal to the main flow direction. Plotted is the distribution of the vorticity component ω_x, with x being the coordinate in the main flow direction, generated by the wing (upper left), with one winglet on the upper side (upper right), two different winglets (lower left), and two the same winglets (lower right), [15], at 4 chord lengths downstream from the wing tip. Further investigations are necessary in order to explain the effects of the winglets on the vorticity distribution.

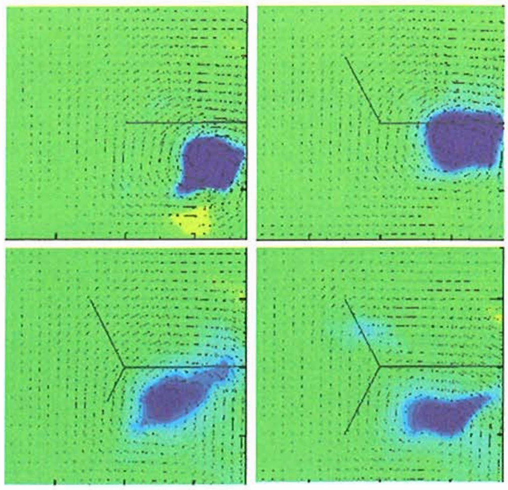

Fig. 18: Vorticity component ω_x in the main flow direction, generated by the wing (black line, upper left), with one winglet (upper right), two different winglets (lower left), and two the same winglets (lower right), [15], at 4 chord lengths downstream from the tip.

Direct destabilization of the tip vortices was attempted by R. Hörnschemeyer et al. in [16], with triangular vortex generators near the wing tips, generating counter-rotating vortices, (Fig. 19).

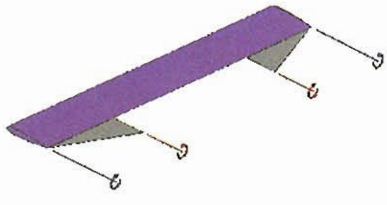

Fig. 19: Destabilization of tip vortices with counter-rotating vortices, generated by triangular vortex generators, mounted near the wing tip, after [16].

The model of the wing was towed in a water tank, followed by a second model of smaller span. By measuring the velocity distribution in the flow field the rolling-moment induced on a smaller follow-up wing model could be determined. In Fig. 20 the induced moment coefficient is plotted versus the dimensionless distance from the trailing edge. The results for the case without the vortex generator are given by the dashed line, and those with the vortex generator by the symbols. Comparison of the two curves reveals a noted reduction of the rolling-moment coefficient: The value measured in the experiment without vortex generators at x/b = 80 is measured in the second experiment with vortex generators at x/b = 22, indicating, that the induced rolling-moment of the tip vortices is substantially reduced.

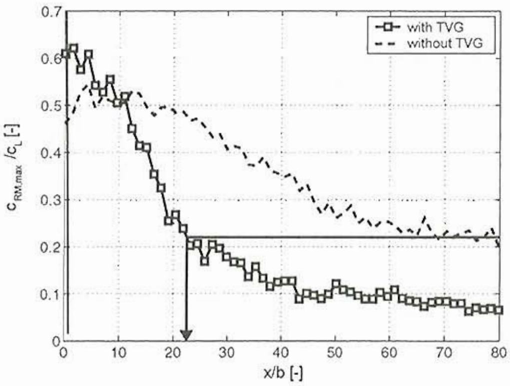

Fig. 20: Reduction of rolling-moment coefficient, induced by triangular vortex generators near the wing tips, after [16].

Hörnschemeyer et al. in [16] also investigated the problem of destabilizing the tip vortices by either preset or oscillating ailerons, mounted on the outboard trailing edge of a wing model. In Fig. 21 the two photographs confirm the destabilization of the tip vortices about 20 chord lengths downstream from the trailing edge.

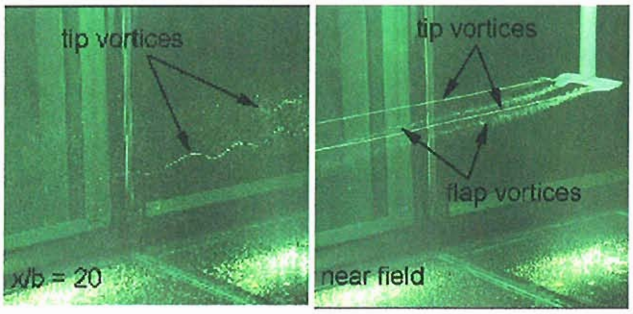

Fig. 21: Destabilization of tip vortices by preset ailerons mounted near the wing tips, [16].

Presently investigations are underway in which pairs of paraphrase oscillating ailerons are used to destabilize the tip vortices. Oscillating ailerons offer the possibility to keep the lift constant, which is not the case, when preset ailerons are used.

Concluding Remarks

It was shown for two technical applications that vortical structures can be controlled and designed so that they can execute technical functions.

In the first example it is demonstrated how in automotive engines an efficient fuel stratification can be provided with a time-dependent in-cylinder vortex structure. The second example summarizes results of investigations aimed at finding means for controlling the roll-up process of wing tip vortices, governed by a complex interaction of the velocity defect of the wing, the fuselage- and flap-edge-vortices, and the jet streams of the engines in the near wake. The answer to the questions, as to whether or not effective alleviation of the strength of the tip-vortices, in particular of large aircraft, is eventually possible, and whether separation times between take-offs and landings at airports can thereby be reduced, needs further investigation in more detailed studies.

Many of the results presented could only be obtained by using modern experimental and numerical techniques, the latter of which were pioneered with great success for more than a quarter of a century by Professor Kunio Kuwahara..

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