EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

B - 15

Paper No 82

MEASUREMENT OF HELICOPTER ROTOR TIP VORTICES USING THE "FLOW VISUALIZATION GUN"-TECHNIQUE

Reinert H. G. Müller
F.I.B.U.S. Research Institute
Germany

September 15-18, 1992

AVIGNON, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

MEASUREMENT OF HELICOPTER ROTOR TIP VORTICES USING THE "FLOW VISUALIZATION GUN" TECHNIQUE

REINERT H. G. MÜLLER

FORSCHUNGSINSTITUT FÜR BILDVERARBEITUNG,
UMWELTTECHNIK UND STRÖMUNGSMECHANIK,
Paul Klee Weg 8, W-4000 Düsseldorf 31, Germany

ABSTRACT

The flow fields of two different helicopter model rotors have been investigated using a special visualization technique – the "Flow Visualization Gun" technique. By the visualization of "time lines" in the flow, the new technique allows the observation of complex flow patterns like the vortex structure over comparatively long time periods. Even turbulent flow regions can be visualized and the flow pictures, besides of providing qualitative information for the physical interpretation of the flow, are used for quantitative measurements of the flow velocities. The "time lines" can be placed even intersecting the rotor disc. Due to the Lagrangian view and the long observation time, the method has advantages over the commonly used Laser Doppler Velocimetry (LDA).

Different visualization photographs of rotor tip vortices and rotor downwash will be presented in this paper, and quantitative velocity data of the flow will be given. Depending on the rotor configuration, a vortex breakdown due to the pressure field of the following blade can be observed. The structure of this burst tip vortex shows a significant enlargement of its core size, lower tangential velocities, and a turbulent character. The overprediction of the blade loads by computer codes which do not take the complex vortex structure into account can be explained by these results.

The results obtained by the new visualization technique will therefore be very useful for comparisons with calculated data sets of the rotor flow or for the enhancement or improvement of new computer codes like the Navier Stokes' codes. These codes promise to provide the theoretical solutions to problems like the bursting of vortices in the future, but they need extensive validation by experimental techniques. It is a very efficient way to obtain a full physical knowledge of complex flow fields by the combination of theoretical efforts and computer calculations with different experimental techniques like the one presented in this paper.

INTRODUCTION

Blade Vortex Interaction (BVI) noise or dynamic blade loads are important factors for the design of helicopter rotors. Calculations, using Biot-Savart law or even CFD codes, still cannot reflect accurately the pressure fluctuations on the blade surface during a vortex encounter. Normally they overpredict the pressure peaks. Reason for this uncertainty is the fact that the vortex structure and its development due to the strong influence of the pressure field of the approaching blade are not very well understood.

Here, the application of various new experimental techniques only will provide the information needed for the understanding of the complex vortex structure. Of these, especially the flow visualization techniques are important tools for the study of complex flow patterns. The visualization images allow the qualitative description of the entire flow field and, in some cases, also the quantitative measurement of flow characteristics like the flow velocities. It is very important to obtain these quantitative data for the verification of flow field calculations using Computational Fluid Dynamics codes (CFD).

Currently used methods, like smoke injection, smoke wire, pulsed smoke wire, the helium bubble technique, the spark tracer technique, or the recent phosphorescent tracer techniques all have distinct disadvantages which prevent their application to special flow fields like the helicopter rotor flow. A more detailed discussion and comparison of these methods is presented in Refs. 2, 3 and 4. Alternatives are the probe-based methods (hot wire) or the Laser Velocimetry (Refs. 5,6). These methods, however, are restricted to the measurement of statistical data of the flow or single point measurements and cannot give the desired Lagrangian view of the flow, which allows the observation and measurement of singular complex flow patterns and their development over space and time. This, however, is very important for the investigation of laminar-turbulent transitions or burst vortices.

In this paper, the "Flow Visualization Gun"-technique and its application to complex helicopter rotor flows will be introduced. This technique, which is based on the ideas of J. Steinhoff (Ref. 1), has several advantages over the currently used methods. After a short principal description of the method (a more detailed description can be found in Refs. 2, 3 and 4), several flow photographs will be presented and discussed, emphasizing the applicability of the new method to the investigation of complex flow fields and the roll-up and bursting of vortices. Initial quantitative results, obtained by using digital image processing techniques, will be presented concerning the tip vortex structure and the downwash in the tip region of two different test rotors.

THE NEW VISUALIZATION TECHNIQUE

The new method is based on the idea to produce, at one instant, an initially straight line of smoke within the flow at an arbitrary direction or location, normally perpendicular to the main flow. The smoke particles in this smoke trace are very small and follow the airflow very closely. Their motion can be used to determine the flow velocities normal to the smoke trace and, under certain circumstances, also along the trace. The smoke traces have sharp edges, are very thin, can cover distances greater than one meter, and can be placed almost everywhere in the flow field. They are created by heating very small titanium pellets and projecting them through the flow. Due to the heating the pellets are burning and produce a trace of dense, white titanium dioxide smoke which fills the wake of the pellets. As a pellet has a diameter of less than 1/10 of a millimeter, its wake and therefore the smoke trace is not wider than 0.5 millimeter. The disturbance of the flow induced by the pellet and its wake is apparently very small and can be neglected, since when the trace is being observed, the pellet has gone beyond the observation region a distance several orders of magnitude greater than its diameter and all disturbances in the wake have decayed. After being placed within the flow, the smoke trace behaves like a time line. Using a stroboscope or several triggered flashes, the light scattered by the smoke can be photographed. Flow velocities can be determined by measuring the displacement of the smoke traces between subsequent flashes.

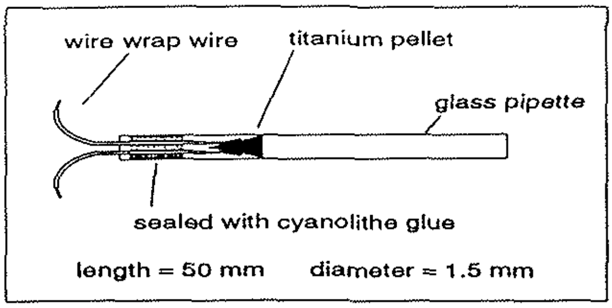

Fig. 1 Glass pipette

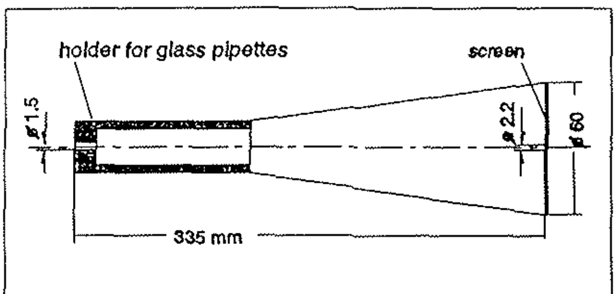

Fig. 2 Flow Visualisation Gun

The shooting mechanism consists of a thin glass pipette and works according to the principle of an exploding wire (Ref. 7 to 9) (see figure 1). A relatively large (1 millimeter diameter) titanium pellet electrically connects two wires. Power is supplied by large capacitors. Due to the wire explosion the relatively large titanium pellet partially disintegrates into extremely small particles, which start burning (diameter less than 1/10 of a millimeter). The rest of the large pellet, which is of no further interest, and all the burning particles are accelerated by the explosion and leave the glass pipette at a spreading angle of approximately 10 degree and at a speed of 200 m/s and more, depending on the energy provided by the capacitors. At the distance of 0.3 m an aluminum screen (figure 2) with a small hole extracts one of these small particles, which then finally continues along its path through the region of interest within the flow. Due to this special screen arrangement, the probability is high that only one particle leaves the apparatus. Final particle speed is between 50 m/s and 150 m/s. If necessary for a high speed flow field, it is possible to extend the particle speed with the present apparatus up to about 250 m/s. The particle, however, will slow down significantly due to the aerodynamic drag for longer shooting ranges.

Usable shooting distance with the gun is about 0.5 m to 2.0 m, depending on the particle speed, size, and temperature. After this distance, the particle becomes thermally unstable and disintegrates or explodes into a firework of even smaller particles.

Since the pellet is incandescent, it leaves a photographic image as it traverses the flow, separate from the illuminated smoke trace. Due to drag forces on the pellet caused by the airflow, its image is not exactly a straight line. This effect can be large and influences the location of the smoke trace. It is therefore not possible to place the line at an exactly predefined position. When the pellet has crossed the whole region of interest, the smoke trace is ready to be photographed. At this time, however, the trace is already influenced by the flow and by flow disturbances. This means that the older parts of the smoke trace may have irregularities. This effect, rather than causing a problem, is helpful for determining the flow velocities even in direction of the smoke line by following distinct recognizable local irregularities over subsequent flashes.

For the illumination of the smoke traces a set of up to four pre-charged flashes is used. Flash rising time is 0.01 ms and decay time to half intensity is about 0.5 ms. Due to this relatively long decay time, the "leading edge" of the smoke trace image, i.e., the edge in the direction of the flow velocity, is diffuse. The trailing edge (this is the position of the line at the flash rise), however, is very sharp due to the very fast flash rising time. Therefore, just the sharp trailing edge should be used for velocity measurements. Since there is one sharp edge, the relatively large width of the line image has no adverse effect. On the contrary, it can be helpful to determine the flow direction by observation of the fading of the smoke trace image.

THE TEST ROTORS AND THE EXPERIMENTAL SET UP

Two different test rotors have been used to perform the experiments discussed througout this paper.

Rotor No 1 has two blades at fixed pitch of 10 degree at the tip with 33 degree twist and is 1.4 m in diameter. The experiments were performed at a rotor speed of 666 rpm, giving a tip speed of 48.6 m/s. Chord length at the tip is 53 millimeters. The rotor was operated in a relative small room with a distance to all walls of about one rotor diameter. For more data see Ref. 2.

Rotor No 2 has four blades at fixed pitch of 10 degree at the tip with no twist and is 1.0 m in diameter. The experiments were performed at a rotor speed of 1200 rpm, giving a tip speed of 62.8 m/s. Chord length is 55 millimeters. This rotor was operated in the large windtunnel hall of the University of Aachen (see figure 3).

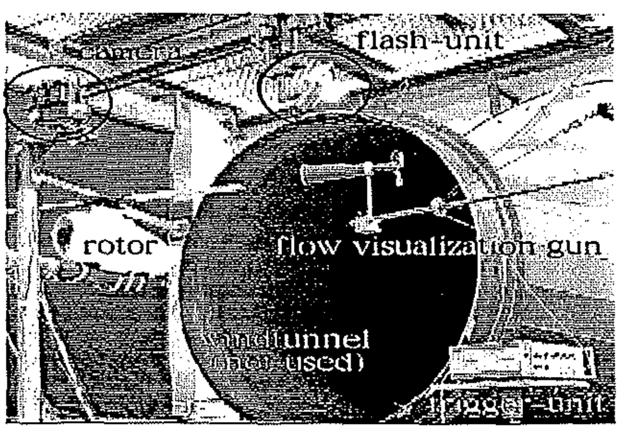

Fig. 3 Hover test set up in the windtunnel section

The tip speeds were actually constraints of the available test rigs. As can be seen in the smoke photographs, however, this should not be a limit for the method.

Two cameras were used simultaneously to provide a stereometric view of the smoke line images. One of these (the oncoming view camera) was set to have a tangential view of the rotor, looking at the blade leading edge and showing the radial flow on the blade and the tangential flow within the vortex. The other one was set perpendicular to the "oncoming view camera", depending on the experimental configuration. For rotor No 1 it was set to have a radial view towards the tip of the rotor blade, showing the chordwise flow on the blade. For rotor No 2 it was set to have a view parallel to the rotor axis. Therefore it had a view on the radial flow of the downwash. For rotor No 1 the viewing angles of the cameras were rotated slightly from these ideal positions to avoid blade surface light reflections while keeping a good view on the smoke traces.

DISCUSSION OF THE FLOW VISUALIZATION IMAGES

Figure 4 gives a first impression of the capabilities of the method in an initial non rotor test. Here, in a simple environment, the wake of an airfoil section in a windtunnel at a very low air speed of 1.3 m/s is shown (Ref. 10). The straight line is the image of the incandescent pellet. In a four-flash-sequence the smoke line shows the flow in the wake of the airfoil.

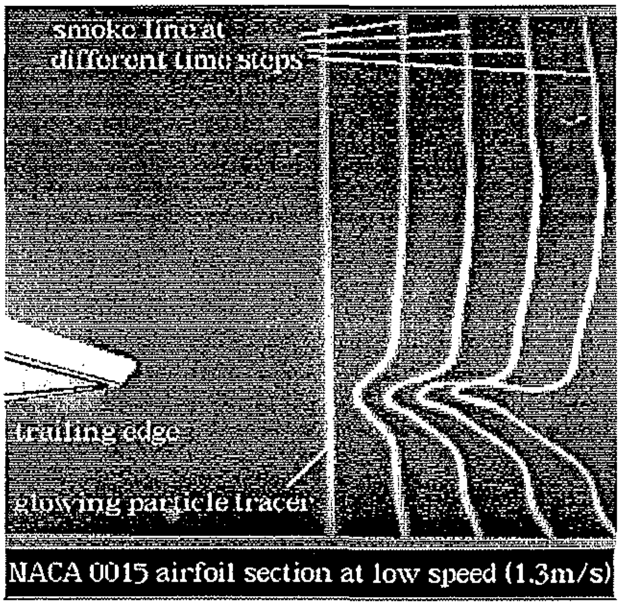

Fig. 4 Wake of an airfoil

Back to the helicopter rotor, figure 5 presents the developing tip vortex of rotor No 1 with maximum tangential velocities in the vortex of 20 m/s. The leading edge of the rotor blade is moving towards the observer. Due to the slight viewing angle of 8 degree relative to the rotor disk which is necessary to avoid light reflections on the twisted blades, the blade moves downward in the image. The smoke line stays at a constant azimuthal rotor position during the four flash sequence, which is in the image plane. The blade (or its quarter chord line), however, moves from a position of shortly behind the image plane at the first flash (uppermost blade image) over the exact image plane position at the second flash to an azimuthal position shortly in front of the image plane at the third flash and finally to the last position, where even the trailing edge has moved in front of the image plane (fourth flash; lowermost blade image).

The roll-up of the smoke trace can be observed as the effect of the roll-up of the tip vortex. At the first flash there is almost no influence of the blade on the smoke trace, whereas at the last flash the tip vortex is almost fully developed. The smoke trace in this figure happened not to be placed exactly in the core of the developing vortex. Nevertheless it is possible to observe the radial station of the largest tangential velocity in the vortex. The smooth velocity profile gives evidence to this fact. If the smoke trace had encountered the vortex at a radial station outside of the maximum tangential velocity, a sharp edge of the velocity profile, raising towards the maximum, would then be observed.

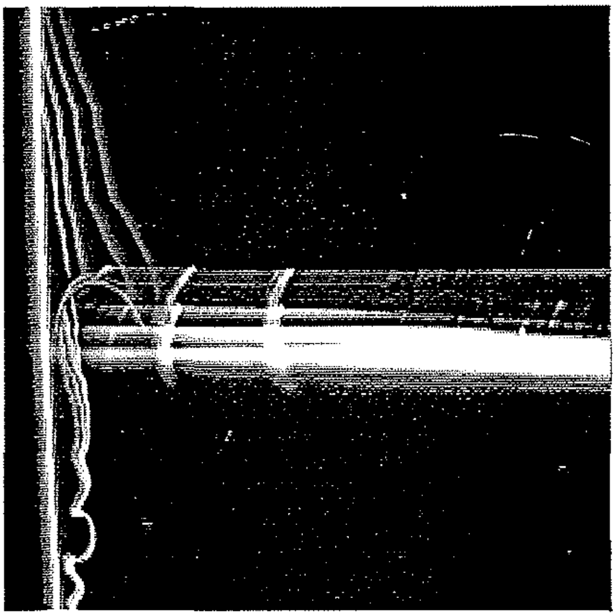

Fig. 5 Tip vortex at rotor No 1

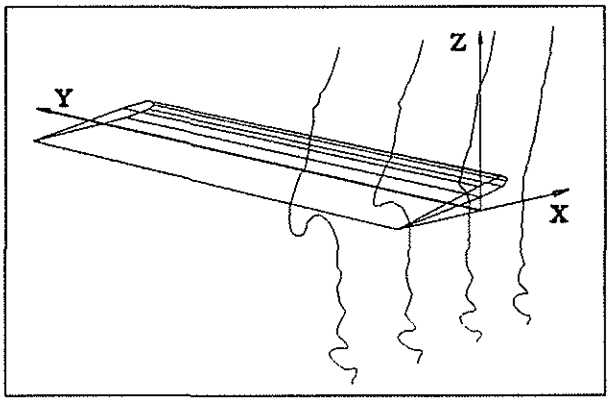

Fig. 6 3D reconstruction of the tip vortex roll-up

Figure 6 shows the development of the tip vortex in a 3-dimensional view, which has been reconstructed using a stereometric set of photographs. For this sketch the relations have been changed to a blade-fixed coordinate system and the smoke line moves past the blade, shaped by the influence of the tip vortex. Figure 7 shows a blow up of the same tip vortex in an inverted (black on white) and contrast-enhanced view. All following flow field images will be presented in a similar technique, which greatly enhances the visibility of small smoke structures or faint smoke lines. The rounding out of the smoke line image at the fourth position indicates a beginning of a vortex ageing at an azimuthal position, before the vortex leaves the trailing edge of the blade. A quantitative look at the tangential velocities of this developing vortex will be shown later in figure 10.

Figures 9 and 10 show the capability of the new method to investigate turbulent flow patterns and the bursting of vortices: Depending on the load of the rotor, the wake contraction, and other characteristics, the tip vortex of one

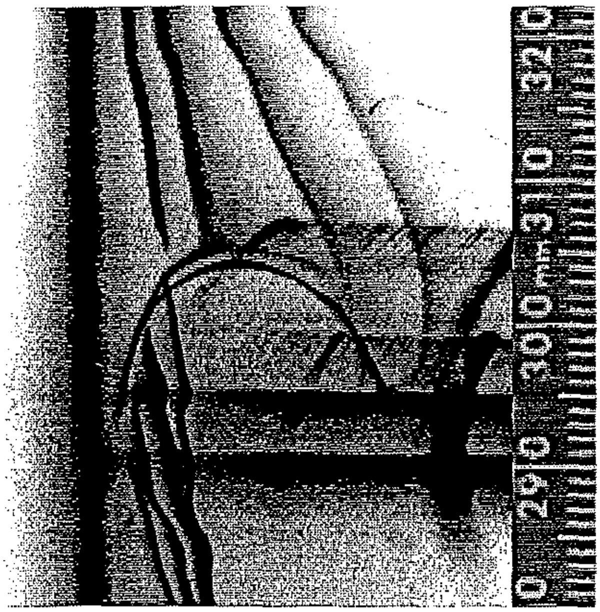

Fig 7 Contrast-enhanced blow up of the tip vortex

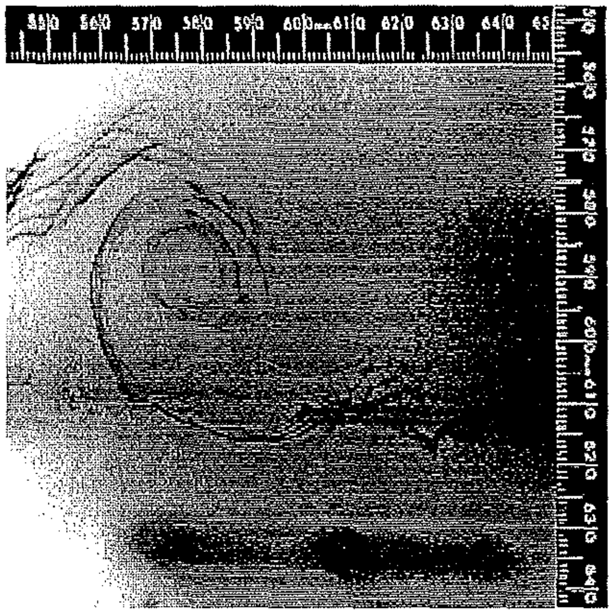

Fig. 8 Tip vortex 4.6 chord lengths (20° azimuth) behind blade

Figure 8 shows the tip vortex at an azimuth angle of 20 degree behind the blade. Two smoke lines have been shot into the flow region and have been flashed four times, resulting in 8 line images. Due to a relative long time interval between the shot and the flash sequence, the vortex has rolled up the lines by more than two revolutions. Apparently the vortex has laminar flow characteristics, because the line images still can be seen as separated lines.

rotor blade can come very near into the vicinity of the following blade and can have a strong influence on this blade. This phenomenon, called "Blade Vortex Interaction" (BVI), causes blade stress, rotor noise, and poor rotor efficiency due to the induced velocities of the vortex. The theoretical investigation of this problem is a very difficult task due to the unknown structure of the vortex during BVI.

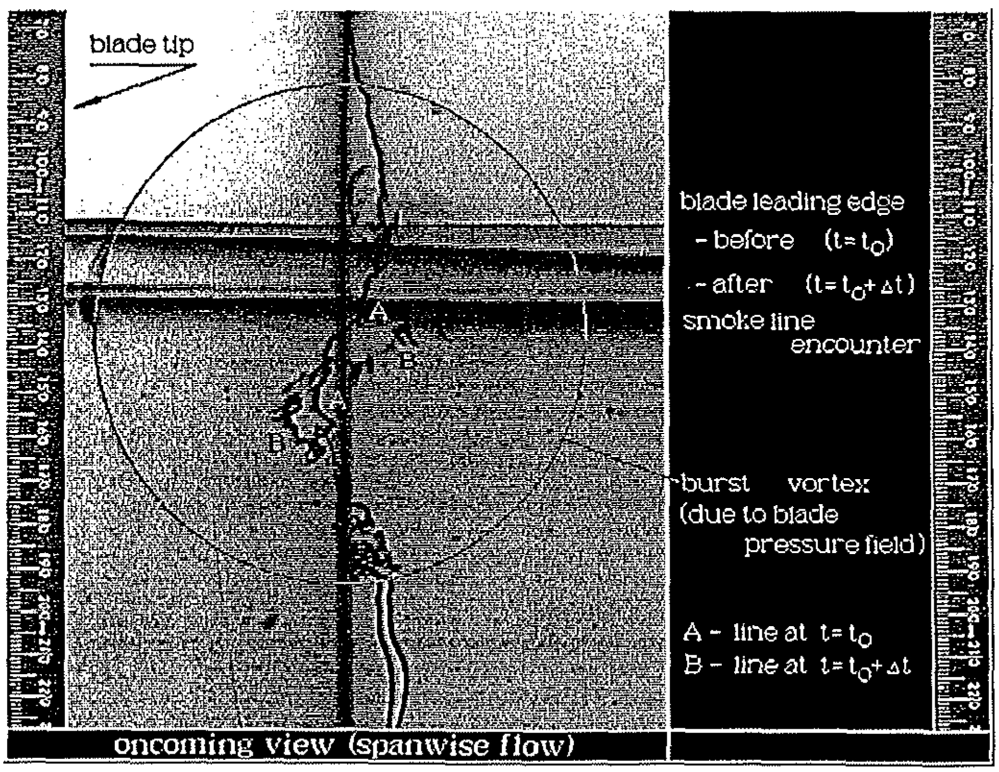

Fig. 9 Burst tip vortex at BVI with the following blade

Depending on the distance between blade and vortex at BVI, the pressure field of the approaching blade can cause the bursting of the vortex and therefore produce an even more complex and unknown structure. While the only other possible method for an experimental investigation of this flow type, the laser velocimetry, can only provide statistical data, which normally have to be gathered over many rotor revolutions, the new method can visualize the complete core of the burst vortex at one instant, showing its dimensions, tangential velocities, and the dimensions of the local turbulent structures. Figure 8 shows such a blade vortex interaction with a burst vortex in a two-flash-sequence and in an oncoming view like the one in figure 5. The blade is turning towards to the observer and it looks like it is moving slightly downward due to the small shift angle of the camera relative to the rotor disk. The tip vortex of the preceding blade encounters the blade at about 90% of the rotor radius. The vortex has moved downward from the rotor disc only a distance of 30% of the blade chord due to the weak downwash of the rotor.

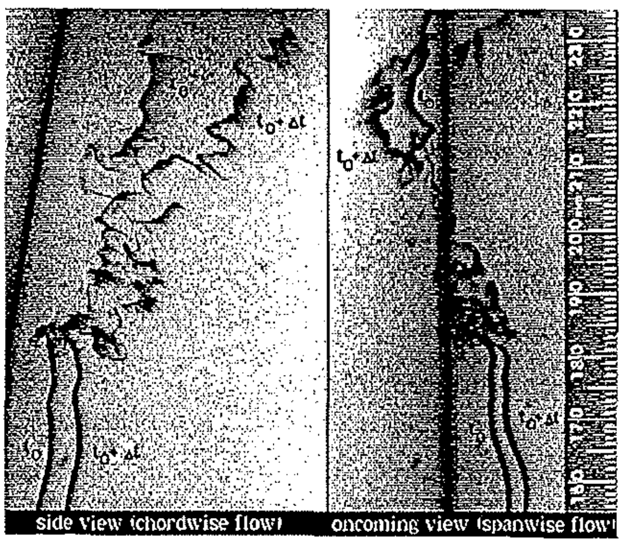

Fig. 10 Right hand side: blow up of lower part of figure 9
left hand side: side view of right hand side,
showing axial velocities of the vortex

At the first flash (upper blade image; smoke line image 'A') the distance between blade leading edge and smoke line is about half of the blade chord and the vortex is already burst due to the pressure field of the approaching blade. There is a very sharp boundary between the burst vortex core and the laminar flow outside that core. Figure 10 shows a blow up of the lower part of figure 9 on the right hand side, together with the side view of the same flow field (looking from the tip inward to the rotor hub - blade moving from left to right) on the left hand side. At the second flash, half a chord after the encounter with the smoke line, the influence of the blade has completely destroyed the smoke line in its vicinity: a little vapour is left only. Figure 10 and the lower part of figure 9, however, can still be used to determine the mean tangential velocity of the lower part of the burst vortex during the encounter with the blade. Of course, the mean downwash velocity has to be considered for this evaluation. The side view of the vortex (left hand side of figure 10) shows very clearly the turbulent shear flow in axial direction of the burst vortex (side view: blade and flow moving from left to right - the vortex center line is the top of the figure).

Figure 11 shows results of a quantitative evaluation of different flow photographs. The tangential velocities in the tip vortex are presented for four different angles of azimuth, counting from the quarter chord line of the blade. At an azimuth of 2 degree, when the vortex starts to develop strong tangential velocities due to the pressure difference between lower and upper surface (still on the blade at about 65% chord), the core radius has a value of about 15% of the blade chord and the tangential velocity is already very high (about 20 m/s). A little later, at an azimuth of 4 degree, the vortex has just left the trailing edge of the blade. Here, a significantly increased core radius can be observed and additionally a rounding out of the initially very sharp velocity peak. This rounding out can be observed in the flow images also (see figure 7). The tangential velocity has stayed constant. Later, at an azimuth of 20 degree, 4.6 chord lengths behind the blade, the tangential velocity has decayed to a little more than half the former value. The core radius cannot be determined exactly due to the lack of good flow photographs in this region. At an azimuth of 180 degree, during BVI with the following blade, the tangential velocity cuts down even more due to the bursting of the vortex and the core radius increases to about twice the initial value.

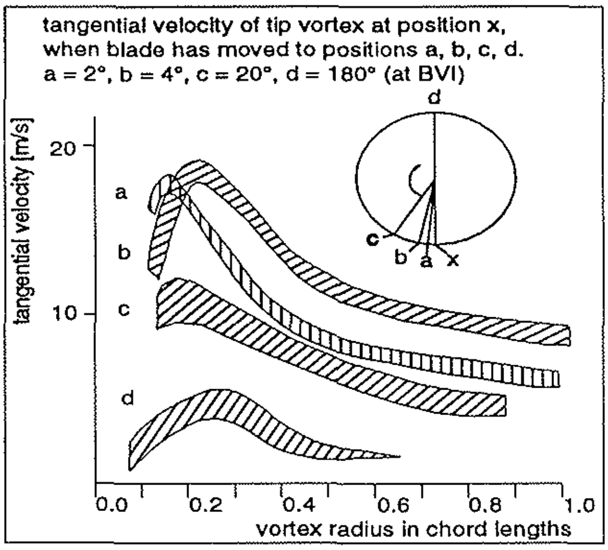

Fig. 11 Measurement of tangential velocities in the
developing tip vortex

By their thickness, these curves indicate the uncertainty in the determination of the tangential velocities. Reason for this uncertainty is the unsteady character of the rotor flow for these hover flight experiments. Due to the small test room with a distance to the walls of about one rotor diameter, there was a large recirculation flow. This resulted in a large band width of different inflow conditions for the rotor flow and therefore of the tangential velocities of the tip vortex at different experiments. The method itself has a very high accuracy - depending on the fine grain of the photographic film material and the technique how to determine the edge of the smoke line images in the photographs only. The smoke particles can be considered to follow these low speed flow types very accurately. For a discussion of the possible errors in the velocity determination using time lines see Ref. 11.

Using digital image processing, the computer can help to produce quantitative data of the velocity field. Corresponding points (the earlier mentioned irregularities) on the smoke line images can be used to calculate the mean local flow velocities between each two subsequent flashes. In the following steps of the procedure, the computer combines two stereometrically taken photographs to produce 3-dimensional plots of the smoke line images like the example of figure 6 or even streamline plots. Even the complete velocity vector plot of a larger flow field can be calculated, using a larger set of stereometric photographs of that flow field and a special 3-dimensional interpolation procedure. Figure 12 shows the interpolated flow around the blade tip including the tip vortex of figure 5. More details regarding the image processing can be found in Refs. 3 and 4.

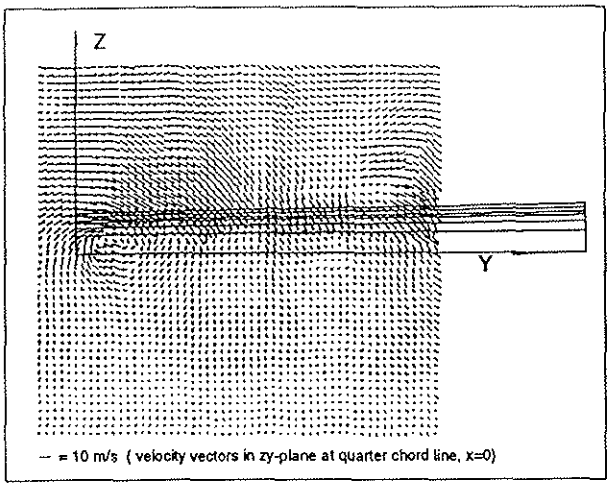

Fig. 12 Interpolated vector plot

In another experiment, using rotor No 2, the downwash velocity near to the rotor disc has been investigated. As this rotor has been used at the Department of Aeronautics at the University of Aachen for many years (see Refs. 12 and 13), many data are available and will be used for comparison in the future. These include probe based downwash measurements and normal smoke visualizations. Additionally there are flow calculations, using a free wake analysis technique.

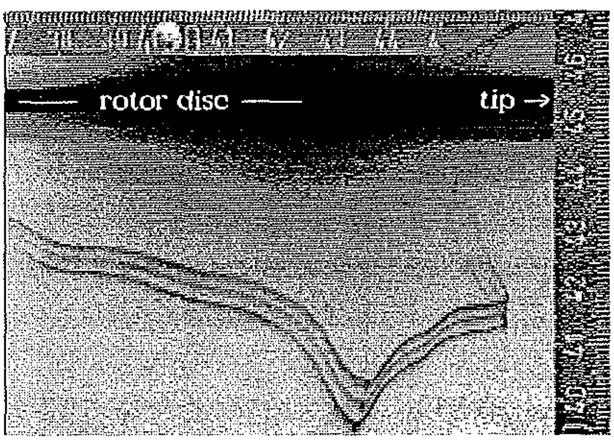

Fig. 13 Downwash at 67.5° azimuth behind the blade

Figure 13 and 14 show the downwash velocity at different azimuthal positions and different distances from the rotor disc. Quantitative velocity data are presented in figure 15, again with the azimuthal angle counting from 0 degree at the quarter chord line of the blade. Due to the large wake contraction in the vicinity of the rotor disc, there is a large acceleration of the downwash. This gives larger downwash velocities beneath the rotor disc than over the disc. The peak of the velocity, induced by the tip vortices, is even more sensitive to the vertical position of the smoke line. Using a set of photographs for each azimuthal position, it will be possible to calculate and interpolate the complete flow field.

Prototypes of the apparatus (figure 16) and the image processing hard- and software are available upon request and can be adapted to different applications.

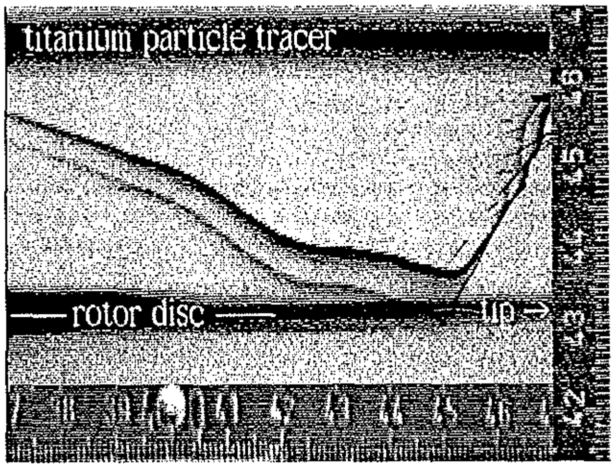

Fig. 14 Downwash at 45° azimuth behind the blade

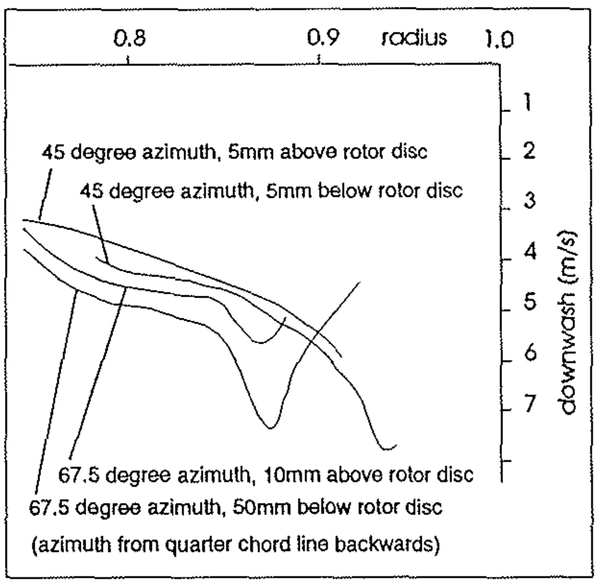

Fig. 15 Initial measurement of downwash velocities (at different azimuthal and vertical positions)

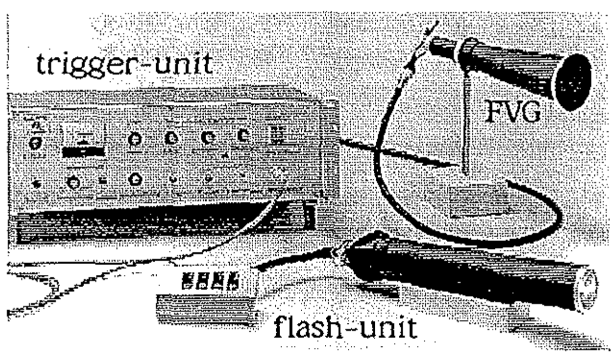

Fig. 16 Flow Visualization Gun apparatus

ACKNOWLEDGEMENT

Parts of the flow visualization study have been supported by the German Research Society (DFG). The experiments have been conducted in the Flow Visualization Lab of the University of Tennessee Space Institute (UTSI) and in the windtunnel of the Institute for Aeronautics of the University of Aachen, Germany. The author is very grateful for the support and the possibility to use the test facilities in both Universities.

REFERENCES

1. Steinhoff, J. S., "A Simple Efficient Method for Flow Measurement and Visualization," Flow Visualization III, Hemisphere Publishing Corporation (1985) Springer-Verlag, Edited by W. J. Yang, pp. 19-24.

2. Müller, R.H.G. and Steinhoff, J. S., "Application of a New Visualization Method to Helicopter Rotor Flow," presented at the 8th AIAA Applied Aerodynamics Conference, Portland, Oregon, August 20-22, 1990.

3. Müller, R.H.G., "Eine neuartige Methode zur Visualisierung von Strömungen sowie Auswertung der Strömungsbilder mittels digitaler Bildverarbeitung," Abschlußbericht DFG (Deutsche Forschungsgemeinschaft) Mu802/1-1, 1990.

4. Müller, R.H.G., "Visualization and Measurement of Helicopter Rotor Flow Using Projected Smoke Filaments and Digital Image Processing," presented at the 16th European Rotorcraft Forum, Sept. 1990, Glasgow, Scotland.

5. Lorber, P.F., Stauter, R.C., Landgrebe, A.J., "A Comprehensive Hover Test of the Airloads and Airflow of an Extensively Instrumented Model Helicopter Rotor," Proceedings of the 45th AHS Annual Forum, May 1989.

6. Thomson, T.L., Kwon, O.J., Kemnitz, J.L., Komerath, N.M., Gray, R.B., "Tip Vortex Core Measurements on a Hovering Model Rotor," AIAA 25th Aerospace Sciences Meeting, Jan.12-15, 1987, Reno, Nevada.

7. Chace, William G., "Liquid Behavior of Exploding Wires," The Physics of Fluids, Vol. 2, No. 2, March-April 1959, pp. 230-235.

8. Scherrer, Victor E., "An Exploding Wire Hypervelocity Projector," Exploding Wires, Vol. 2, Plenum Press New York, 1962, pp. 235-244.

9. Bohn, J. L., Nadig, F. H., Simmons, W. F., "Acceleration of Small Particles by Means of Exploding Wires," Exploding Wires, Vol. 3, Plenum Press New York, 1964, pp. 330-351.

10. Steinhoff, J. S. and Mersch, T., "Flow Field Measurement and Visualization Using Projected Smoke Trails," 30th Aerospace Sciences Meeting and Exhibit, January 6-9, 1992, Reno, NV

11. Lusseyran, D. and Rockwell, D., "Estimation of Velocity Eigenfunction and Vorticity Distributions from the Time Line Visualization Technique," Experiments in Fluids 6, pp 228-236 (1988).

12. Müller, R. H. G., and Staufenbiel, R., "The Influence of Winglets on Rotor Aerodynamics," Vertica Vol 11, No 4, pp 601-618, 1987

13. Müller, R. H. G., "Winglets on Rotor Blades in Forward Flight - A Theoretical and Experimental Investigation," Vertica Vol 14, No 1, pp 31-46, 1990

14. Müller, R. H. G., and Hackeschmidt, M., "A New Method for Visualization and Measurement of Turbulent Flow Patterns," Eight Symposium on Turbulent Shear Flows, Technical University of Munich, September 9-11, 1991