WAKE TURBULENCE HAZARD ANALYSIS FOR A GENERAL AVIATION ACCIDENT

Carsten Schwarz, Dietrich Fischenberg
Institute of Flight Systems, German Aerospace Center
(Deutsches Zentrum für Luft- und Raumfahrt)
Lilienthalplatz 7, 38108 Braunschweig
Germany

Keywords: wake vortex evolution, wake vortex encounter, accident investigation

Abstract

Whereas wake turbulence is commonly a topic within commercial aviation which is involving large/ heavy transport aircraft, there can also be a hazard for general aviation flight operations. This has been investigated for a specific case of an accident where an aircraft of class E (one engine with a maximum takeoff weight up to 2 tons) took off behind an aircraft with 5.5 tons maximum takeoff weight. Based on available information and several assumptions the potential wake turbulence situation for the specific aircraft combination has been assessed. The roll axis was the dominating factor in this case. Accordingly, the wake induced rolling moment was analysed and related to the assumed available roll control power. Furthermore, the wake vortex behaviour was simulated. The results indicate that wake turbulence can likely be considered to be the main reason for the accident.

Zusammenfassung

Das Thema Wirbelschleppen ist überwiegend für die Verkehrsfliegerei von Bedeutung, typischerweise unter Beteiligung von größeren Verkehrsflugzeugen. Eine Gefährdung kann allerdings auch im Bereich der allgemeinen Luftfahrt bestehen. Dies wurde für einen speziellen Flugunfall untersucht, bei dem ein Luftfahrzeug der Klasse E (einmotorig mit einem maximalen Abfluggewicht bis 2 Tonnen) hinter einem Luftfahrzeug mit einem maximalen Abfluggewicht von 5,5 Tonnen startete. Aufgrund der verfügbaren Informationen und mehrerer Annahmen wurde die mögliche Wirbelschleppensituation für diese spezielle Flugzeugkombination bewertet. In diesem Fall war die Rollachse der dominierende Faktor. Entsprechend wurde das wirbelinduzierte Rollmoment bestimmt und auf die verfügbare Rollsteuerautorität bezogen ausgewertet. Weiterhin wurde das Wirbelverhalten simuliert. Die Ergebnisse deuten darauf hin, dass die Wirbelschleppe wahrscheinlich als Hauptfaktor für den Unfall angesehen werden kann.

1. INTRODUCTION

In September 2012 a Robin DR 400 conducted flight tours in the context of a local airfield event. The flights were operated from a grass runway. When the DR 400 took off at 5:08 pm behind an An-2, the DR 400 experienced a strong rolling motion of about 90° at a low altitude (FIG 1) and crashed to the ground in the vicinity of the airfield [1].

The German Federal Bureau of Aircraft Accidents Investigation (BFU) investigated this accident [2], supported by the German Aerospace Center (DLR), Institute of Flight Systems [3]. The goal of this support was to analyse the possibility that the DR 400 encountered the wake turbulence of the An-2. In a first step the wake vortex of the An-2 was analysed and subsequently the possible effect on an encountering DR 400.

FIG 1. DR 400 shortly before impact with the ground [2]

2. SCENARIO AND AIRCRAFT DATA

2.1. General Scenario

The altitude of the airfield is 294 m above mean sea level. The length of the grass runway is about 500 m. The day was a hot summer day with almost no wind and visual meteorological conditions. Neither flight data nor cockpit voice data were recorded, corresponding to the applicable requirements. Based on photo material it is estimated that the two aircraft took off between 20 s and 60 s after another, likely around 40 s [2].

2.2. Aircraft Data

Both involved aircraft are of ICAO weight category 'light' [1]. The Robin DR 400 is a four-seat wooden sport airplane with one engine (FIG 2). The Antonov An-2 is a single-engine biplane utility/agricultural aircraft (FIG 3). The main aircraft data is listed in TAB 1, with assumptions for the actual initial climb speed.

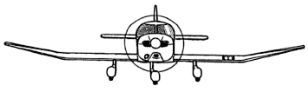

FIG 2. DR 400 front view (approximately to scale with FIG 3) [5]

FIG 3. An-2 front view (approximately to scale with FIG 2) [6]

aircraft type	**DR 400/180 R**	**An-2**
maximum takeoff mass	1.0 t [7]	5.5 t [8]
wing span	8.72 m [7]	16.21 m (mean) 18.18 m (upper) 14.24 m (lower) [9]
initial climb speed (assumptions)	130 km/h [5]	120 km/h [10]

TAB 1. Main aircraft data

3. WAKE VORTEX

3.1. Initial Circulation

For the determination of the vortex strength (circulation) of the An-2 biplane it is assumed that the wing tip vortices of the upper and lower wing are merging relatively fast since the distance between the wings is not large [11]. Hence the circulation is determined in the same way as for a monoplane. According to the KUTTA-JOUKOWSKY theorem (equation 1) the initial circulation Γ_0 is a function of the lift L_L and airspeed V_L of the leading aircraft ('L') and the air density ρ [12].

$$(1)\quad \Gamma_0 = \frac{L_L}{\rho V_L b'}$$

The separation of the two vortices b' is calculated with the leading aircraft wing span, b_L (mean value of upper and lower wing assumed, see TAB 1), for the reference case of elliptical lift distribution (equation 2) [12].

$$(2)\quad b' = b_L \frac{\pi}{4}$$

For the calculation of the initial circulation the mass of the An-2 is assumed to be the maximum takeoff mass (see TAB 1), which is the worst case for the highest circulation. And the lift is assumed to be equal to the aircraft weight. The initial climb speed is assumed to be 120 km/h (see TAB 1, [10]). For the altitude of the airfield (approximately 300 m above mean sea level, see section 2.1) the standard atmosphere air density is ρ = 1.2 kg/m³ [13].

With these input values and equations 1 and 2 the initial circulation of the An-2 for the considered scenario is Γ_0 = 106 m²/s. This value is about three times larger than the corresponding value for the DR 400 under the same circumstances. Is has to be noted that the airspeed of the An-2 for this flight phase is considered to be relatively small for an aircraft of that size, which can be attributed to the configuration with two wings and accordingly a comparatively large wing area. The relatively small airspeed is contributing to a comparatively large circulation (equation 1) for an aircraft of that size.

3.2. Wake Behaviour and Decay

3.2.1. General Wake Properties

Generally wake vortices are sinking due to their mutual self-induced downdraft [12]. In ground effect the minimum vortex altitude is considered to be 50 % of the separation b' between the two vortices (equation 2) [11]. In case of the An-2 the vortex separation is estimated b' = 12.7 m. Ground effect is not deemed to play a significant role in the investigated scenario.

The turbulence in the wake behind an aircraft generally forms a vortex pair during a roll-up phase. The roll-up phase is considered to be completed after a reference time t_0. This reference time t_0 is defined as the time in which the vortex pair propagates the distance of the spacing between the vortices (equation 3) [12].

$$(3)\quad t_0 = 2\pi \frac{b'^2}{\Gamma_0}$$

In this case the reference time and hence the duration of the roll-up phase is approximately t_0 = 10 s. Based on the observations for the separation between the two aircraft (section 2.1) it is concluded that any An-2 wake potentially encountered by the DR 400 would have been rolled-up.

3.2.2. Wake Vortex Decay

Based on the initial circulation (section 3.1) it is of interest to determine the wake decay. The validated DLR wake vortex evolution model P2P/ D2P (probabilistic/ deterministic two phase model, [14]-[16]) predicts vortex position and strength. In this case only the strength is calculated with D2P for a case of no atmospheric turbulence (decay only driven by diffusion, worst case in terms of slow decay, in accordance with the reported meteorological conditions, section 2.1). This gives an estimation of the encountered vortex strength Γ for a given vortex age t_{WV} (FIG 4). For the vortex age of interest, i.e. around 40 s, the circulation is still of significant strength for the considered conditions.

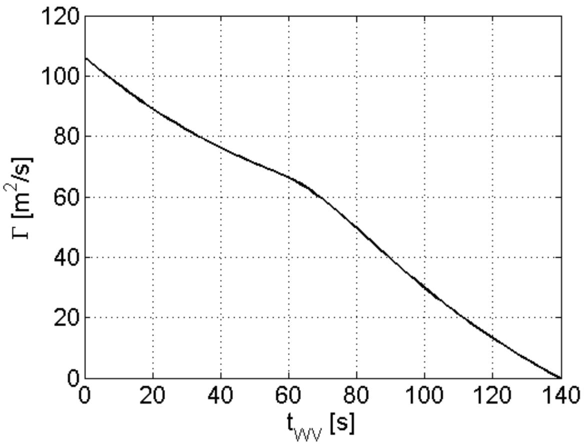

FIG 4. An-2 wake decay without atmospheric turbulence (D2P model, [14])

3.2.3. Wake Vortex Propagation

Lateral wake vortex transport is typically mainly influenced by the wind. In this case the effect of wind is considered to be negligible according to the reported meteorological conditions (section 2.1). Hence it is assumed that no lateral wake vortex movement took place.

As mentioned above the principal effect for vortex sinking w_{WV} is the mutual self-induced downdraft [12], which is depending on the wake vortex tangential (potential) velocity V_{WV} which is a function of the actual vortex strength (according to section 3.2.3, FIG 4)

(4) $$V_{WV,pot} = \frac{\Gamma(t)}{2\pi r}$$

and the separation of the two vortices, with $r = b'$ (equation 2)

(5) $$w_{WV} = \frac{2\Gamma(t)}{\pi^2 b_L}$$

For the vortex age of interest for a potential encounter of about 40 s (section 2.1) the sinking distance is estimated to about 40 m to 50 m.

In principle a wake vortex encounter scenario like this seems to be possible. Therefore the wake flow field and subsequently the potential induced aircraft reaction will be determined in the following sections.

3.3. Flow Field

The wake vortex induced velocities are calculated by superimposing two single vortices with opposite circulation, using the analytical tangential velocity ($V_{WV,BH}$) model of Burnham–Hallock [17] (based on Rosenhead [18]), which yields good results for wake vortex encounters [19], [20] with a core radius r_c of 3.5% of the generator wing span ($r_c = 0.035\ b_L = 0.57$ m).

(6) $$V_{WV,BH} = \frac{\Gamma(t)}{2\pi} \frac{r}{r_c^2 + r^2}$$

The corresponding velocity distribution (in the vertical plane perpendicular to the vortex axes) according to the respective vortex decay (section 3.2.2) is shown in FIG 5.

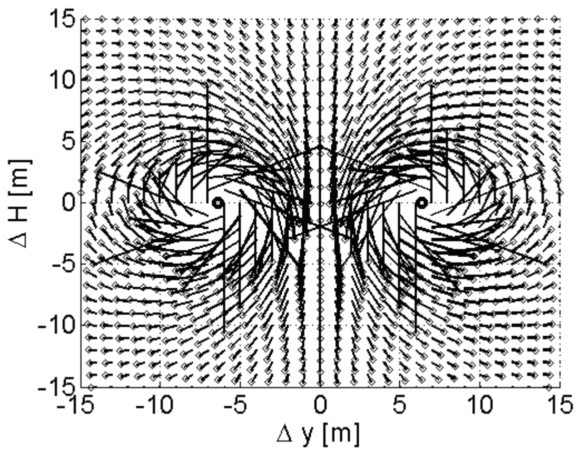

FIG 5. An-2 wake vortex velocity distribution (vortex age t_{WV} = 40 s, Γ = 76 m²/s, velocity vector length of 1 m corresponds to 1 m/s)

FIG 6 depicts the lateral distribution of vertical wake vortex velocity for the vertical position of the vortex centers.

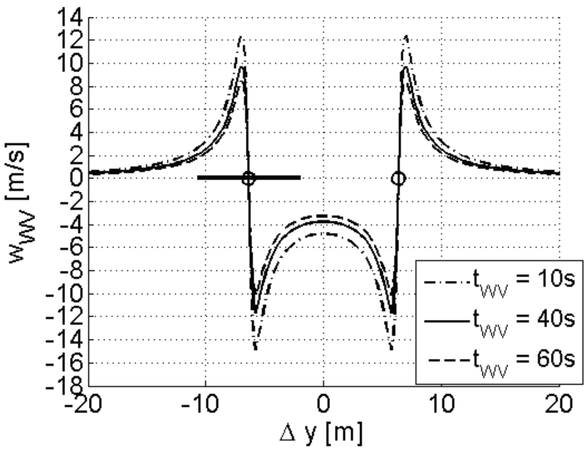

FIG 6. Lateral distribution of wake vortex vertical velocity for the vertical position of the vortex centers (with vortex cores and DR 400 wing span (positioned at the left vortex center), both drawn to scale)

The magnitude of the wake vortex velocity in the vertical plane perpendicular to the vortex axes is shown in FIG 7.

The results indicate that within approximately the first minute of the vortex lifetime of the An-2 wake vortex a maximum velocity of more than 10 m/s can be expected under the considered conditions. Significant velocities are induced in an area of about twice the generator wing span laterally and once the generator wing span vertically.

The vortex flow field is applied in the next section in order to determine the wake induced aircraft reaction.

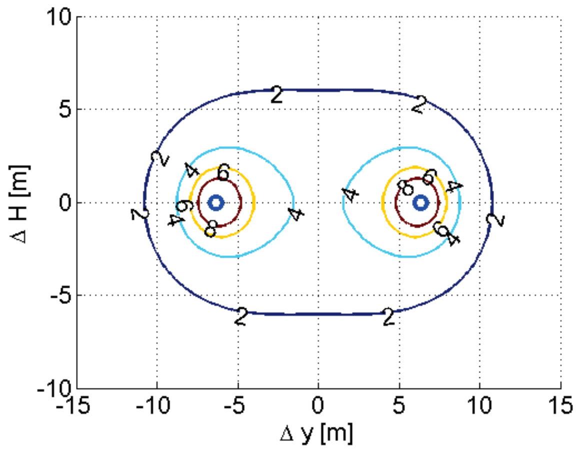

FIG 7. Magnitude of wake vortex velocity (vortex age t_{WV} = 40 s, Γ = 76 m²/s) in the vertical plane perpendicular to the vortex axes

4. WAKE INDUCED AIRCRAFT REACTION

For the determination of the vortex induced aircraft reaction, specifically the forces and moments acting on the encounter aircraft the strip method can be used [21]. Using the strip method as aerodynamic interaction model the lift generating surfaces are subdivided into sections for which the vortex influence is determined. This method was deemed feasible in [22], verified against wind tunnel tests in [23] and validated with flight test data in [20] and [24].

For the wake encounter situation under consideration here, with a predominant rolling motion and an assumed flight path approximately parallel to the vortex axes, the wake vortex induced rolling moment is primarily of interest. This can be determined particularly well with the strip method.

For the first order effect in the rolling axis the wing of the DR 400 is subdivided into 16 strips (FIG 8).

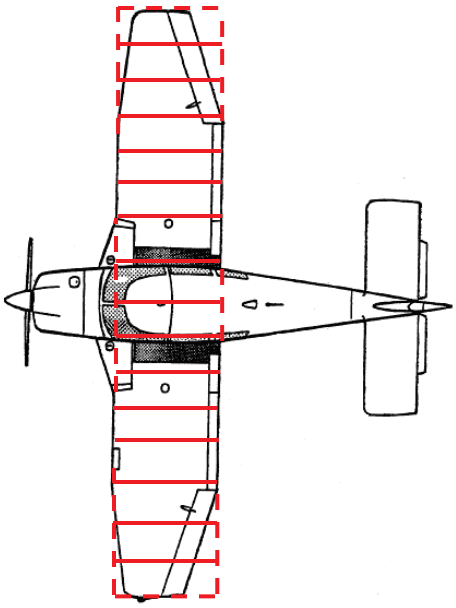

FIG 8. Strip method: DR 400 wing with 16 strips indicated [5]

The additional local angle of attack induced by the wake vortex is determined at the 25% chord line for each strip. Then the additional lift is calculated for each strip, weighted elliptically along the span to take into account the lift distribution. The effect on the rolling moment is computed with the respective lever arms and summed up for all strips.

For the lift curve slope of the DR 400 a value of 6 is assumed, which is somewhat below the theoretical value for thin airfoils of 2π and can be considered to be representative for typical aircraft.

In order to assess the potential severity of the wake impact on the encountering aircraft the induced rolling moment (coefficient $C_{l,WV}$) is related to the controllability of the encountering aircraft, specifically to the maximum roll control power [25], [26]. This defines the dimensionless wake vortex induced roll control ratio RCR.

(7) $RCR = |C_{l,WV} \,/\, C_l(\delta_{a,max})|$

This is a widespread measure for wake vortex encounter evaluations [27] - [30], [24].

For the maximum roll control power of the DR 400 a value of $C_l(\delta_{a,max})$ = -0.1 is assumed for the rolling moment coefficient due to maximum roll command based on available data for corresponding aircraft types [31].

The magnitude of the RCR values for a DR 400 behind an An-2 in the vertical plane perpendicular to the vortex axes are shown in FIG 9. The results show that a considerable effect is imposed on the encountering aircraft in the rolling axis under the considered conditions. For further analysis the areas with more than 100% RCR are describe with bounding ellipses (black ellipses in FIG 9).

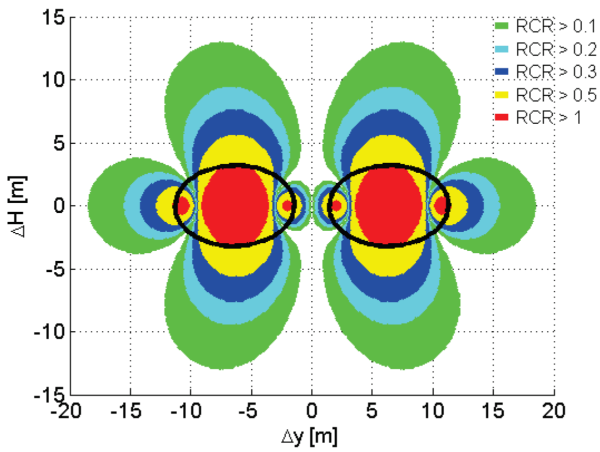

FIG 9. Distribution of RCR magnitude for DR 400 behind An-2 with bounding ellipses (in black) for areas with more than 100% RCR (vortex age t_{WV} = 40 s, Γ = 76 m²/s)

The development of the 100% RCR areas over time is shown in FIG 10 (for vortex decay according to section 3.2.2 and FIG 4) without taking into account vortex sinking. (Vortex sinking will be taken into account in section 5.) For approximately the first minute of its lifetime the An-2 wake vortex – under the considered conditions – can be considered to severely affect an encountering DR 400 within an area of about twice the encounter aircraft wing span laterally and once the encounter aircraft wing span vertically.

5. OVERALL SCENARIO SIMULATION

The overall takeoff scenario of the An-2 is simulated with the assumption stated above. A flight path angle of $\gamma = 14°$ is assumed as this constitutes a feasible scenario. Vortex decay and vortex sinking are modeled as described in the previous sections. The enveloping 100% ellipses from the previous section are marking the areas with severe imposed aircraft reaction for the DR 400 encountering aircraft. FIG 11 shows the overall wake situation 46 s after the An-2 takeoff as a potential wake encounter scenario.

The results from the overall scenario simulation, given the vortex strength, decay, propagation and severity impact, show that a wake vortex encounter of the DR 400 behind the An-2 may well have been occurred, with severe vortex induced impact on the DR 400 aircraft.

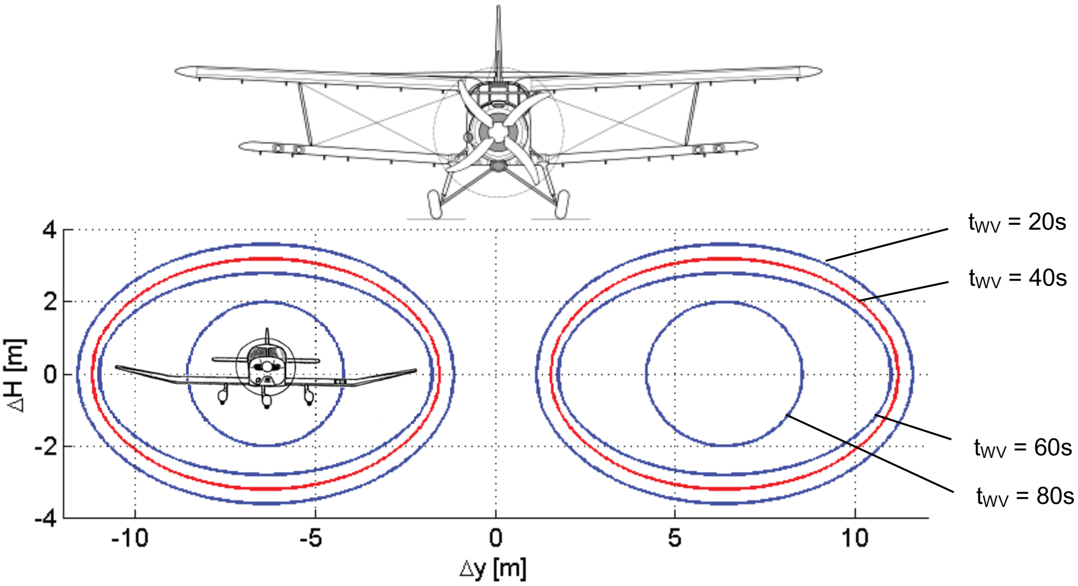

FIG 10. RCR areas with more than 100% for DR 400 behind An-2 (vortex age 20 s, 40 s (in red), 60 s and 80 s, vortex sinking not taken into account; both aircraft approximately to scale)

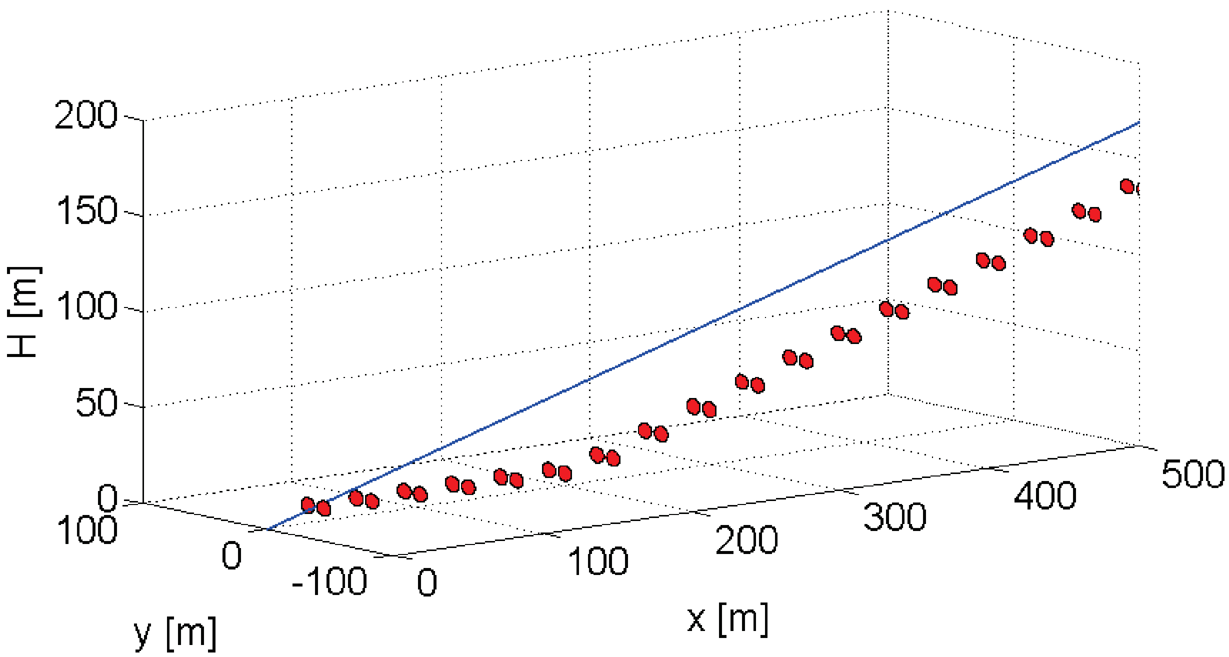

FIG 11. Overall wake scenario for An-2 takeoff (flight path in blue) with bounding ellipses (in red) for areas with more than 100% RCR for DR 400 encounter aircraft (for t = 46 s after An-2 lift-off)

6. VALIDATION EXPERIMENT

To validate the analysis results, flight test experiments were conducted in July 2014 with an An-2 and a DR 400 aircraft in Reinsdorf, Germany. First, the wake evolution in ground effect was visualised by low level fly-bys through the smoke of two smoke generators positioned on the airfield (FIG 12). The experiments were flown in dawn at low turbulence and nearly zero wind conditions. It was observed that after a wake roll-up phase (Fig. 12) two single vortices established with high rotational velocities up to nearly 60 seconds after generation in ground effect. This remarkable validation result confirms the computed An-2 wake decay without atmospheric turbulence, compare FIG 4.

FIG 12. Wake roll-up of the An-2 visualised by smoke

For validation of the aircraft reaction flying into in the An-2 wake, flight tests were flown with a DR 400 aircraft encountering the wake of an An-2 in 1000m safety altitude. The position of the left An-2 vortex was marked by a smoke generator, and the smoke was visible up to 1000m behind the aircraft. Several wake encounters were flown with strong aircraft reaction in roll. Bank angles around 90°, with maximum of 110° (FIG 13) were experienced within less than 2 seconds from level wings, while the control stick was kept fixed in center position or was deflected to compensate the wake rolling moment. During recovery, an altitude loss of more than 50m was observed.

These first results from flight test clearly confirm the computed An-2 wake strength, the An-2 wake decay and the risk for small general aviation aircraft. A detailed analysis is ongoing.

FIG 13. DR 400 wing view at maximum bank angle after an encounter into an An-2 wake

7. CONCLUSIONS

A flight accident involving two general aviation aircraft was analyzed with special regard to wake vortex influence. The analysis shows that the wake turbulence generated by an An-2 aircraft can likely be considered to be the main reason for the accident of a Robin DR 400 aircraft shortly after takeoff, which is also supported by initial results of a dedicated flight experiment.

The main aspects of the analysis are as follows.

Wake turbulence can be characterized by two counterrotating single vortices. In the considered scenario, the spatial range of the disturbed flow field is about twice the generator wing span laterally and once the generator wing span vertically in a plane perpendicular to the generator flight path.

Wake turbulence of an An-2 aircraft (maximum takeoff mass 5.5 t) can potentially severely affect small size aircraft up to about one minute at very calm weather conditions (no wind, no turbulence).

The wake induced rolling moment is of maximum size if the encountering aircraft flies in the center of the left single vortex (rolling to the right) or in the center of the right single vortex (rolling to the left).

For the investigated scenario, the computed wake induced rolling moment taking effect on the DR 400 can have a magnitude which cannot be compensated by full DR 400 roll control authority in a spatial range of about a DR 400 wing span laterally and vertically to the flight path for each vortex.

It should be noted that these conclusions are based on computations and several assumption, e.g. the roll control power and lift gradient of a DR 400, wake decay acc. to P2P/D2P wake evolution model with no atmospheric turbulence, wake flow field acc. to Burnham/Hallock, and an aerodynamic interaction model (strip method).

8. ACKNOWLEDGEMENTS

The cooperation with the German Federal Bureau of Aircraft Accidents Investigation (BFU), funding for this work and the fruitful collaboration is greatly acknowledged. Furthermore the discussions and exchange with Frank Holzäpfel (DLR Institute of Atmospheric Physics) were particularly valuable and are highly appreciated, as well as the input provided by Klaus-Peter Krückeberg, DLR Institute of Aerodynamics and Flow Technology.

9. REFERENCES

[1] BFU Bulletin, Accidents and serious incidents of civil aircraft ("Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge"), German Federal Bureau of Aircraft Accidents Investigation, Braunschweig, Germany, September 2012

[2] Stahlkopf, F., BFU Investigation Report BFU 3X134-12, German Federal Bureau of Aircraft Accidents Investigation, Braunschweig, Germany, 2014 (to be published)

[3] Schwarz, C, Fischenberg D, Flugunfall Backnang-Heiningen BFU 3X134-12 Nachrechnung

Wirbelschleppeneinfluss, DLR IB 111-2014/13, DLR Institute of Flight Systems, Braunschweig, Germany, March 2014
[4] International Civil Aviation Organization (ICAO), Doc 4444-ATM/501, Procedures for Air Navigation Services - Air Traffic Management, 15th Edition – 2007
[5] Flight Manual DR 400/180, Robin Aviation, April 2000
[6] Kaboldy, P., Antonov An-2 3view.svg, http://commons.wikimedia.org/wiki/File:Antonov_An-2_3view.svg [cited 22 August 2014], Creative Commons CC BY-SA 3.0
[7] Type Certificate Data Sheet DR300 and DR400 series, European Aviation Safety Agency EASA.A.367, Issue 01, 10 MAY 2013
[8] Type Certificate Data Sheet Antonov AN-2, Luftfahrt-Bundesamt Kennblatt-Nr. 2069/SA, 2 APR 2012
[9] Donald D, The Encyclopedia of World Aircraft, Bookmart Ltd, December 31, 1997, ISBN-13: 978-1856053754
[10] Krückeberg, K.-P., DLR Institute of Aerodynamics and Flow Technology, flight instructor, DR 400 pilot, personal communication
[11] Holzäpfel F., DLR Institute of Atmospheric Physics, personal communication
[12] Gerz T., Holzäpfel F., Darracq D., Commercial Aircraft Wake Vortices, Prog. Aerosp. Sci., Vol. 38, No. 3, pp. 181-208, 2002
DOI: 10.1016/S0376-0421(02)00004-0
[13] ICAO Doc 7488/3, Manual of the ICAO standard atmosphere – extended to 80 kilometres (262 500 feet), third edition, 1993
[14] Holzäpfel F., Probabilistic two-phase wake vortex decay and transport model, Journal of Aircraft, Vol. 40, No. 2, March - April 2003, 2003, DOI: 10.2514/2.3096
[15] Holzäpfel F., Robins, R. E., Probabilistic two-phase aircraft wake vortex model: application and assessment, Journal of Aircraft, Vol. 41, No. 5, September - October 2004, 2004, DOI: 10.2514/1.2280
[16] Holzäpfel F., Probabilistic two-phase aircraft wake-vortex model: further development and assessment, Journal of Aircraft, Vol. 43, No. 3, May–June 2006, 2006, DOI: 10.2514/1.16798
[17] Burnham, D.,, Hallock, J.N., Chicago Monoacoustic Vortex Sensing System, vol. 4, Wake Vortex Decay, National Information Service, Springfield, VA, 1982
[18] Rosenhead, L., The formation of vortices from a surface of discontinuity, Proc. Roy. Soc. London Ser. A 134 (1932) 170–192
[19] Fischenberg, D., Bestimmung der Wirbelschleppencharakteristik aus Flugmessdaten, in: German Aerospace Congress, Stuttgart, 23–26 September 2002, DGLR-JT2002-170, DGLR-Jahrestagung 2002, Jahrbuch, Deutsche Gesellschaft für Luft- und Raumfahrt, Bonn, 2002
[20] Jategaonkar, R., Fischenberg, D., Gruenhagen, W.V., Aerodynamic modeling and system identification from flight data – recent applications at DLR, J. Aircraft 41 (4) (2004) 687
[21] Schwarz, C., Hahn, K.-U., Full-Flight simulator study for wake vortex hazard area investigation, Aerospace Science and Technology, 10 (2), Elsevier. DOI: 10.1016/j.ast.2005.09.005, 2006
[22] Barrows, T. M., Simplified methods of predicting aircraft rolling moments due to vortex encounters, in: AIAA 14th Aerospace Sciences Meeting, Washington, DC, AIAA 76-61, January 1976
[23] de Bruin, A., WAVENC, Wake vortex evolution and wake vortex encounter, Publishable Synthesis Report, National Aerospace Lab., NLR-TR-2000-079, Amsterdam, 2000
[24] Schwarz, C., Hahn, K.-U., Fischenberg, D., Wake Encounter Severity Assessment Based on Validated Aerodynamic Interaction Models. AIAA ASE Conference 2010, 2.-5.8.2010, Toronto, Canada, 2010
[25] Hahn, K.-U., Coping with Wake Vortex, 23rd International Congress of Aeronautical Sciences, Toronto (Canada), 8 - 13 Sept. 2002, ICAS, 23rd International Congress of Aeronautical Sciences Proceedings, p. 732.1-732.14, 2002
[26] Hahn, K.-U., Schwarz, C., Friehmelt, H., A Simplified Hazard Area Prediction (SHAPe) Model for Wake Vortex Encounter Avoidance, 24th International Congress of Aeronautical Sciences (ICAS), Yokohama (Japan), 29 Aug. - 3 Sept. 2004
[27] Rossow, V. J., Tinling, B. E., Research on Aircraft/Vortex-Wake Interactions to Determine Acceptable Level of Wake Intensity, Journal of Aircraft, Vol. 25, No. 6, 1988
[28] Stewart, E. C., A piloted simulation study of wake turbulence on final approach, AIAA Paper 98-4339, Atmospheric Flight Mechanics, 10 - 12 Aug. 1998, Boston, MA, United States, 1998
[29] Luckner, R., Höhne, G., Fuhrmann, M., Hazard Criteria for Wake Vortex Encounters during Approach, Aerospace Science and Technology, Vol. 8, No. 8 (673–687), 2004, DOI: 10.1016/j.ast.2004.06.008
[30] Höhne, G., Reinke, A., Verbeek, M., Wake Vortex Encounter Flight Simulation: Metrics, Hazard Criteria, and Influence of Cockpit Motions, EU project S-Wake Technical Note TN-320-1-v1, Airbus Deutschland, 2002
[31] Schwarz, C. Hahn, K.-U., DLR institute report IB 111-2011/31, Simplified Hazard Area Prediction Method SHAPe, DLR Institute of Flight Systems, Braunschweig, December 2011