Wake vortex detection using Flight Data Recorder data registered on board aircraft

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Summary

- Introduction
- Detection of wake vortex encounters
- The WAVENDA algorithm described
- Discussion of 2 sample cases
- Conclusions and outlook
Introduction - motivation

- Reduction of separation minima to increase airport capacity, ----> increased risk of a Wake Vortex Encounter (WVE)
- More wake vortex encounters occur than reported
- Improved (reliable) WVE statistics is needed
- Analysis of detected WVEs (from Flight Date Recorder, FDR) can assist in finding cause and effects, in defining new or improved flight procedures, in developing severity criteria
- For this cause the “WAVENDA” computer program was developed:
  WAVENDA = \textit{WA}ke \textit{V}ortex \textit{EN}counter \textit{D}etection \textit{Algorithm}
The WAVENDA algorithm: pros and cons

- WAVENDA is based on determination of (pseudo-) non-dim. vorticity \( \text{‘GbVa’} \) from on-board registered FDR data

- Advantages:
  - general application
  - independent of the orientation of the vorticity (vector)
  - provides an easy reference of determining the severity of the encounter

- Difficulties / needs:
  - trajectory reconstruction (sophisticated Kalman filtering and smoothing, etc.)
    - requires some advance knowledge on data quality (esp. the accelerometers)
  - angle of attack \( \alpha \) calibrations (aircraft-type specific)
    \[
    \alpha(t) = a_0 + a_1 \cdot AOA(t + \tau) + a_2 \cdot Flap(t) + a_3 \cdot AOA(t + \tau) \cdot Flap(t)
    \]
    - Obtained from the FDR data using multiple regression
    - time lag \( \tau \) determined from cross-correlation
    - may be different for landings and take-offs
  - estimate of sideslip angle (also aircraft-type specific)
    - correction factor may be applied (aircraft-type specific)
  - values for stability derivatives, per aircraft type, per configuration (usually not available).
    - So far obtained from multiple linear regression on the available data (per aircraft type, per configuration (i.e. flaps up, down)
Detection of wake vortex encounters ‘WVE’

- Detection is done using on-board recorded FDR data

- Uncommanded aircraft attitude changes or accelerations indicate velocity disturbances in the air, e.g. due to a wake vortex

- NLR’s approach:
  - Reconstruction of the (air) flow field, determining “vorticity” as the rotation in the airflow
  - Correlation of “vorticity” with other atmospheric variables, associated with the (probability of) existence of vortices (e.g. atmospheric stability, eddy dissipation rate, etc.)
  - Use of severity measures (uncontrolled attitudes, roll control ratio) which indicate the magnitude of the disturbance
The WAVENDA algorithm process:

The algorithm WAVENDA consists of two steps:

1. **Computation of wind gradients & vorticity:**
   - Computes wind vector $\mathbf{V}_g$
   - Computes spatial gradients of this wind vector
   - Computes (non-dim.) vorticity (vector) and derivatives (e.g. SNR)

2. **Detection of Wake Vortex Encounters:**
   - **NLR method:**
     - Detection logic using threshold exceedances on vorticity magnitude & SNR, and other logic:
       - False alerts possible
       - Threshold values arbitrary
   - **In CREDOS project:**
     - Use of discriminant analysis to determine “best fit” of classification functions to discriminate at each time moment between a ‘no WVE’, a ‘probable WVE’ or a ‘WVE’
       - Parameters used are e.g. vorticity, signal-to-noise ratio SNR in these parameters, uncontrolled roll angle, etc.
Processes involved in determining the wind vector $\vec{V}_g$

\[ \vec{V}_g = \vec{V}_{inertial} - \vec{V}_{aero} \]

**FDR**
- aerodyn. data
- inertial data
- nav. data
- controls

Kalman Filter-Smoother (KFS)

- alpha calibration
- beta computation
Vorticity calculation:

- Vorticity = rotation in the flow due to a vortex nearby

- rotation estimated from:
  - wind gradients
  - linear model assumption

- vorticity: \( \vec{\gamma} = \text{rot} \vec{V}_g = \nabla \times \vec{V}_g \) = \[
\begin{pmatrix}
\frac{\partial w_g}{\partial y} - \frac{\partial v_g}{\partial z} \\
\frac{\partial u_g}{\partial z} - \frac{\partial w_g}{\partial x} \\
\frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y}
\end{pmatrix}
\]
Effect of wind gradient:

- Wind gradient may induce rolling motion

\[
\text{gradient } \frac{\partial w_g}{\partial y} \cong p_g
\]
obtaining angular gust terms:

- Rotational flow induces rolling-pitching-yawing motion:
  - The airplane’s response estimated from a linearized dynamical model:
    - Model inputs: angular gusts due to vorticity, linear gusts (i.e. wind vector) and control moments (function of control inputs)
    - Stability derivatives (the coefficients) are a function of speed and flap setting

\[ I_\chi \ddot{\chi} = L_v(v - v_g) + L_p(p - p_g) + ... + L_\delta_a \delta_a \]

- Angular acceleration
- “Linear gust”
- Angular gust due to vorticity
- Aileron control input
Basic outputs of WAVENDA:

- **Time series of the following parameters:**
  - aircraft’s position \((x, y, z)\)
  - 3 wind components \(U_w, V_w, W_w\) (runway ref. frame)
  - 3 vorticity components \(\gamma_p, \gamma_q, \gamma_r\), + derivatives (intercept angle, standardized values, magnitude, SNR, etc.)
  - WVE severity indices (control ratios (inst. + 3” averaged), uncontrolled attitudes)
  - meteo data:
    - eddy dissipation rate,
    - turbulence rms \((x,y,z)\), turbulent kinetic energy
    - temperature lapse rate, air temperature
    - Richardson’s number
  - windshear hazard factor \((F, \text{Fav})\)

- **output of WVE encounter, if detected:**
  - same parameters as above, for only the peak moment(s) where WVE is detected (multiple events are possible)
Wake vortex encounter classification using discriminant analysis

- Types of possible classification:
  - no WVE
  - probable WVE
  - WVE

- Database (landing) cases (171) from ‘S-Wake’ project classified using visual inspection of each likely candidate

- Discriminant analysis performed using prescribed set of parameters (other searches/sets are possible, e.g. step-wise):
  - non-dim. vorticity GbVa
  - abs value of d(Alpha)/dt
  - abs. value of non-dim. roll acceleration
  - abs. values of vorticity components GbVax, GbVay, GbVaz
  - abs. value of SNR_cm (central-moving avg) of 3 vorticity components
  - abs. values of SNRs_ap (a-priori moving avg) of the same 3 vorticity components
  - abs. value of uncontrolled roll rate and roll angle
Results of classification/discriminant analysis: scatter between SNR_ap & GbVa for observed & classified (comp.) WVE

- not all (landing) cases have been selected (otherwise too many ‘non-WVE’ s)
- Hit score overall 85%:
  - 78% on ‘WVE’
  - 38% on ‘prob. WVE’
  - 100% on ‘no WVE’
- a-priori SNR & GbVa alone do not give exclusiveness (more parameters are used in classification)
- many observed ‘non-WVE’ have fairly large SNRs or GbVa
Application of WAVENDA to 2 cases:
Case 1: F100 WVE during landing approach @ EHAM

- Preceding aircraft was a B747
- Roll angle upset starts at about t=65s.
- Peak roll angle upset ±8°
- Uncontrolled roll angle has high correlation with roll angle, except for magnitude (factor of 4!):
  - pilot’s reaction time of 3 sec could be reduced to get a better match
  - sensitive to proper value for derivatives (esp. roll damping Lp)
  - pilot is steering!!
Case 1 (cont’d): TKE and EDR

- TKE and EDR behave very similarly
- After 40s a rise in both as the airplane enters increasingly turbulent air
- Turbulence level starts off at ‘nil’, then becomes ‘light’, ending in near ‘moderate’

(turbulence level related to EDR values)
Case 1 (cont’d): vorticity components

- Preceding aircraft was a B747

- early in time history (\(\sim t=20s\)) there is some activity in vorticity components
  - earlier encounter of remnant of B747-vortex?

- at detected WVEs especially the roll component (GBVAX) has largest activity
  - at 2\(^{nd}\) WVE the roll vorticity is larger than for 1\(^{st}\) WVE
  - +ve roll vorticity means right-rotating vortex (i.e. from left-wing tip)
Case 1 (cont’d): vorticity and SNRcm

- early in time history (~20S) there is already much signal (high SNR), but small vorticity:

- at detected WVEs both SNR and vorticity are large(r)

![Graph showing vorticity and SNRcm](image)

- **Product of SNRcm and GbVa shows better pattern of where it really matters:**
  - at first peak there is a WVE
  - second peak was actually detected 0.25s later than shown
Case 2: A319 landing approach - Heathrow roll and uncontrolled roll angle

- At $t=170s$ the uncontrolled roll angle deviates from the roll angle itself:
  - magnitude of uncontrolled roll angle about $\pm 15^\circ$

- Roll disturbance from $+2.5^\circ$ to $-10^\circ$, occurring just after right roll/turn
Case 2 (cont’d): TKE and EDR

- WVE occurs at largest peak in EDR, at t~170s
- TKE and EDR are quite similar in trend
- Difference between TKE and EDR is mainly in the horizontal wind components (for TKE)
- Average turb. level ‘Nil’ to ‘Light’ (after t=400s)

(turbulence level connected to EDR values)
Case 2 (cont’d): vorticity components

- WVE occurs at first peak in vorticity component (y-comp. is the larger one)

- Most activities are in x- and y-components (i.e. roll and pitch)

- Beyond 400-500s the "noise" level increases, thus SNR decreases
Case 2 (cont’d): vorticity and a-priori SNR

- **vorticity magnitude:**
  - first peak at t=170s (actually two very close ones)
  - several other outlying peaks, e.g. at t=500s and 620s

- **a-priori SNR:**
  - value at interval end compared to interval
  - peak at t=170s is larger one
  - much “noise” all along the run
Case 2 (cont’d):
‘central-moving’ vs ‘a-priori’ SNR

- **central-moving SNR * GbVa (R):**
  - peak at t=170s almost the largest
  - 2 more peaks
  - between peaks only small signals

- **a-priori SNR * GbVa (L):**
  - peak at t=170s is the largest
  - peak is also larger than central-moving SNR peak (11 vs 7.0)
  - 2 more smaller peaks
  - other “signals” very small
Conclusions and outlook

- Vorticity is a good measure for detection of a WVE --- but more parameters are needed for a valid detection (no false alert or missed alert)

- WAVENDA gives 78% hit score on WVEs in the WVE database. This must be improved to e.g. 90-95%. To be achieved by (e.g.):
  - Better estimates of stability derivatives (certainly when uncontrolled attitudes are to be taken into consideration)
  - Better/different combination of (other) parameters in classification functions, which may need to be made aircraft-type specific
  - More validated WVE cases (also for take-offs) (e.g. from PIREPS and airlines or from simulations)
  - Eliminating the ‘probable WVE’ category, if possible (relatively few events) by re-visiting the WVE database

- Outlook for further developments:
  - Application of WAVENDA as part of a safety monitoring aid (e.g. assessments of WVEs before and after policy change)
  - To confirm and correlate WVEs determined by ground-based LIDAR (for turbulence investigation Hong Kong Observatory is comparing a LIDAR with outputs from a derived version of WAVENDA)
  - Support in evaluation of WVE severity criteria
  - Further (long-term) development into a real-time pattern recognition for WVE onset on-board (“early indicator”), or as quick analysis tool after the event?
Thank you!