Angle-of-Attack Estimation for Analysis of Wind Shear Encounters

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Recent studies of severe wind shear encounters involving wide-body airliners have been based on flight-path wind estimates, made by analyzing digital flight-data-recorder (DFDR) records and radar records. Such estimates require a time history of the aircraft angle of attack, a record that is not usually included in the DFDR measurement set. This paper describes a method for reconstructing angle of attack that utilizes available flight records and aircraft-specific information associated with an aerodynamic model of the lift coefficient. Results from two airliner incidents in which vane measurements of angle of attack were recorded show good agreement between measured and calculated time histories. This research has been performed in cooperation with the National Transportation Board to provide a better understanding of wind shear phenomena.

Nomenclature

a_x, a_z	= body-axis accelerations
$\bar{c}$	= mean aerodynamic chord
C_L^a, C_L^s	= lift-force coefficient
$C_L(\alpha, M)$	= lift table, untrimmed, no thrust effects
C_{L_α}	= derivative with respect to angle of attack
C_{L_δ}	= derivative with respect to elevator deflection
$C_{L_{\hat{q}}}$	= derivative with respect to normalized pitch rate
m	= aircraft mass
M	= Mach number
q	= pitch rate
$\hat{q}$	= normalized pitch rate
Q	= dynamic pressure
S	= wing area
T_x, T_z	= body-axis thrust forces
V	= true airspeed
α	= angle of attack (AOA)
δ	= elevator deflection
$\delta\alpha$	= change in angle of attack
δ_{a_z}	= change in vertical acceleration

Introduction

FOR several years Ames Research Center has been assisting the National Transportation Safety Board and the military services in its investigations of aircraft accidents. During this period, we have developed methods to determine aircraft motions along a flight path from the limited data available following an accident.[1-3] In related studies of severe wind shear encounters involving wide-body airlines, we have estimated winds along the flight path by analyzing data from the onboard digital flight-data recorder (DFDR), along with position information from en route radar sites.[4-8] A state estimation procedure is employed to reconstruct the aircraft trajectory or to estimate winds along the flight path.[9] This technique utilizes a six-degree-of-freedom model of the aircraft to generate least-square fits to all the flight records.

A measurement of aircraft angle of attack (AOA) is seldom included in any data set, even in the relatively complete set provided by a DFDR. An AOA time history is essential, however, to estimate vehicle Euler angles from radar position data or to estimate the vertical wind in a turbulence encounter. In this paper, we describe a method for calculating an AOA time history that utilizes available DFDR records and certain other information, primarily concerning the aircraft lift coefficient. The computational procedure has evolved from an earlier method for analyzing general aviation and narrow-body airliner accidents in which the only data were from air-traffic control centers and metal-foil crash recorders.[1] For the method described here, the data set is considered to come from a DFDR and contains records of aircraft attitude, acceleration, altitude, airspeed, control-surface positions, and engine parameters.

The next section of the paper outlines the computational procedure for estimating angle of attack and describes the flight records and aircraft information required to perform the calculations. An error analysis is included. A subsequent section presents results from two recent airliner incidents in which AOA measurements were recorded that permit comparisons of measured and estimated time histories. Finally, some remarks concerning the general utility of the method are presented.

AOA Computation

The calculation of angle of attack is performed by evaluating two expressions for the lift-force coefficient until equality is obtained. The first expression is an aerodynamic model for the lift coefficient, valid near cruise, given by

$$C_L^a = C_L(\alpha, M) + C_{L_\delta}\delta + C_{L_{\hat{q}}}\hat{q}, \quad \hat{q} = \bar{c}q/2V \tag{1}$$

This model requires certain aircraft-specific information, the most important of which is a set of tabular data expressing

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the lift coefficient as a function of angle of attack and Mach number, here called the lift table. (For a landing or takeoff configuration, the lift table can be specified as a function of angle of attack and flap setting.) The first term on the right side of Eq. (1) represents the lift table and can be evaluated by a two-dimensional interpolation. Next in order of importance are the lift-coefficient derivatives with respect to elevator deflection and pitch rate. The second and third terms of Eq. (1) involve these derivatives, which are considered adequate to express the contributions to lift caused by elevator deflection and pitch rate in cruise. Pitch rate is not usually measured, and must be estimated from DFDR attitude measurements.

The second expression for evaluating the lift-force coefficient is in terms of body-axis acceleration and thrust measurements and is given by

$$C_L^s = [(ma_x - T_x)\ \sin\alpha - (ma_z - T_z)\ \cos\alpha]/(QS) \tag{2}$$

Thrust is determined from tabular data relating actual thrust to the particular engine parameter recorded. However, the thrust usually has little effect on the evaluation of the lift coefficient in Eq. (2). The necessary time histories of true airspeed, Mach number, and dynamic pressure are derived from the usual air-data calculations[10] using the measurements of altitude, indicated airspeed, and air temperature included with the DFDR records.

The value of angle of attack that equates Eqs. (1) and (2) at each point in time is obtained using an iterative procedure. The algorithm, a Newton-Raphson method, is given by

$$\delta\alpha = (C_L^a - C_L^s)/[(D - QSC_{L_\alpha})/(QS)]$$

$$D = (ma_x - T_x)\ \cos\alpha + (ma_z - T_z)\ \sin\alpha \tag{3}$$

Each solution is started with the AOA value from the previous time point; after each iteration, the AOA estimate is updated by $\delta\alpha$. Convergence is generally obtained in two or three iterations. Note that C_{L_α} in Eq. (3) is evaluated as part of the lift-table interpolation.

Careful inspection of the lift-coefficient expression given in Eq. (2) reveals that the calculation of angle of attack will be sensitive to a change in vertical acceleration. A simple error analysis can be derived by taking the partial derivative of lift with respect to angle of attack and vertical acceleration and solving the result for the AOA change in terms of the acceleration change. That expression is given by

$$\delta\alpha = [m\ \cos\alpha/(D - QSC_{L_\alpha})]\delta a_z \tag{4}$$

For a typical wide-body airliner in cruise at a small angle of attack, evaluation of Eq. (4) predicts that the error in the AOA estimate will be about 0.05 deg for a 1% error in acceleration. Another source of error is the uncertainty concerning the aerodynamic model of Eq. (1) caused by incomplete knowledge of the lift table, as well as the presence of unmodeled dynamic effects. It is easy to show that the error in the AOA estimate will also be about 0.05 deg for a 1% error in the lift coefficient.

Comparison with AOA Measurements

L-1011 Incident

A recent L-1011 aircraft wind shear encounter, an incident for which AOA measurements were included with the DFDR records, provided a first opportunity to compare measured and computed AOA time histories. The aircraft was equipped with two symmetrically located, servo-positioned differential pressure AOA "vanes." Each vane was sampled at a rate of 2 Hz. The DFDR measurement records used in the calculation of angle of attack for this incident are listed in Table 1, along with their respective data sample rates. Notice that vertical acceleration is sampled at 8 Hz, faster than any other variable. Although a thrust parameter was recorded, the analysis was performed without benefit of thrust table information.

Time histories for a 30-s interval that includes a severe disturbance are shown in Figs. 1–4. The raw vane data (left and right vanes) are plotted in Fig. 1. Note that the differences in the vane records suggest the possibility of dissimilar calibrations for correcting the angle of attack. The AOA time history calculated using the method of this paper

Table 1 DFDR records and sample rates (Hz) used in AOA calculation for two incidents

Record	L-1011	B-747SP
Vertical acceleration	8	4
Lateral acceleration	4	4
Longitudinal acceleration	4	4
Roll angle	1	1
Pitch angle	1	1
Heading angle	1	1
Indicated airspeed	1	1
Pressure altitude	1	1
Air temperature	1	a
Elevator deflection	1	1
Thrust parameter	1	¼
Angle of attack	2	2

[a]Not included among DFDR records.

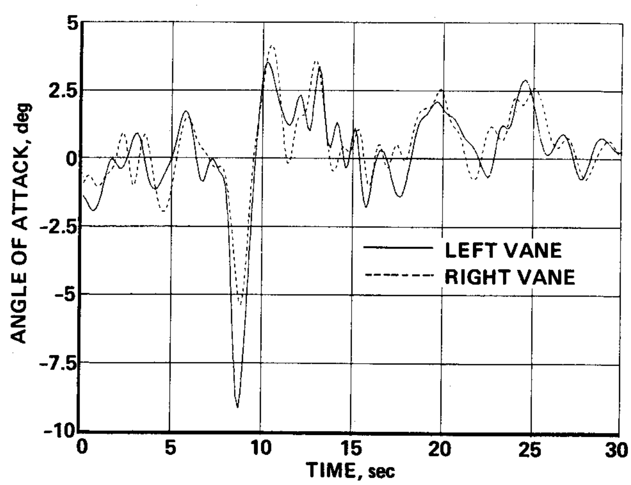

Fig. 1 Left and right vane records for L-1011 incident.

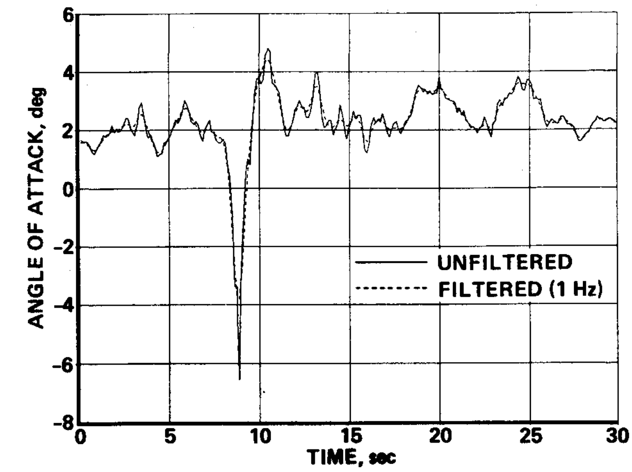

Fig. 2 Calculated angle-of-attack records for L-1011 incident.

is shown in Fig. 2. Also shown is a 1-Hz filtered version to facilitate comparison with the apparently band-limited vane records. The comparisons are shown in Figs. 3 and 4, where each vane record has been "calibrated," with bias and scale factor chosen to match the computed AOA record in a least-squared-error sense. As can be seen, the largest discrepancy (about 3 deg) occurs with the right vane (Fig. 4) during the worst "bump." Otherwise, the measured and computed records now agree quite well, although the calibrations are indeed different.

B-747SP Incident

A second opportunity for comparing measured and computed AOA records came with the acquisition of DFDR records from a B-747SP incident that occurred during a transoceanic flight. In this case, only one vane measurement was recorded, again at 2 Hz. The measurements and corresponding sample rates for the DFDR records used in the calculations of angle attack are included in Table 1. Notice that all the body accelerations are sampled at 4 Hz. Although a measurement of air temperature was not recorded by this DFDR, the temperature was available from the flight log.

Time histories for a 90-s interval having a large change in angle of attack are given in Figs. 5 and 6. Figure 5 illustrates the time histories of the thrust contribution in Eq. (2) compared to the actual lift coefficient. As might be expected, the thrust contribution is negligible. The comparison of measured and computed AOA time histories is presented in Fig. 6, where the measurement record was calibrated to match the computed record in a least-squared-error sense. Again, the agreement after calibration is quite good, with the largest discrepancy occurring during the maximum angle excursion.

Concluding Remarks

This paper has presented a method for reconstructing a time history of angle of attack using data typically recovered from a digital flight-data recorder, along with aircraft-specific performance information. Results were shown from two wide-body airliner incidents in which angle of attack had been recorded that indicate good agreement between measured and computed time histories. We note that in both incidents discussed, the wind analyses were performed using the computed AOA records, even though the vane records were available. For incidents of this type, it is often difficult to obtain reliable vane calibration data. Furthermore, the higher data rate of the vertical-acceleration record (compared to the vane record) provides an AOA time history that can better reproduce the abrupt wind changes that occur during an encounter with wind shear.

We should mention that, in general, the time histories of force coefficients derived from flight data can be quite useful

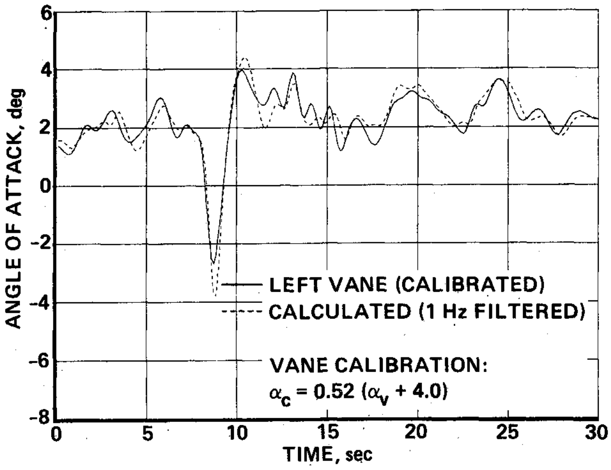

Fig. 3 Comparison of left vane and calculated angle-of-attack records for L-1011 incident.

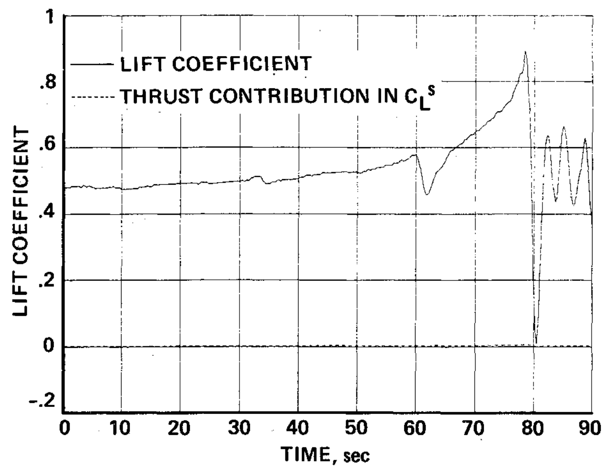

Fig. 5 Lift coefficient with its thrust component for B-747SP incident.

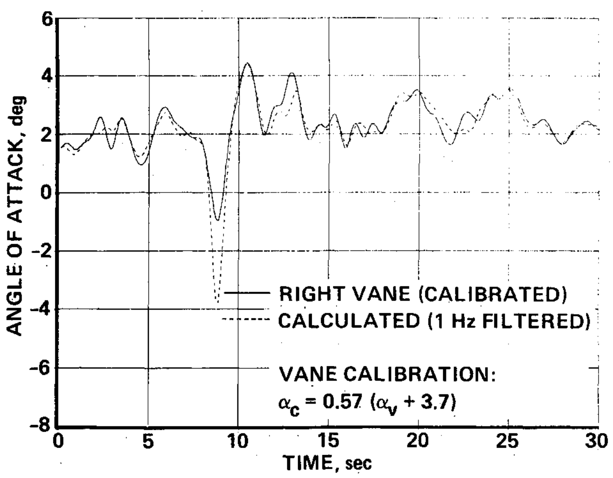

Fig. 4 Comparison of right vane and calculated angle-of-attack records for L-1011 incident.

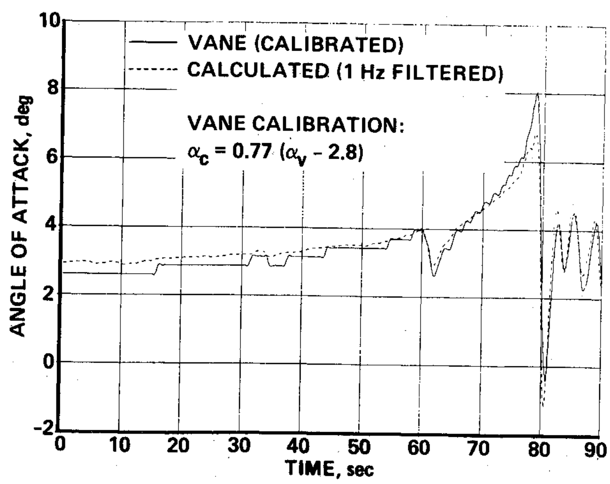

Fig. 6 Comparison of vane and calculated angle-of-attack records for B-747SP incident.

in accident investigations. In this paper, we have shown how the lift coefficient may be used to estimate angle of attack; a similar procedure can be used to reconstruct the sideslip angle from a time history of the side-force coefficient. In addition, both the lift and drag coefficients can be used to study the possibility of performance degradation that might have been caused by heavy rain or ice.

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