On the Airborne Measurement of Vertical Air Velocity

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ABSTRACT

The basic design requirements and dynamic performance evaluation techniques are discussed for a vertical air velocity system (VAVS) installed on a Learjet. An empirical technique is presented which compensates the measured angle of attack for the effects of upwash. Flight tests of the VAVS indicated dynamic errors on the order of 0.6 m s^{-1} plus 3–12% of the aircraft induced vertical velocity during maneuvers where horizontal accelerations were <0.2 m s^{-2}. Substantially larger dynamic errors were seen in the VAVS during maneuvers where the horizontal acceleration exceeded about 0.5 m s^{-2}.

1. Introduction

In a previous paper Lawson (1979) describes an airborne computer-directed system which measures vertical air velocity using a vertical gyro, vertical accelerometer, incidence vane, true airspeed and pressure measurements. The onboard computer controls engagement of the gravity erection mechanism in the vertical gyro in order to minimize the effects of local accelerations on the vertical reference.

The vertical air velocity system (VAVS) as flown on board an Aero Commander during the 1976 HIPLEX[1] was component designed to achieve a 0.5 m s^{-1} rms error band in the absence of significant local accelerations. Flight tests consisting of unaccelerated climbs, descents and gradual airspeed changes substantiated this magnitude of error. In addition, the agreement of spectral density functions measured using the VAVS and those measured by an INS air motion system during a two-aircraft formation flight was very good. However, the effects of aircraft maneuvers and atmospheric horizontal accelerations on system accuracy were not well quantified.

Here we present data from a VAVS housed in the Colorado International Corporation (CIC) Learjet which has been used as an on-top seeding and cloud physics aircraft during the 1978–79 HIPLEX programs. The Lear VAVS is identical in principal to the VAVS flown on board the Aero Commander. The two systems differ slightly on the component level, in that 1) parameters were sampled at 10 Hz by the Lear VAVS instead of at 1 Hz, 2) the Lear system measures angle of attack from a vane located slightly aft of the nose of the aircraft (Fig. 1) instead of on a nose boom, and 3) the vertical reference for the Lear VAVS is a two-gyro three-axis gravity erected system. This contribution is intended to assist users in quantifying the dynamic accuracy of this type of vertical air velocity measurement system and elucidate the design requirements for higher performance aircraft.

2. Design requirements and evaluation techniques

The measurement of vertical air velocity W is accomplished through the vector addition of the vertical velocity of the air relative to the airplane W_a and the vertical velocity of the airplane relative to the earth W_p; the reader is referred to Lawson (1979) for a discussion of the governing equations. For the Lear, the response of W_p to input frequencies higher than about 1 Hz is negligible. Therefore, any aliasing errors in the measurement of the W_a term of frequencies >1 Hz will be significant. Consequently, we sample pitch and angle of attack at 10 Hz and then average over a one second interval.

Since the Lear VAVS utilized an incidence vane located aft of the nose (Fig. 1), it was necessary to correct the measured angle of attack for the effects of upwash. In essence, this means that the measured angle of attack is corrected to better estimate the angle of attack actually seen by the aircraft wing. The corrected value is a function of measured angle of attack and airspeed. The method used to determine this function consisted of flying the aircraft in a calm atmosphere over the aircraft's operational speed range (because the Lear is a high performance jet aircraft, it is also necessary to fly at various altitudes to determine the effect of compressibility). One then plots true airspeed versus the difference between pitch and measured angle of attack to empirically determine corrected angle of attack for that particular pressure level. The procedure is then repeated at other pressure levels to establish the functional dependence on compressibility. Alternatively, airspeed may be divided by the theoretical compressibility factor ρ_0/ρ to obtain equivalent air-

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FIG. 1. Photograph of Colorado International Corporation (CIC) Learjet showing angle of attack vane (circled) and door pod with research instrumentation (behind).

speed (calibrated airspeed corrected for compressibility); however, we found that the actual flight test procedure produced more reliable results.

A simple regression technique was used to determine an empirical equation for corrected angle of attack of the form

$$\alpha = \alpha_0 - F(u,p), \tag{1}$$

where α is the corrected angle of attack at the point of measurement (deg), α_0 the uncorrected angle of attack (deg) and

$$F(u,p) = C_1u[1 - (p_0 - p)/C_2] - b,$$

where

u true airspeed (m s^{-1})
p pressure (mb)
p_0 sea level pressure (mb)
C_1 Constant (~0.063)
C_2 Constant (~4000)
b Constant (~6.4).

As seen from (1) the empirical calibration procedure adjusts the measured angle of attack for upwash as a function of airspeed and pressure, but this does not affect the overall dynamic phase response characteristics of vertical air velocity computation.

Fig. 2 shows the Lear VAVS output over an airspeed range of 100–175 m s^{-1}, using uncorrected and corrected angle of attack, for an early morning flight at 400 mb on 30 August 1979. The rms error in vertical air velocity using the corrected angle of attack in Fig. 2 and assuming a calm atmosphere is 0.6 m s^{-1}.

Other factors which change the upwash on the Lear and affect the dynamic angle of attack calibration are the application of flaps and spoilers. Currently, the Lear data system does not record flap or spoiler positions; however, with this information, calibration flights like those described above could serve to correct the angle of attack measurement for these flight conditions.

The 2-gyro 3-axis attitude and heading reference system (AHRS) used in the Lear VAVS is more

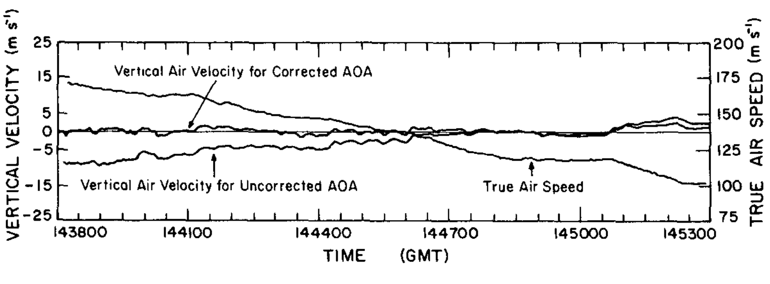

FIG. 2. Graph of true air speed (right ordinate) and VAVS computed vertical air velocity (left ordinate) for corrected and uncorrected angle of attack (AOA) on 30 July 1979.

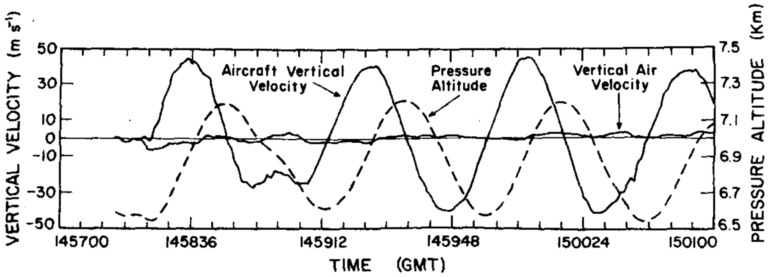

FIG. 3. Graph of pressure altitude (right ordinate), vertical velocity of the aircraft and VAVS computed vertical air velocity (both referenced to left ordinate) during porpoising maneuvers on 30 July 1979.

sophisticated and accurate than the vertical gyro which was employed in the Aero Commander. The free spinning drift rate is 0.0011° s^{-1} in the AHRS compared with 0.0042° s^{-1} for the vertical gyro. Also, the AHRS has an internal analog computer which adjusts the gyro erection rate based on longitudinal acceleration, roll and heading rates. This added degree of sophistication is necessary because of the large accelerations produced by the Lear. Even so, the Lear AHRS may introduce significant errors in verticality when subjected to rapid accelerations. A flight test on 30 July 1980 showed that longitudinal accelerations on the order of 1 m s^{-2} for 30 s (a normal "maneuvering" acceleration for cloud seeding operations with a jet) induced an error of 3° in pitch reference. This corresponds to an error of 8 m s^{-1} in vertical air velocity. In comparison, the longitudinal acceleration encountered during the flight test shown in Fig. 2 was on the order of 0.2 m s^{-2} for 30 s periods. Sustained accelerations >0.2 m s^{-2} can be avoided in normal data collection flight patterns (notwithstanding large sustained horizontal atmospheric accelerations), but are usually unavoidable when the jet maneuvers for cloud seeding runs where expedience is crucial.

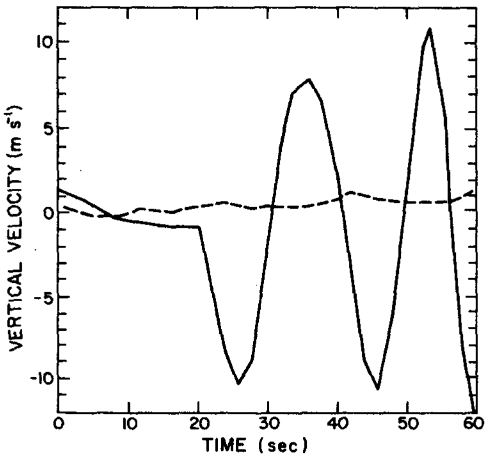

FIG. 4. Graph of aircraft vertical velocity (solid line) and output of vertical air velocity (dashed line) computed from an INS-based air motion sensing system on an NCAR Queen Air. Figure reproduced with permission of Lenschow *et al.* (1978)².

Errors in the AHRS verticality can be addressed in various ways. With knowledge of the gyro free drift rate, erection rates, the algorithms employed by the analog computer and the magnitude of the horizontal accelerations, one could theoretically compensate for the induced errors. This is a very tedious and complex computation. A simpler solution to the problem is to use a state-of-the-art AHRS (the AHRS used in the Lear uses 1965 technology) where flight test comparisons with an INS have documented rms errors in verticality of 0.3–0.4° during high acceleration maneuvers (military attack profiles). Another solution, which is less costly than the purchase of a new AHRS, is to add a high accuracy pitching rate gyro to the VAVS. The rate gyro is not gravity erected and could provide accurate relative pitch information. When used with a horizontal accelerometer, the onboard digital computer could orchestrate the pitch data such that it used the AHRS value during flight where accelerations are <0.2 m s^{-2} and the rate gyro data during high acceleration maneuvers. Since the rate gyro output must be integrated, it will eventually degrade during extended high acceleration maneuvers but these (rare) situations may be flagged by the computer. We intend to incorporate horizontal accelerometers and a rate gyro into the Lear VAVS in the near future.

The method for estimating the unaccelerated dynamic response of the Lear VAVS in straight flight consisted of flying the aircraft in a porpoising manner through an (assumed) calm atmosphere. If the atmosphere does not contribute to the vertical motion of the aircraft, then the deviation of the VAVS output from zero represents the "pilot induced" or artificial portion of the signal.

Fig. 3 is an example of the Lear VAVS data output for a test flight on 30 August 1979. In this case, the oscillations have a period of about 40 s and reach peak amplitudes of about ±45 m s^{-1}. The rms error value of the VAVS output during the porpoising maneuvers is 1.4 m s^{-1} or 3.1 % of the maximum amplitude of the pilot induced aircraft vertical velocity. However, porpoising maneuvers at lower amplitudes and higher frequencies tend to create proportionally higher induced errors. For example, a 10 m s^{-1} peak amplitude and a 10 s period produced an rms error of 12% or 1.2 m s^{-1}. For the Lear, very rapid pitching moments (periods <5 s) can induce even greater errors due to the static defect in the aircraft static system. This induces errors in the aircraft static pressure and airspeed measurements which are transferred to errors in the computation of W_a (airspeed dependent) and W_p (pressure altitude dependent through the pressure altitude feedback loop). These cumulative errors can be as large as 20–30% of the aircraft induced vertical velocity, however, these very high pitching moments are generally not encountered during normal operations. The VAVS user can generally expect rms errors in straight unaccelerated flight on the order of 3–12% of the aircraft induced vertical velocity, plus an rms offset of about 0.6 m s^{-1} (Fig. 2).

In comparison, Fig. 4 is a reproduction from Lenschow *et al.* (1978)[2] showing data from a porpoising maneuver conducted by an NCAR Queen Air equipped with a nose boom and an INS based air motion sensing system. Lenschow *et al.* indicate that the NCAR system performance is satisfactory when the vertical air velocity is $<10\%$ of the aircraft vertical velocity during ± 10 m s^{-1} porpoising maneuvers.

3. Summary

We have discussed the design requirements and error bands associated with a vertical air velocity system (VAVS) installed in a Learjet, and compared some of these features to a VAVS designed for a lower performance Aero Commander described in Lawson (1979). A technique was presented for correcting the Lear angle of attack measured from an incidence vane located aft of the nose for the effects of upwash. The corrected angle of attack is a function of measured angle of attack, pressure and airspeed. Speed runs with horizontal accelerations on the order of 0.2 m s^{-2} conducted in a calm atmosphere produced an rms error of 0.6 m s^{-1} over a range of 100–175 m s^{-1} using the corrected angle of attack value. Porpoising maneuvers in straight unaccelerated flight produced rms errors of 3.1% of a ± 45 m s^{-1} peak-to-peak aircraft induced vertical velocity and 12% of a ± 10 m s^{-1} maneuver. Therefore, users can expect rms error bands on the order of 0.6 m s^{-1} plus 3–12% of the aircraft-induced vertical velocity in straight flight under nominal horizontal accelerations (<0.2 m s^{-2}). This performance was shown to compare very well with similar dynamic flight tests conducted by an INS-based air motion sensing system on an NCAR Queenair.

Larger errors are introduced into the VAVS during high acceleration maneuvers and turning flight, e.g., when the Lear is positioning for a cloud-seeding run. These larger dynamic errors are primarily associated with the 1965 vintage attitude and heading reference system (AHRS) currently being used on the Lear; a state-of-the-art AHRS could nearly eliminate the larger dynamic errors. Another alternative is the incorporation of a pitch rate gyro which could supply good short-term pitch information during high acceleration maneuvers.

Data from the Lear VAVS presented here and the VAVS described in Lawson (1979) imply that the system concept is applicable to different aircraft over a wide performance range. However, the system design and component selection must be commensurate with aircraft application and performance.

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