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SOME IMPLICATIONS OF THE ISOTROPIC MOMENTARILY FROZEN ASSUMPTIONS FOR THE SPAN-MAT PROGRAM

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ABSTRACT

Potential tests using turbulence velocity histories measured in the SPAN-MAT program are outlined to determine validity of the homogeneous, momentarily frozen assumptions for the vertical turbulence velocity component and the homogeneous, isotropic, momentarily frozen assumptions for the horizontal turbulence velocity components. In addition, methods are reviewed for prediction of the crosscorrelation function between any two spatially separated turbulence velocity components using the homogeneous, isotropic, momentarily frozen assumptions and measurements of the transverse and longitudinal turbulence velocity components.

INTRODUCTION

This memorandum outlines potential tests using turbulence velocity histories measured in the SPAN-MAT program to determine validity of the homogeneous, momentarily frozen assumptions for the vertical turbulence component and the homogeneous, isotropic, momentarily frozen assumptions for the horizontal turbulence components. In addition, methods are reviewed for prediction of the crosscorrelation function between any two spatially separated turbulence components using the homogeneous, isotropic, momentarily frozen assumptions and measurements of the longitudinal and transverse turbulence components made using a single probe.

Turbulence measurements are being carried out in the SPAN-MAT program using a B57-B aircraft equipped with probes at three separate locations. There is a nose probe and a probe located under each wing tip on a pylon designed to accept fuel pods. The wing-tip probes are about 60 feet apart. All three probes lie approximately in the same (horizontal) plane. The nose probe is substantially forward of the two wing-tip probes. The probe configuration is illustrated in Figure 1, where the two wing-tip probes are labeled a and c, and the nose probe is labeled b. Each probe is capable of measuring three components of turbulence velocities: the forward component u, lateral component v, and vertical component w.

The directions of the turbulence velocity components u, v, and w are oriented with respect to the direction and position of the measurement aircraft flight path. In describing turbulence correlation measurements, one also must be concerned with the orientation of the straight line connecting the positions of the two measurement points relative to the direction of the turbulence velocity vector of the component of turbulence being measured. In this memorandum, two such components are dealt

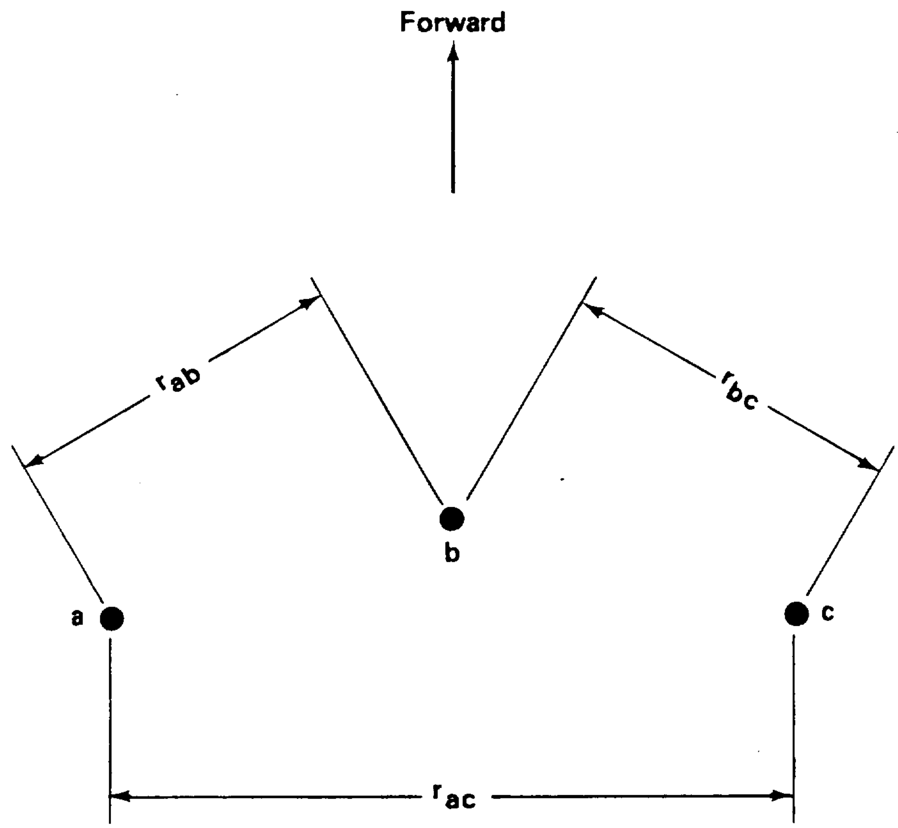

Fig.1. Probe positions located on the aircraft in an approximately horizontal plane.

with: the longitudinal and transverse velocity components. The directions of these two components relative to the two measurement locations are illustrated in Figure 2.

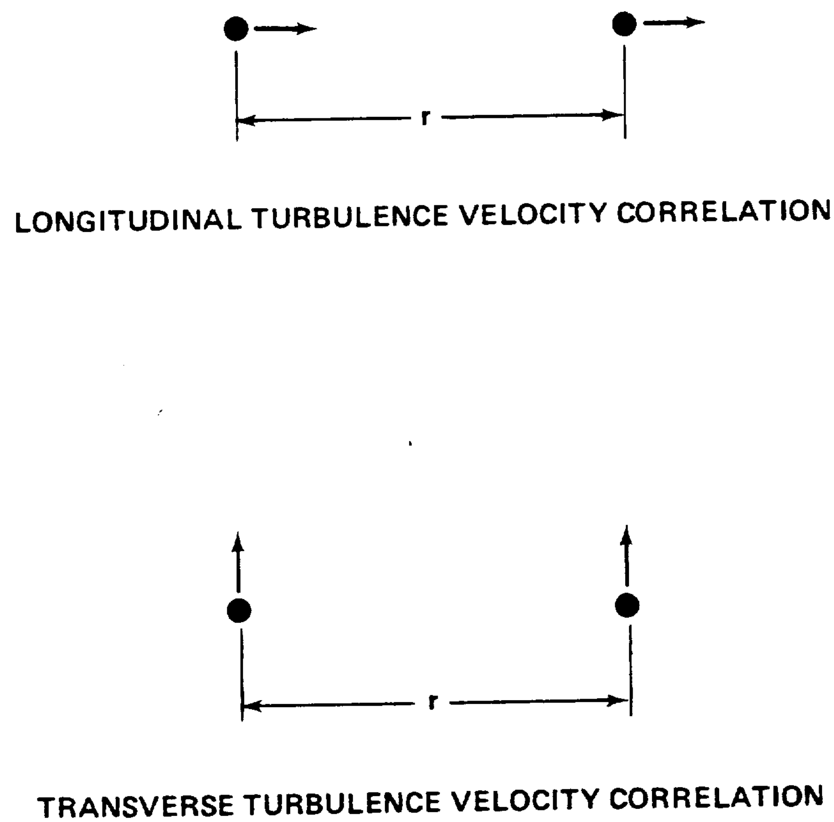

Fig. 2. Longitudinal and transverse turbulence velocity correlations.

TESTS OF HOMOGENEOUS MOMENTARILY FROZEN HYPOTHESIS FOR THE VERTICAL (TRANSVERSE) TURBULENCE COMPONENT

On physical grounds, we would expect the vertical component of atmospheric turbulence to be statistically spatially homogeneous over areas in a horizontal plane large in comparison with the dimensions of an aircraft. The simplest test of such spatial homogeneity of the vertical turbulence component is to measure and compare the autocorrelation functions of the vertical turbulence component obtained from each of the three SPAN-MAT probes. In reality, such a comparison probably is more of a test of the uniformity of the probes and associated electronics than it is of spatial homogeneity. In particular, the rms velocities of the vertical turbulence components obtained from each of the three probes should be compared.

A second simple test employs both the spatially homogeneous assumption and the momentarily frozen assumption (Taylor's hypothesis). Denote by angular brackets $\langle\cdots\rangle$ a long time average; i.e.,

$$\langle f(t)\rangle \overset{\Delta}{=} \frac{1}{T}\int_{t'}^{t'+T} f(t)dt \ , \tag{1}$$

which for very large T is independent of both t' and T if f(t) is a stationary random function. Denote the vertical turbulence component measured at each of the three probes a, b, and c in Figure 1 by w_a, w_b, and w_c, respectively. Denote the distances between probes a and b, b and c, and a and c by r_{ab}, r_{bc}, and r_{ac}, respectively. Denote the autocorrelation function of the vertical turbulence component as a function of a generic spatial separation r in a horizontal plane by $R_{ww}(r)$. Then, if the vertical turbulence component is assumed spatially homogeneous in a horizontal plane, we have

$$R_{ww}(r_{ab}) = \langle w_a(t)w_b(t)\rangle \ , \tag{2}$$

$$R_{ww}(r_{bc}) = \langle w_b(t)w_c(t)\rangle \ , \tag{3}$$

and

$$R_{ww}(r_{ac}) = \langle w_a(t)w_c(t)\rangle \ . \tag{4}$$

Denote the aircraft speed by V. Furthermore, if the spatial homogeneity and momentarily frozen assumptions are both employed, we also have

$$R_{ww}(r_{ab}) = \langle w_a(t)w_a(t+\tau_{ab})\rangle \ , \qquad \tau_{ab} \triangleq r_{ab}/V \tag{5}$$

$$R_{ww}(r_{bc}) = \langle w_a(t)w_a(t+\tau_{bc})\rangle \ , \qquad \tau_{bc} \triangleq r_{bc}/V \tag{6}$$

and

$$R_{ww}(r_{ac}) = \langle w_a(t)w_a(t+\tau_{ac})\rangle \ , \qquad \tau_{ac} \triangleq r_{ac}/V \ . \tag{7}$$

Each of the relations (5) through (7) describes the autocorrelation function of the vertical turbulence component measured at the <u>same</u> sensor "a" at a time delay τ computed from the aircraft speed V and the distance r between two of the sensors. Sets of relations analogous to equations (5) through (7) can be written by replacing each w_a by w_b or w_c.

The homogeneous and momentarily frozen assumptions of the vertical turbulence component can be tested by comparing the crosscorrelation measurements described by the right-hand sides of equations (2), (3), and (4) with the autocorrelation measurements described by the right-hand sides of equations (5), (6), and (7), respectively.

The above test can be generalized using the method suggested in Figure 3. Employing the homogeneous and momentarily frozen assumptions, for any value of r_a, we have

$$R_{ww}(r_a) = \langle w_a(t)w_a(t+\tau_a)\rangle \tag{8a}$$

$$= \langle w_b(t)w_b(t+\tau_a)\rangle \tag{8b}$$

$$= \langle w_c(t)w_c(t+\tau_a)\rangle \ , \tag{8c}$$

where

$$\tau_a \triangleq r_a/V \ . \tag{9}$$

Furthermore, for any value of $r_a > r_{ac}$, we also have

$$R_{ww}(r_a) = \langle w_a(t)w_c(t+\tau_a')\rangle \ , \tag{10}$$

where from Figure 2, it follows that

$$r_a^{\ 2} = r_{ac}^{\ 2} + V^2(\tau_a')^2$$

or

$$\tau_a' = \left(\frac{r_a^{\ 2} - r_{ac}^{\ 2}}{V^2}\right)^{1/2} \ , \ r_a > r_{ac} \ . \tag{11}$$

If the homogeneous and momentarily frozen assumptions are satisfied by the vertical turbulence component, for any value of $r_a > r_{ac}$, the autocorrelation function computed by the right-hand side of equation (8a), (8b), or (8c) with τ_a given by equation (9) should equal the crosscorrelation function computed by equation (10) with τ_a' is given by equation (11).

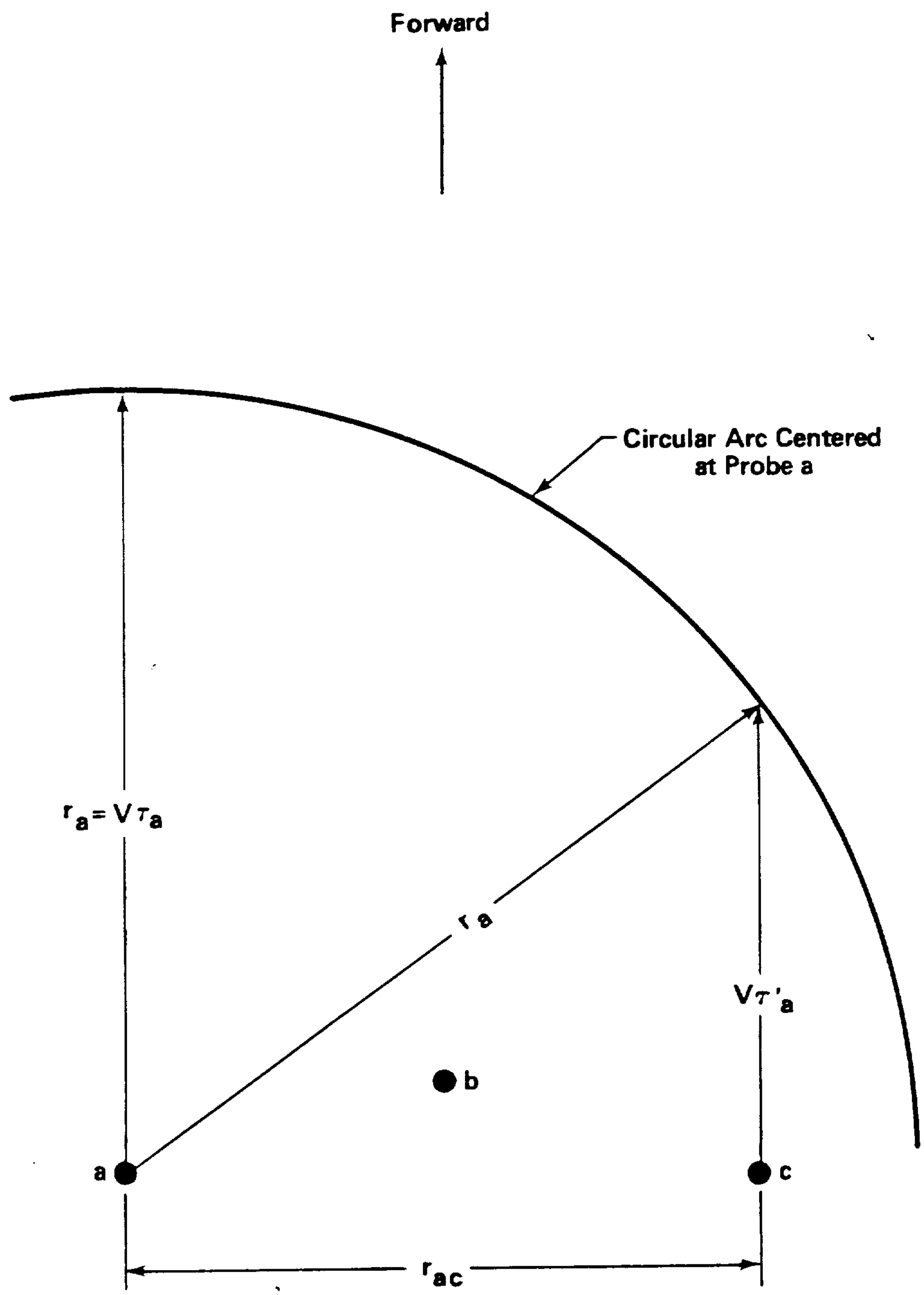

Fig. 3. Temporal delays τ_a and τ'_a for testing the homogeneous and momentarily frozen assumptions for the vertical (transverse) turbulence component.

TESTS OF ISOTROPIC MOMENTARILY FROZEN HYPOTHESIS FOR THE HORIZONTAL (LONGITUDINAL AND TRANSVERSE) TURBULENCE COMPONENTS

Homogeneity in the horizontal plane requires that the "forward" turbulence velocity component u pointing in the direction of aircraft motion have the same statistical properties at each of the three probe locations a, b, and c. In particular, this assumption implies that each of these three measurements $u_a(t)$, $u_b(t)$, and $u_c(t)$ possess the same autocorrelation function. Homogeneity also implies that each of the lateral components $v_a(t)$, $v_b(t)$, and $v_c(t)$ also possess the same autocorrelation function, which generally will differ from that of the u's.

Furthermore, isotropy in the horizontal plane requires directional independence of the character of the turbulence. In particular, isotropy requires that $\langle u_a^2(t)\rangle = \langle v_a^2(t)\rangle$ with analogous relations for the other two probes b and c.

The configuration of the probes permits other tests of isotropy in the horizontal plane utilizing the momentarily frozen assumption. The autocorrelation function $R_{LL}(r_{ac})$ of the longitudinal turbulence component with spatial lag r_{ac} can be evaluated directly from the lateral turbulence velocities $v_a(t)$ and $v_c(t)$ illustrated in Figure 4 by

$$R_{LL}(r_{ac}) = \langle v_a(t) v_c(t)\rangle \ . \tag{12}$$

Furthermore, utilizing the isotropic and momentarily frozen assumptions, $R_{LL}(r_{ac})$ also can be evaluated from the forward turbulence component at any of the three probes, as illustrated in Figure 4 for the middle probe b; i.e.,

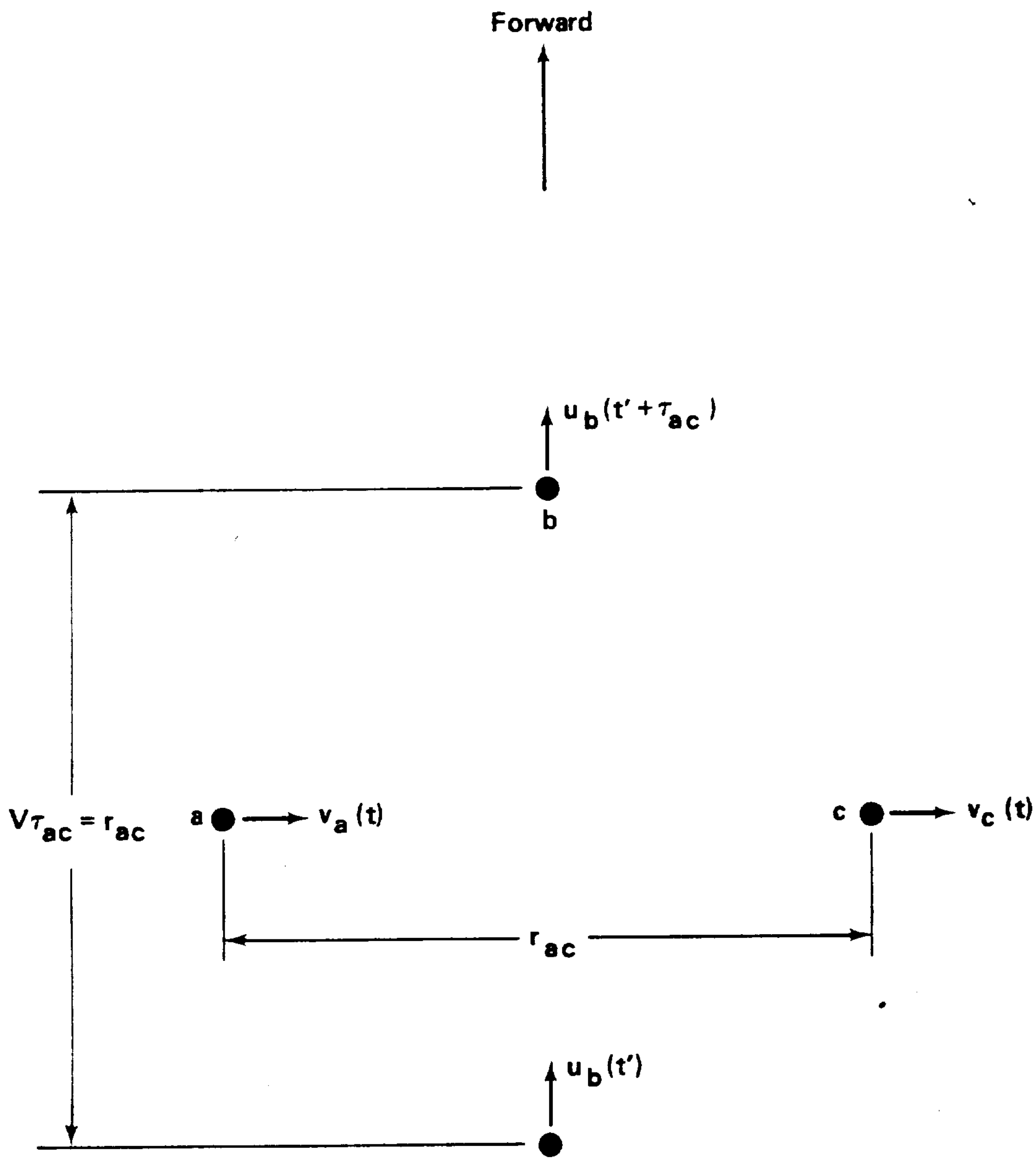

Fig. 4. Configuration for testing isotropic and momentarily frozen assumptions for the longitudinal turbulence component in the horizontal plane.

$$R_{LL}(r_{ac}) = \langle u_b(t)u_b(t+\tau_{ac})\rangle \tag{13a}$$

$$= \langle u_a(t)u_a(t+\tau_{ac})\rangle \tag{13b}$$

$$= \langle u_c(t)u_c(t+\tau_{ac})\rangle \ , \tag{13c}$$

where

$$\tau_{ac} \triangleq r_{ac}/V \ . \tag{14}$$

Thus, the isotropic and momentarily frozen assumptions in the horizontal plane can be tested by comparing experimental measurements described by the right-hand side of equation (12) with those described by the right-hand sides of equations (13a), (13b), or (13c).

A similar set of relations can be written for the autocorrelation function of the transverse or normal turbulence component as illustrated in Figure 5. For the autocorrelation function of the transverse turbulence component $R_{NN}(r_{ac})$ evaluated at the spatial lag r_{ac}, we have from Figure 5,

$$R_{NN}(r_{ac}) = \langle u_a(t)u_c(t)\rangle \ , \tag{15}$$

which involves the forward turbulence components measured at a and c with no temporal lag. From Figure 5, we also see that

$$R_{NN}(r_{ac}) = \langle v_b(t)v_b(t+\tau_{ac})\rangle \tag{16a}$$

$$= \langle v_a(t)v_a(t+\tau_{ac})\rangle \tag{16b}$$

$$= \langle v_c(t)v_c(t+\tau_{ac})\rangle \ , \tag{16c}$$

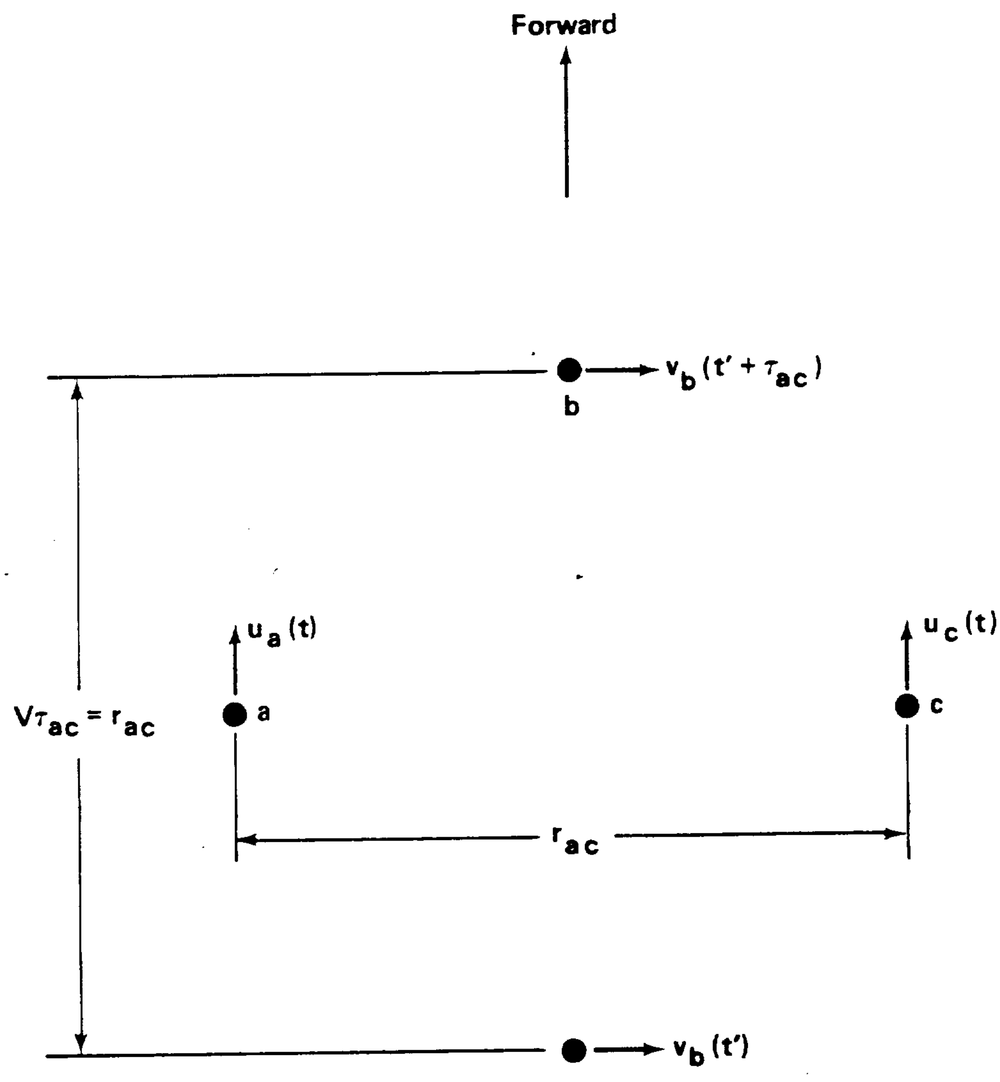

Fig. 5. Configuration for testing isotropic and momentarily frozen assumptions for the transverse turbulence component in the horizontal plane.

where τ_{ac} is given by equation (14). Each of the equations (16) employs the momentarily frozen assumption. Isotropy and homogeneity in the horizontal plane require that turbulence measurements described by the right-hand side of equation (15) equal to those described by each of equations (16a), (16b), and (16c).

The assumptions of homogeneity and isotropy, and the momentarily frozen assumption, all in the horizontal plane, imply certain other relations among correlation measurements of the forward and lateral turbulence components. First, we note that the longitudinal and transverse autocorrelation functions $R_{LL}(r)$ and $R_{NN}(r)$, respectively, can be measured for any value of r from the forward and lateral turbulence components, u(t) and v(t), of any probe. For example, using probe b, we have

$$R_{LL}(r) = \langle u_b(t)u_b(t+\tau)\rangle \ , \qquad \tau = r/V \tag{17}$$

and

$$R_{NN}(r) = \langle v_b(t)v_b(t+\tau)\rangle \ , \qquad \tau = r/V \ , \tag{18}$$

where Figure 4 is helpful in understanding equation (17) and Figure 5 is helpful in understanding equation (18). Using $R_{LL}(r)$ and $R_{NN}(r)$, obtained as above, together with the homogeneous, isotropic, and momentarily frozen assumptions, crosscorrelation functions of the various turbulence components can be predicted to compare with their measured values. For example, using a well-known relationship [1], we have for the crosscorrelation functions of the forward component u and the lateral component v, at probe locations a and c, respectively,

$$R_{u_a u_c}(r) = [R_{LL}(r) - R_{NN}(r)] \frac{r_c^2}{r^2} + R_{NN}(r)$$

$$= \frac{r_c^2}{r^2} R_{LL}(r) + \left(1 - \frac{r_c^2}{r^2}\right) R_{NN}(r)$$

$$= \frac{r_c^2}{r^2} R_{LL}(r) + \frac{r_{ac}^2}{r^2} R_{NN}(r) \tag{19}$$

$$R_{v_a v_c}(r) = [R_{LL}(r) - R_{NN}(r)] \frac{r_{ac}^2}{r^2} + R_{NN}(r)$$

$$= \frac{r_{ac}^2}{r^2} R_{LL}(r) + \left(1 - \frac{r_{ac}^2}{r^2}\right) R_{NN}(r)$$

$$= \frac{r_{ac}^2}{r^2} R_{LL}(r) + \frac{r_c^2}{r^2} R_{NN}(r) , \tag{20}$$

and

$$R_{u_a v_c}(r) = [R_{LL}(r) - R_{NN}(r)] \frac{r_c r_{ac}}{r^2} , \tag{21}$$

where the turbulence components and relevant geometry are illustrated in Figure 6. There is a temporal delay of the measurements u_c and v_c relative to the measurements u_a and v_a by the amount

$$\tau_c = \frac{r_c}{V} = \frac{(r^2 - r_{ac}^2)^{1/2}}{V} , \tag{22}$$

which follows directly from Figure 6.

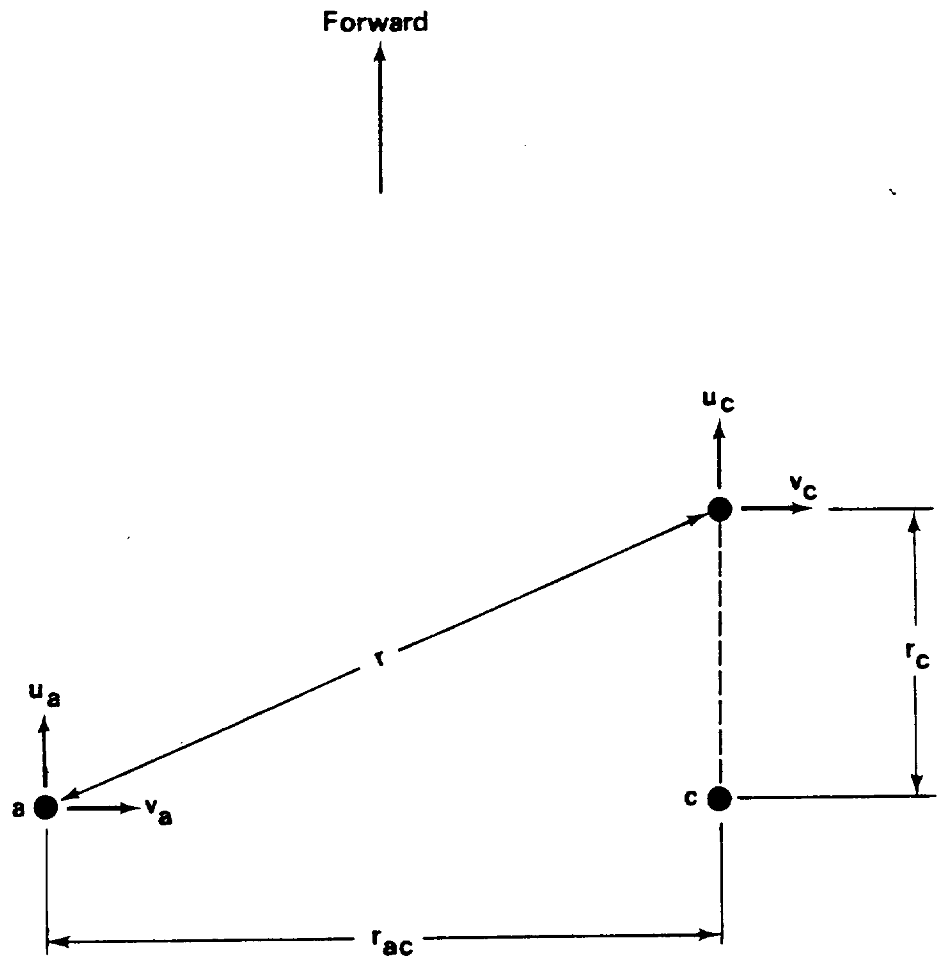

Fig. 6. Configuration for testing isotropic and momentarily frozen assumptions for turbulence velocity components in the horizontal plane.

Using measurements of $R_{LL}(r)$ and $R_{NN}(r)$ obtained as in equations (17) and (18), the crosscorrelation functions $R_{u_a u_c}(r)$, $R_{v_a v_c}(r)$, and $R_{u_a v_c}(r)$ can be predicted by equations (19) through (21), respectively, for any value of $r > r_{ac}$. These predictions can be then compared with direct measurements of these crosscorrelation functions to test the homogeneous, istropic, momentarily frozen assumption, where the direct crosscorrelation measurements are

$$R_{u_a u_c}(r) = \langle u_a(t) u_c(t+\tau_c) \rangle , \tag{23}$$

$$R_{v_a v_c}(r) = \langle v_a(t) v_c(t+\tau_c) \rangle , \tag{24}$$

and

$$R_{u_a v_c}(r) = \langle u_a(t) v_c(t+\tau_c) \rangle , \tag{25}$$

where τ_c is given by equation (22).

An alternative to the above approach is to use equations (19) and (20) to solve for $R_{LL}(r)$ and $R_{NN}(r)$ in terms of $R_{u_a u_c}(r)$ and $R_{v_a v_c}(r)$. The result is:

$$R_{LL}(r) = \frac{r_c^2 \, R_{u_a u_c}(r) - r_{ac}^2 \, R_{v_a v_c}(r)}{r_c^2 - r_{ac}^2} , \tag{26}$$

and

$$R_{NN}(r) = \frac{r_c^2 \, R_{v_a v_c}(r) - r_{ac}^2 \, R_{u_a u_c}(r)}{r_c^2 - r_{ac}^2} , \tag{27}$$

provided that $r_c \neq r_{ac}$. The values of $R_{LL}(r)$ and $R_{NN}(r)$ for $r > r_{ac}$ predicted by equations (26) and (27) from the cross-correlation measurements (23) and (24) then can be compared with the values of $R_{LL}(r)$ and $R_{NN}(r)$ measured as in equations (17) and (18). However, this latter procedure might be somewhat ill-conditioned [2].

PREDICTION OF CROSSCORRELATION FUNCTION BETWEEN ANY PAIR OF TURBULENCE COMPONENTS

When the homogeneous, isotropic, and momentarily frozen assumptions are employed, it is possible to predict the crosscorrelation function between any pair of spatially separated turbulence velocity components from the longitudinal and transverse autocorrelation functions $R_{LL}(r)$ and $R_{NN}(r)$, respectively, measured at a single probe location. Let us define, for any spatial location, the three turbulence velocity components by

$$u_1 = u \;, \quad u_2 = v, \quad u_3 = w \tag{28}$$

where u is the forward component, v is the lateral component, and w is the vertical component. Let $\underset{\sim}{x}$ denote a given location in a 3-dimensional frozen turbulence field, and $\underset{\sim}{x} + \underset{\sim}{r}$ denote a second location in the field, where $\underset{\sim}{r}$ is the 3-dimensional vector connecting the two locations. Let r denote the length of the vector $\underset{\sim}{r}$; i.e.,

$$r \triangleq \sqrt{r_1^2 + r_2^2 + r_3^2} \;, \tag{29}$$

where r_1 is the component of the vector $\underset{\sim}{r}$ in the $u_1 = u =$ forward direction; r_2 is the component of $\underset{\sim}{r}$ in the $u_2 = v =$ lateral direction; and, r_3 is the component of $\underset{\sim}{r}$ in the $u_3 = w =$ vertical direction. Let

$$R_{j\ell}(\underset{\sim}{r}) \triangleq \langle u_j(\underset{\sim}{x}) \; u_\ell(\underset{\sim}{x}+\underset{\sim}{r})\rangle \tag{30}$$

denote the crosscorrelation function between any two turbulence velocity components $u_j(\underset{\sim}{x})$ and $u_\ell(\underset{\sim}{x}+\underset{\sim}{r})$ at the above-mentioned two locations. For example,

$$R_{12}(\underset{\sim}{r}) = \langle u(\underset{\sim}{x})\ v(\underset{\sim}{x}+\underset{\sim}{r})\rangle \tag{31}$$

is the crosscorrelation function of the forward turublence velocity component u at location $\underset{\sim}{x}$ and the lateral turbulence velocity component v at location $\underset{\sim}{x}+\underset{\sim}{r}$. Similarly,

$$R_{33}(\underset{\sim}{r}) = \langle w(\underset{\sim}{x})\ w(\underset{\sim}{x}+\underset{\sim}{r})\rangle \tag{32}$$

is the crosscorrelation function of the vertical turbulence velocity component at location $\underset{\sim}{x}$ and location $\underset{\sim}{x}+\underset{\sim}{r}$.

The general form [1] expressing $R_{j\ell}(\underset{\sim}{r})$ in terms of the longitudinal and transverse turbulence velocity autocorrelation functions is

$$R_{j\ell}(\underset{\sim}{r}) = [R_{LL}(r) - R_{NN}(r)]\,\frac{r_j r_\ell}{r^2} + R_{NN}(r)\ \delta_{j\ell}\ , \tag{33}$$

where the distance r is defined by equation (29), r_j and r_ℓ; j,ℓ = 1,2, or 3 are described in the text following equation (29); and, $\delta_{j\ell}$ is Kronecker's delta; i.e.,

$$\delta_{j\ell} = \begin{cases} 1, & j = \ell \\ 0, & j \neq \ell \end{cases} \ . \tag{34}$$

The geometry relevant to equation (33) is sketched in Figure 7.

When both components j and ℓ in equation (33) represent the vertical component $u_3 = w$, we have $j = \ell = 3$; hence, $\delta_{j\ell} = 1$. When the positions $\underset{\sim}{x}$ and $\underset{\sim}{x}+\underset{\sim}{r}$ of both vertical components lie in the horizontal plane (normal to the direction of $u_3 = w$), we have $r_j = r_\ell = r_3 = 0$. In this case, equation (33) reduces to

$$R_{33}(\underset{\sim}{r}) \equiv R_{ww}(\underset{\sim}{r}) = R_{NN}(r)\ , \tag{35}$$

which is the case discussed in equations (8) and (10).

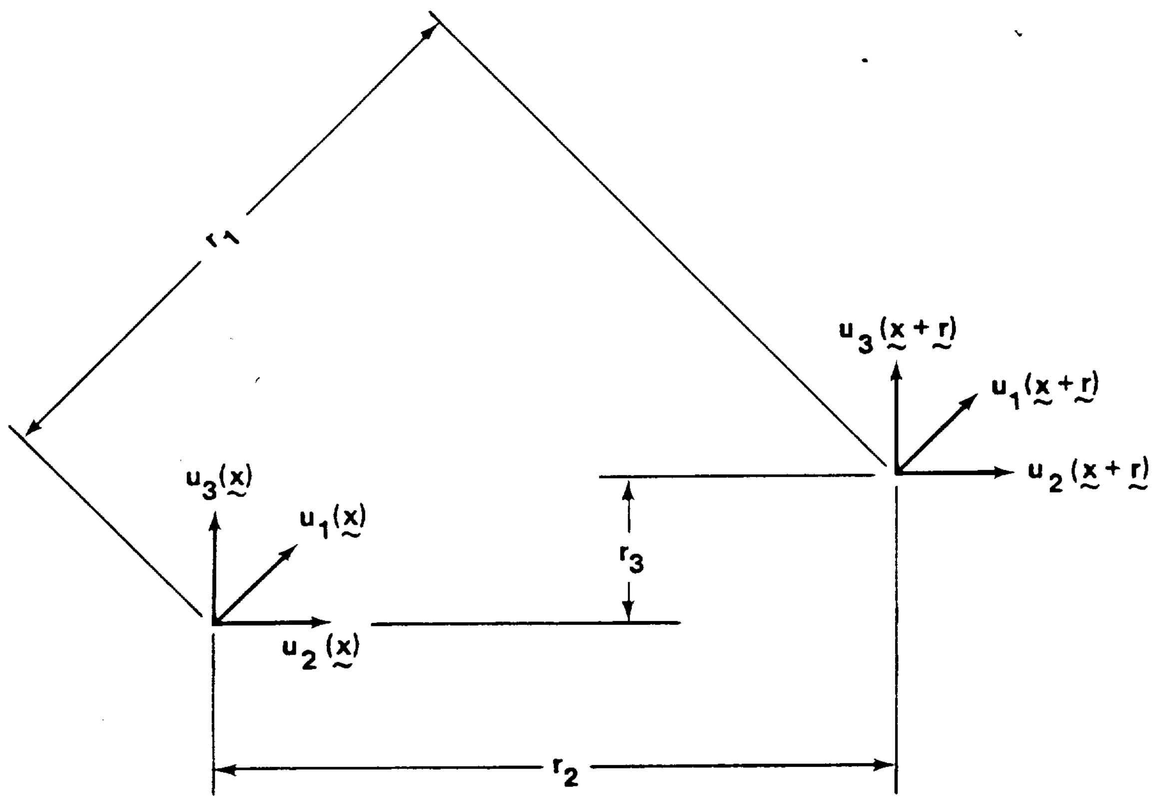

Fig. 7. Geometry required for understanding equation (33).

When j and ℓ in equation (33) both represent the forward component $u_1 = u$; i.e., $j = \ell = 1$, we also have $\delta_{j\ell} = 1$, and $r_j = r_\ell = r_1$. In this case, equation (33) reduces to

$$R_{11}(\underset{\sim}{r}) \equiv R_{uu}(\underset{\sim}{r}) = \left[R_{LL}(r) - R_{NN}(r)\right] \frac{r_1{}^2}{r^2} + R_{NN}(r) \ , \qquad (36)$$

which is the same as the first line in equation (19) when r_1 is set equal to r_c.

Similarly, when j and ℓ in equation (33) represent the lateral component $u_2 = v$; i.e., $j = \ell = 2$, then $\delta_{j\ell} = 1$ and $r_j = r_\ell = r_2$. In this case, equation (33) becomes

$$R_{22}(\underset{\sim}{r}) = R_{vv}(\underset{\sim}{r}) = \left[R_{LL}(r) - R_{NN}(r)\right] \frac{r_2{}^2}{r^2} + R_{NN}(r) \ , \qquad (37)$$

which is the same as the first line in equation (20) when r_2 is set to r_{ac}. When $j = 1$ and $\ell = 2$, we have $\delta_{j\ell} = 0$, and equation (33) reduces to

$$R_{12}(\underset{\sim}{r}) \equiv R_{uv}(\underset{\sim}{r}) = \left[R_{LL}(r) - R_{NN}(r)\right] \frac{r_1 r_2}{r^2} \ , \qquad (38)$$

which is the same as equation (21) when $r_1 = r_c$ and $r_2 = r_{ac}$.

The SPAN-MAT configuration allows the longitudinal autocorrelation function $R_{LL}(r)$ to be measured at each of the three probes using the forward turbulence velocity component u; i.e.,

$$R_{LL}(r) = R_{uu}(r) = \langle u(t)u(t+\tau)\rangle \ , \qquad \tau = r/V \qquad (39)$$

where V is the aircraft speed, and both $u(t)$ and $u(t+\tau)$ are measured at the same probe. The transverse autocorrelation function $R_{NN}(r)$ can be measured using the lateral turbulence velocity component $v(t)$ at any of the probes; i.e.,

$$R_{NN}(r) = R_{vv}(r) = \langle v(t)v(t+\tau)\rangle, \quad \tau = r/V \tag{40}$$

or using the vertical turbulence velocity component $w(t)$ at any of the probes

$$R_{NN}(r) = R_{ww}(r) = \langle w(t)w(t+\tau)\rangle \ , \quad \tau = r/V \tag{41}$$

where both $v(t)$ and $v(t+\tau)$ in equation (40) are measured at the same probe, and both $w(t)$ and $w(t+\tau)$ in equation (41) are measured at the same probe.

When one or both of the two components j or ℓ in equation (33) represents either v or w, but not j representing v, and ℓ representing w, or j representing w and ℓ representing v, either the measurement (40) or (41) should be used depending on which component (v or w) is represented in equation (33). When j represents v and ℓ represents w, or j represents w and ℓ represents v, then judgement will have to be used as to which of the two measurements, equation (40) or equation (41), should be used to represent $R_{NN}(r)$ in equation (33).

To express equation (33) as a crosscorrelation function with temporal (rather than spatial) lag, Taylor's hypothesis must be used for the particular geometric configuration of interest. For the configuration where both $\underset{\sim}{x}$ and $\underset{\sim}{x}+\underset{\sim}{r}$ are in the horizontal plane on a line normal to the fuselage centerline, the transformation to temporal lag becomes

$$r_1 = V\tau \ , \tag{42}$$

where V is the aircraft speed and τ is the temporal lag. The cross-spectrum of the two turbulence velocity components is obtained by forming the Fourier transform of equation (33) with respect to τ after employing Taylor's hypothesis as in equation (42).

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16. Abstract

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