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EVALUATION OF THE DIRECTIONAL BIAS IN THE M.S.C. TYPE 45B WIND SYSTEM

Instrument Research and Development Report No. 8

by

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ABSTRACT

Preliminary evaluation of the directional bias in the M.S.C. Type 45B wind system shows that the percentage frequency distribution of wind direction is biased toward the intermediate (non-cardinal) wind directions. The analytical evaluation suggests that this bias is due to the relatively long time interval during which the wind direction is sampled. The magnitude of the directional bias is found to be a function of wind speed, stability, and surface roughness. The analysis of the observational data reveals that for most practical purposes the bias toward the intermediate directions may be removed by the use of a pulse-limiter.

Furthermore, some evidence is given to suggest that there is a secondary bias, directed toward cardinal wind directions, resulting from the uneven brush-commutator contact. Laboratory tests indicate that the magnitude of the secondary bias is a complex function of time over which the anemometer was used and of the anemometer's initial conditions. It is shown that the secondary bias can be significant when the non-cardinal bias is reduced, and further work remains to be done to reduce it to acceptable limits.

ÉVALUATION DE LA DÉVIATION DANS LE SYSTÈME DE MESURE DES VENTS M.S.C. DE TYPE 45B

Rapport n^{o} sur la recherche et le perfectionnement des instruments

par

Oscar Koren

RÉSUMÉ

Une première évaluation de la déviation directionnelle dans le système de mesure des vents M.S.C. de type 45B indique que la distribution, en pourcentage, de fréquence de la direction du vent donne une fréquence trop forte pour les directions intermédiaires (non-cardinales). L'évaluation analytique montre que la deviation est causée par la durée élevée de la mesure de la direction des vents. On a trouvé que l'amplitude de la déviation directionnelle est fonction de la vitesse du vent, de la stabilité de l'appareil et des accidents de terrain. L'analyse des données d'observation révèle qu'à toutes fins pratiques la déviation vers les directions intermediaires peut être supprimée par l'emploi d'un limiteur d'impulsions.

De plus, il semble qu'il y ait une déviation secondaire vers les directions cardinales causée par le contact irrégulier des balais et de la commutatrice. Les essais en laboratoire indiquent que l'amplitude de la déviation secondaire est une fonction complexe de la durée d'emploi de l'anémomètre et de l'état initial de l'appareil, que la déviation secondaire est importante quand la déviation non-cardinale est corrigée et qu'il reste beaucoup à faire pour la ramener dans des limites acceptables.

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1. INTRODUCTION

Recent analyses of the wind data obtained from four M.S.C. Type 45B anemometers at Halifax International Airport[1] showed that there was a strong bias in the wind direction data toward the intermediate (non-cardinal) directions. It was suggested that the directional bias may be due to the peculiarities of the M.S.C. Type 45B wind system. Consequently, it was decided to evaluate the performance of the Type 45B system and to investigate the factors which may contribute to the directional bias.

The problem concerning the directional bias in the data obtained by the Type 45B system is not new. Clink[2] (1970) reported that the Type 45B anemometer had to be modified because of the directional bias when it was adopted for use at the Suffield Experimental Station, Alberta during the early 1950's. It was concluded from the Suffield measurements that the bias was related to the time interval during which the one-mile contact was closed and to the distance between the brushes. Consequently, the Suffield anemometer was modified by replacing the brush system with a CAM operated microswitch system which gave an instantaneous readout.

Middleton and Spilhaus (1953) suggested that the distance between the brushes should be such that the angle subtended at the shaft center by the outside tangents to the brushes is equal to 45 degrees plus that corresponding to the width of the slot between each pair of the four commutator plates.

Wiggins[3] (1956) showed by actual calculations, using the Type 45B measurements, that the inter-brush angle suggested by Middleton and Spilhaus (1953) was correct assuming that the entire face of the brush was in contact with the commutator. As a result of Wiggin's calculations, in 1965 the angle subtended by the outside tangents to the brushes, in the Type 45B anemometer, was changed from the previous value of 47°40′ to a new value of 47°22′.

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[1] Reference: Memorandum 6752-1640 (MBCR), dated, Aug. 14, 1970.

[2] W.L. Clink: "Factors in the Design of the Brush Plate in the M.S.C. Type 45B Anemometer". Instrument Division Memorandum 5992-1 (MBIR), dated, Aug. 7, 1970.

[3] W.L. Wiggins: "Directional Quadrant Contact Plungers, Anemometer Type 45B". Instrument Division report, dated, Mar. 3, 1966.

In order to reduce the time interval during which the wind direction is sampled, Stodolak[4] (1968) designed to pulse-limiter which supplies a single pulse of 0.3 seconds duration to the anemomograph for each closure of the one-mile contact. To study the relationship between the sampling interval and the directional bias, a Type D anemograph, equipped with a pulse-limiter, was used in conjunction with other recorders, at the Scarborough Field Station; Ontario, to collect data. The results obtained from the analyses of these data will be discussed in section 6.

2. INSTRUMENT DESCRIPTION

The details of the M.S.C. Type 45B wind system are described elsewhere (Instrument Manual 51) hence only a brief description of the system will be presented. The complete M.S.C. Type 45B wind system, as shown in Fig. 1, is comprised of three instruments: 1. Anemometer (cupwheel and wind vane); 2. Anemograph; and 3. Flashing light indicator. The direction signal from the vane and the speed signal from the cupwheel are displayed visually by the flashing light indicator and recorded by the anemograph. The speed signal is produced by a contact closure for every one-one hundred and twentieth of a mile and for every one mile of wind passing the cupwheel. The position of the wind vane is indicated electrically by a transmitter equipped with two pairs of oilite bronze brushes. As shown in Fig. 2 the upper pair of brushes, connected to the flashing light indicator, make contact with one or two silicon bronze octants. Similarly, the lower pair of brushes, connected to the anemograph, make contact with one or two quadrants.

For the sake of brevity the subsequent discussion in this paper will be confined to the anemograph eight-direction recording. The recording of the wind direction by the Type D anemograph is essentially done by a set of pens operated by four electromagnets. Either pen can be pulled upwards or downwards indicating the four cardinal directions. The intermediate directions are indicated by the four possible ways in which the two pens are moved simultaneously.

[4] John Stodolak: "The Coil Current Control Unit (CCCU) is Designed for Type D Anemograph". Instrument Division Report, dated, Sept. 26, 1968.

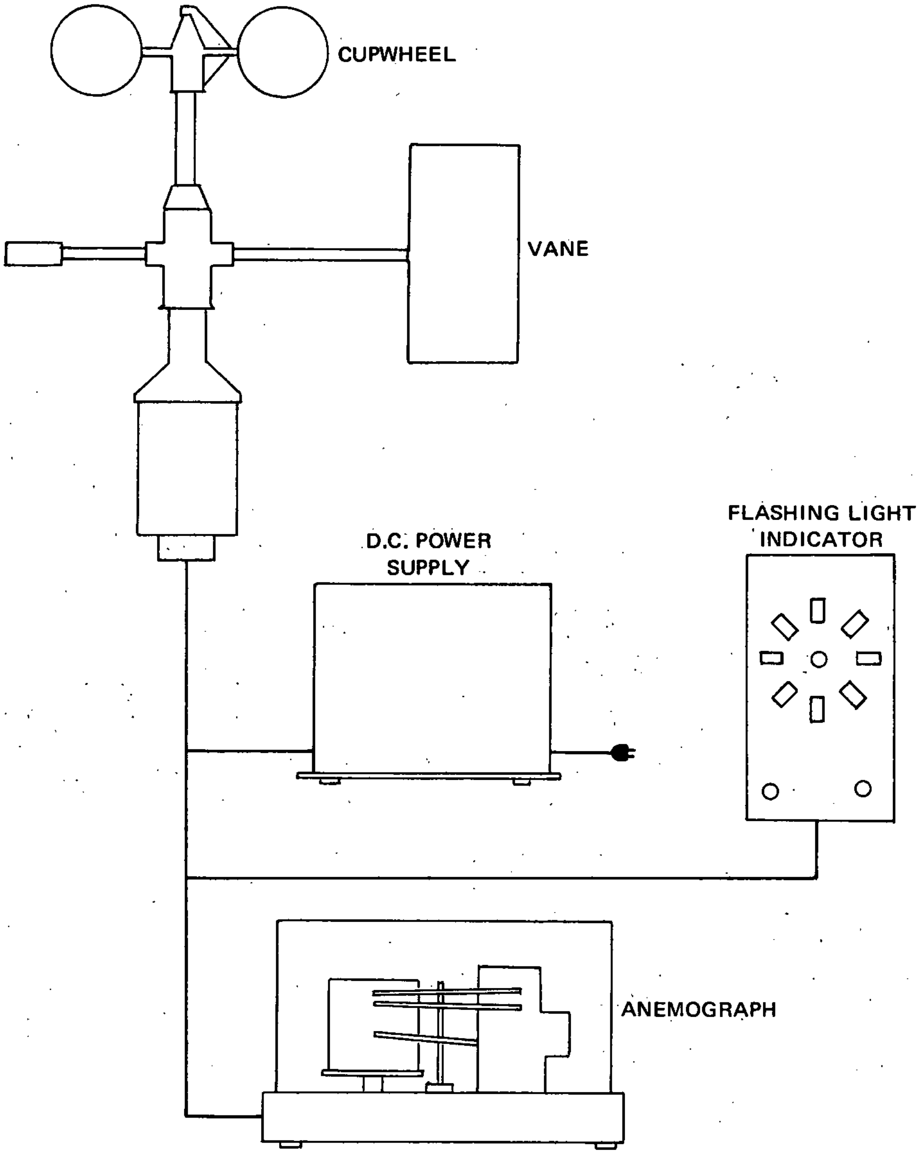

Fig. 1. The M.S.C. Type 45B wind system.

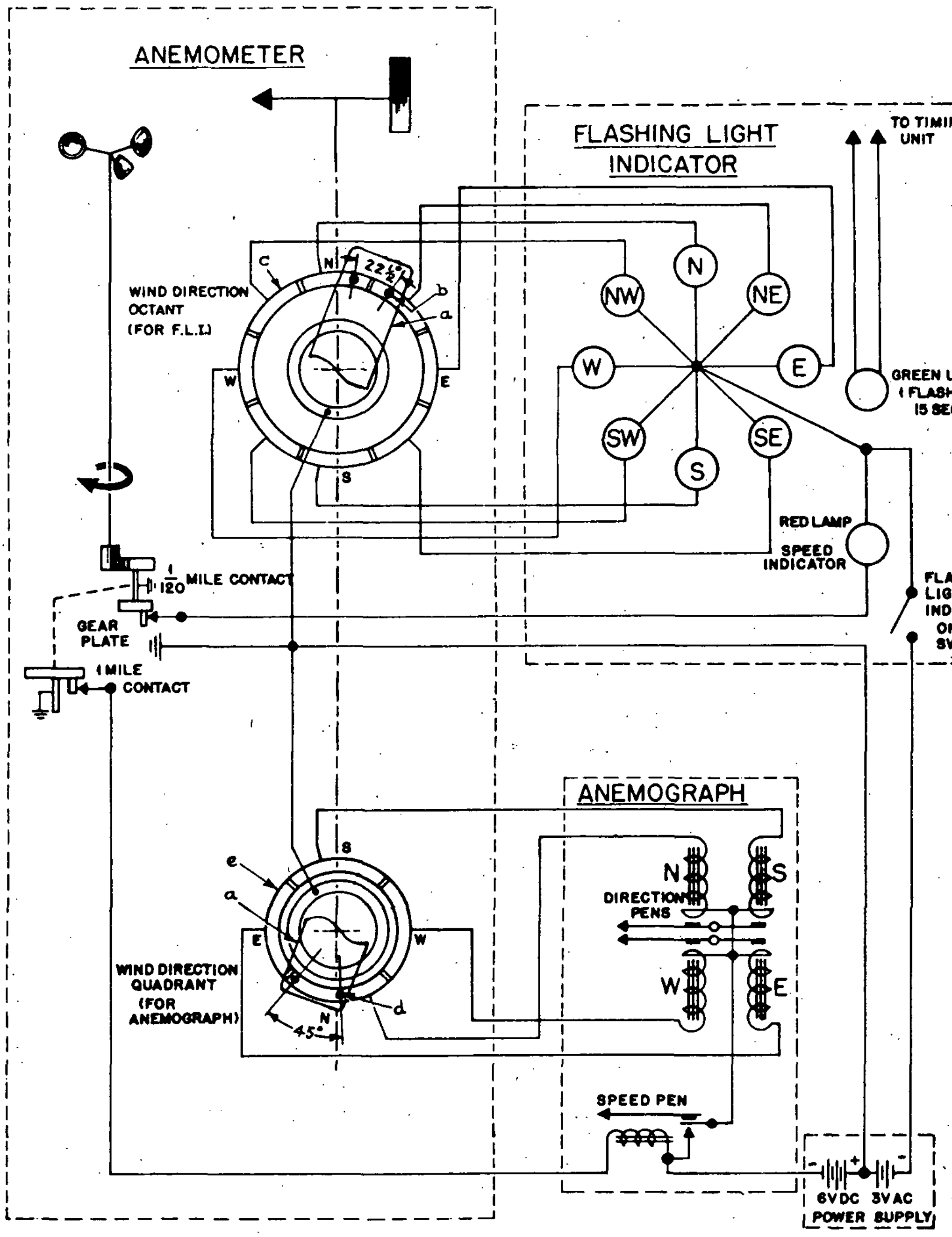

FIG. 2. PICTORIAL DIAGRAM OF THE M.S.C. TYPE 45B WIND SYSTEM.

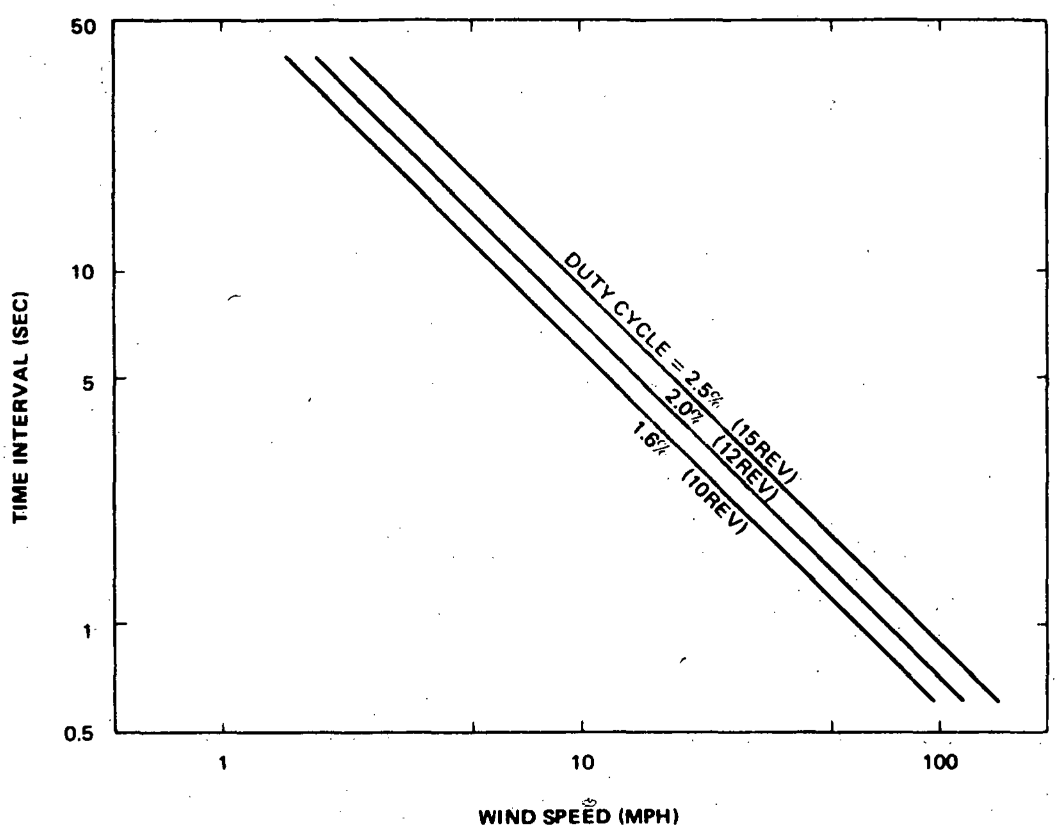

FIG. 3 Relationship between the time interval during which the one-mile contact is closed and the wind speed.

3. ANALYTIC INVESTIGATION

Following the suggestions, made in section 1, that the directional bias in the Type 45B wind system was related to the time interval during which the one-mile contact is closed and to the inter-brush spacing it was decided to investigate each part of the problem separately.

a. Contact closure time interval.

According to the Type 45B anemometer specification,[5] the one-mile contact duty-cycle (D), defined as

$$D = \frac{\text{No. cupwheel revs. while the contact is closed}}{\text{No. cupwheel revs. while the contact is open}} \times 100\% \qquad (1)$$

must be between 1.6% and 2.5%. In other words, the one-mile contact must be closed for not less than 10 and not more than 15 cupwheel revolutions (88 to 132 ft. of wind flow). As a result of this specification the duration of the contact closure is a function of wind speed as

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[5] W.L. Wiggins: "Type 45B Anemometer". Instrument Division Report, dated Feb. 8, 1966

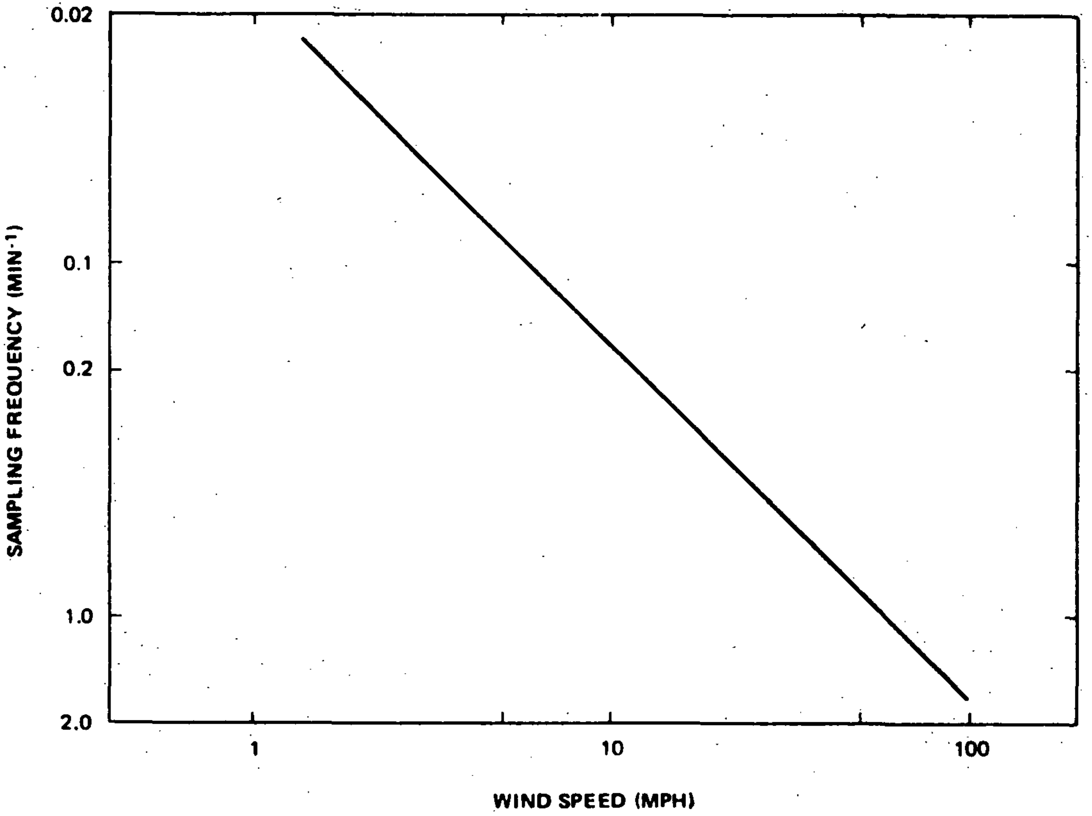


FIG. 4. Relationships between the sampling frequency and the wind speed.

shown in Fig. 3. It may be observed from Fig. 3 that the time interval, during which the contact is closed, decreases rapidly with increasing wind speed. For example, at 2 mph. and a duty cycle of 2% the contact is closed for 30 seconds while at 60 mph. it is closed only for one second. In addition to the sampling interval: wind speed relationship the sampling frequency is also a function of wind speed as shown in Fig. 4. It may be observed from Fig. 4 that the sampling frequency increases with increasing wind speed.

As discussed earlier, the wind direction is sampled when the one-mile contact is closed; therefore, any lateral fluctuations of the vane, while the contact is closed, could produce an intermediate wind direction recording, even though the mean wind blows from a cardinal direction. To illustrate, a vane pointing to a cardinal direction and fluctuating in either direction by more than 22.5 degrees, while the one-mile contact was closed, would produce an intermediate wind direction recording. For a vane pointing a few degrees away from the cardinal direction the fluctuations, producing an intermediate wind direction recording, would be correspondingly smaller. Thus it appears that a functional relationship

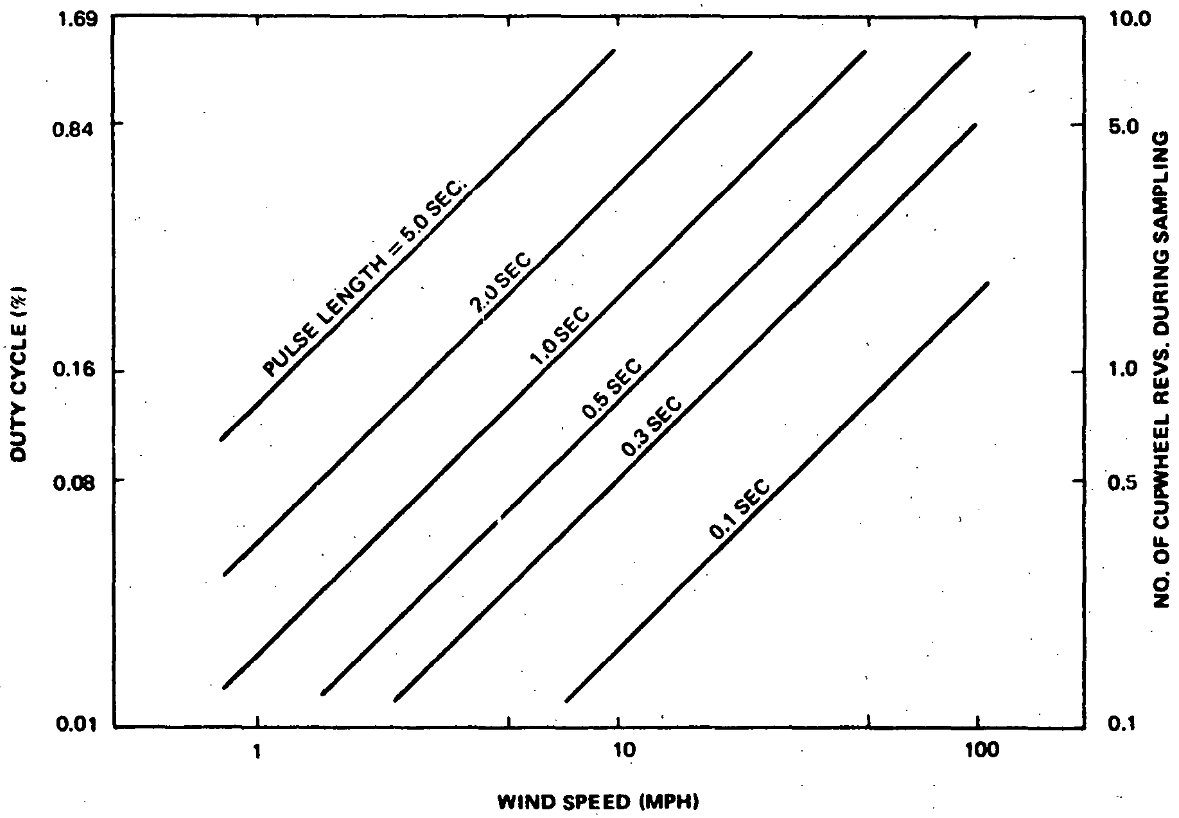


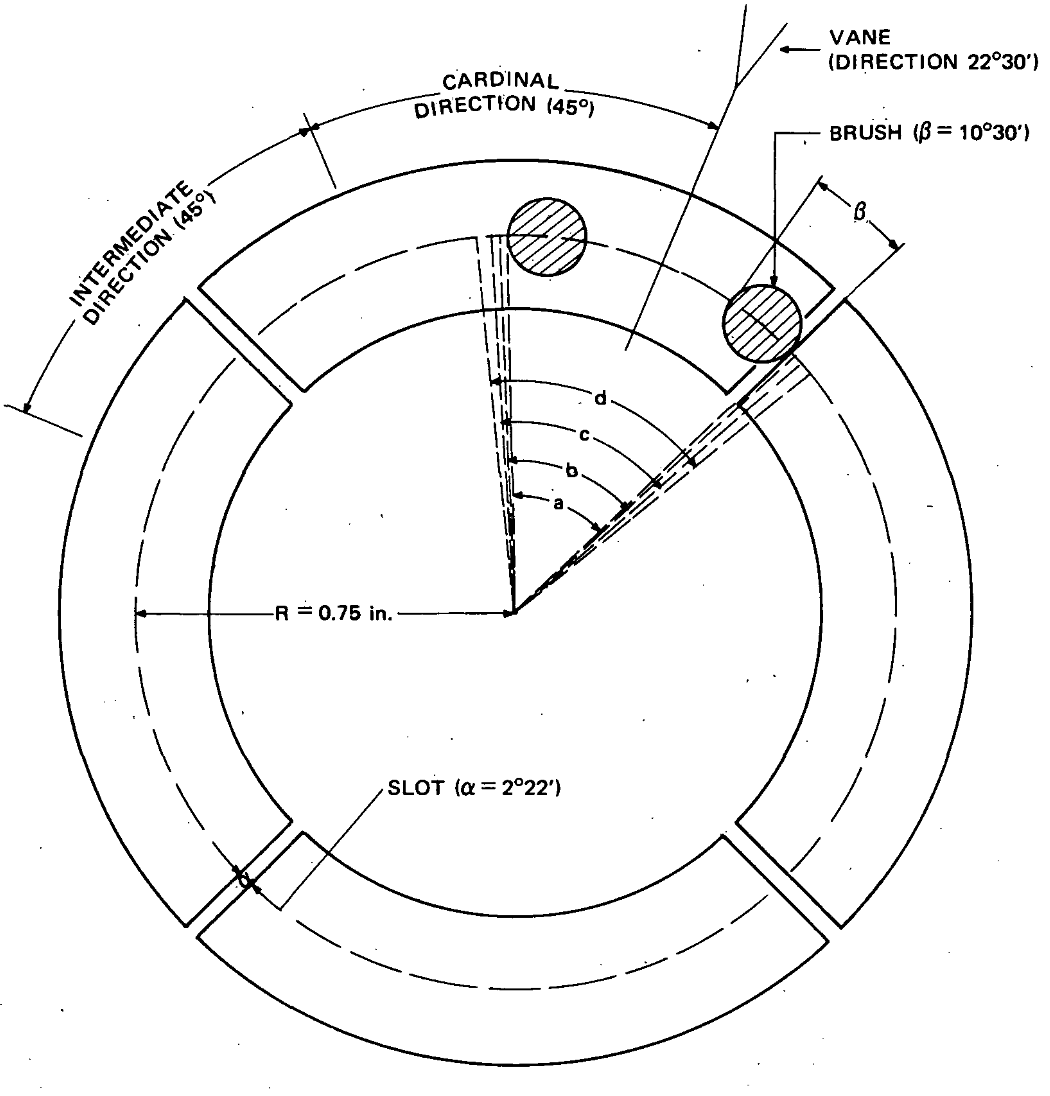
FIG. 5. Relationship between the duty cycle and the wind speed for different pulse lengths. The right side scale shows the number of cupwheel revolutions during sampling as a function of wind speed.

exists between the directional bias and the amplitude and frequency of the lateral wind fluctuations. Further attention to the lateral wind fluctuations will be given in section 4.

The introduction of the pulse-limiter, discussed in section 1, into the Type 45B wind system results in the sampling interval becoming a constant. However, due to this restraint the duty cycle becomes a function of wind speed as shown in Fig. 5. It may be observed from Fig. 5 that, for a pulse length of 0.3 seconds, the duty cycle varies from 0.01% at 2 mph. to 0.84% at 100 mph.

b. The inter-brush angle

At the present time the angle subtended by the outside tangents to the brushes, in the M.S.C. Type 45B anemometer, is 47° 22′. This value is based on the assumption that the contact between the brush and the commutator is established as soon as the edge of the brush is vertically above the edge of the commutator as shown in Fig. 6. According to



a = 47°22' (Presently used value)
b = 47°40' (Value used prior to 1966)
c = 51°16' (Empirical optimum value from this study)
d = 56°30' (Empirical optimum value from Suffield)

FIG. 6. Brush-commutator wind direction system. A comparison among the different values of the inter-brush angle is shown.

Clink[6] (1970) the Suffield measurements, referred to in section 1, strongly suggested that, in the mean, the effective contact between the brush and the commutator-segment was established when the center of the brush was in the middle of the slot. This anomaly was explained by the fact that due to wear and rotation of the brushes, the brush face in contact with the commutator becomes slightly conical. It is clear from Fig. 6 that if the contact between the commutator and the brush was made when the center of the brush was in the middle of the slot; the angle subtended at the shaft center, by the chords to the brush centers, would have to be equal to 45 degrees. In other words, the angle subtended by the outside tangents to the brushes would have to be changed from the present value of 47° 22′ to a new value of 56° 30′. In order to obtain an empirical value for the inter-brush angle laboratory tests were carried out using several anemometers. The results from these tests will be discussed in section 5.

4. THE CHARACTERISTICS OF LATERAL WIND FLUCTUATIONS

Before relating the empirical results of the lateral wind fluctuations to the Type 45B wind system it is necessary to briefly review the theory of turbulent fluctuations.

Mathematically, it is convenient to separate the turbulent flow into a mean motion and into a fluctuation. Denoting the time averages of the instantaneous velocity components and pressure (u, v, w, p) at (x, y, z) by u, v, w, p and the corresponding fluctuations by u′, v′, w′, p′; then the instantaneous velocity components and pressure become:

$$u=\bar{u}+u', \quad v=\bar{v}+v', \quad w=\bar{w}+w', \quad p=\bar{p}+p' \tag{2}$$

Substituting the velocity components and pressure given in Eq. (2) into the Navier-Stokes equations for incompressible flow and time averaging as shown in Appendix I, we obtain the Reynolds equations in the form:

$$\begin{aligned}
\rho\left(\bar{u}\frac{\partial\bar{u}}{\partial x}+\bar{v}\frac{\partial\bar{u}}{\partial y}+\bar{w}\frac{\partial\bar{u}}{\partial z}\right)&=-\frac{\partial\bar{p}}{\partial x}+\mu\nabla^2\bar{u}-\rho\left[\frac{\partial\overline{u'^2}}{\partial x}+\frac{\partial\overline{u'v'}}{\partial y}+\frac{\partial\overline{u'w'}}{\partial z}\right]\\
\rho\left(\bar{u}\frac{\partial\bar{v}}{\partial x}+\bar{v}\frac{\partial\bar{v}}{\partial y}+\bar{w}\frac{\partial\bar{v}}{\partial z}\right)&=-\frac{\partial\bar{p}}{\partial y}+\mu\nabla^2\bar{v}-\rho\left[\frac{\partial\overline{u'v'}}{\partial x}+\frac{\partial\overline{v'^2}}{\partial y}+\frac{\partial\overline{v'w'}}{\partial z}\right]\\
\rho\left(\bar{u}\frac{\partial\bar{w}}{\partial x}+\bar{v}\frac{\partial\bar{w}}{\partial y}+\bar{w}\frac{\partial\bar{w}}{\partial z}\right)&=-\frac{\partial\bar{p}}{\partial z}+\mu\nabla^2\bar{w}-\rho\left[\frac{\partial\overline{u'w'}}{\partial x}+\frac{\partial\overline{v'w'}}{\partial y}+\frac{\partial\overline{w'^2}}{\partial z}\right]
\end{aligned}\tag{3}$$

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[6] Personal communication

where $-\rho\overline{u'^2}$, $-\rho\overline{v'^2}$, $-\rho\overline{w'^2}$ and $-\rho\overline{u'v'}$, $-\rho\overline{u'w'}$, $-\rho\overline{v'w'}$ are the normal and the shear stresses respectively. These stresses, also known as the Reynolds stresses, were the subject of considerable research in the past (Lumley and Panofsky, 1964). It is interesting to note that the above equations contain ten unknowns and hence it is not possible to solve them for a general case. Nevertheless, the Reynolds equations constitute the starting point for the mathematical treatment of turbulent flow problems and provide a justification for experimental investigations.

Since the Reynolds equations cannot be solved without further information regarding the turbulent stresses it is now generally believed that experiment should be called upon whenever possible to furnish the desired information. In experimental work on turbulent flow the quantities measured conveniently are the mean values of velocity while the measurements of the fluctuating components or their mean values require more elaborate equipment. In the present study the lateral fluctuations v′ and the root-mean-square values $(\overline{v'^2})^{1/2}$ are of prime interest. Extensive wind tunnel measurements performed by Klebanoff (1955) indicate that in the boundary layer the lateral fluctuations do not vary greatly with height while the longitudinal fluctuations exhibit a pronounced steep maximum very close to the wall.

Measurements of the turbulent fluctuations in the atmosphere were performed by Giblet et al. (1932), MacCready (1953), Panofsky and McCormick (1954) and others. It was found that in the atmospheric boundary layer the low frequency components of the lateral-velocity spectra are mostly dependent on lapse rate while the high frequency regions are sensitive both to surface roughness and wind speed. Panofsky and Deland (1959) obtained spectral distributions of the three velocity components at a height of 12 meters from the data collected at O'Neill, Nebraska. The spectra show that in the unstable atmosphere the turbulence is approximately horizontally isotropic for frequencies greater than 60 cycles hour^{-1}. On the other hand, in stable air the lateral fluctuations are characterized by little low frequency energy as compared to the longitudinal fluctuations. In spectral models the parameter of importance is the variance of the turbulent components. According to Bowne and Anderson (1968) the variance of the lateral turbulent fluctuations may be obtained from the equation:

$$\sigma_v = \frac{0.80U}{\ln (z/z_o)}$$

where U is the wind speed, z is the height above ground and z_o is the surface roughness.

To relate the lateral wind fluctuations to the Type 45B wind system it becomes convenient to use the empirical gustiness classification proposed by Smith (1951) and modified by Singer and Smith (1953). This classification is based on the amplitude of the lateral wind fluctuations as shown by the direction trace. For reference purposes the gustiness classification proposed by Singer and Smith (1953) is given below:

A: Fluctuations of the wind direction exceeding 90 deg. (peak-to-peak).
B_2: Fluctuations ranging from 45 to 90 deg.
B_1: Similar to A and B_2, with fluctuations confined to 15– and 45– deg. limits.
C: Distinguished by the unbroken solid core of the trace, through which a straight line can be drawn for the entire hour, without touching "open space". The fluctuations must reach 15 deg. but no upper limit is imposed.
D: The trace approximates a line. Short-term fluctuations do not exceed 15 deg.

A summary of the results obtained by Singer and Smith (1953), using two years of data collected at the Brookhaven National Laboratory, is given in Table 1.

Table 1. Mean wind speed and lapse rate associated with each gustiness classification.

Gustiness category	Percentage of occurrence %	Mean wind speed (m sec^{-1})	Mean lapse rate ($T_{410}-T_{37}$)°C
A	1	1.8	−1.25
B_2	3	3.8	−1.6
B_1	42	7.0	−1.2
C	14	10.4	−0.64
D	40	6.4	2.0

The wind data, on which the results in Table 1 are based, was collected by a standard Bendix-Friez aerovane mounted 335 ft. above ground. Hence it should be emphasized that the results given in Table 1, while adequate within the scope of this study, cannot be considered as representative of those obtained at the airport anemometer level.

In addition to the amplitude of the lateral fluctuations the frequency of fluctuations is also related to the magnitude of directional bias. Jones (1966) showed that the Eulerian frequency (f_E) for the maximum lateral velocities may be given as:

$$f_E = \frac{\bar{u}}{2D} \qquad (5)$$

where D is the effective diameter of circular eddies and $\bar{u}$ is the velocity at which the eddies are travelling. In simple terms, Eq. (5) states that the frequency of the lateral fluctuations produced at a point by eddies of equal effective size will increase with the mean wind speed.

The question now remains how to relate the frequency and amplitude of the lateral fluctuations to the magnitude of the directional bias in the Type 45B wind system. This question will be discussed in section 6.

5. EXPERIMENTAL INVESTIGATION

During June and July 1964, surface wind observations ($z = 10$m) were made at the Scarborough Field Station as part of a study to determine the magnitude of the directional bias in the Type 45B wind system. The instrumentation consisted of a standard Type 45B anemograph, a pulse-limiter equipped anemograph, and an Esterline Angus strip chart recorder. All three instruments were connected to the same Type 45B anemometer. Daily abstracts of wind-direction were made from the anemograph and Esterline Angus charts. The daily values of the wind direction data from each recording instrument were then combined. Next, the percentage frequencies of the wind-run (anemograph record) and wind-duration (Esterline Angus record) were plotted as a function of wind direction. Figs. 7-9 show the percentage frequencies of wind-run and wind-duration corresponding to each recorder. The comparison among all three recorders is presented in Fig. 10. A discussion of these graphs will be given in the next section.

In order to obtain an empirical value for the inter-brush angle, discussed in section 3.b, laboratory tests were conducted. The aim of these tests was to determine the mean position of the brush, with respect to the slot, when the brush-commutator contact was established or broken. The apparatus consisted of the DIRECTION BIAS FIXTURE, shown in Appendix II, and six Type 45B anemometers. Three of the anemometers were newly rebuilt, ready for field use, while the remaining three were returned from the field after extensive use. By using the DIRECTION BIAS FIXTURE it was possible to make relatively accurate measurements of the brush-commutator overlap distance when the actual contact was made or broken.

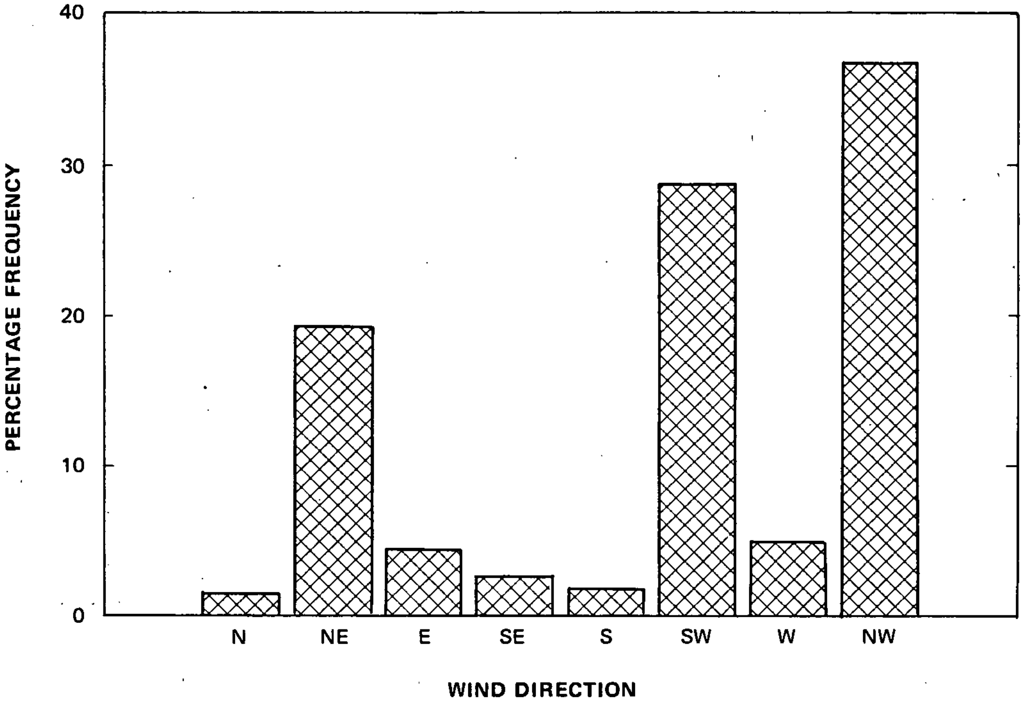

FIG. 7. Percentage frequency of the wind run plotted against the wind direction. The data was obtained using the standard M.S.C. Type 45B anemograph.

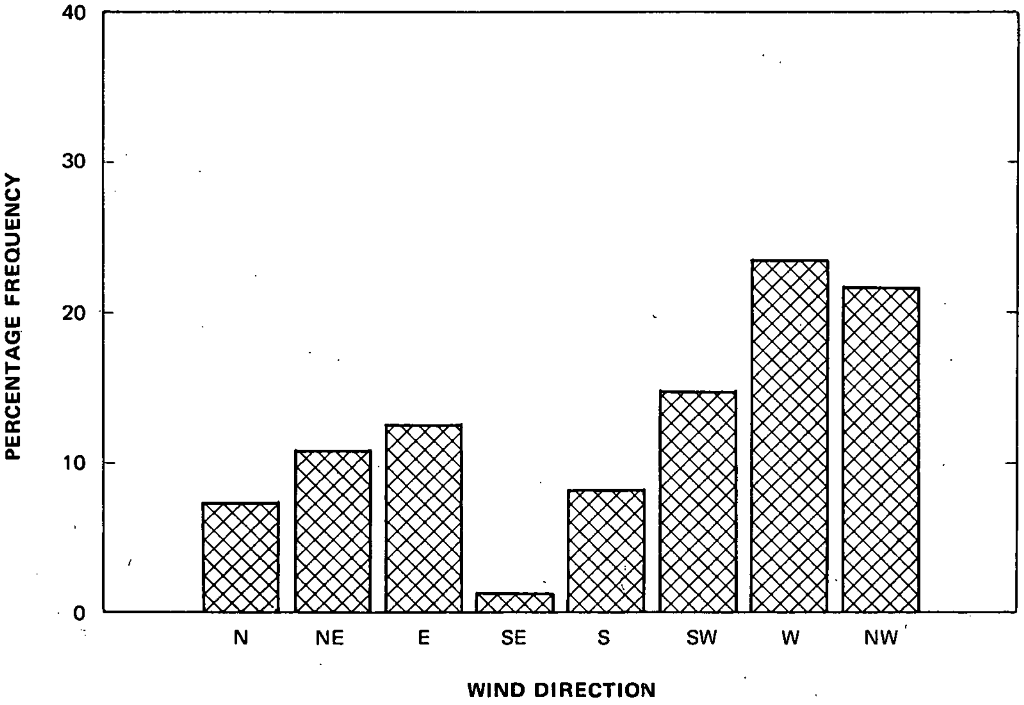

FIG. 8. Percentage frequency of the wind run plotted against the wind direction. The data was obtained using the M.S.C. Type 45B anemograph equipped with a pulse limiter.

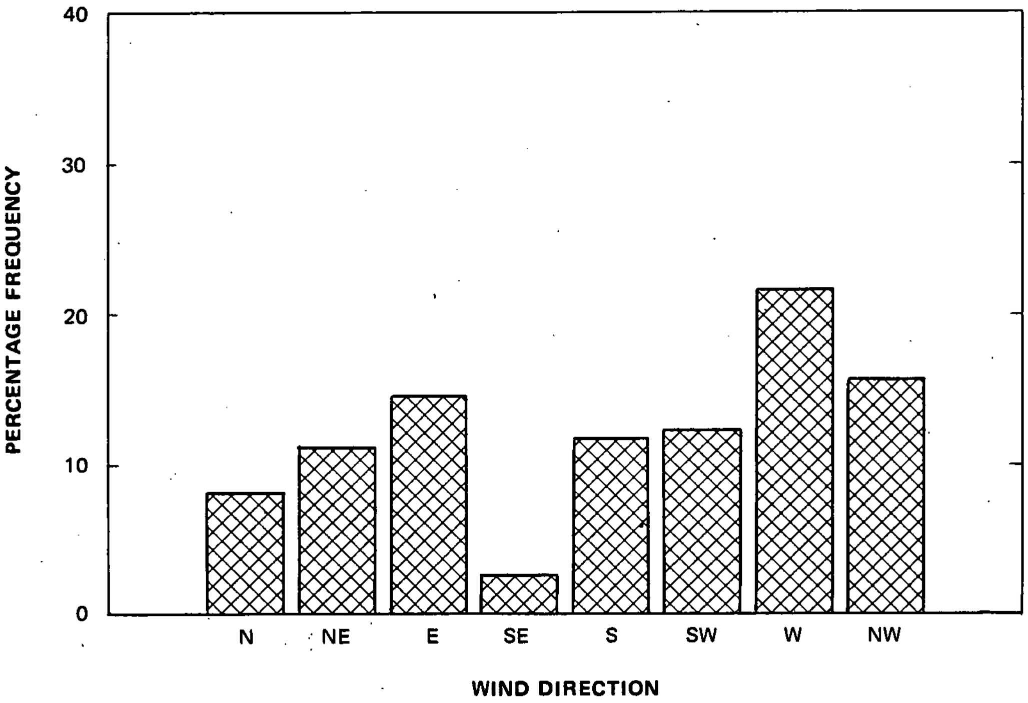

FIG. 9. Percentage frequency of wind duration plotted against the wind direction. The data was obtained using the Esterline Angus strip chart recorder.

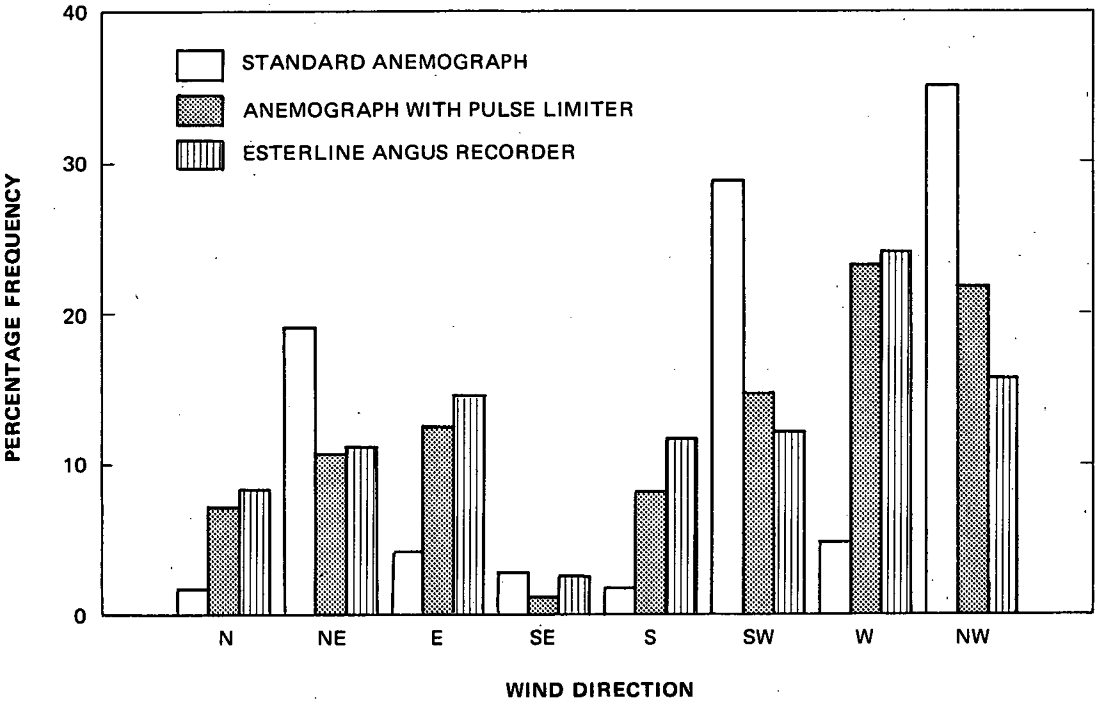

FIG. 10. Comparison between the percentage frequencies obtained by three recorders connected to the same wind vane.

The measurements of the overlap distances obtained from each anemometer are shown in Tables 2a and 2b. To compare the mean overlap distance when the contact was broken to that when it was established, the frequency distribution diagrams were constructed for each case (Fig. 11). Furthermore frequency distribution diagrams were also constructed to compare the mean brush-overlap distance between rebuilt and used anemometers. These diagrams are shown in Fig. 12.

This concludes the experimental investigation and in the following section the results here presented will be assessed.

6. DISCUSSION

Before discussing the results it is desirable to consider some of the obvious sources of error. There was an indication that the Esterline Angus strip chart and the anemograph charts became de-synchronized each day after a few hours of operation. As a result of this error the wind-duration, rather than the wind-run, was abstracted from the Esterline Angus charts. The brush-commutator overlap distance was measured with a precision of ± 0.25 degrees which corresponds to ± 0.003 inches. The brush-commutator overlap measurements were remarkably reproducable without any noticable fluctuations. The small number of anemometers available for laboratory tests and a rather short field test period resulted in relatively small sample sizes. Consequently, it was decided to discuss the experimental results qualitatively rather than through the use of significance tests.

A study of Figs. 7-9 reveals that for the standard Type D anemograph the percentage frequency of the wind-run is significantly higher for the intermediate wind directions as compared to the cardinal directions. Furthermore, by comparing Figs. 7 and 8 it may be noted that for the pulse-limiter equipped anemograph the high intermediate-direction frequencies are not present. In addition, the frequencies of wind direction obtained by the Esterline Angus, (Fig. 9), are reasonably close to those obtained by the pulse-limiter equipped anemograph. The comparison of the percentage frequencies in Fig. 10 shows that the difference between the wind-run and wind-duration sampling methods is relatively small provided that the pulse-limiter equipped anemograph is used.

TABLE 2a

Brush-commutator overlap distance when the contact is made.

Serial No.	Brush No.	Amount of overlap (deg.)* for each quadrant				Mean Value (deg.)
		N-E	E-S	S-W	W-N	
		Rebuilt anemometers				
456/50	1	3.5	2.0	2.0	3.5	2.75
456/50	2	3.5	4.0	3.0	0.5	2.75
384/53	1	1.0	1.0	1.5	1.0	1.12
384/53	2	8.5	6.0	6.0	9.0	7.38
76/47	1	0.0	0.0	0.0	0.0	0.00
76/47	2	4.0	1.0	0.0	0.0	1.25
		Used anemometers				
164/50	1	3.0	5.0	3.0	4.5	3.87
164/50	2	3.0	4.0	3.0	3.5	3.38
225/50	1	6.0	7.0	5.0	6.0	6.00
225/50	2	4.0	5.0	4.0	4.0	4.25
157/50	1	5.0	4.0	6.0	2.5	4.38
157/50	2	2.5	2.0	5.5	2.5	3.11

* 1 deg. = 0.013 inches

TABLE 2b.

Brush-commutator overlap distance when the contact is broken

Serial No.	Brush No.	Amount of overlap (deg.) for each quadrant				Mean Value (deg.)
		N-E	E-S	S-W	W-N	
Rebuilt anemometers						
456/50	1	5.0	3.0	2.5	4.0	3.62
456/50	2	5.0	5.5	4.0	2.5	4.25
384/53	1	0.0	0.0	2.5	2.0	1.12
384/53	2	8.5	9.0	8.5	8.0	8.50
76/47	1	2.0	1.5	2.5	0.0	1.50
76/47	2	8.0	7.5	7.0	6.0	7.12
Used anemometers						
164/50	1	5.0	4.5	5.0	5.0	4.87
164/50	2	4.0	4.5	3.5	4.5	4.12
225/50	1	7.0	6.0	5.5	7.0	6.35
225/50	2	5.0	6.0	5.5	5.0	5.37
157/50	1	6.0	4.0	6.5	3.0	4.87
157/50	2	2.5	2.0	5.0	3.0	3.12

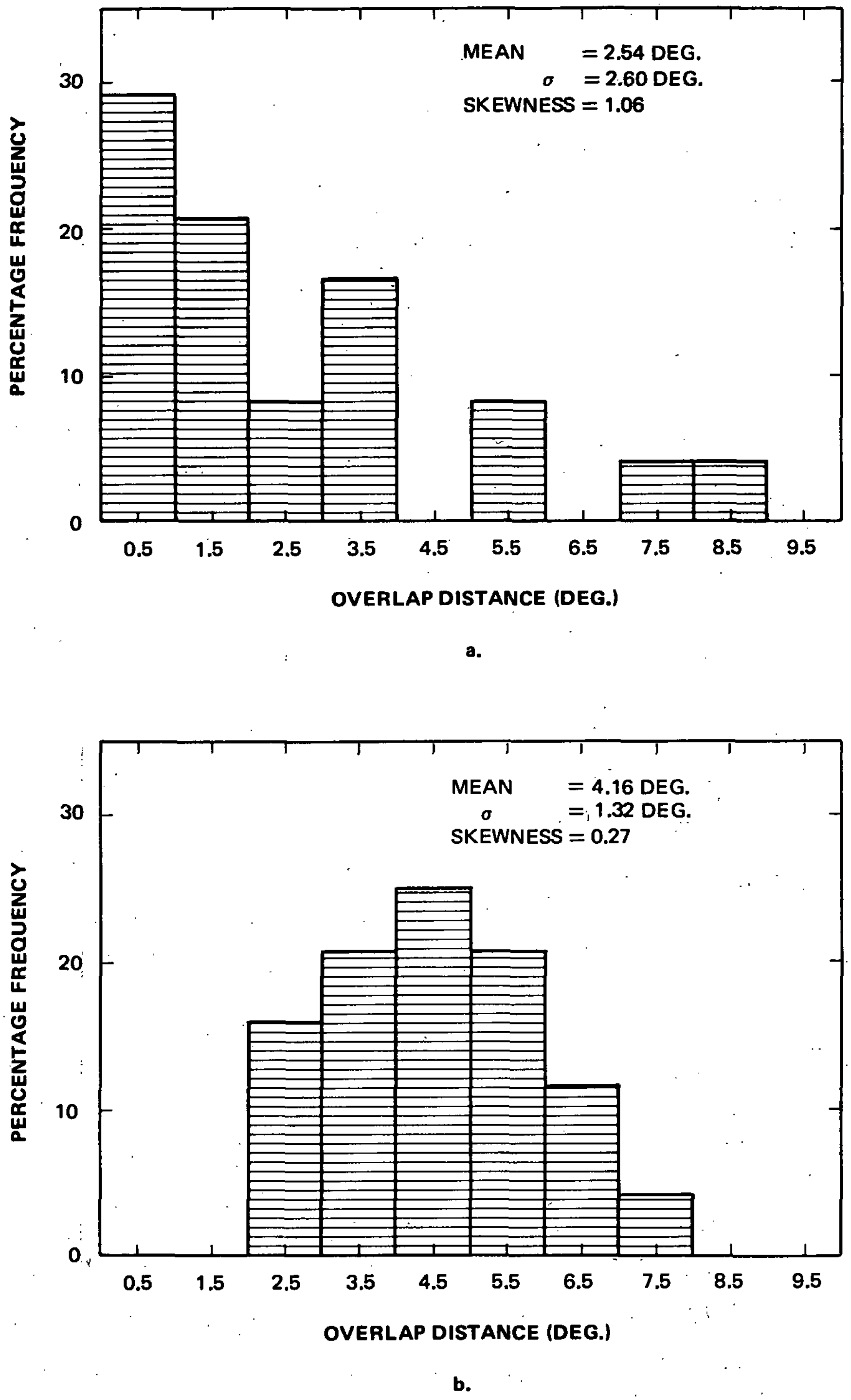

FIG. 11. Percentage frequency of the brush overlap distance before the actual contact with the commutator is made. The measurements were obtained: a. from rebuilt anemometers, and b. from used anemometers. (1 DEG. = 0.013 INCHES).

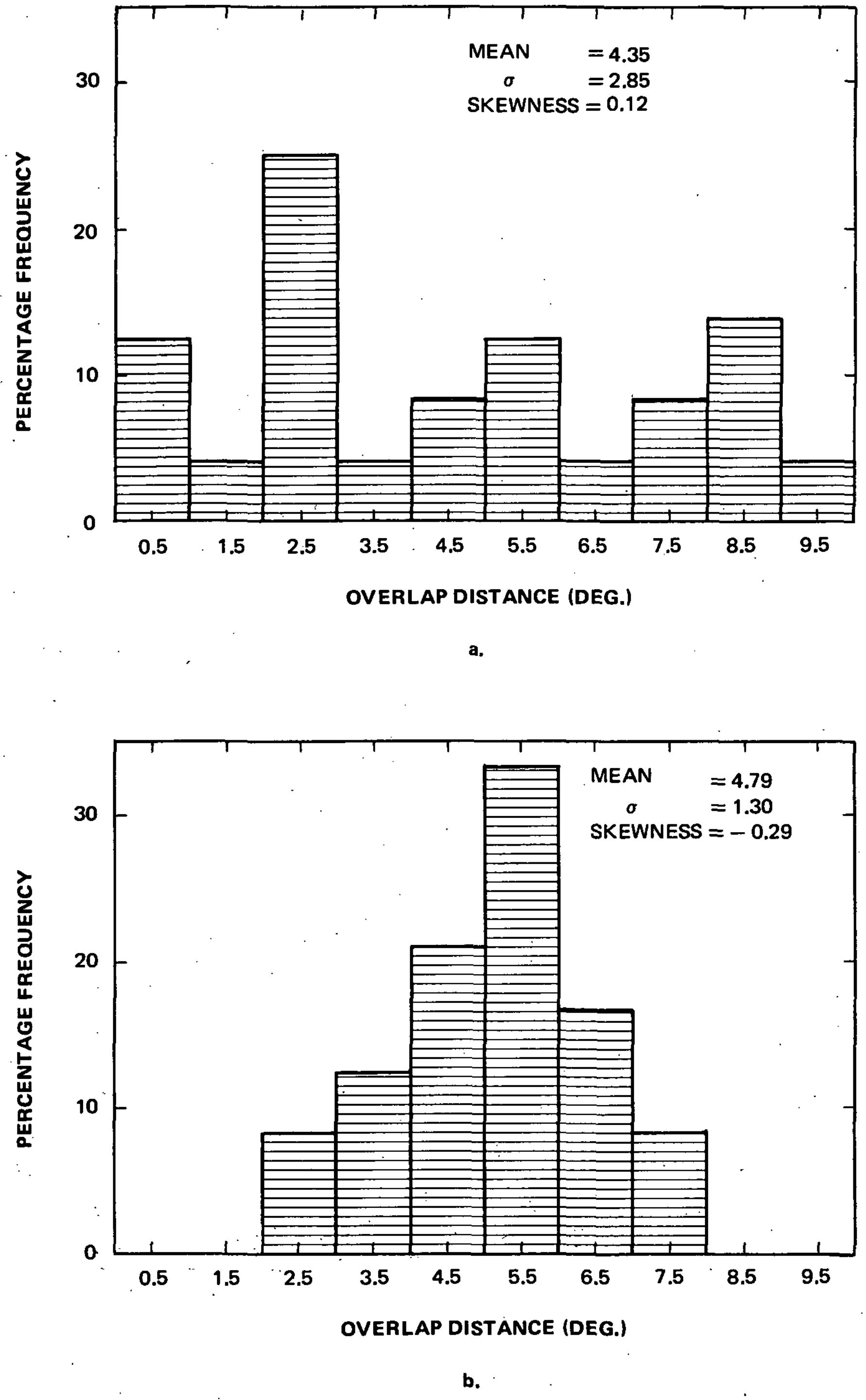

FIG. 12. Breaking the brush – commutator contact. Percentage frequency of the brush overlap distance when the actual contact is broken. The measurements were obtained: a. from rebuilt anemometers, and b. from used anemometers. (1 DEG. = 0.013 INCHES).

Fig. 4. shows the relationship between the sampling frequency and the wind speed. So far, few studies have been done to determine the relationship between the wind-run and wind-duration sampling methods. Middleton and Spilhaus (1953) suggested that, at low wind speeds, sampling at fixed intervals has an advantage over the wind-run sampling. From the practical point of view it may be argued that the importance of the wind-direction increases with increasing wind speed and hence wind-run sampling may be desirable. It appears that only a study based on theoretical analyses can provide the answer as to the superiority of one sampling method over the other for any particular application.

The question as to what the inter-brush angle should be will be discussed next. Fig. 11 shows the percentage frequency distribution of the brush-commutator overlap distance when the contact is made. It may be observed from Fig. 11 that the mean value of the overlap distance is a function of the length of time that the instrument has been used. To illustrate, the mean distance increases from 2.54 deg. in rebuilt anemometers to 4.16 deg. in the used ones. This result agrees with the fact that the brush face in contact with the commutator becomes slightly conical due to wear, as explained in section 3b. Similarly, Fig. 12 shows that the percentage frequency of the brush-commutator mean overlap distance, when the contact is broken, increases from 4.35 deg. for rebuilt anemometers to 4.79 deg. for the used ones. Furthermore, it may be observed from Figs. 11 and 12 that the standard deviation of the overlap distance is greater for rebuilt anemometers than for the used ones. This observation suggests that, at the present time, each anemometer has its intrinsic initial conditions lacking in the desirable uniformity. Nevertheless, by utilizing the mean value of the brush-commutator overlap distances it is possible to obtain an empirical value for the inter-brush angle. Such an empirical value would reduce the directional bias toward cardinal directions in most of the Type 45B anemometers. However, in practice this procedure may not be entirely satisfactory since the aim is to reduce or eliminate the directional bias in all anemometers. To illustrate, suppose that the inter-brush angle in anemometers with serial numbers 76/47 and 456/50, reported in Table 2a, were adjusted for the mean overlap distance. Then in the anemometer 76/57 the directional bias toward cardinal directions would be reduced while a slight bias toward the intermediate directions would be introduced into the anemometer 456/50.

Finally, the question of how the frequency and amplitude of lateral fluctuations are related to the magnitude of the directional bias will be discussed. It may be observed from Table 1 that the gustiness categories A and B_2, with peak-to- peak fluctuations exceeding 45 degrees, occur only 4% of the time. However, since these fluctuations are associated with relatively low mean wind speeds i.e. long sampling periods (see Fig. 3) they make a significant contribution to the overall magnitude of the intermediate-direction bias. It is believed that the main contribution to the directional bias toward intermediate directions is made by B_1 gustiness category which occurs 42% of the time and is also associated with relatively low mean wind speed. The next gustiness category C, is due to mechanical turbulence. Hence its contribution to the intermediate-direction bias increases with increasing surface roughness. Finally, the D gustiness category produces little or no intermediate-direction bias.

In regard to the secondary bias it is conjectured that its magnitude is greatest during the D gustiness category. Moreover, the secondary bias is likely to reduce the magnitude of the intermediate-direction bias during the remaining gustiness categories.

The relationship between the wind speed and the magnitude of the directional bias is rather complex. It would appear from Eq. (5) that the magnitude of directional bias toward intermediate wind directions would increase with increasing wind speed. However, it was shown in Fig. 3 that the sampling interval decreases with increased wind speed. Furthermore, Swanson and Cramer (1965) found that there is a sharp decrease in the intensity of turbulence as the wind speed increases. This decrease in turbulence intensity is particularly pronounced during unstable conditions. Consequently, further study is required to determine what is the effect of the wind speed on the magnitude of the directional bias.

To the first approximation the magnitude of the directional bias toward cardinal and intermediate wind directions may be obtained by making a number of simplifying assumptions.

In regard to the intermediate direction bias it may be observed from Fig. 6 that, as a result of the brush-commutator overlap distance, the effective cardinal direction segment arc is increased by the distance equal to the overlap distance, while the intermediate direction segment arc is decreased by the same distance. Assuming that the turbulence at the anemometer level is laterally isotropic and that there are no prevailing wind directions the mean bias toward the cardinal wind directions, due to the overlap distance, was computed for each anemometer. The results of these computations are given in Table 3. It may be noted from Table 3 that the bias toward the cardinal wind directions varies between 11.0 and 24.4 per cent.

TABLE 3

Mean brush-commutator overlap distance and mean bias toward cardinal wind directions associated with each anemometer.

Serial No.	Mean overlap distance (deg.)	Mean bias (%)
	Rebuilt anemometers	
456/50	3.3	14.8
384/53	4.5	20.2
76/47	2.5	11.0
Mean	3.4	15.3
	Used anemometers	
164/50	4.0	18.0
225/50	5.5	24.4
157/50	3.9	17.2
Mean	4.5	19.9

Next it was desired to obtain a quantitative estimate of the directional bias toward the intermediate wind directions due to the 0.3 sec sampling length associated with the pulse-limiter. From the gustiness classification data obtained by Singer and Smith (1953), and presented in Table 1, it may be deduced that the mean peak-to-peak fluctuation is approximately 20 degrees. The problem now becomes to determine the frequency of the mean fluctuations. Assuming that the effective diameter of the circular eddies at the anemometer level is equal to the height above ground then, for a mean wind speed of 15 mph, the Eulerian frequency, from Eq. 5, is equal to 0.33 $\sec^{-1}$. In other words, during the sampling interval of 0.3 sec the average angular displacement of the vane is approximately two degrees. Retaining the assumptions of lateral homogenuity and the absence of the prevailing wind directions, the directional bias toward the intermediate wind directions due to the 0.3 sec sampling interval is found to be approximately 2.5 per cent.

It must be emphasized that the foregoing quantitative estimates of directional bias are based on a number of simplifying assumptions. The overall justification for the assumptions made is that the results provide an acceptable fit to the qualitative results obtained earlier. Thus clearly, when a pulse limiter is used, the bias toward cardinal directions will be unacceptably large. Further work should be directed toward reducing it to acceptable limits.

7. CONCLUSIONS

The experimental results verify the inference that there exists a directional bias toward the intermediate wind directions in the M.S.C. Type 45B wind system. The analytical evaluation suggests that the bias is caused by the relatively long time interval during which the wind direction is sampled. The magnitude of the directional bias is found to be a function of wind speed, stability, and surface roughness. The analysis of the observational data reveals that for most practical purposes the bias toward the intermediate wind directions may be removed with a pulse-limiter.

The comparison between the wind-run and wind-duration sampling methods shows that, qualitatively, the difference between the two methods is not large. However, further studies are necessary to determine which method is superior.

Evidence is given to suggest that there is a secondary bias, in the Type 45B wind system, directed toward the cardinal wind directions. This bias results from the uneven brush-commutator contact. Laboratory tests indicate that the magnitude of the secondary bias is a complex function of the time period over which the anemometer was used, and the anemometer's initial conditions. Based on a sample of six anemometers the empirical angle, subtended by the outside tangents to the brushes, which would statistically reduce the secondary bias to a minimum was found to be 51°16′. Because of lack of field data it was not possible to determine the magnitude of the secondary bias empirically. However, by using a number of simplifying assumptions it was shown analytically that the magnitude of the secondary bias can be significant as far as practical applications are concerned.

8. RECOMMENDATIONS

Based on the foregoing study the following recommendations are made with respect to the M.S.C. Type 45B wind system.

1. To reduce the statistical directional bias on M.S.C. Type 45B anemograph records a short duration recording pulse is required. A pulse limiting system should be added to all Type 45B anemometer installations as soon as possible.

2. The reduction of directional bias to negligible limits will further require the development, evaluation, and installation of an improved directional commutator. This should proceed without delay.

3. Individuals or agencies using the Type 45B wind system should be advised of the systems shortcomings. Publication of this report would be a suitable means.

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APPROVED,

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Canadian Meteorological Service.

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APPENDIX I

Following the Reynold's assumption that the description of the turbulent flow at every instant may be given by the Navier-Stokes equations, the instantaneous velocity and pressure components given in Eq. (2) may be substituted into the Navier-Stokes equations. For simplicity and to avoid repetition only the u-component of the Navier-Stokes equations, for incompressible flow, will be considered. This component may be written as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \nabla^2 u \qquad \text{(i)}$$

where ρ is the density, ν is the kinematic viscosity and ∇^2 denotes the Laplace's operator.

By using the continuity equation,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad \text{(ii)}$$

Eq. (i) can be written as:

$$\frac{\partial u}{\partial t} + \frac{\partial(u^2)}{\partial x} + \frac{\partial(uv)}{\partial y} + \frac{\partial(uw)}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \nabla^2 u \qquad \text{(iii)}$$

By substituting the instantaneous values from Eq. (2) and time averaging, Eq. (iii) becomes:

$$\overline{\frac{\partial}{\partial t}(\bar{u} + u')} + \overline{\frac{\partial}{\partial x}(\bar{u} + u')^2} + \overline{\frac{\partial}{\partial y}(\bar{u} + u')(\bar{v} + v')} + \overline{\frac{\partial}{\partial z}(\bar{u} + u')(\bar{w} + w')} = \overline{\frac{1}{\rho}\frac{\partial}{\partial x}(\bar{p} + p')} + \overline{\nu \nabla^2 (u+u')} \qquad \text{(iv)}$$

Using the rules of operating on mean time-averages (Lumley and Panofsky 1964, p 7) and assuming that the mean flow is constant with time Eq. (iv) becomes:

$$\frac{\partial}{\partial x}(\bar{u}^2 + \overline{u'^2}) + \frac{\partial}{\partial y}(\overline{uv} + \overline{u'w'}) + \frac{\partial}{\partial z}(\overline{uw} + \overline{u'w'}) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \nu \nabla^2 \bar{u} \qquad \text{(v)}$$

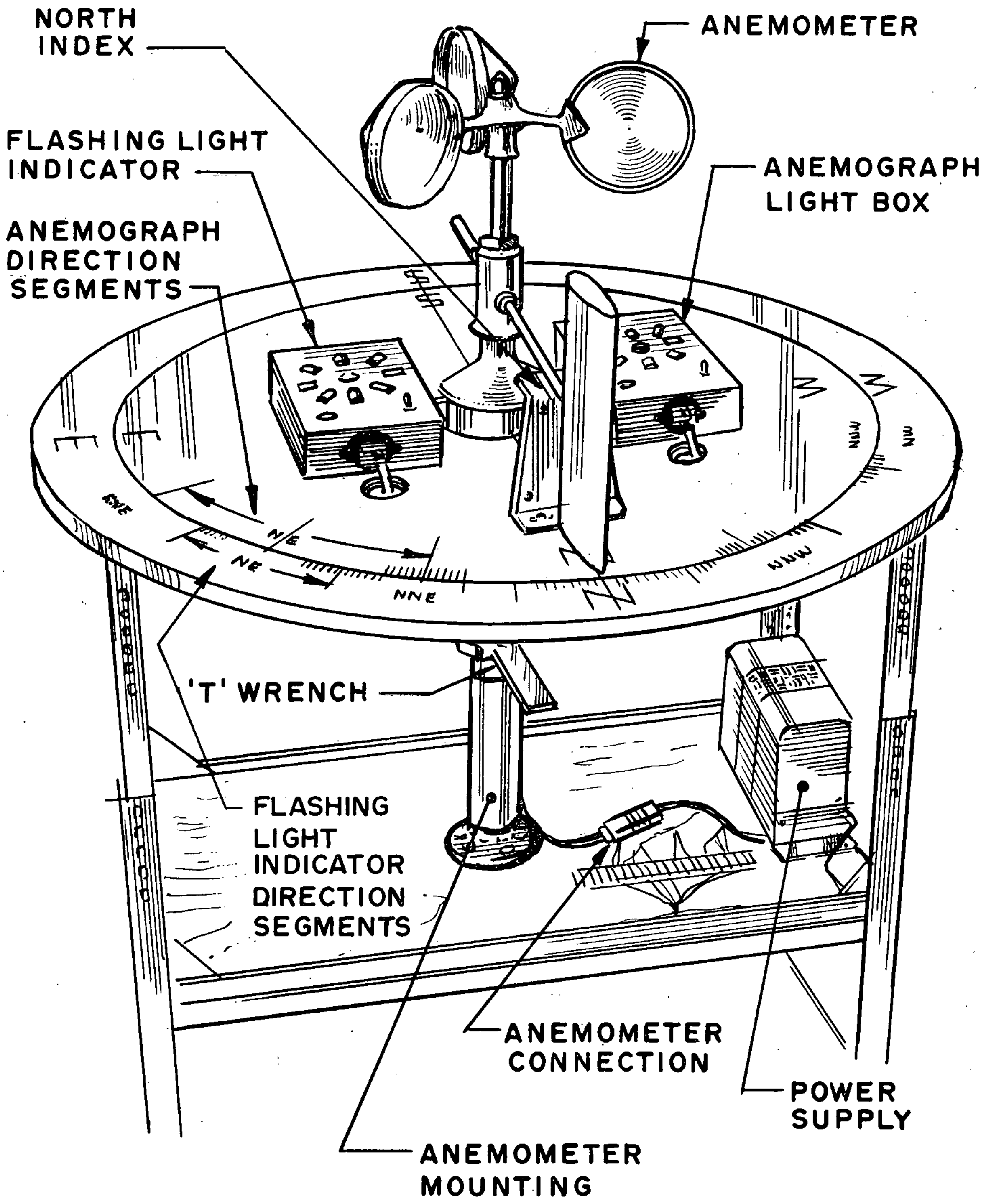
Differentiating and re-arranging:

$$2\,\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{u}\frac{\partial \bar{v}}{\partial y} + \bar{v}\frac{\partial \bar{u}}{\partial y} + \bar{u}\frac{\partial \bar{w}}{\partial z} + \bar{w}\frac{\partial \bar{u}}{\partial z} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \nu \nabla^2 \bar{u} - \left(\frac{\partial \overline{u'^2}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right) \qquad \text{(vi)}$$

By virtue of the continuity equation for the mean flow Eq. (vi) simplifies to:

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} + \bar{w}\frac{\partial \bar{u}}{\partial z} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \nu \nabla^2 \bar{u} - \left(\overline{\frac{\partial u'^2}{\partial x}} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right) \qquad \text{(vii)}$$

Similar procedure is used for the remaining coordinate directions.



DIRECTION BIAS FIXTURE
ANEMOMETER MOUNTED IN POSITION

TEC 750
28 January 1971

UDC 551-508-53
551-501-75

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