The Measurement of Atmospheric Fluxes near the Surface: A Generalized Approach

B. B. HICKS

Div. of Meteorological Physics, CSIRO, Aspendale, Victoria, Australia

(Manuscript received 2 September 1969)

ABSTRACT

A covariance computer capable of accepting analog signals representing any two atmospheric variables is described. The instrument computes the covariance in a frequency band governed at high frequencies by the sensor response times and at low frequencies by capacitive filters.

With vertical wind velocity as one input, the instrument has been successfully used for measurement of Reynolds stress, sensible heat flux, and the sum of sensible and latent heats. Given suitable sensors, direct measurement of other fluxes, such as those of CO_2 and water vapor, should be possible.

The instrument is small and portable. Power consumption is ~2 W.

1. Introduction

The eddy correlation technique for measurement of atmospheric fluxes is well proven in the cases of sensible and latent heat transfer (H and E, respectively). The "Evapotron" (Dyer and Maher, 1965) was a relatively complex instrument designed for this purpose, and was used to obtain the flux data of the various CSIRO micrometeorological expeditions between 1962 and 1966.

A simplification of the general eddy correlation technique was used in the "Fluxatron" (Dyer *et al.*, 1967). Whereas, in the case of sensible heat flux, the earlier device computed the covariance of temperature T and vertical wind velocity w from (usually) half-hour averages obtained instrumentally, the later version employed a band-pass system such that only those fluctuations which are known to contribute to the covariance were analyzed. The mean temperature was removed by means of a lagged thermometer in a bridge circuit.

A revised version of the Fluxatron, intended for the direct measurement of Reynolds stress τ, was described by Hicks (1969). This instrument correlated voltages representing horizontal and vertical wind components. Basically, it was a simple computer capable of calculating the covariance between any two analog variables within a frequency range determined by the sensor characteristics (at high frequencies) and by circuit time constants (at low frequencies). The low-frequency cut-off was set at 60 sec. The machine measured momentum flux with an accuracy of ~ 20%, but tended to underestimate the stress at low wind speeds. Although this was attributed to the integration system employed (a modified kilowatt-hour meter), it may have resulted in part from an inadequate low-frequency response of the electronics.

A further revision has now been completed. The new instrument differs from previous designs in that the use of integrated circuits and analog multiplication allows generalized inputs. It is capable of calculating the covariance of any two signals falling in a frequency band between $\sim 10^4$ and 6×10^{-3} sec^{-1}. In this report, the application of the instrument to measurement of H, $E+H$ and τ will be described.

2. The instrument

Fig. 1 is a block diagram of the instrument. An analog multiplier[1] is used to compute the instantaneous product $Gx'y'$ resulting from inputs x and y (where primes denote deviations about mean levels determined by the filters composed of R_1-C_1 and R_2-C_2 and where the gain G depends on amplifier feedback and the multiplier scale factor). Integration is by means of a mess-motor[2] as described by Dyer *et al.* (1967).

Voltage followers provide the large input impedances necessary for ease of adjustment of the filter time constants, which are normally set at 160 sec (about 2.5 times those employed in the earlier versions of the Fluxatron).

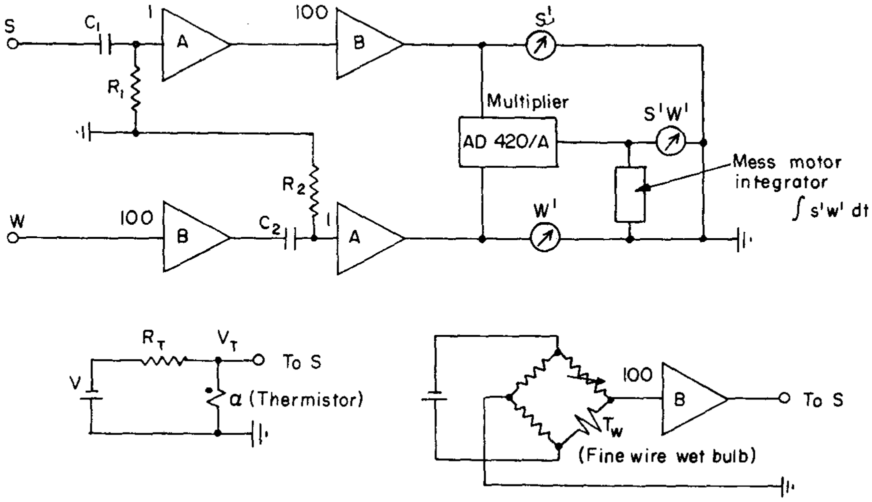
Conventional integrated circuits are used throughout. Their application is quite normal and detailed discussion is unnecessary. The only aspect of importance is the use of filtering after amplification in one channel (see Fig. 1) to remove long-term amplifier drifts.

The electronic console is small and lightweight. It operates from a ±15 V supply and consumes ~2W. Power supplies for either mains or 12 V accumulator usage are simple to construct and the equipment has been operated with both. No adjustments are required in the field.

The vertical velocity sensor employed is a propeller anemometer[3], modified by extending the shaft beyond

---

[1] Analog Devices Inc., Cambridge, Mass.
[2] Fernsteuergeate, 1 Berlin 47, Brisz, Jahnstrasse 68, Germany.
[3] R. M. Young & Co., Ann Arbor, Mich.



T circuit (for H)

T_w circuit (for E + H)

FIG. 1. Block diagram of the Fluxatron, in its most recent form. A and B are voltage followers (LM302 or similar) and amplifiers (LM709, etc.), respectively. Filters R_1-C_1 and R_2-C_2 are adjusted for a 160-sec time constant. The input s represents a general micrometeorological variable. Those discussed in the text are horizontal wind speed u, temperature T, and wet-bulb temperature T_W. Note that by applying filtering after amplification of the w signal, long-term amplifier drifts are removed.

the plane of the blades to provide a symmetrical geometry. This modification is essential (acknowledgment to Prof. K. M. King is due here). Typical outputs are about 50 mV per m sec^{-1} change in w, derived from a low torque dc generator.

Sensors employed in the various applications discussed later will be described when relevant.

The instrument is calibrated in terms of known dc inputs. Typically, inputs of the order 50 mV on each channel give integrator count rates of $\sim$ 10 min^{-1}. Resolution on the integrator is 0.1 count.

Cable lengths employed are typically 100 m, although on some occasions, lengths of up to 200 m have been used.

In the following experimental applications, the sensing head was at a height of 4 m. The high-frequency performance is governed in each case by the slowest sensor, generally the anemometer with a response length of 0.6 m.

If we consider that the highest frequency contributing to a flux is $f=u/z$, where u is wind speed and z the height (this is a commonly used criterion for the inertial subrange in neutral or unstable conditions), then a response length of 0.6 m implies that the equipment could be operated as low as about 2 m. Operation at 4 m provides a further factor of safety, although necessitating a larger uniform upwind fetch.

In the following discussion, greatest importance will be attached to the shear stress application, since the other modes of operation are more conventional, and, to a large extent, have already been proved.

3. Sensible heat flux H

In Fig. 1 the sensor arrangement for measuring H is shown. A bead thermistor is used as a temperature sensor (time constant $\sim$0.1 sec). The resistance R_T is adjusted so that the voltage across the thermistor V_T is exactly half the supply voltage V. The output is then $\Delta V_T = aV\Delta T/4$, where a is the temperature coefficient of the thermistor [usually $\sim$0.05(°C)$^{-1}$]. Self heating is kept below 0.01 C in still air.

At Edithvale, Victoria, sensible heat flux measurements were checked against predictions obtained from temperature gradients, wind profiles and u_* (friction velocity) on the basis that $\mathrm{Ri}=z/L$ (usual notation), near neutral. Heat fluxes were low, since the experiment was performed in mid-winter, when the surface was freely evaporating. A maximum heat flux of 10 mW cm^{-2} was observed.

Although conditions were not ideal for the type of comparison required, the instrument appeared to operate well. Over the entire period of operation, measured and predicted fluxes agreed to within 0.5 mW cm^{-2}. The instrument has not been used in conditions of high heat flux, but it is expected that an improved performance will result from the simplification of the circuitry and the broadening of the band-pass filter.

4. Total heat flux, $E+H$

Using a fine wire, wet-bulb sensor (Dyer and Maher, 1965), the instrument measures the total energy flux of sensible plus latent heats. This method is exact and

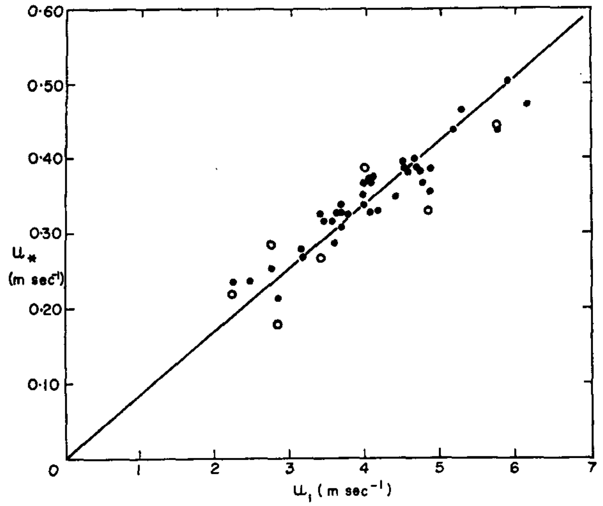


FIG. 2. Friction velocity u_* obtained with the Fluxatron as a function of wind speed at 1 m. Circles represent estimates of u_* from neutral wind profiles. The line drawn represents a friction coefficient of 0.085.

can be readily verified by consideration of the psychrometric equation. The factor to be applied for conversion of the Fluxatron outputs into conventional flux units is determined from the ambient wet-bulb temperature.

In Fig. 1, a wet-bulb bridge with dc preamplifier is shown as one of the alternative inputs. This type of input was used successfully at Lake Wyangan, near Griffith, N.S.W., where energy balance requirements were satisfied to better than 5%. In this case, heat storage in the water body was estimated from temperature profiles in the water (Linacre *et al.*, in preparation).

5. Shear stress τ

The simplest format in which the present machine can be used is as a shear stress meter. A sensor arrangement identical with that employed in the earlier version (Hicks, 1969) is used, with a second propeller anemometer as horizontal component sensor.

The instrument performed satisfactorily on both occasions it was used in this way. For example, Fig. 2 presents the results of a series of half-hour measurements made at Edithvale, Victoria, expressed as a plot of friction velocity vs wind speed at 1 m. Some scatter is evident, partly attributable to a change of drag coefficient with wind direction. In the micrometeorological sense, the site used here is not as good as those at Hay, N.S.W., or Kerang, Victoria, for example. Also shown in the figure are the estimates of u_* obtained from seven neutral wind profiles. These data appear to be more scattered than the Fluxatron results.

It is clear that the instrument provides a measure of the friction velocity which is nearly proportional to the wind speed near the surface (the commonly accepted means of estimating u_*). It is particularly pleasing that there is no visible evidence of underestimation of the stress at low wind speeds. The value of von Kármán's constant obtained from the neutral wind and stress measurements is 0.42 ± 0.02, in accord with values found elsewhere (e.g., Deacon, 1959).

6. Conclusion

The latest version of the Fluxatron operates satisfactorily in three modes. Since earlier models were capable of measuring sensible and total heat fluxes with acceptable accuracy, the most obvious improvement in performance is in the measurement of shear stress.

In its present form, the Fluxatron appears suitable for measurement of eddy fluxes at a height of 4 m. It must be remembered that these fluxes will equal the surface fluxes only for a sufficiently uniform site.

The instrumentation could be used for measurement of other atmospheric fluxes if the appropriate fast-response sensors were available. Obvious uses include the measurement of carbon dioxide flux and the direct measurement of evaporation. It is to be hoped that suitable sensors will become available.

Acknowledgments. Mr. G. Grauze constructed the instruments and conducted much of the field testing. The Fluxatron technique was developed by Dr. A. J. Dyer.

REFERENCES

Deacon, E. L., 1959: The measurement of turbulent transfer in the lower atmosphere. *Advances in Geophysics*, Vol. 6, New York, Academic press, 211–228.

Dyer, A. J., and F. J. Maher, 1965: The "Evapotron": An instrument for the measurement of eddy fluxes in the lower atmosphere. CSIRO, Div. Meteor. Phys. Tech. Paper No. 15, 31 pp.

——, B. B. Hicks and K. M. King, 1967: The Fluxatron—a revised approach to the measurement of eddy fluxes in the lower atmosphere. *J. Appl. Meteor.*, **6**, 408–413.

Hicks, B. B., 1969: A simple instrument for the measurement of Reynolds stress by eddy correlation. *J. Appl. Meteor.*, **8**, 825–827.