Application of NIFTI Method for Field Measurement of Turbulent Fluxes

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Abstract

Evaluation of turbulent fluxes at the air-sea interface is an essential problem in the study of air-sea interation. For the measurement of turbulent fluxes, the eddy correlation method is the most accurate practical method. However, its application is often technically limited, because it requires intricate instrumentation, stable platform and large amount of computation in data processing. Therefore, simple but satiscaftory accurate means of turbulent flux estimation have been required to detect flux distributions over a wide area. NIFTI (Near Isotropic Flux Turbulence Instrumentation) proposed by Hicks and Dyer[1] is instrumentation along this line. However, only its basic theory has been published and no practical examples have been shown. Therefore, the present author has developed a practical method to apply this new method by the use of nomographs. This method has proved to have satisfactory accuracy to estimate turbulent fluxes through a field experiment by the present author over Lake Biwa.

1. Introduction

Hicks and Dyer[1] proposed a new method of indirect estimate of turbulent fluxes, and named it NIFTI (Near Isotropic Flux Turbulence Instrumentation). The basic principle of this method is based on the Kolmogoroff hypothesis and MoninObukhov Similarity in spectral densities in the inertial subrange. This is promising from the points that this method has a clear physical background and is easy in data reduction and that the instrumentation required for this method is very simple. However, Hicks and Dyer[1] have presented in their original paper only the theoretical grounding of this method and no results of its application are shown. As this method was decided to be used in the field experiment of Air Mass Transformation Experiment together with direct method by the use of a sonic anemometer-thermometer, the present author had intended to make an independent check of this method comparing this method with the direct method of turbulent flux measurement which the present author has been using. The comparison experiment was made over the water surface of Lake Biwa in November 1972, and had proved satisfactory agreement between two methods.

2. Basic Principle of NIFTI

According to the Kolmogoroff Hypothesis, the spectral density of longitudinal velocity in the inertial subrange is expressed as follows.

$$F_u(\kappa)=a_u\epsilon^{2/3}\kappa^{-5/3} \tag{2.1}$$

For temperature and specific humidity spectra, Corrsin[2] introduced the following expressions,

$$F_\theta(\kappa)=a_\theta N_\theta\epsilon^{-1/3}\kappa^{-5/3} \tag{2.2}$$

$$F_q(\kappa)=a_q N_q\epsilon^{-1/3}\kappa^{-5/3} \tag{2.3}$$

where a_u, a_θ and a_q are constants called Kolmogoroff constants, while ϵ, N_θ and N_q represent dissipation rates of kinetic energy, temperature variance and humidity variance respectively and κ represents wave number (in rad/cm). Eqs. (2.1)–(2.3) can be rewritten in dimensionless form with the aid of Monin-Obukhov Similarity[3],

$$\frac{f\cdot F_{uu}(f)}{u_*^2}=a_u\phi_\epsilon^{2/3}(2\pi kf)^{-2/3} \tag{2.4}$$

$$\frac{f\cdot F_{\theta\theta}(f)}{T_*^2}=a_\theta\phi_{N\theta}\phi_\epsilon^{-1/3}(2\pi kf)^{-2/3} \tag{2.5}$$

$$\frac{f\cdot F_{qq}(f)}{q_*^2}=a_q\phi_{Nq}\phi_\epsilon^{-1/3}(2\pi kf)^{-2/3} \tag{2.6}$$

where u_*, T_* and q_* are the characteristic velocity, characteristic temperature and characteristic humidity respectively defined as follows,

$$u_*=\sqrt{\tau/\rho}, \quad T_*=-H/c_p\rho u_* \quad q_*=-E/\rho u_* \tag{2.7}$$

in which ϕ_ϵ, $\phi_{N\theta}$ and ϕ_{Nq} are dimensionless forms of the dissipation rates.

Considering the variance budget equations, these terms can be approximated by the use of dimensionless wind shear ϕ_m, dimensionless temperature gradient ϕ_h and dimensionless humidity gradient ϕ_q as follows[4],

$$\phi_\epsilon=\phi_m-z/L, \quad \phi_{N\theta}=\phi_h, \quad \phi_{Nq}=\phi_q \tag{2.8}$$

The following expressions of dimensionless gradients were given by Dyer[5], and Dyer and Hicks[6] for the unstable case,

$$\phi_m=(1-15\zeta)^{-1/4} \tag{2.9}$$

$$\phi_h=\phi_q=(1-15\zeta)^{-1/2} \qquad \zeta=z/L<0 \tag{2.10}$$

and for the stable case by Webb[7]

$$\phi_m=\phi_h=\phi_q=1+5.2\zeta \qquad \zeta>0 \tag{2.11}$$

Combining these relations with the equations (2.4)-(2.6) the following equations are obtained;

$$\frac{f\cdot F_{uu}(f)\cdot(2\pi kf)^{2/3}}{u_*^2}=\begin{cases} a_u((1-15\zeta)^{-1/4}-\zeta)^{2/3} & :\zeta<0 \quad (2.12) \\ a_u(1+4.2\zeta)^{2/3} & :\zeta>0 \quad (2.13) \end{cases}$$

$$\frac{f\cdot F_{\theta\theta}(f)\cdot(2\pi kf)^{2/3}}{T_*^2}=\begin{cases}a_\theta(1-15\zeta)^{-1/2}((1-15\zeta)^{-1/4}-\zeta)^{-1/3} & :\zeta<0 \quad (2.14)\\ a_\theta(1+5.2\zeta)(1+4.2\zeta)^{-1/3} & :\zeta>0 \quad (2.15)\end{cases}$$

$$\frac{f\cdot F_{qq}(f)\cdot(2\pi kf)^{2/3}}{q_*^2}=\begin{cases}a_q(1-15\zeta)^{-1/2}((1-15\zeta)^{-1/4}-\zeta)^{-1/3} & :\zeta<0 \quad (2.16)\\ a_q(1+5.2\zeta)(1+4.2\zeta)^{-1/3} & :\zeta>0 \quad (2.17)\end{cases}$$

The right hand sides of these equations are the functions of $\zeta=z/L$ only, except for Kolmogoroff constants. Therefore it is possible to estimate the values of u_*, T_* and q_* from the observed values of $F_{uu}(f)$, $F_{\theta\theta}(f)$ and $F_{qq}(f)$ at a certain frequency f, if the stability, $\zeta=z/L$, is given. These are the fundamental equations to obtain turbulent fluxes from spectral densities, because u_*, T_* and q_* are directly related with fluxes by definition equation (2.7). Estimation of z/L can be made as follows;

$$\frac{z}{L}=-\frac{kgz}{\Theta}\frac{H}{C_p\rho}\frac{1}{u_*^3}=\frac{kgz}{\Theta}\frac{T_*}{u_*^2} \quad (2.18)$$

in which u_* and T_* can be replaced with the aid of eqs. (2.4)-(2.6) and the result is

$$\left(Y(z/L)=\right)\frac{z}{L}\phi_{N_\theta}^{1/2}\cdot\phi_\epsilon^{-5/6}=\frac{\delta_\theta\sqrt{F_{\theta\theta}(f)}}{F_{uu}(f)}\frac{kgz}{\Theta}f^{-5/6}(2\pi k)^{-1/3}\frac{a_u}{\sqrt{a_\theta}} \quad (2.19)$$

ϕ_ϵ and ϕ_{N_θ} are replaced with eq. (2.8) then the left hand side of this equation is a unique function of z/L. While, right hand side of this equation is evaluated from the measurement of spectral densities. With this relation, the value of z/L is evaluated and turbulent fluxes are also evaluated with eqs. (2.12)-(2.17). This is the basic principle of NIFTI (Near Isotropic Flux Turbulent Instrumentaion) proposed by Hicks and Dyer[1].

3. Calculation Scheme

Only the basic principle as shown above is shown in the original paper without any example of practical application by Hicks and Dyer[1], the present author has developed a simple method to evaluate turbulent fluxes from the observed spectral densities of wind speed, air temperature and humidity by the use of nomographs.

The flow chart of the practical procedure developed by the present author is shown in Fig. 1. The observed quantities, required for the analysis are, mean values of wind speed, air temperature and specific humidity at the height of measurement, air temperature and humidity near the surface and the spectral densities of wind speed, air temperature and humidity fluctuations at the frequency near the inertial subrange.

The frequency band chosen by the original authors is $0.38\pm\Delta n$ Hz at the lowest frequency end of inertial subrange for the height range 5-10 m. According to this proposal, the present author has adopted the frequency range from 0.2 to 0.5 Hz for the band path filter in the present study. The frequency response curve of this filter is shown in Fig. 2.

In order to estimate turbulent fluxes, the value of $\mathcal{Y}$ should be evaluated by Eq.

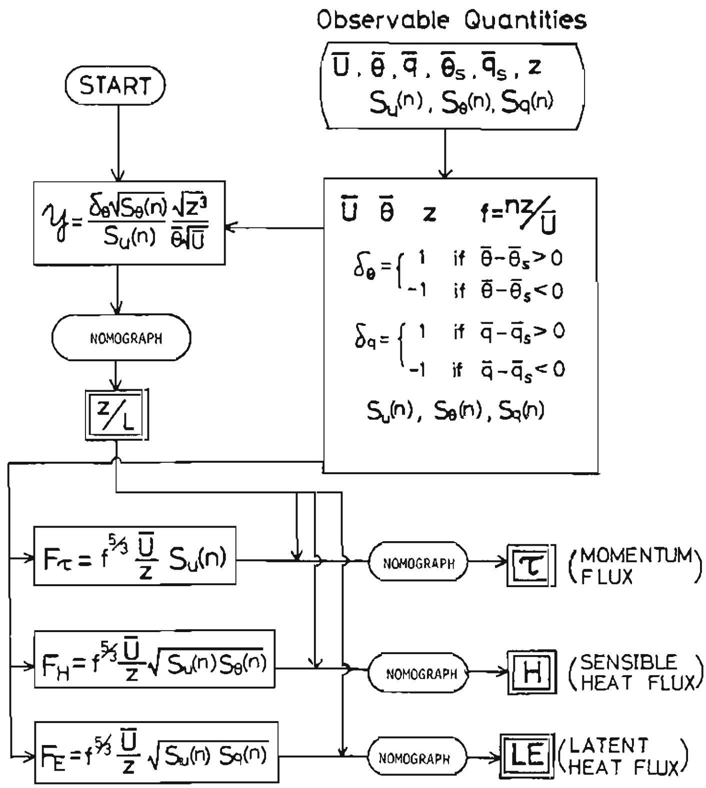

Fig. 1 Flow chart of flux estimation by NIFTI method.

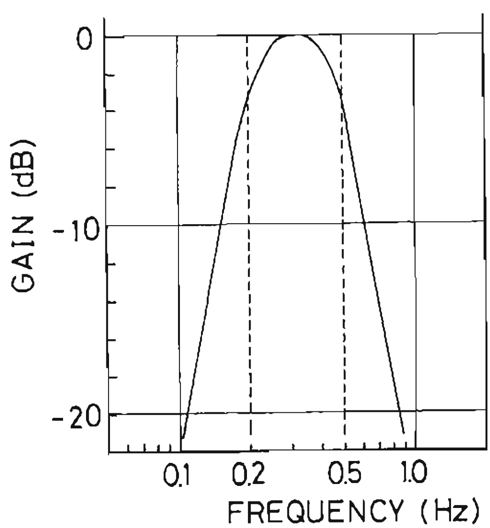

Fig. 2 Frequency response of the band pass filters. (Solid line represents the analog filter and dashed line represents the digital filter.)

(3.1) from the observed values. This gives a measure of stability. Here δ_θ is to be determined according to the sense of temperature lapse rate as shown in Fig. 1. Then the value of stability ratio, z/L, can be read from the nomograph shown in Fig. 3, where f is normalized frequency of n as defined by Eq. (3.2).

The momentum flux parameter F_τ, sensible heat flux parameter F_H and latent heat flux parameter F_E can be calculated by Eqs. (3.3), (3.4) and (3.5) from spectral densities by the use of the stability ratio as a parameter. This procedures can be made graphically by the nomograph shown in Figs. 4, 5 and 6.

$$\mathcal{Y}=\frac{\delta_\theta\sqrt{S_\theta(n)}}{S_u(n)}\cdot\frac{\sqrt{z^3}}{\theta\sqrt{U}} \tag{3.1}$$

$$f=nz/\bar{U} \tag{3.2}$$

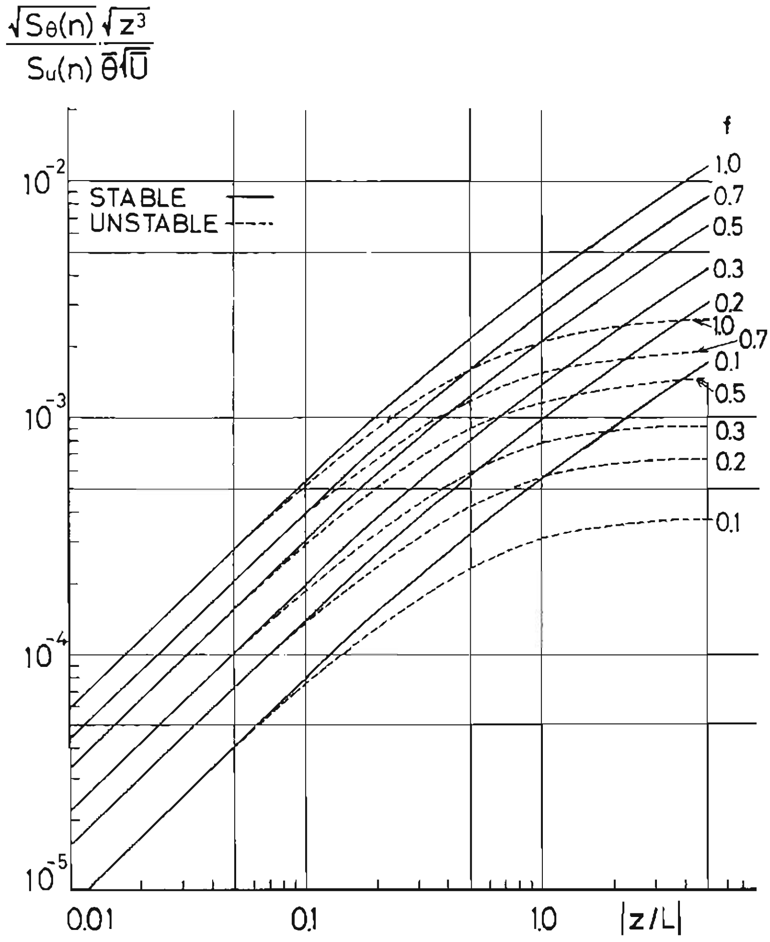

Fig. 3 Nomograph for the estimation of stability(z/L).

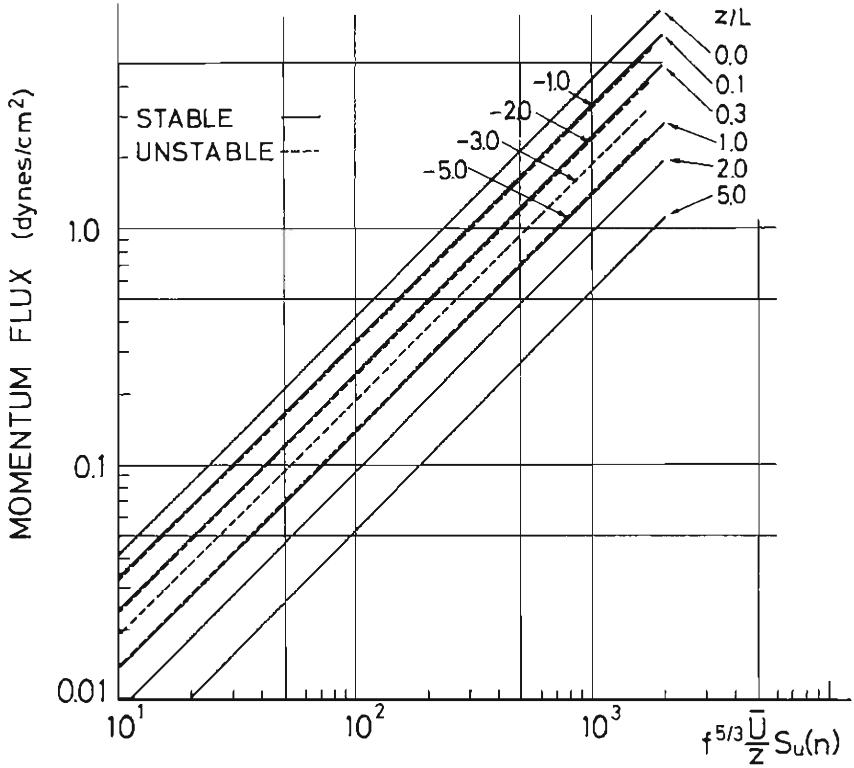

Fig. 4 Nomograph for the estimation of momentum flux(τ).

$$F_\tau = f^{5/3}\frac{\bar{U}}{z}S_u(n) \tag{3.3}$$

$$F_H = f^{5/3}\frac{\bar{U}}{z}\sqrt{S_u(n)\cdot S_\theta(n)} \tag{3.4}$$

$$F_E = f^{5/3}\frac{\bar{U}}{z}\sqrt{S_u(n)\cdot S_q(n)} \tag{3.5}$$

4. Field Measurement

The field test of NIFTI was made at the east coast of Lake Biwa. Three dimensional sonic anemometer and thermocouple psychrometer were installed at the height of 5.7 m. The fluctuations of three components of wind velocities and of dry- and wet-bulb temperatures were processed with HYSAT in real time to obtain turbulent flux estimates in direct method, and at the same time these analog signals were recorded on the magnetic tapes. The details of this observation is shown in Mitsuta et al[8]. The recorded analog signals were reproduced in the laboratory and analysed in the method shown in the previous section to obtain turbulent flux estimates in NIFTI

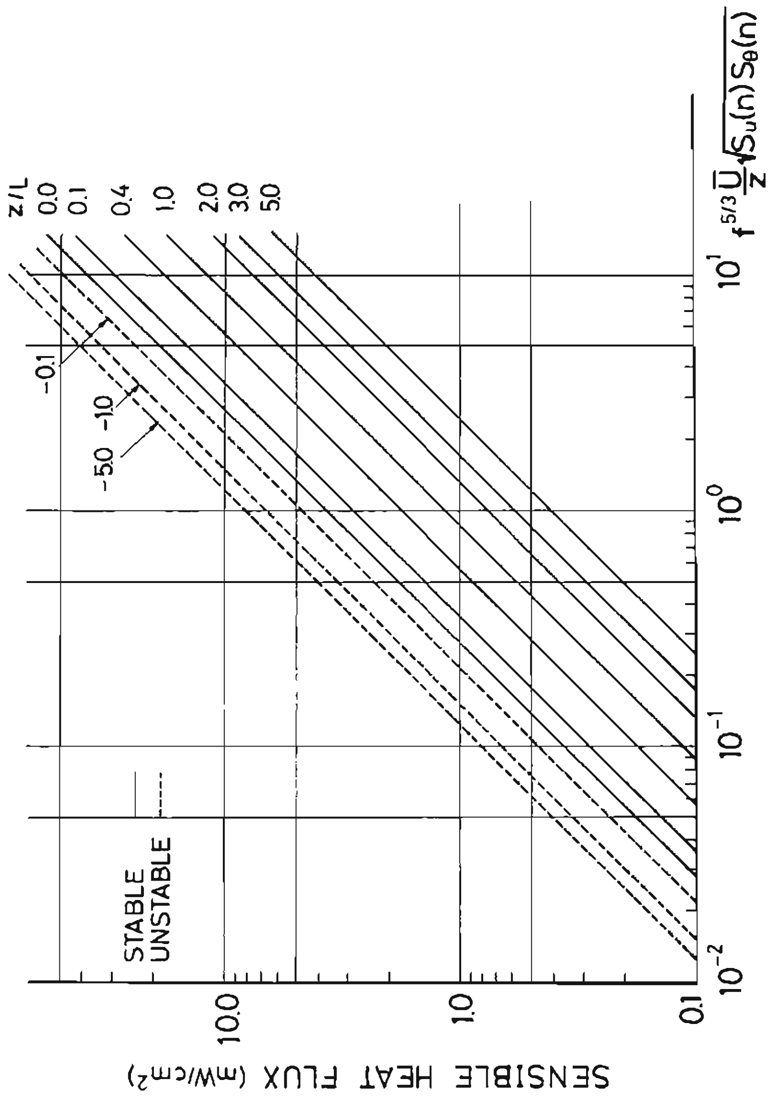

Fig. 5 Nomograph for the estimation of sensible heat flux(H).

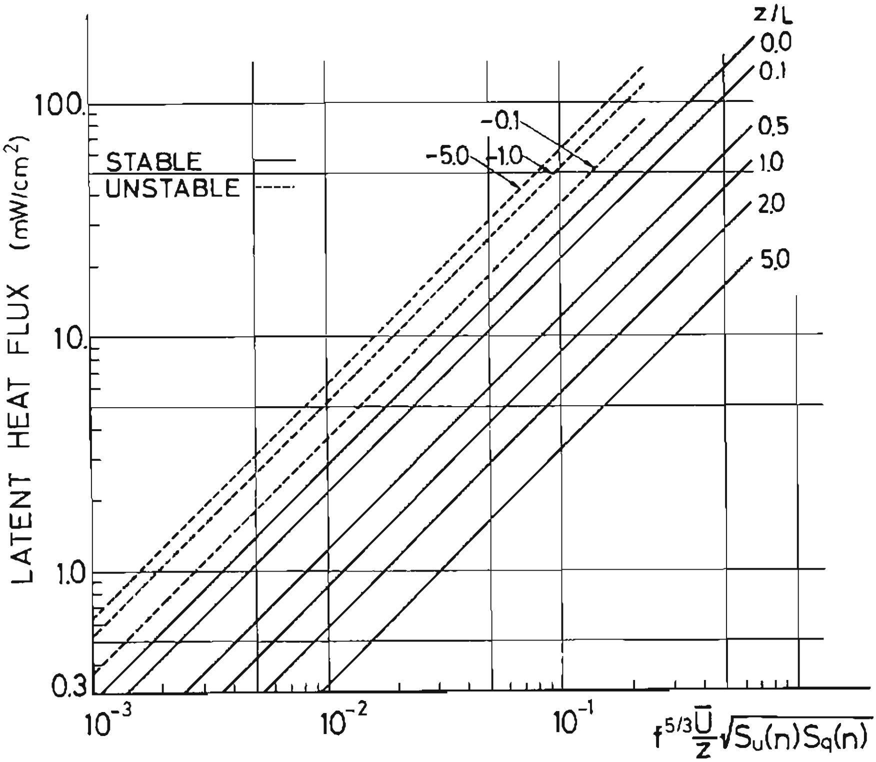

Fig. 6 Nomograph for the estimation of latent heat flux (LeE).

method. In the process of spectral analysis for NIFTI, digital processing was also made together with analog filtering method to check the differences. Thus, two sets of the values of spectral densities of u, θ and q in the frequency range of 0.2–0.5 Hz, were obtained and compared with the flux estimates in NIFTI method obtained by the direct method.

5. Results and Discussions

Turbulent fluxes obtained by eddy correlation method and NIFTI method are compared in Figs. 7–9. Roughly speaking, NIFTI method gives fairly good estimates of turbulent fluxes. Satisfactory good agreement is seen for sensible heat flux but for momentum flux and latent heat flux their scatters are fairly large. Especially, for latent heat flux, NIFTI values are systematically smaller than the values by eddy correlation method. Their correlation coefficients are 0.75, 0.97, 0.86 as for τ, H, L_eE.

In the present estimation, the values of Kolmogoroff constants are chosen to be $\alpha_u=0.54$, $\alpha_\theta=\alpha_q=0.71$. However, the values of these constants are not universally accepted. Kaimal et al[9] obtained the another form of ϕ_ϵ from the direct measure-

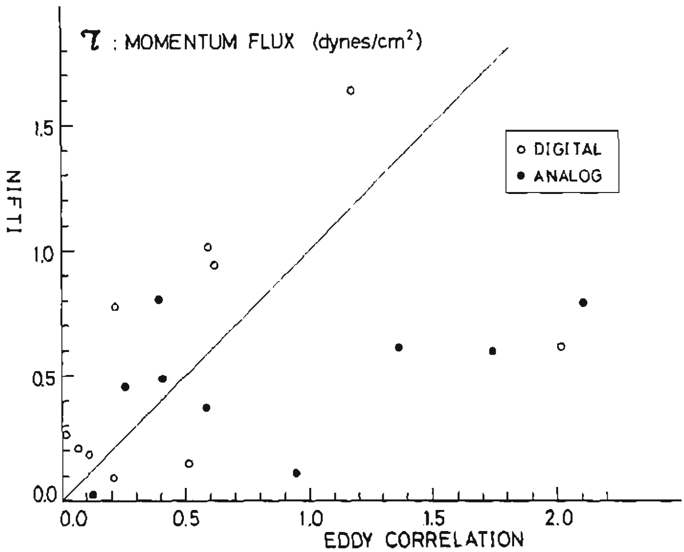

Fig. 7 Comparison of momentum flux evaluated by NIFTI method with those by eddy correlation method.

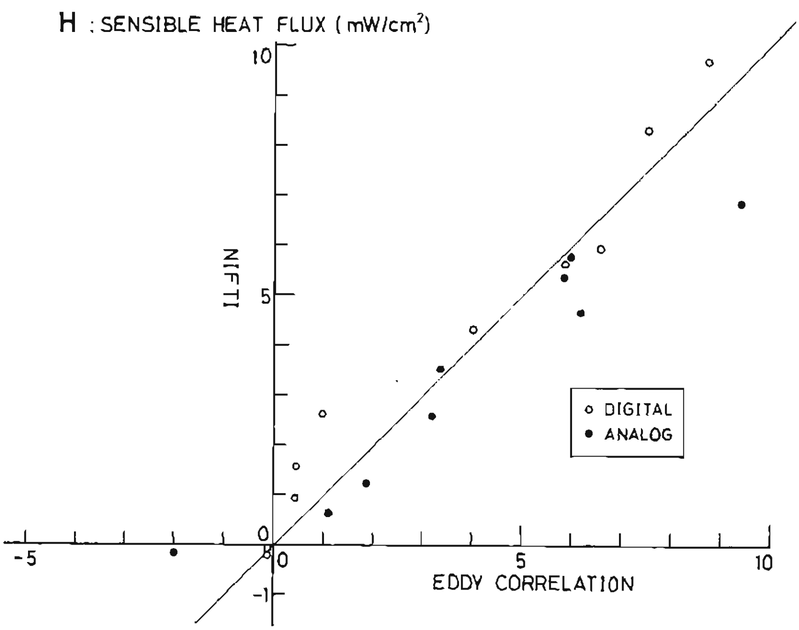

Fig. 8 Comparison of sensible heat flux evaluated by NIFTI method with those by eddy correlation method.

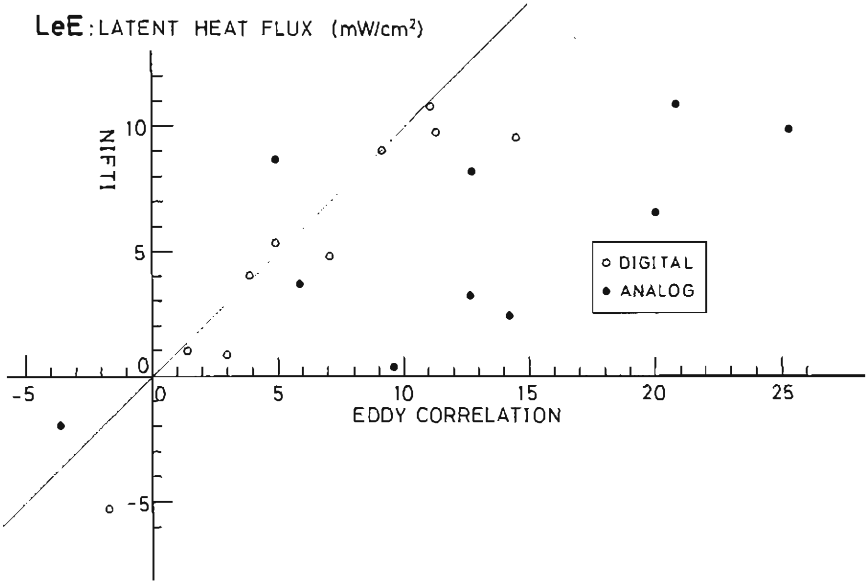

Fig. 9 Comparison of latent heat flux evaluated by NIFTI method with those by eddy correlation method.

ment of dissipation rate ε, and Businger et al[10]. published another form for ϕ_h. These discrepancies shown in nondimensional spectral densities are shown in Figs. 10, 11 and 12 with the experimental data on this case. In these figures, the results of Kaimal et al[9]. and Businger et al[10]. are drawn with a dashed line (Kansas) and the results of Dyer[5], Dyer and Hicks[6] and Webb[7] in the present method are drawn in solid line (CSIRO). But the experimental data shown in Figs. 10–12 are so scattered and it is difficult to say which curve is well fitted to the data. So this is not the essential problem.

An another cause of errors is the effect of water vapor. Especially over water, as the case of this experiment, virtual temperature should be used including the effect of water vapor as pointed out by McBean[11]. So we should rewrite the stability z/L.

$$\frac{z}{L_v}=-\frac{kgz}{u_*^3\theta_v}\overline{w'\theta'}\left(1+0.608\theta\frac{\overline{w'q'}}{\overline{w'\theta'}}\right) \tag{5.1}$$

With this relation we should rewrite Eq. (2.19) as follows.

$$Y\left(\frac{z}{L}\right)=\frac{\delta_\theta\sqrt{F_{\theta\theta}(f)}+0.608\delta_q\overline{\Theta}\sqrt{F_{qq}(f)}}{F_{uu}(f)}\frac{kgz}{\Theta}f^{-5/6}(2\pi k)^{1/3}\frac{a_u}{\sqrt{a_\theta}} \tag{5.2}$$

This may cause an error of about 20% in the value of z/L and as the result, calculated values of the fluxes should be corrected. This correction has a tendency to give better

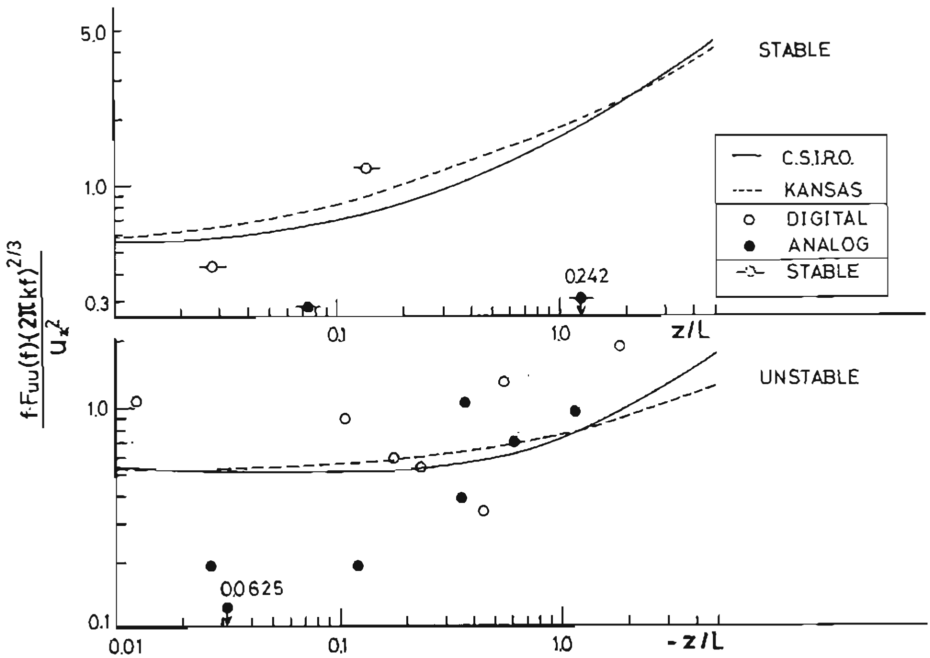

Fig. 10 Dimensionless spectral density of longitudinal velocity versus z/L.

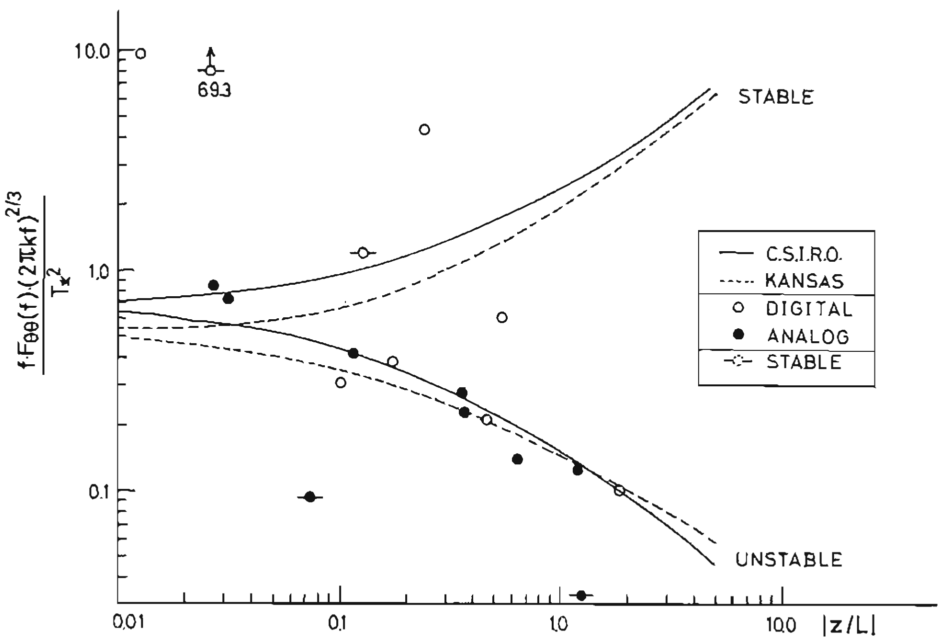

Fig. 11 Dimensionless spectral density of temperature versus z/L.

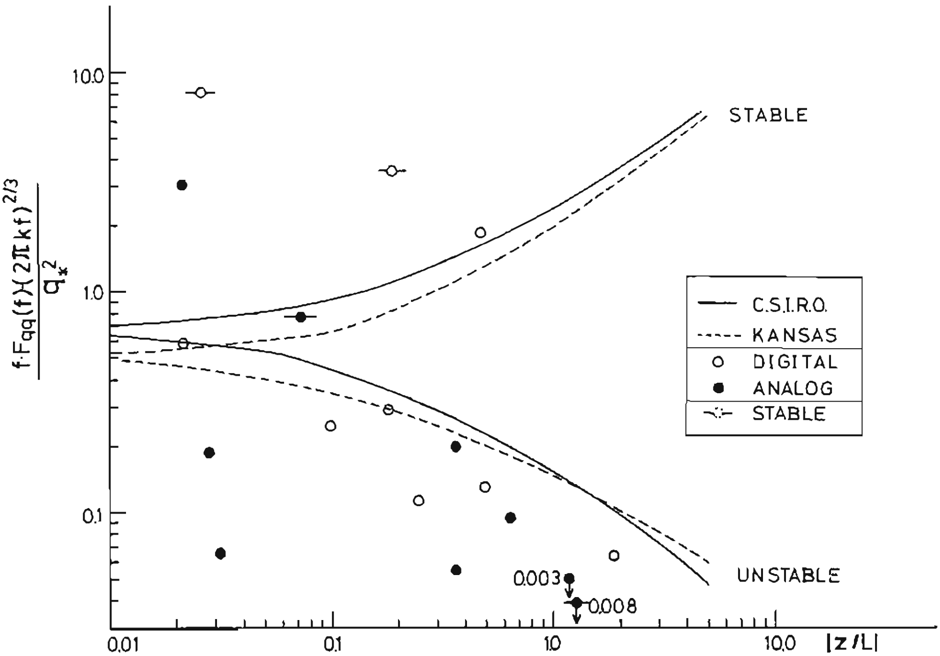

Fig. 12 Dimensionless spectral density of specific humidity versus z/L.

results qualitatively. And as for specific humidity spectral density is underestimated due to the limit of response of the instrument[12]. So a better instrument should be required.

6. Conclusions

Comparing the results of NIFTI method with eddy correlation method, sensible heat flux is obtained without large error. But as for momentum flux and latent heat flux their agreement is not so good. The discrepancies of this may due to the effect of water vapor and the response of the instrument. However, in practical sense, this method is very simple and its applicability is very wide, and the accuracy of this method will be able to be increased with the further investigations of spectral similarity.

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