THE EFFECT OF PERIODICAL FLAP MOTION ON BOUNDARY LAYER AND WAKE

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ABSTRACT

The effect of periodical flap motion on the boundary layer and the wake of the ONERA-RA16SC1 profile was studied experimentaly in incompressible two-dimensional turbulent flow. The measurements were made using hot wire anemometry for two frequencies and two mean flap angles. Instantaneous velocity and turbulent values measured in the boundary layer and the wake, were expressed with their mean value, amplitude and phase magnitude by using the harmonic analysis method. The mean flow in these frequencies was not affected by the periodical flow. Within the boundary layer, up to the flap region, the velocity amplitude was less than or equal to the amplitude of the external flow velocity, whereas around the flap, it has increased when the frequency and mean flap angle were increased. The results related to the wake showed that the turbulence level has decreased significantly within the far wake region. Turbulence amplitudes were affected by frequency and mean flap angle and its phase values have decreased linearly in the x-direction. The evolution mechanism of the wake region could be explained by the convection because of the fact that the phase of the external velocity is a linear function of the x-direction.

I. INTRODUCTION

The influence of an oscillation flap on the turbulent boundary layer and wake development has been investigated experimentaly within the framework study of generalised active control of aircrafts(10,12).

In order to correctly interprete the results, the following experimental studies in periodic unsteady turbulent flows realised by other authors were examined:

(i) Boundary layers in pulsed flows with or without mean pressure gradient(2-8,11,13-15,17,18).
(ii) Development of the turbulence in a channel flow(1,6,19,20).
(iii) The flow around the NACA 0012 oscillating airfoil profile(9).

Some general conclusions of these studies are as follows:

(1) Mean flow is not influenced by the periodic effect.
(2) Amplitude of the velocity is high in the boundary layer and increases with positive mean pressure gradient.
(3) Phase lag of the velocity is low for an external flow without phase lag in x-direction.
(4) Phase lag of the turbulence components is low in the vicinity of the wall but it can take every value towards the exteriour of the boundary layer.
(5) Influence of the unsteady motion on the turbulence production can not be clearly explained.
(6) In the wake, unsteady effects are low, except in the case of separeted flow on the profile.

In this paper, the results related to the boundary layer and the wake region, are presented using the harmonic analysis method. The mean values of the velocity and the longitudinal component of the turbulence in the boundary layer on the ONERA-RA16SC1 airfoil profile are compared with the results carried out in the steady case. Amplitude and phase lag profiles are presented for four configurations. The evolution of the external velocity has shown clearly the influence of the perturbation created by the oscillating flap. The results of the harmonic analysis of the wake axis position, defined as the line of minimum velocities, highlighted the effect of the mean flap angle and the frequency.

II. EXPERIMENTAL APPARATUS AND CONDITIONS

The wind tunnel has a test section of 30cm x 40cm and a length of 1,5m. The flow velocity is regulated by a charge loss intermediate in the downstream of the aerodynamic circuit.

The ONERA-RA16SC1 airfoil profile used in these experiments has a chord length of 180 mm and is equipped with a flap which swivels around an axis situated at 75% of the chord length from the leading edge (Fig. 1). Oscillation mechanism of the flap is of the type of connecting rod-eccentric. Eccentric is assembled on an inertial wheel driven by an electric motor with constant revolution. A mechanic speed variator serves to obtain frequencies between 10 and 60 Hz.

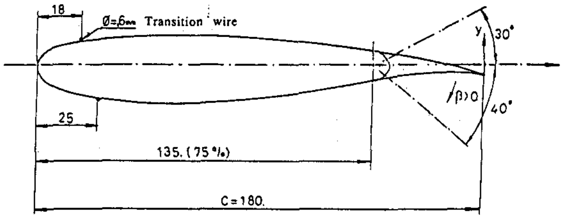

Fig. 1 ONERA-RA16SC1 airfoil profile.

Velocity measurements - Data reduction technique

All unsteady velocity measurements have been made using hot wire anemometry, with a single wire in the boundary layer and a cross wire in the wake. The data coming from these instruments must be analysed in terms of ensemble averages. On the other hand, the flow is periodic and each cycle is considered as a particular realisation of the same phenomenon. To perform the ensemble averages, the samples must be taken at the same phase angles in each cycle. To obtain this, a marking in time is necessary, which is insured by a rotating cogwheel with a photocell assembled on the oscillating mechanism of the flap (Fig. 2). The cycle is divided in 48 points. The mean velocity is calculated on 900 periods and the relative error of this sampling is 0,5% for the velocity, with the probability of 0,9 for a turbulence ratio of 0,1 (8).

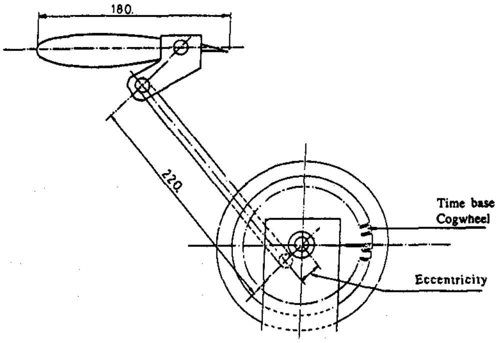

Fig. 2 Oscillating mechanism of the flap.

The data acquisition is done by using a HP21MX computer which also controls the displacement of the hot wire with a microcontrol ground intermediate, as well as the digitalisation of the measurements with 5 milivolts resolution. The volume of the data is kept on magnetic band and the reduction is made on DPS68.

Experimental conditions

The experiments were carried out for two frequencies and two mean flap deflections which give the total of four configurations. The freestream velocity is 35 m/s. The Reynolds number based on the chord length is 400 thousand. The angle of attack of the profile is 0°. The turbulence is artificially triggered by using a wire located at 10% of the chord length from the leading edge on the upperside and at 14% at the lowerside of the profile. The reduced frequency ($k=\omega c/2U_{inf}$) based on the freestream velocity and the chord is k=0,35 and 0,89 corresponding to the frequencies of the flap motion of 21,5 and 51,4 Hz respectively. The equation of the flap motion is:

$$\beta=\bar{\beta}+\Delta\beta\sin\omega t$$

where $\bar{\beta}$ is the mean flap angle of 0° and 5°. The $\Delta\beta$ is the amplitude of 1°.

III. PRESENTATION OF RESULTS

External velocity

Harmonic analysis of the external velocity is presented for the configuration $\bar{\beta}=0°$ and k=0.35 (Fig.3). Mean velocity gradient is rather important on the upperside of the profile, whereas it is constant in the wake. On the profile, the effects of the periodical flap motion, go back to the upstream of the mean flow. This transmission phenomenon of the information, from the downstream to the upstream, is one of the well known characteristics of the subsonic flows. The amplitude and phase values decrease progressively from the flap hinge to the upstream, whereas they decrease abrubtly from the hinge to the downstream until 85% of the chord length where the phase gradient reaches its maximum when the amplitude reaches its minimum value.

External velocity phase lag is 180° between the upper and lower wake . The evolution mechanism of the wake region could be explained by the convection because of the fact that the external velocity phase is a linear function of the x-direction. The convection velocity calculated with the phase lag is $0,9U_{inf}$ to $0,98U_{inf}$.

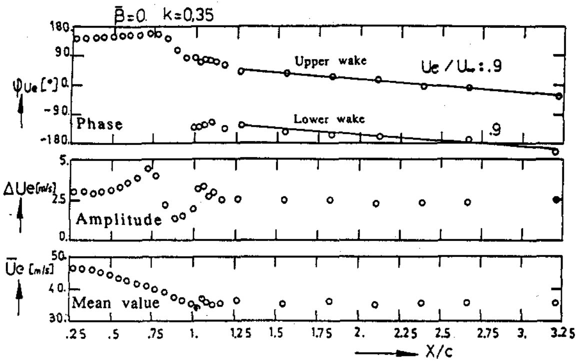

Fig. 3 Harmonic analysis of the external velocity. $\bar{\beta}=0°$ and k=0,35.

Results related to the boundary layer

Measurements of the boundary layer profiles on the upperside of the airfoil profile had not been made on the flap in the unsteady case. First, a comparison between the steady and the unsteady case is presented. The velocity and the longitudinal component of the turbulence are shown in Fig. 4a and 4b respectively. The mean velocity and turbulence profiles of the unsteady flow and the velocity and turbulence profiles of the steady flow, give analogous results. This fact shows that the mean flow in these frequencies is not affected by the flap motion.

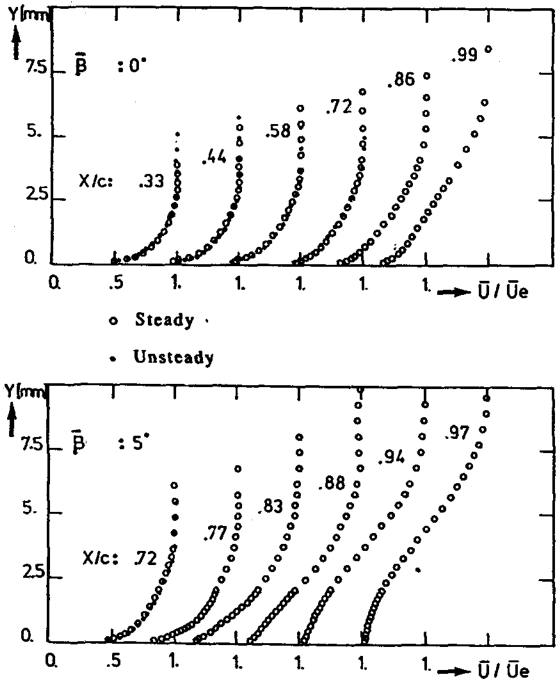

Fig. 4a Mean velocity comparisons

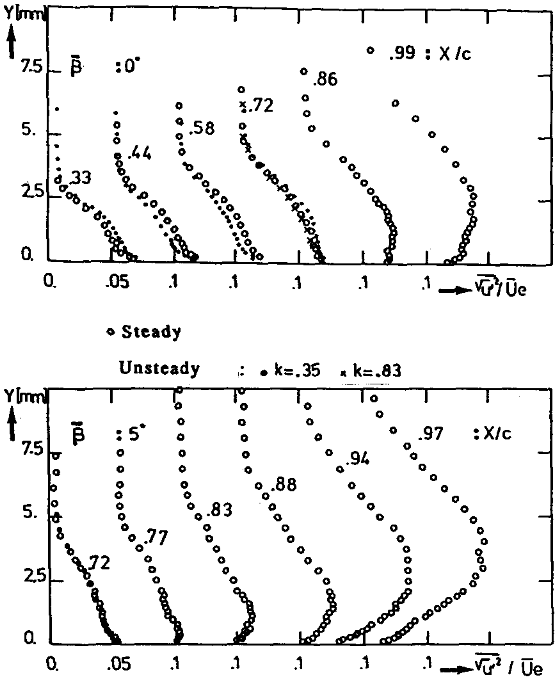

Fig. 4b Comparisons of longitudinal component of turbulence.

Instantaneous velocity and turbulence profiles near the flap hinge are expressed by a sinusoidal function and there is a 180° phase lag between them (Fig. 5). COOK(5) found similar results for the boundary layer on flat plate, the Strouhal number being less than 5. Using the harmonic analysis method, the velocity values are expressed as follows:

$$U(t)=\overline{U}+\sum_{n=1}^{N}\Delta U_n\sin(n\omega t+\phi_n)$$

where $\overline{U}$ is the mean velocity, ΔU is the amplitude and ϕ_n is the phase angle.

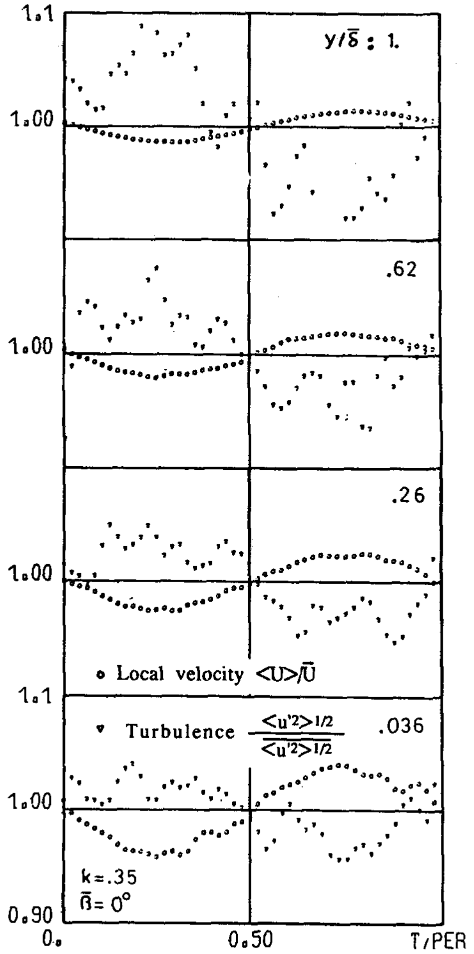

Fig. 5 Instantaneous velocity and turbulence values at x/c=0,72, for four stations normal to the wall.

In the boundary layer, up to the flap region, velocity amplitude is less than or equal to the amplitude of external flow. But near the flap hinge (x/c=0,72), for the reduced frequency k=0,35 and for both mean flap deflections, it increases to $1,6\Delta U_e$. When the reduced frequency is increased to k=0,83, the velocity amplitude for $\bar{\beta}=0^{\circ}$ and 5°, is $2,4\Delta U_e$ and $3,2\Delta U_e$ respectively (Fig. 6). These results show that the increase of the frequency and mean flap angle increase the amplitude.

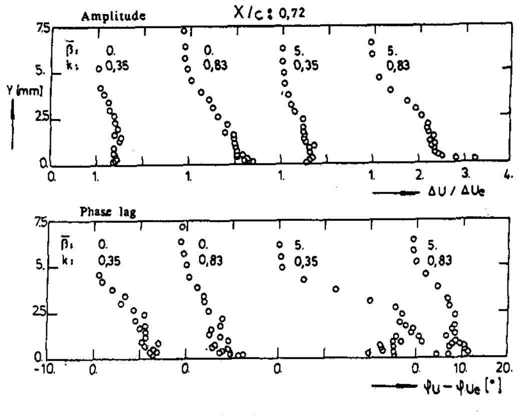

Fig. 6 Amplitude and phase lag profiles for four configurations at x/c=0,72.

In the vicinity of the wall, the phase lag between external and local velocities is 10° to 15°. For the reduced frequency k=0,35 and the mean flap angle $\bar{\beta}=5°$, a higher phase lag of 30° is observed. The reason is the flow separation because in the steady case the velocity and longitudinal turbulence component profiles show that, the separation occures on th flap when the deflection is higher than 5°. In the unsteady case, the deflection angle becomes 6° in the period, and an unsteady separation appears on the flap, which affects also the upstream phase profiles. But, in spite of the same $\bar{\beta}$ angle, the phase lag decreases again for k=0,83. This surprising behaviour can be explained by the reattachment of the flow on the flap when the frequency is increased. DE RUYCK and HIRSCH(9) obtained similar results during their experience with oscillating profile.

Results related to the wake

Measurements were carried out at 14 stations until 400 mm from the trailing edge of the flap. The x-axis is parallel to the tunnel axis and the y-axis is normal to the previous one with its origin at the trailing edge of the flap in average position.

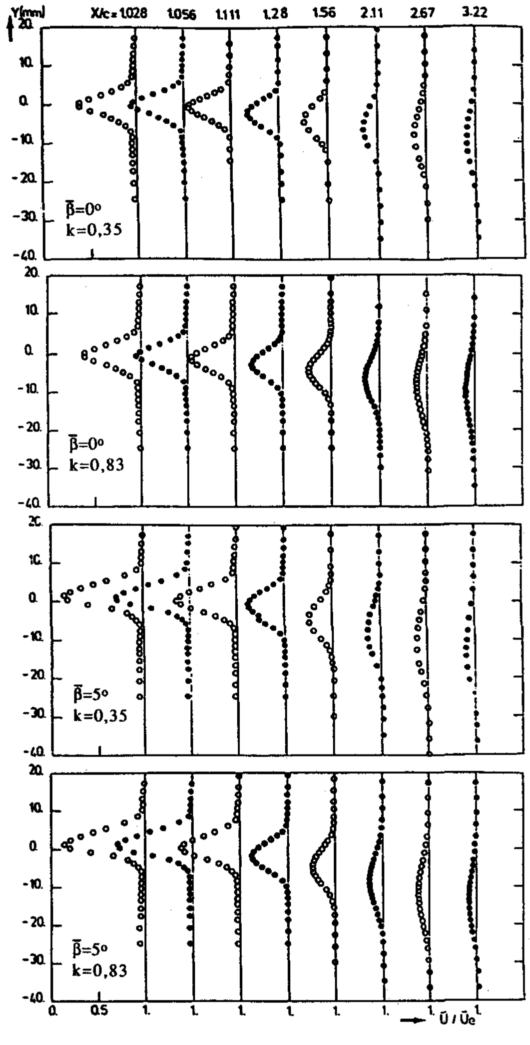

Fig. 7a Mean velocity profiles in the wake.

Mean velocity profiles show essentially the mean position of the wake axis and the thickness of the wake (Fig. 7a), on the other hand the amplitude decreases progressively in the wake (Fig. 7b), and both are influenced mainly by the mean flap angle.

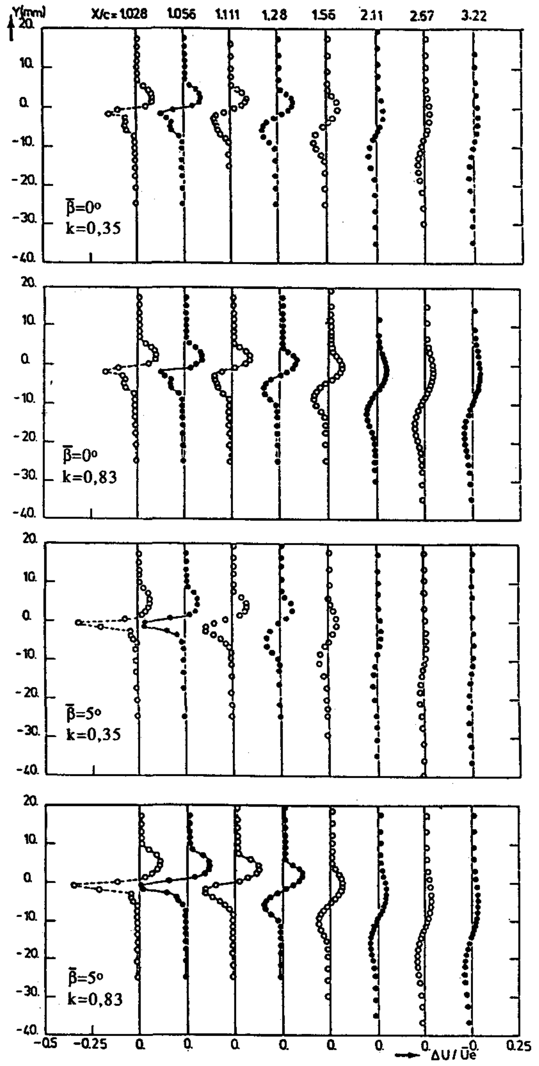

Fig 7b Amplitude profiles in the wake.

The origin of the phase is defined with the mean position of the flap. The velocity phase lag is approximately constant at each given x-station and is in advance compared to the external velocity phase lag for $\bar{\beta}=0°$ (Fig. 7c). For $\bar{\beta}=5°$ and k=0,35 the effect of the separation on the flap, appears also on the phase profiles in the wake (Fig 7c).

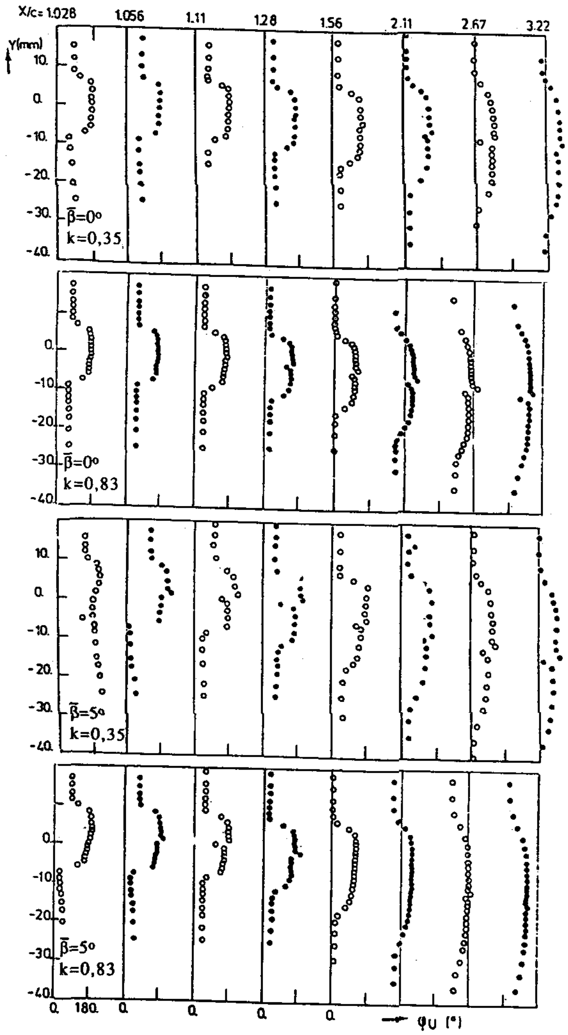

Fig. 7c Phase profiles in the wake.

The conclusions of the harmonic analysis of the wake axis position $y_o(x,t)$, defined as the line of minimum velocities, are as follows :

(1) The mean value is affected by the mean flap angles in the far wake region (Fig. 8a).

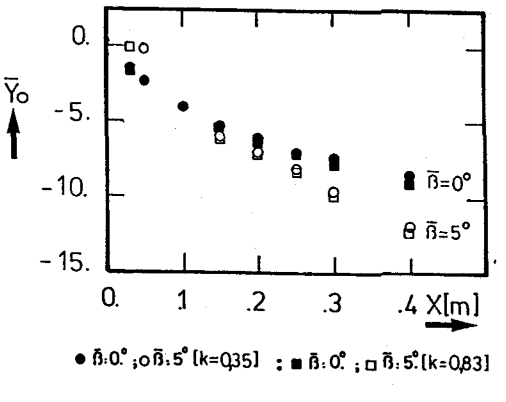

Fig. 8a Mean value of the wake axis position.

(2) The amplitude is affected by the frequency, where a linear increase is observed as a function of x (Fig. 8b).

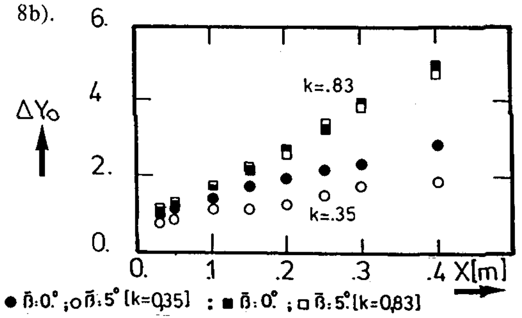

Fig. 8b Amplitude of the wake axis position.

(3) The phase lag decreases linearly in x, and the convection velocity has a value close to the freestream velocity U_{inf} with the increasing frequency (Fig 8c).

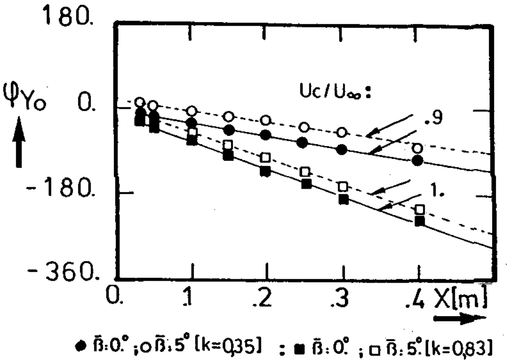

Fig. 8c Phase value of the wake axis position.

Harmonic analysis of $<(u')^2>^{1/2}$ the longitudinal component of the turbulence and $-<u'v'>$ the Reynolds stress are presented for k=0.35 and $\bar{\beta}=0^o$ & 5^o in Fig. 9a, 9b and Fig. 9c, 9d respectively. The evolution of the mean profiles show important decrease of the turbulence level. In the far wake, maximum value of the longitudinal component $<(u')^2>^{1/2}$ is half of its value near the trailing edge. Profiles are almost symmetric for $\bar{\beta}=0^o$. On the other hand, for $\bar{\beta}=5^o$, the shape of the mean profiles changes, the maximum of the upper wake becomes greater than the maximum of the lower wake.

Amplitude profiles are modified by the change of the mean flap angle. The frequency has an influence on the amplitude only in the far wake. We note that the amplitude profiles seem to be the derivative function of the mean profiles. On the amplitude profiles of the longitudinal component of the turbulence, four layers are observed, where the amplitude changes sign. For $\bar{\beta}=5^o$, these different layers appear very clearly on the phase profiles, whereas for $\bar{\beta}=0^o$, the phase value is practically constant in y for each given x-station. But the phase lag in x is observed for all cases. The phase lags of $<(u')^2>^{1/2}$ and $-<u'v'>$ on the wake axis are presented in function of the x (Fig.10). The linear development brings to the fore, a convection velocity of the turbulence components, $0{,}7U_{inf}$ and $0{,}8U_{inf}$ for the reduced frequency k=0,35 and 0,83 respectively.

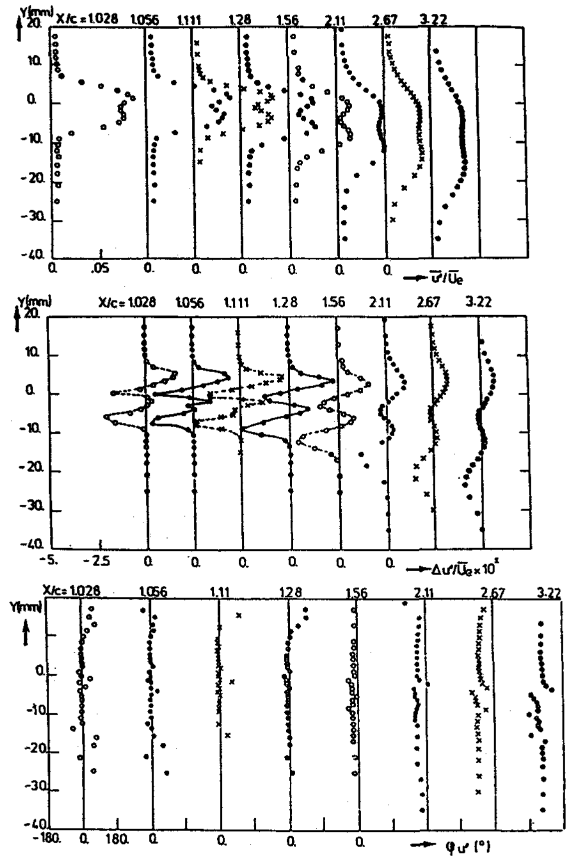

Fig. 9a Harmonic analysis of the longitudinal component of turbulence. β̄=0° and k=0,35.

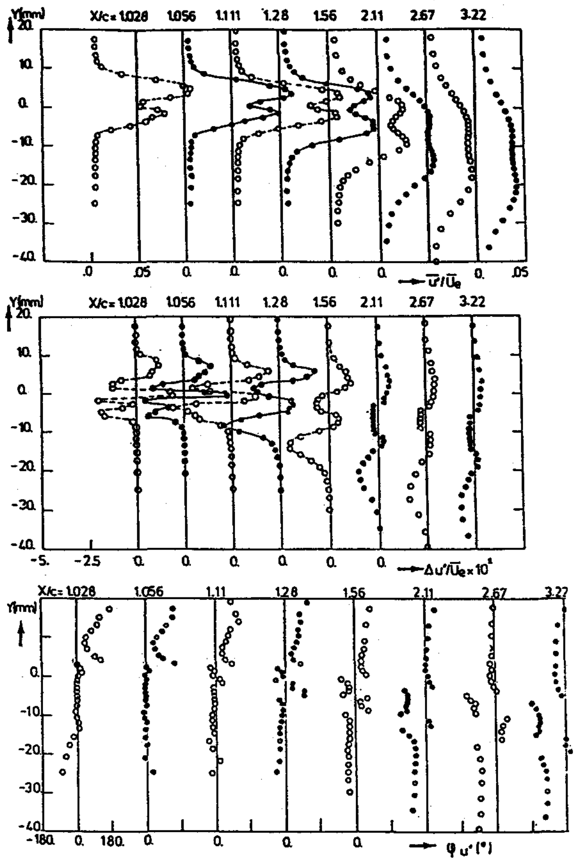

Fig. 9b Harmonic analysis of the longitudinal component of turbulence. β̄=5° and k=0,35.

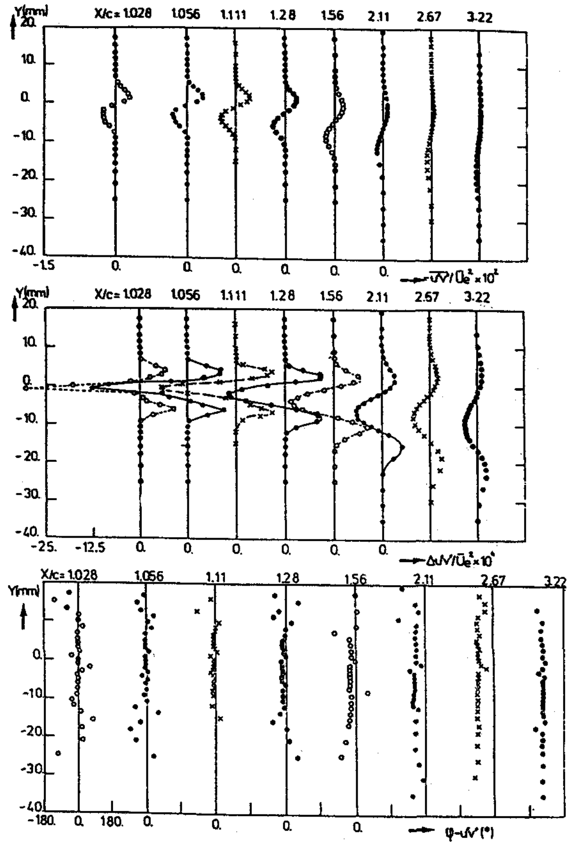

Fig. 9c Harmonic analysis of the Reynolds stress. β̄=0° and k=0,35.

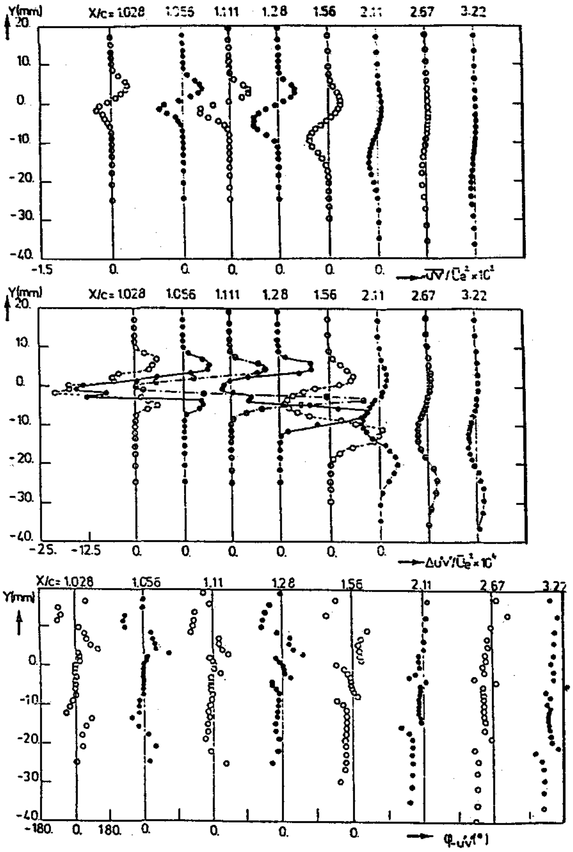

Fig. 9d Harmonic analysis of the Reynolds stress. β̄=5° and k=0,35.

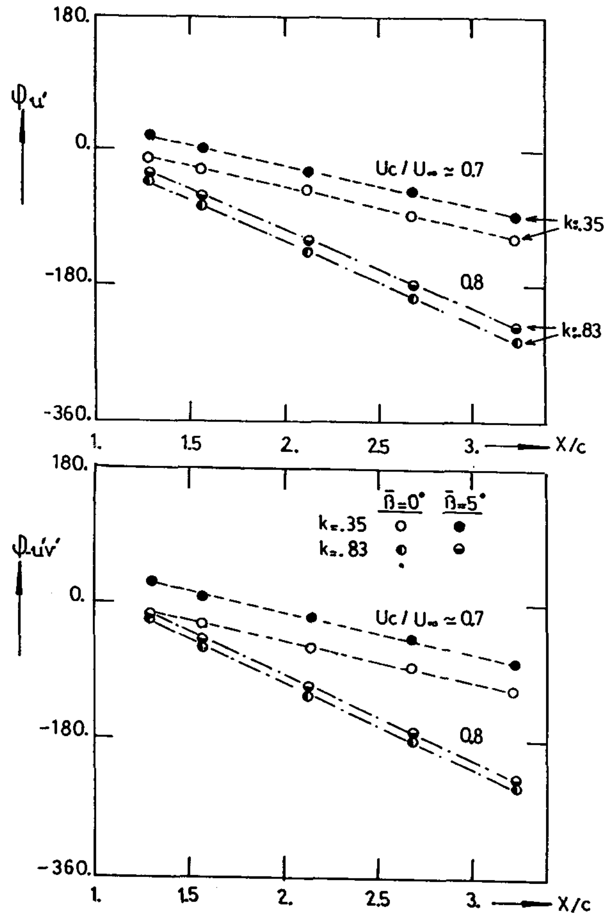

Fig. 10 Phase lag of the longitudinal component of the turbulence and the Reynolds stress.

IV. CONCLUSIONS

This experimental study has allowed the analysis of a certain number of specific points concerning the unsteady incompressible two-dimensional turbulent flows. Various flow behaviours due to the peridical flap motion, have been observed within the boundary layer and the wake. Perturbations created by the flap oscillation, reach and affect the boundary layer on the wing, by diffusion and pressure waves, whereas it spreads in the flow direction mainly by convection to affect the wake region. In other words, the phase value of the external velocity decreases on the wing and increases in the wake.

The mean flow in the boundary layer and the wake is not affected by the periodical motion of the flap for the frequencies studied in this work.

Instantaneous velocity and turbulence values around the flap have 180° phase lag between them.

In the boundary layer, especially near the flap hinge, the velocity amplitude increases when the frequency and mean flap angle increase. Near the wall, the phase lag between the external and local velocities is 10° to 15°.

The influence of the unsteady separation on the velocity phase value at this near hinge boundary layer station, decreases for higher frequency. This surprising behaviour is explained by the reattachment due to the increased frequency.

The effect of the mean flap angle and the frequency is observed very clearly by the harmonic analysis of the wake axis position. The amplitude profiles of the velocity and the turbulence components are influenced mainly by the mean flap angle. Phase values decrease linearly in the flow direction. In addition the rather important value of the convection velocity calculated with the phase lag of the external velocity, shows the important effect of the convection in the wake region.

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