FLOW VELOCITY INVESTIGATION BY EMBEDDED LASER DOPPLER VELOCIMETRY ON 3D OSCILLATING WINGS

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Abstract

The present paper concerns an experimental investigation of the unsteady boundary-layer on a flat plate model oscillating in a 3D flow configuration. The study emphasizes on the characterization of the tangential and normal velocity field (U,V) in the immediate vicinity of the moving surface. In the present study, a new Embedded Laser Doppler Velocimetry (ELDV) measurement method, suited for unsteady boundary-layer investigation has been developed.

Using this ELDV method, unsteady flow features on transition and separation/reattachment of the boundary-layer are investigated in both steady and unsteady flow configurations. The flow unsteadiness is generated by oscillating the model either in pitch or in translation, and also in a combined translation/pitch motion, at a fixed upstream Reynolds number $Re=10^5$ and for various conditions of mean incidence of the airfoil (α_0), reduced frequency and reduced amplitude of oscillations (k, λ). Steady and unsteady measurements of the (U,V) components have been performed along the upper-side of the flat plate model and at different spanwise locations. Especially the results obtained on the (U,V) velocity profiles clearly exhibit the influence of the finite span of the model, on the transition, separation and reattachment phenomena of the boundary-layer.

1 General Introduction

From an aerodynamic point of view, a detailed knowledge of the boundary-layer response to unsteadiness induced by oscillating models is one of the major goals to be reached by numerical predictive methods [1-5]. For example, one of the main problems when computing the boundary-layer is to well initialize the transition location occurrence from laminar to turbulent.

To gain a better understanding of the boundary-layer response to flow unsteadiness, previous works from the present research laboratory have been focused on the development of an Embedded Laser Doppler Velocimetry (ELDV) method, suited for unsteady boundary-layer measurements on an oscillating flat plate model [6]. The measurement principle has been based on an ELDV optical fibre option using an optical head embedded inside the oscillating flat plate model. The result was a 1D longitudinal velocity measurement in the reference frame linked with the moving wall.

Such an ELDV method has been then extended to characterize unsteady boundary-layer separation and reattachment phenomena occurring around oscillating airfoils [7-10]. From the above mentioned works, the ELDV methodology appears currently to be a very efficient tool for detailed nonsteady flow measurements near a moving surface. Using this methodology, the boundary-layer behavior and the associated specific local aerodynamic phenomena can be easily detected and directly analyzed in a frame linked to the wall.

The present study is more specially focused on the application of the ELDV method to study the transition of the boundary-layer on a flat plate model oscillating in a 3D flow configuration with 3 different kinds of motion : pitch, translation and combined translation/pitch motion. Unsteady boundary-layer characteristics are then deduced from measurements of the 2D instantaneous velocity components (U,V), tangent and normal to the local surface of the oscillating model. As described below, the measurement principle basically consists in using a specific arrangement of the ELDV optical fibres option, which are installed outside the airfoil but always linked with the oscillating frame and thus with the motion of the model.

2 Experimental Set-Up and Measurements Methods

As sketched in Figure 1, experiments are conducted at LABM laboratory in the S2-Luminy subsonic wind-tunnel (rectangular cross section : 0.5 x 1.0 m2 ; length : 3m ; velocity $U_\infty \leq 20\ ms^{-1}$), by means of an oscillating device located beneath the wind-tunnel test section. The flat plate model is supported in a vertical position and attached to the oscillating frame by means of a support shaft located at the quarter-chord axis. Different kinds of model motions can be simulated [6]: fore-and-aft translation, plunging, pitching and translation coupled to pitching.

The present study more specifically concerns unsteady boundary-layer measurements on flat plate model oscillating :

- in pitching motion (instantaneous incidence variation around a mean incidence) :

$$\alpha(t) = \alpha_0 + \Delta\alpha\cos\omega t \qquad (1)$$

- in fore-and-aft translation motion (instantaneous velocity variation) :

$$U_{rel}(t) = U_\infty + A\omega\cos\omega t \qquad (2)$$

- in combined translation/pitch motion (fore-and-aft coupled to pitching) :

$$\alpha(t) = \alpha_0 + \Delta\alpha(\cos\omega t + \phi), \qquad (3)$$

$$U_{rel}(t) = U_\infty + A\omega\cos\omega t$$

The upstream Reynolds number based on the chord of the model is fixed at $Re=10^5$. To analyze the influence of the tip vortex due to the finite span of the model, steady and unsteady measurements of the normal and tangential velocity (U,V) have been performed at 3 different spanwise sections z/h=0.42, 0.54, 0.73 and 3 chordwise stations distributed along the upper side surface, namely at : x/c=0.38; 0.50; 0.60. For each given spanwise and chordwise station (z/h=constant, x/c=constant), the survey of the flow is performed along the local normal to the wall surface (about 20-25 altitudes y ranging from y=0.2mm to 100mm with a displacement accuracy of 0.1 µm).

The flat plate model has 37 cm in chord, 40 cm in span. The optical head is mounted on a supporting turntable, which is attached to the oscillating frame as shown in Figure 2. The optical head is equipped with a beam-expander to increase the focal distance up to 400 mm, so that the laser beams are focusing at mid-span in the boundary-layer through a 45° mirror. Due to the fact that the supporting turntable is linked with the oscillating frame, the U and V velocity components are directly measured in the reference frame in relative motion.

Figure 3 presents the acquisition system of the bidimensional ELDV system operating in the back scatter mode. This chain includes the Argon laser source (5 W), the beam splitter and the transmitter block where the four beams (2 blue for the U-component, 2 green for the V-component) are connected by means of four optical fibres to the optical head linked with the airfoil motion. The light reception is realized through an additional optical fibre connected to a beam splitter and two photomultipliers PM1 and PM2 (see Figure 3). The main characteristics of such an ELDV system are as follows : On the blue color (wavelength : 488 nm), the measurement volume is 0.23 x 0.23 x 5.74 mm3 ; and the interfringe is i = 6.10 mm. On the green color (wavelength : 514.5 nm), the measurement volume is 0.24 x 0.24 x 6.08 mm3 ; and the interfringe is i = 6.44 mm.

Data acquisition is made on a micro-computer from two Burst Spectrum Analyzers delivering for each velocity component (U,V) the Doppler frequencies and the arrival validation time for each frequency measurement (Figure 3). The arrival validation times are counted from a time origin delivered by a photoelectric cell mounted on the oscillating device and providing the airfoil position at each phase of the oscillation. The software (COMBSA) used for acquisition and data reduction has been developed at the L.A.B.M. [7-9] under Apple-LabVIEW system.

The unsteady data reduction technique is made using an ensemble average procedure suited for periodic flow investigation. In fact, each period is considered as a specific sample of the same phenomenon. Each velocity component, U(t) or V(t), can be obtained at each phase angle ωt, as the averaged value of the velocity samples recorded at the same given phase angle and over a large number of oscillations (higher than 150). The simultaneousness of the 2D measurement is then obtained from a synchronization procedure of the acquisition chain, providing the phase averaged value of the mean velocity components and their associated turbulent quantities [9-11].

The seeding of the flow is provided by means of burned oil generators producing particles of about 1µm in diameter. As shown in Figure 1 the freestream flow is seeded by means of a streamlined tubes located in the suction chamber of the wind-tunnel.

3 Results and discussion

3.1 Steady flow configuration

Considering first the flat plate model in a steady 3D flow configuration, Figure 4 shows the evolution of the mean tangential velocity components $U/Ue=U/Ue(\eta)$ measured as a function of η (reduced Blasius normal distance to the surface) at U_∞=5 m/s, z/h=0.73, x/c=0.38, 0.60 and for α_0=0deg, 6deg, 12deg. Figure 4 compares the evolution of the experimental boundary-layer profiles with theoretical velocity profiles corresponding to a laminar (Pohlhausen law) or turbulent (1/N laws) boundary-layers. Figure 4 shows a laminar boundary-layer behavior for α_0=0deg while the velocity profiles measured at α_0=6deg and 12deg exhibit a transition of the boundary-layer which is shown to strongly increases the values of the boundary-layer thickness δ.

The development of the steady boundary-layer along the span of the half-wing model, is analyzed in Figure 5 (α_0=12deg, $Re=10^5$, x/C=0,382). For 3 different spanwise sections z/h=0.42, 0.54, 0.73, Figure 5 presents the evolution of the (U,V) velocity profiles as a function of y. It has been shown in previous works [11] that for α_0=0 deg, the U=U(y) profile appears to be not much sensitive to the variation of z/h. On the other hand, the results obtained at α_0=12deg indeed show strong variations on the tangential and normal velocities (U,V) with a significant decrease at z/h=0.73 of the boundary-layer thickness δ when compared with the inner parts of the half wing (z/h=0.42, 0.54). This phenomenon has to be attributed to the influence of the strong intensity of the tip vortex at α_0=12deg.

3.2 Unsteady Flow Configuration

The pitching motion effect on boundary-layer transition is illustrated on Figures 6 and 7 trough the oscillating conditions defined as : $Re=10^5$, U_∞=5m/s z/h=0.42, k=0.188, α_0=6deg, $\Delta\alpha$=6deg which involves instantaneous incidence variation $0deg<\alpha(t)<12deg$. Figure 6 presents the evolutions $U/Ue=U/Ue(\eta)$ for 8 successive phases ωt along the oscillation period ($0deg\leq\omega t\leq 360deg$) at x/c=0.38. As for the steady flow case, the boundary-layer evolution is compared at each phase ωt, with theoretical velocity profiles. Thus, Figure 6 exhibits a cyclic process of transition/laminarisation of the boundary-layer. Moreover, the plots corresponding to ωt=315deg and $0deg\leq\omega t\leq 45deg$, show an increase of the boundary-layer thickness δ which is due to the transition phenomenon occurring in the flow region very near to the surface.

The validation of the unsteady transition criterion established in previous works [6-10] on oscillating models in 2D flow, has been extended in the present study to the flat plate model oscillating in a 3D flow configuration with different kinds of motion: pitch, translation and combined translation/pitch motion. This criterion is based on the integral energy thickness parameter δ'_3, and has been formulated as shown in Figure 7.

In Figure 7, the instantaneous values of $R\delta'_3$ are plotted as a function of Re_x at different phases of the period. The $R\delta'_3$ evolution is represented by a hysteresis loop in the Re_x-$Re\delta'_3$ diagram which is typical of the instantaneous transitional response of the boundary-layer as a function of the unsteadiness parameters generated by the forced airfoil motion. The results clearly indicate the capability of this transition criterion for delimiting accurately the laminar regime (white symbols) from the transitional/turbulent regime (black symbols), as a function of phase ωt.

An example of an extension which confirms the validity of the above transition criterion for the conditions of unsteadiness generated by the combined motion is also shown in Figures 8 and 9. The boundary-layer survey is performed in this case for the following parametric conditions: α_0=6deg, Δα=6deg, $Re=10^5$, k=0.188, λ=0.251, x/c=0.382, z/h=0.42. Figure 8 presents the evolution of the U/Ue=U/Ue(η) profiles along the oscillation period. The velocity measurements obtained are alternately well matched by theoretical velocity profiles corresponding to transitional/turbulent boundary-layer (1/N laws) and by laminar boundary-layer (Polhausen law). In this case, the phases ωt corresponding to a turbulent boundary-layer regime are shown to correspond to more than the half of the oscillation period (315deg≤ωt<180deg). The validity and the efficiency of the previous transition criterion for the conditions of unsteadiness generated by the translation/pitch combined motion are shown in Figure 9.

For 3 abscissa x/c and 2 spanwise locations z/h, the characteristic evolutions of the (U, V) velocities during a cyclic separation /reattachment process of the boundary-layer, are exhibited in Figure 10 to 11 (pitching motion : α_0=12deg, Δα=6deg, $Re=10^5$, k=0.188).

Figure 10 show that at z/h=0.54, the profiles corresponding to the 3 reduced abscissa x/c=0.38; 0.50; 0.60 show a separation process of the boundary-layer. It can be noticed that the oscillation period corresponding to a separation of the boundary-layer is more important at x/c=0.38 than x/c=0.5 and 0.6. In fact, the phase ωt =90deg in Figure 10 corresponds to a separated flow for x/c=0,38 and to an attached boundary-layer regime for x/c=0.5 and 0.6. The separation process appears to be initiated prior to the maximum incidence value (α=18°) and is shown to propagate from the leading edge of the oscillating flat plate model. The dynamic reattachment of the boundary-layer then occurs during the incidence upstroke of the pitching motion.

The Sandborn & Kline separation criterion [12] previously checked to characterize the separation process occurring on the NACA0012 airfoil either in steady flow or in pitching motion [7-9], has been also applied in Figure 11 to the present pitching oscillation conditions. As shown in Figure 11, the Sandborn & Kline criterion is based on the instantaneous shape factor H which is expressed as a function of δ1/δ. This criterion should be able to detect attached flow regimes and to differentiate intermittent from fully developed separation regimes.

From the results in Figure 11, it is shown that the Sandborn & Kline criterion appears to be well suited in accurately delimiting the attached boundary-layer regime (black symbols) and the separated flow regimes (white symbols) for the unsteady flow generated by the pitching motion.

4 Conclusions

In the present study, the Embedded Laser Doppler Velocimetry (ELDV) method has been successfully applied to 2D velocity measurements (U,V) both in steady flow case and around a moving flat plate model oscillating in pitch, translation, and translation/pitch combined motions. Using this ELDV method, the boundary-layer dynamic behavior and the specific local unsteady flow features concerning separation and transition, have been investigated over a large range of non-steady parametric conditions.

The influence of coupling incidence and velocity variations on the development of the unsteady boundary-layer (2D velocity field, thickness, separation and transition) have been accurately identified as a function of the phase ωt.

From the present results it has been shown that the Sandborn & Kline criterion appears to be well suited in delimiting attached and separated flow regimes in pitching motion. Moreover, the unsteady transition criterion previously established on oscillating models in 2D, is shown to be also valid on the flat plate model oscillating in a 3D flow configuration and submitted to more general conditions of forced flow unsteadiness generated by coupling incidence and velocity variations by means of the translation/pitch combined motion.

5 Acknowledgments

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6 References

[1] TELIONIS, D.P. "Unsteady viscous flow.", Springer Verlag Editor, N.Y., 1981.

[2] SIMPSON, R.L. “Turbulent Boundary-Layer Separation.”, Ann. Rev. Fluid Mech., 21, pp 205-234, 1989.

[3] COUSTEIX, J. and HOUDEVILLE, R. "Effects of unsteadiness on turbulent boundary-layers.", Fluid Dynamics Lecture Series of V.K.I, 1988.

[4] BRERETON, G.J., CARR, L.W., and REYNOLDS, W.C. “Unsteady turbulent boundary-layer experiments with rapidly changing free-stream conditions”, AGARD CP 386, pp. 11.1-11.10, 1985.

[5] FAVIER, D., AGNES, A., BARBI, C. and MARESCA, C. "Combined translation/pitch motion : a new airfoil dynamic stall simulation.", Journal of Aircraft, Vol. 25, N° 9, pp. 805-814, 1988.

[6] FAVIER, D., MARESCA, C. and BELLEUDY, J. "Unsteady flows around an oscillating flat plate model using an embodied technique of fibre optics laser velocimeter", Proceedings of the 17th Congress of Aeronautical Sciences, I.C.A.S.-A.I.A.A., Stockholm, 1990.

[7] FAVIER, D., MARESCA, C., RENON, P. and AUTRIC, J.M. “Boundary-layer measurements on oscillating models using an optical fibre LDA technique”, Proceedings of the 6th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, 1992.

[8] PASCAZIO, M., AUTRIC, J.M., FAVIER, D. and MARESCA, C. “Etude de la couche limite sur une plaque plane oscillant en tangage par vélocimétrie laser emlbarquée”, Proceedings du 11ème Congrès Français de Mécanique, Lille-Villeneuve d’Ascq, 1993.

[9] FAVIER, D., MARESCA, C. and PASCAZIO, M. “Etude expérimentale et numérique du décollement de la couche limite instationnaire sur un modèle oscillant en écoulement 2D/3D.”, D.G.A./D.R.E.T. Contract n° 91/158, Synthesis Report, 1994.

[10] PASCAZIO, M. "Contribution Experimentale et Numérique de la Couche Limite se Développant sur un Profil d'Aile Oscillant : Phénomènes de Transition et de Décollement en Ecoulement Instationnaire", Thesis of the University of Aix-MarseilleII, 1995.

[11] FAVIER, D., MARESCA, C. and BERTON, E. “Etude expérimentale et numérique du développement de la couche limite instationnaire sur modèles oscillants en écoulement 2D/3D.”, D.G.A./D.R.E.T. Contract n° 95/052, Synthesis Report, 1996.

[12] SANBORN, V.A. and KLINE, S.J. "Flow Models in Boundary-Layer Stall Conception", J. Basic Eng., pp. 317-327, 1961.

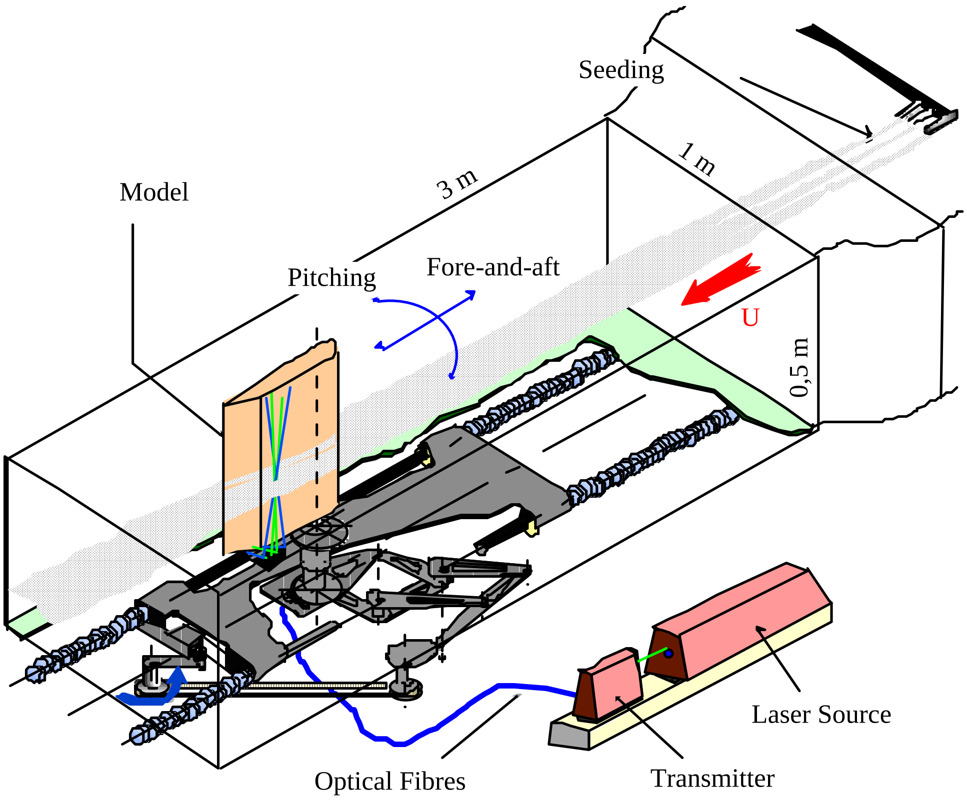

Fig. 1 S2 Luminy wind-tunnel Experimental set-up.

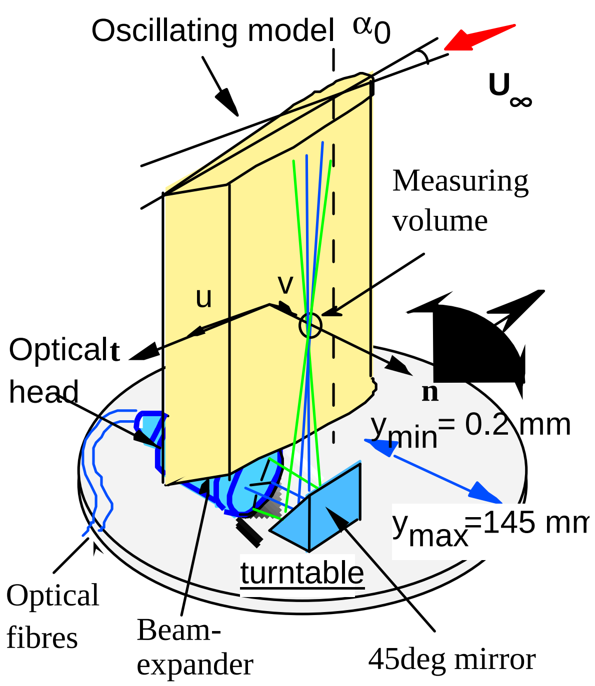

Fig. 2 Embedded optical head linked with the oscillating model.

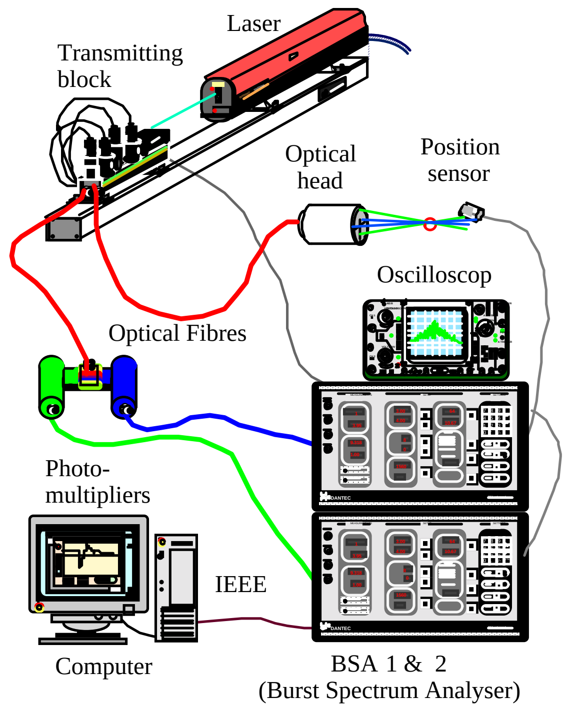

Fig. 3 ELDV data acquisition system.

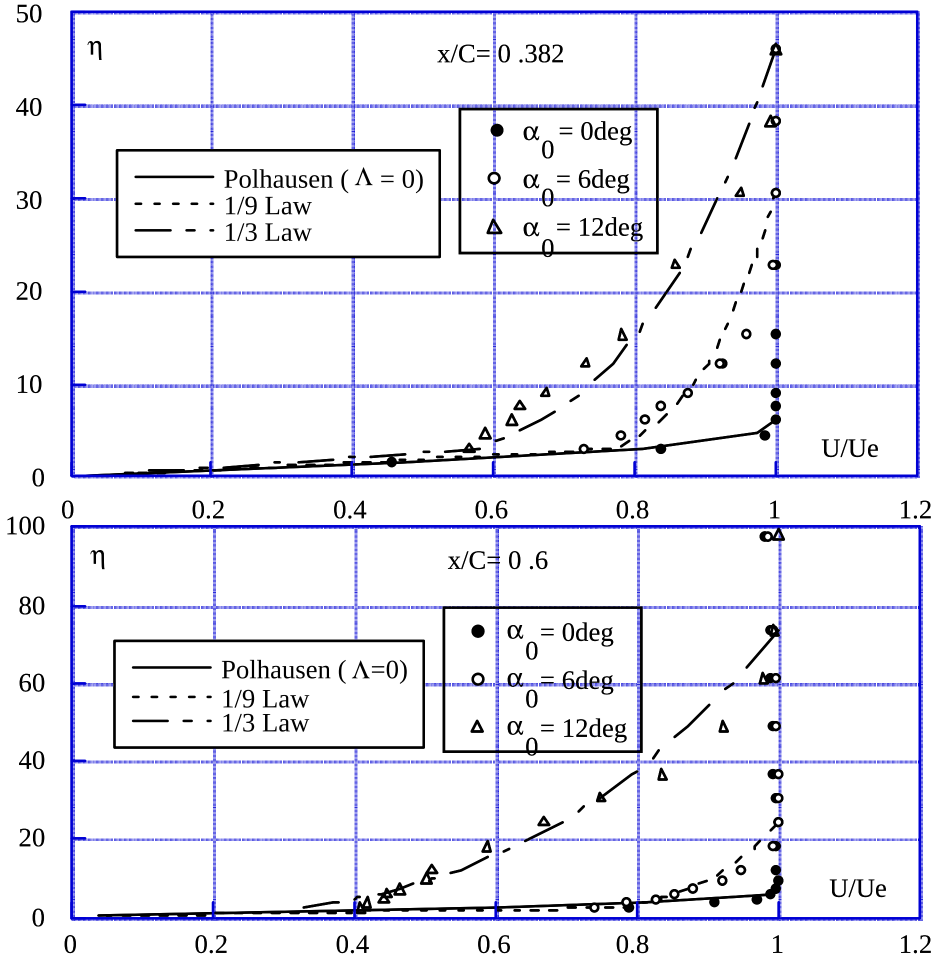

Fig. 4 U-velocity distribution, Steady flow as a function of α_0.

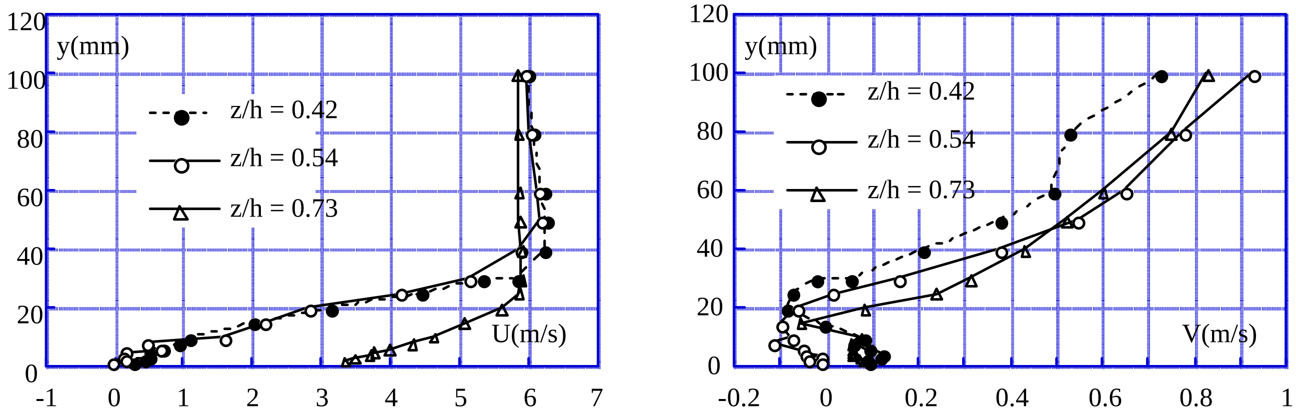

Fig. 5 U-velocity distribution, Steady flow as a function of z/h.

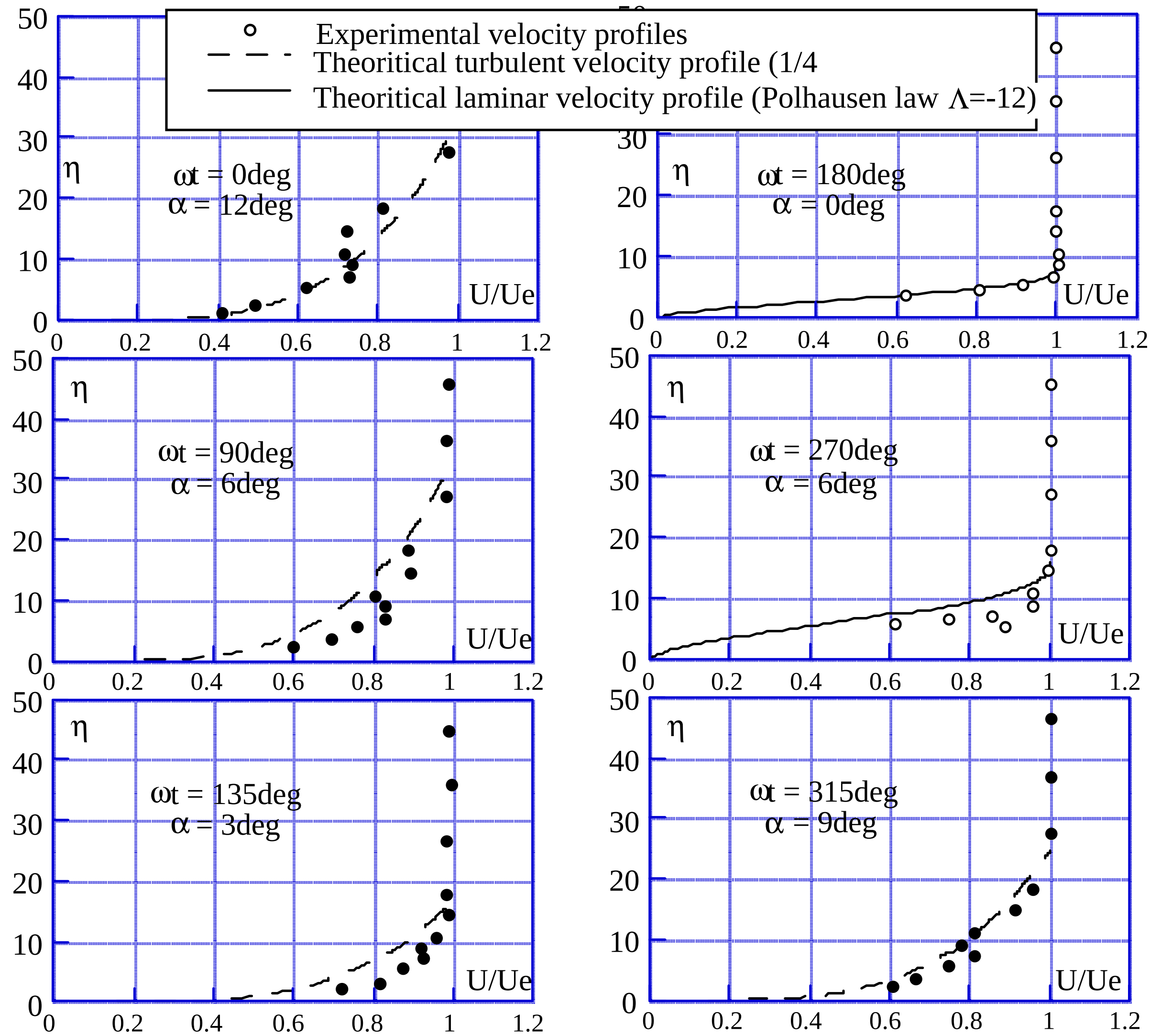

Fig. 6 U/Ue = U/Ue(η) in pitching motion.

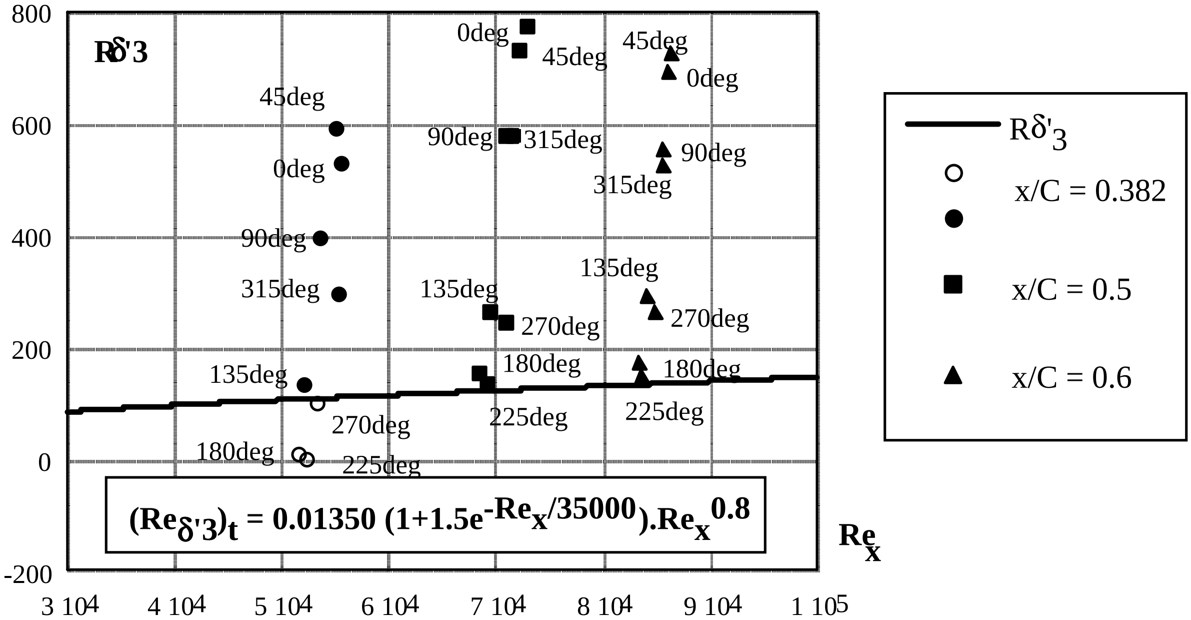

Fig. 7 Transition criterion in pitching motion.

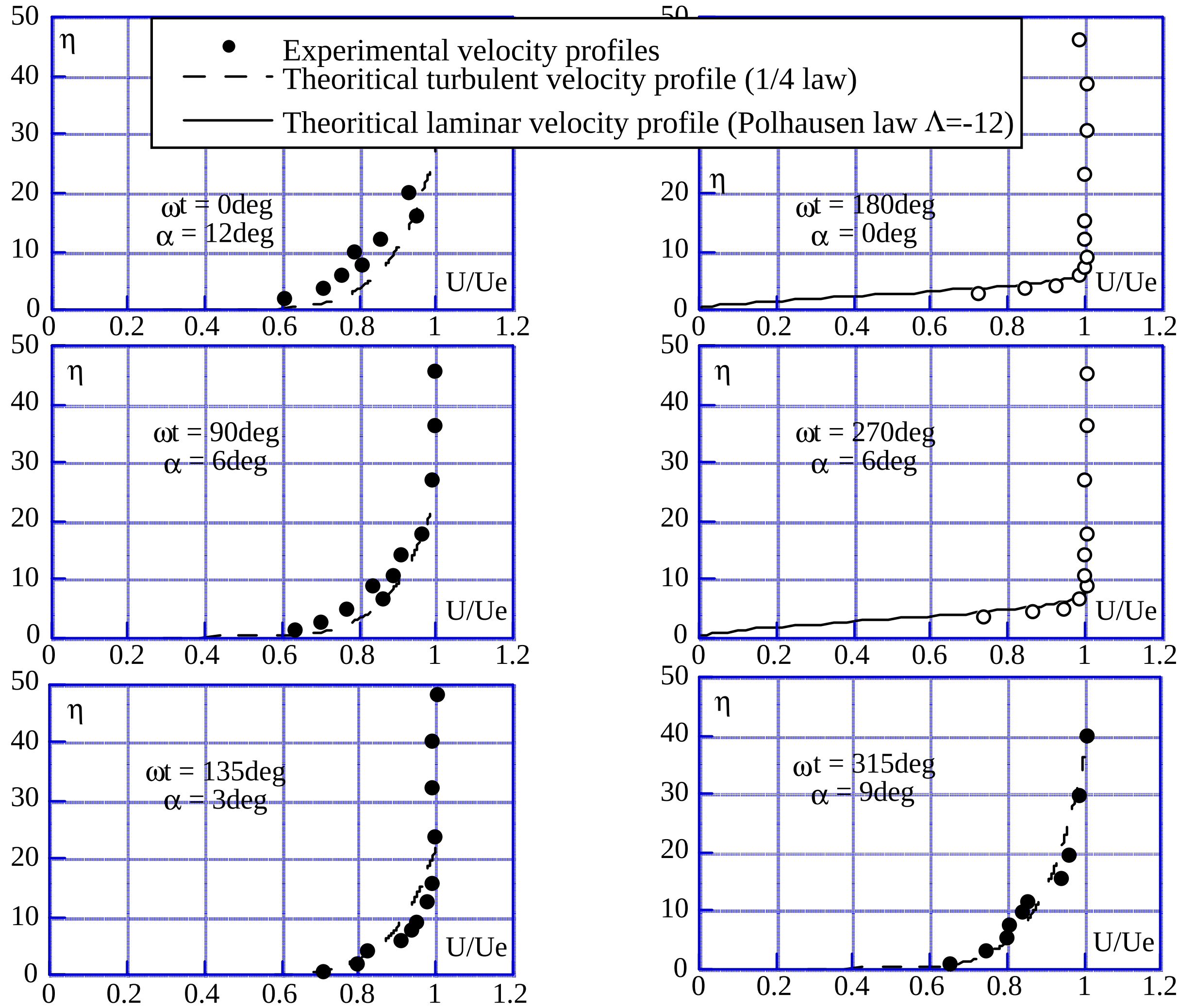

Fig. 8 U/Ue = U/Ue(η) in translation/pitch motion.

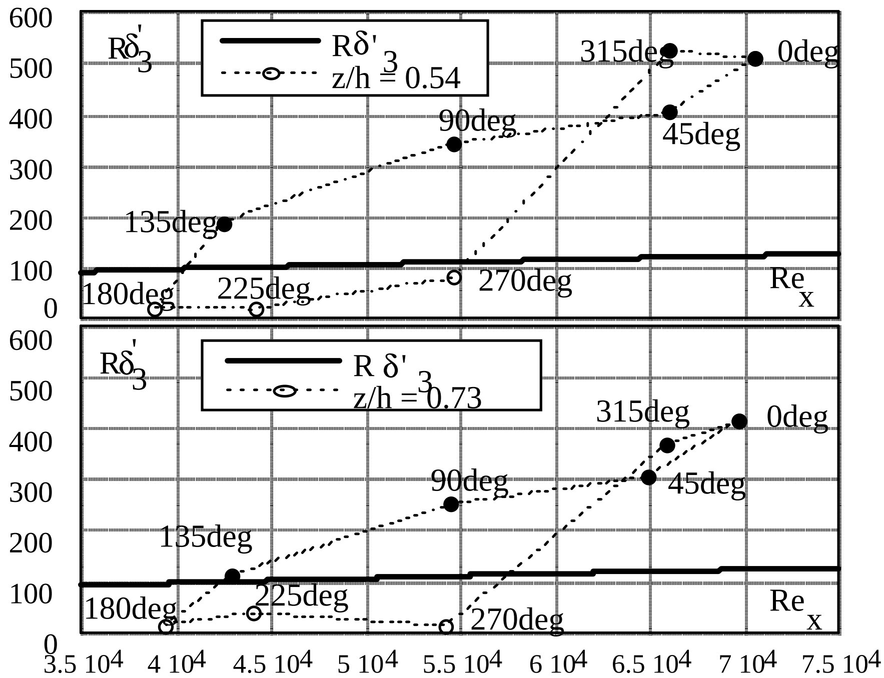

Fig. 9 Transition criterion in translation/pitch

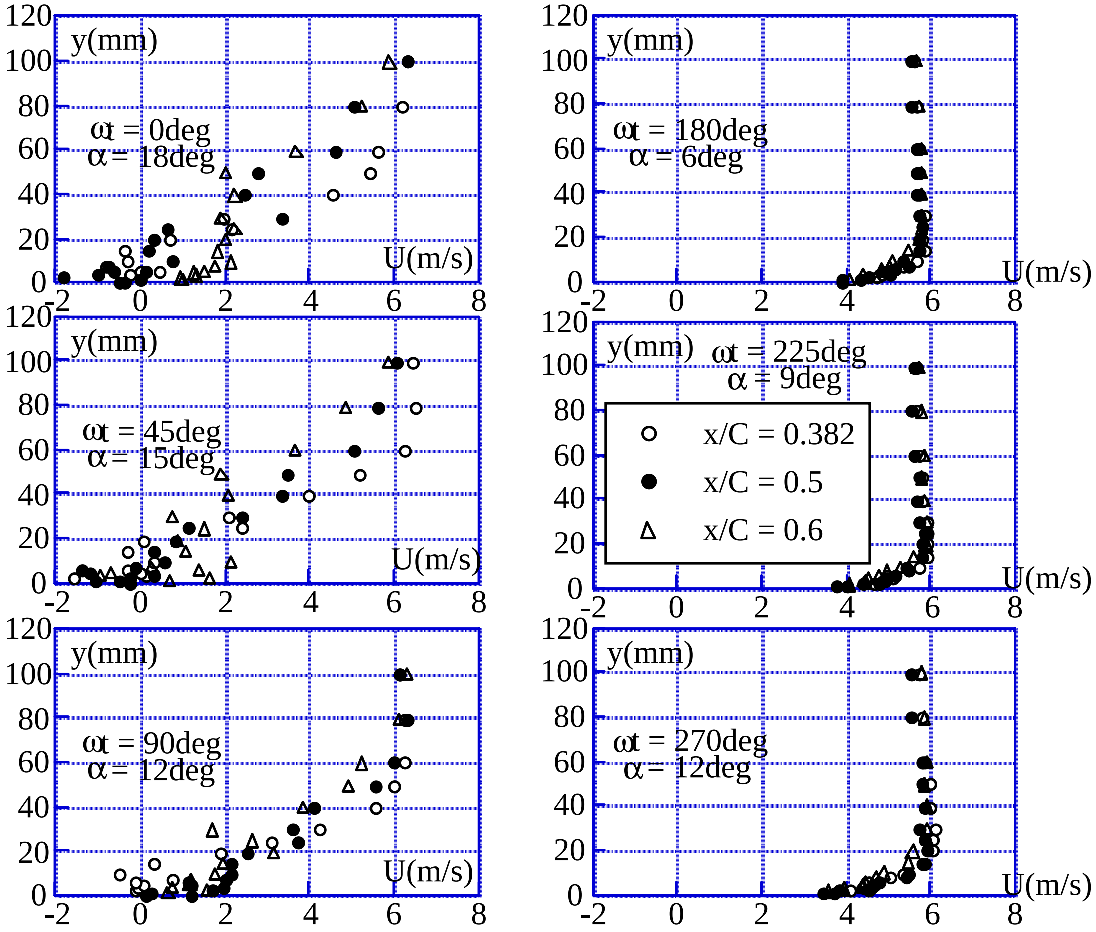

Fig. 10 U = U (y) in pitching motion-α_0=12deg.

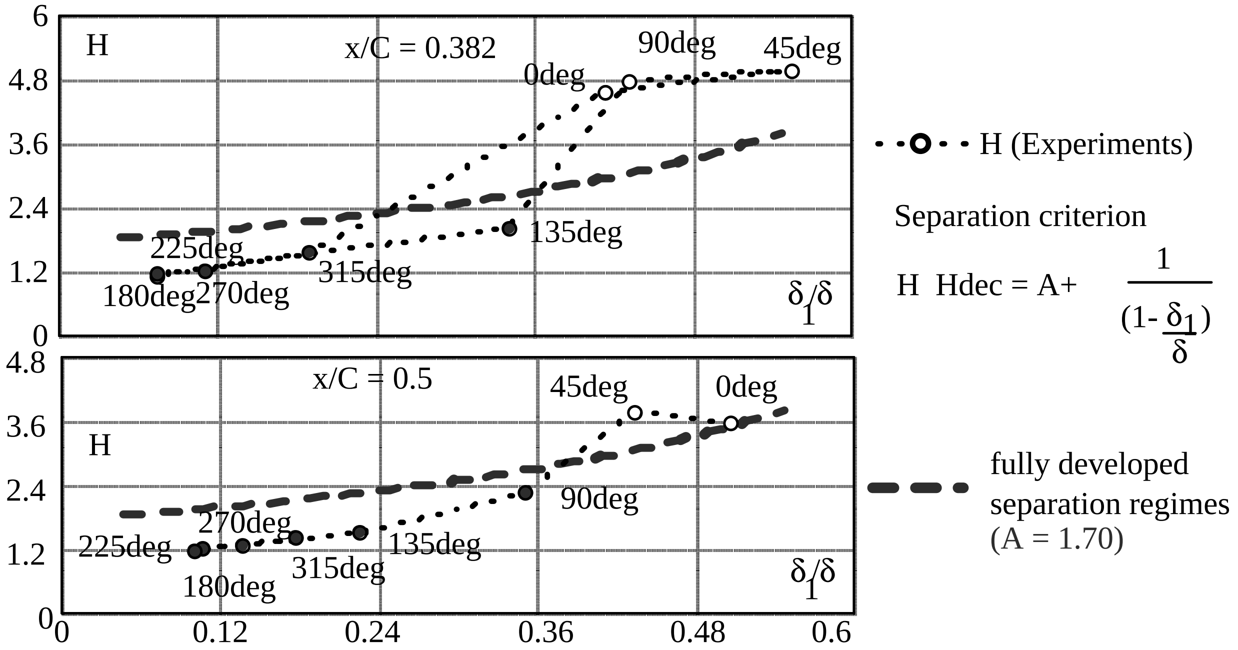

Fig. 11 Separation criterion in pitch-α_0=12deg.