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EXPERIMENTAL INVESTIGATION OF A WING PERFORMING PITCH-UP MOTION UNDER GUST ENVIRONMENT

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ABSTRACT

A NACA0012 wing undergoing ramp-type pitch-up motion in presence of a periodic vortex gust is investigated experimentally. Force measurements are performed simultaneously with PIV measurements while the wing pitched at two different rates: fast (1 sec/45 deg) and slow (6 sec/45 deg). Vortex formations during the pitch-up motion and after the motion is completed are obtained and correlated with the force measurements. Then the cases are examined in presence of three different vortex gusts which are attained by a gust generator plate, pitching and plunging upstream of the wing. The gust affects formation, shedding and timing of the vortices generated by the pitching wing and consequently loading on it, depending on the strength and frequency of the gust, and its encounter time.

INTRODUCTION

Fundamental research on low speed unsteady aerodynamics has received a great deal of interest in the past years and investigations are still widely under progress in order to find out if biomimetics is an effective solution to MAVs. Applications include perching, gust response, maneuvering flight and flapping wings [Ol et al., 2009]. The variation of angle of attack over a large amplitude in a pitch-up motion represents the maneuver of perching [Reich et al., 2009]. An extensive number of studies investigate force production in relation to the motion kinematics and flow structures either in translational [Pitt Ford and Babinsky, 2013; Garmann and Visbal, 2011; Baik et al., 2010] or rotational [Carr et al., 2013; Venkata and Jones, 2013; Schlueter et al. 2014] pitch-up motion. The rectilinear pitch-up motion was also one of the canonical cases of the Applied Vehicle Technology Panel Task Group AVT-202 “Extension of Fundamental Flow Physics to Practical MAV Aerodynamics” and has been investigated extensively [Son et al., 2016; Son and Cetiner, 2017]. Based on the observations on the vortex formations and evolutions, low-order force models are developed and found to be capable of making reasonable predictions of force histories and magnitudes [Pitt Ford and Babinsky, 2013]

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Gust response is also one of the popular topics in unsteady aerodynamics. In recent years, the flow control and gust effect in general are getting increased interest (Jones and Ol [2014a]; Irving and Smith [2013]). However, the effects of gust on the flow structures around an airfoil and on the unsteady aerodynamic forces and moments are not yet readily known (Jones and Ol [2014b]). Other than the unmanned air vehicles, the gust effect also draws attention for helicopter blades, flapping wing micro-air vehicles (MAVs) and wind turbines due to the unsteady flow conditions of their working environment and/or their motion. Those small air vehicles and aforementioned systems need to correct their positions and directions when encountered with high altitude winds and gust.

First theoretical studies on gust dates back to early 20th century; Küssner developed an analytical solution for the unsteady lift on a wing entering a sharp-edged transverse gust. However, he assumed that the gust velocity was much smaller than the steady flow velocity and the flow is always attached to the suction surface of the wing, which is mainly dependent on the same small perturbation limit. As an extension of Küssner's solution, Miles (1955) solved for the forces cause by a sharp-edged gust that is traveling through the fluid (in addition to the wing moving through the fluid). On the other hand, recent studies mainly focus on large-scale gust and deal with massive flow separations. Therefore, there is a need for experimental studies to investigate large-scale gust responses for the development of low-order models, which will be an important input to control algorithms. Hence, the Applied Vehicle Technology Panel Task Group AVT-282 "Unsteady Aerodynamic Response of Rigid Wings in Gust Encounters"is recently established. On the other hand, the recent paper of (Fisher et al., 2016) on the study of gust effects on flapping wings and the publication in press of Perrotta and Jones (2017) on the unsteady loading due to transverse gusts are some of the examples to current research on large-scale gusts.

Previously, periodic vortex gusts are generated in the water channel [Biler et al., 2015]. The spectral analysis of the velocity field in the wake of the oscillating plate are used to characterize the gust. Three different gust types with varying frequencies and amplitudes have been obtained and identified such that all can be considered as spanwise gusts where the streamwise fluctuations are minimized. The transverse gust is therefore a periodic vortex gust.

In this study, the pitching-up wing is placed into the generated gust environment to investigate the effects of the spanwise gust on vortex formations and force variations.

METHOD

The experiments are performed in the water channel of Trisonic Laboratory at Istanbul Technical University. Experimental setup including the models, motors, PIV system and water channel is shown in Figure 1.

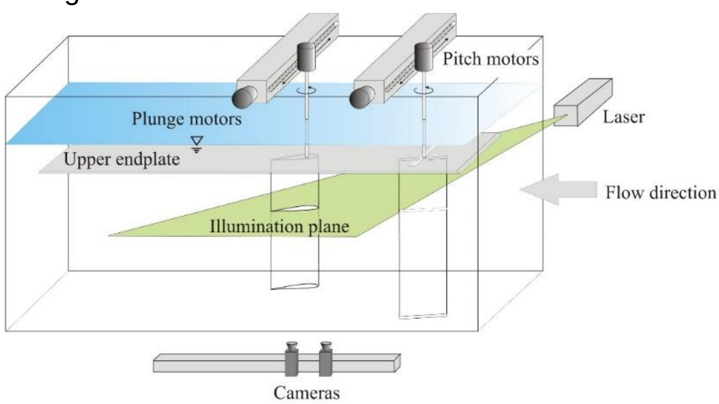

Figure 1: Experimental setup

The water is seeded with 10 μm diameter silver coated hollow glass spheres. An Nd:YAG laser is used to illuminate the flow and 10 bit cameras with a resolution of 1600 × 1200 are placed beneath the water channel. Gust is generated by a flat plate pitching and plunging upstream of the NACA0012 wing. Pitch-up motion of the wing is performed by a Kollmorgen/Danaher

Motion AKM33E servo motor with an accuracy of 0.15°. The forces acting on the model are measured by a ATI NANO-17 IP68 six-component Force/Torque sensor (ATI Industrial Automation, Inc., NC, USA). The sensor is mounted on the rod between the model and the servo motor, as its z-axis oriented perpendicular to the pitch plane.

The model performs two types of motion: fast pitch-up and slow pitch-up. It starts from 0° and attains its final angle of attack of 45° in 1 second for the fast pitch-up motion and in 6 seconds for the slow pitch-up motion; corresponding to 1 and 6 convective times, respectively.

The pitching NACA0012 airfoil is subjected to three gust types, as given in Table 1. In addition to the gust cases, No Gust case is also investigated. Four gust encounter times have been studied; the pitch-up motion is synchronized with the gust generator plate with phase angles of ϕ = 0°, 90°, 180° and 270°.

Table 1. Characteristics of the gust types

Gust Type	Frequency	Amplitude
1	0.5 Hz	0.9 U
2	0.25 Hz	0.3 U
3	0.25 Hz	0.9 U

RESULTS

In the fast pitch-up, the motion starts at t=4s and ends at t=5s. When we examine the fast case without gust (Figure 2) trailing edge vortices (TEV) form as the motion starts and leading edge vortex (LEV) formation can be observed at t=5.5s. Then, LEV grows and separates from the surface and consequently a new TEV forms at t=8.5s. Those consecutive vortex formations end at t=14s and after that instant, shear layer separation is observed from the leading and trailing edge of the wing.

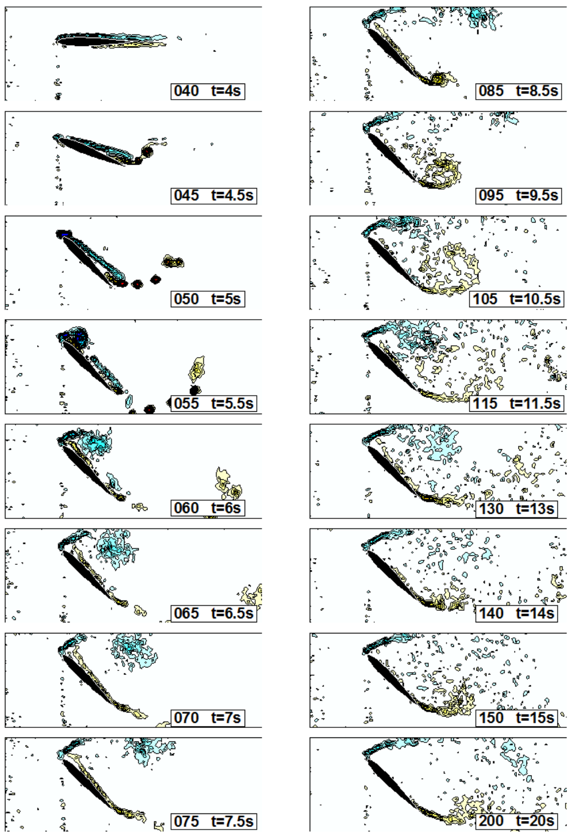

Figure 2: Fast pitch-up motion in the absence of gust

In Figure 3, the same motion is presented under one of the gust types, namely Gust No.1. For the fast motion and encounter time of 0°, the LEV lift off from the surface earlier (t=6s) and bursts quickly (t=7s). The LEV, which is not observed after t=14s in the absence of gust, can be distinguished at t=14s and t=20s in its presence. However, when the encounter time is shifted to 90°, the leading edge vortex forms faster under the effect of the gust and we observe that it is totally dispersed at t=6.5s. Similar to the case of 0° phase angle, instead of shear layer separation at later times after the motion ends, the case of 90° phase angle yields periodic leading edge vortex formation which is evident at t=14s an t=20s. The observations for the case of 180° phase angle are similar and made approximately 1s earlier compared to the case of 0° phase angle; e.g, the early stage of the leading edge vortex formation is at t=8.5s for ϕ = 180° and t=9.5s for ϕ = 0°. The time difference of 1s is in accordance with a phase difference of 180° considering that the gust has a frequency of 0.5Hz. This relation, or in other words vortex formation timing is consistently observed also for ϕ = 90° and ϕ = 270°.

When we examine the fast pitch-up motion under the effect of Gust No. 2 (Figure 4), for the phase angle of 0°, a larger leading edge vortex is formed at t=6s in comparison with the case in the absence of gust. There are several leading edge vortex formations, i.e., at t=9.5s and t=13s, which are not observable for the case in the absence of gust. As the phase angle varies, the shift in time for vortex formations and shedding is also evident for Gust No. 2. Upstream of the wing reveals the lower strength of Gust No.2 in comparison with the upstream vorticity concentration obtained for Gust No.1. On the other hand, regardless of the phase angle, the image couples of either (t=6.5s and t=10.5s) or (t=7.5s and t=11.5s) which have 4s of difference exhibit the same vortex gust front upstream of the wing in accordance with the frequency of Gust No.2 (f=0.25Hz).

Although Gust No. 3 has the same frequency as Gust No. 2, it is almost three times stronger in comparison. Accordingly, Figure 5, presenting the results obtained the fast pitch-up motion under the effect of Gust No. 3, shows stronger vortex formations in the gust front upstream of the wing, similar to what is observed for Gust No. 1. Although it is more difficult to track vortex formations, interactions and evolutions for Gust No. 3, it is still possible to note that the leading edge and trailing edge vortices are strongly affected by the gust.

For the slow pitch-up, the motion starts at t=4s and ends at t=10s. In the absence of gust, similar to fast motion pitch-up a LEV formation can be observed at t=8.5s (Figure 6). The LEV then sheds and moves downstream. At t=11.5s a new TEV formation can be observed. Later on, the shear layer separation is apparent from the leading and trailing edges of the wing.

In slow motion (Figure 7) under the effect of Gust No. 1, especially when we observe the case of 0° phase angle, the gust causes the LEV formation and lift-off even during the motion phase (t=6.5s and t=8.5s), which, on the contrary is not observed in the absence of gust. Furthermore, the shear layer separation observed at t=20s in the absence of gust transforms to a periodic LEV shedding at t=20s in the presence of gust. Similar observations are also valid for other cases with different phase angles. The shift in time for vortex formations and shedding, previously observed in fast pitch-up motion between cases with different phase angles, is also evident for the slow pitch-up motion.

Figure 8 shows the case of slow pitch-up motion under the effect of Gust No. 2 for the phase angle of 0°. The first leading edge vortex formation is observed at t=6.5s while it occurs at t=8.5s in the absence of gust. Therefore, it is possible to state that the gust causes an earlier formation and evidently an earlier shedding. On the other hand, for the case of 180° phase angle, the flow on the suction surface of the wing still remains attached at t=7.5s. It should be noted that there exist a separation at the same instant for the case in absence of gust. Although the gust keeps the flow attached till t=7.5s, right after, leading edge vortex forms and sheds in the near-wake, evident at t=8.5s and t=9.5s. The shear layer separations observed in the absence of gust are transformed to periodic vortex shedding, the formation of the leading edge vortex are evident at t=11.5s, 13.5s and 15.5s based on the case with a phase angle of 180°. The repetition rate is again in accordance with the gust frequency, which is 0.5Hz.

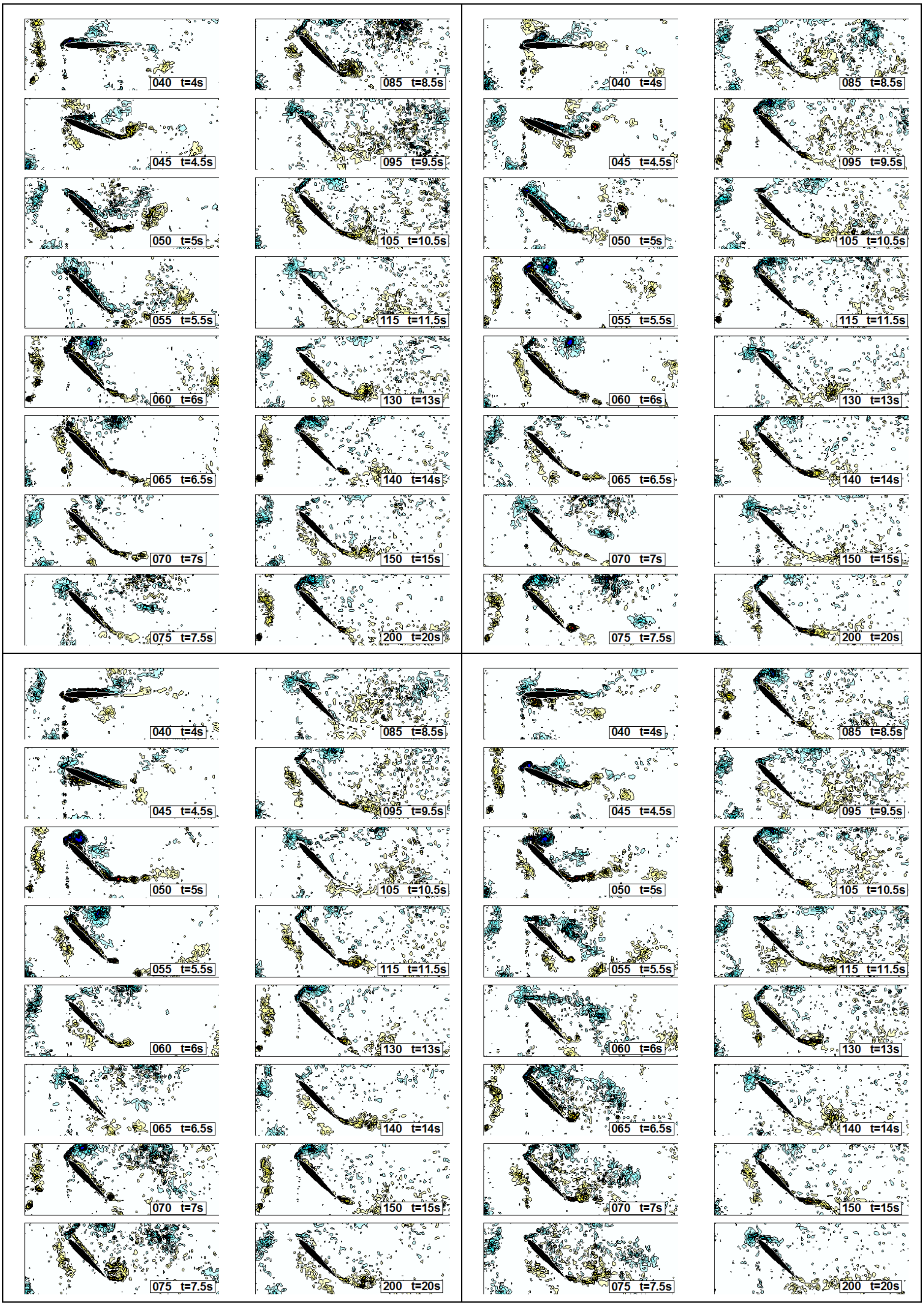

Figure 3: Fast pitch-up motion with Gust No.1 at different encounter times (top left: ϕ = 0°, top right: ϕ = 90°, bottom left: ϕ = 180°, bottom right: ϕ = 270°)

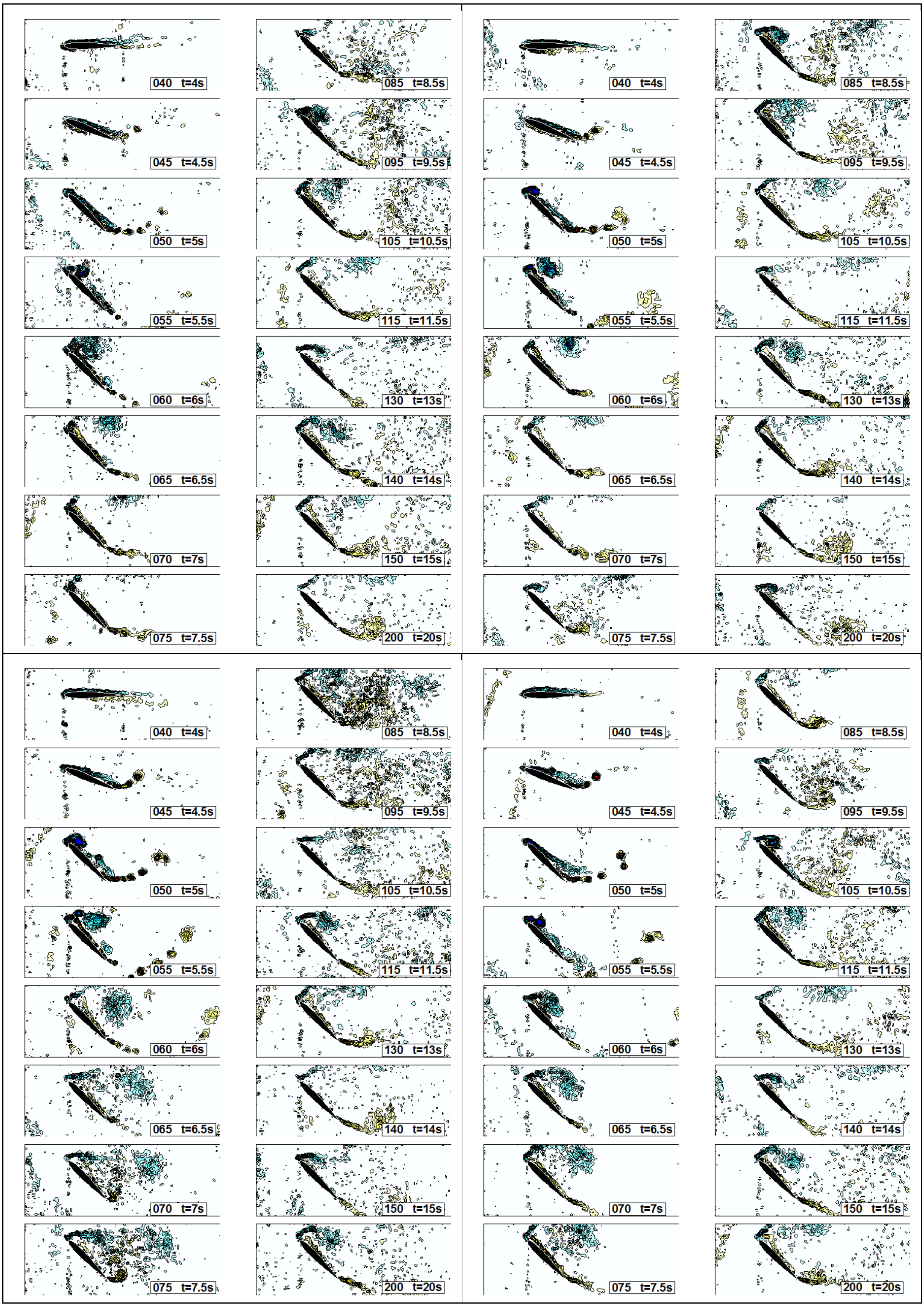

Figure 4: Fast pitch-up motion with Gust No.2 at different encounter times (top left: $\phi = 0°$, top right: $\phi = 90°$, bottom left: $\phi = 180°$, bottom right: $\phi = 270°$)

Figure 5: Fast pitch-up motion with Gust No.3 at different encounter times (top left: ϕ = 0°, top right: ϕ = 90°, bottom left: ϕ = 180°, bottom right: ϕ = 270°)

As aforementioned for fast pitch-up motion, Gust No. 3 having the same frequency as Gust No. 2, is almost three times stronger in comparison. This strong vortex gust interacting with the vortices which are formed due to the pitch-up motion causes a loss of integrity in vorticity distributions and the observations become more difficult. As an example, based on the case of 90° phase angle given in Figure 9, the leading edge vortex forming at t=5.5s is dispersed at t=6s under the effect of the incoming gust front and separates from the suction surface at t=6.5s.

When the force measurement results are studied (Figure 10) for the fast pitch-up case, in the absence of gust, related to the motion starting at t=4s and ending at t=5s, the lift coefficient peaks and then decreases due to both sudden acceleration/deceleration and consequent vortex formations. After the motion ends, the lift coefficient variation shows a local increase and decrease, the increasing values are obtained starting at around t=10s. This moment coincides with the instant where leading edge and trailing edge vortices observed together on the suction surface of the wing (Figure 2, t=10.5s). Later on, the leading edge vortex becomes dominant at t=11.5s and t=13s and consequently the lift coefficient increases. As it is shed and convected downstream, the lift coefficient decreases again until it reaches its static value for angle of attack of 45°. Similar observations are also valid for the drag coefficient variation.

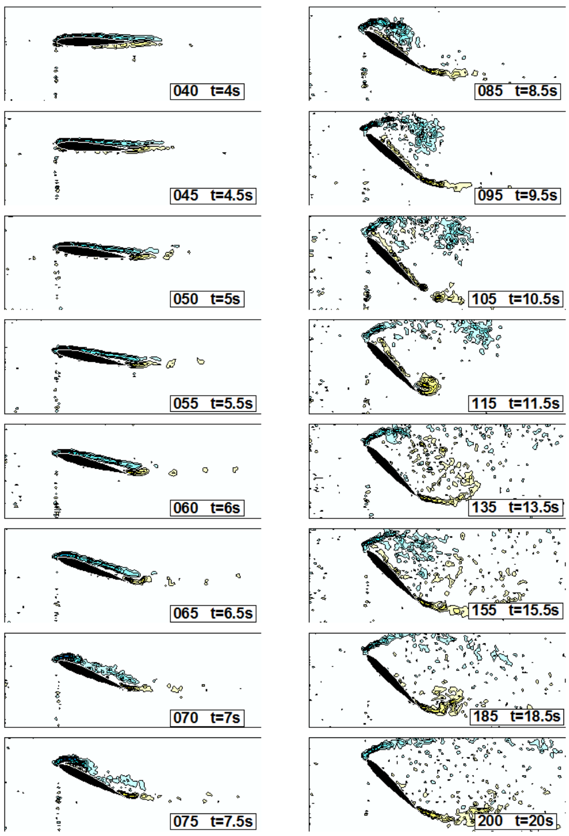

Figure 6: Fast pitch-up motion in the absence of gust

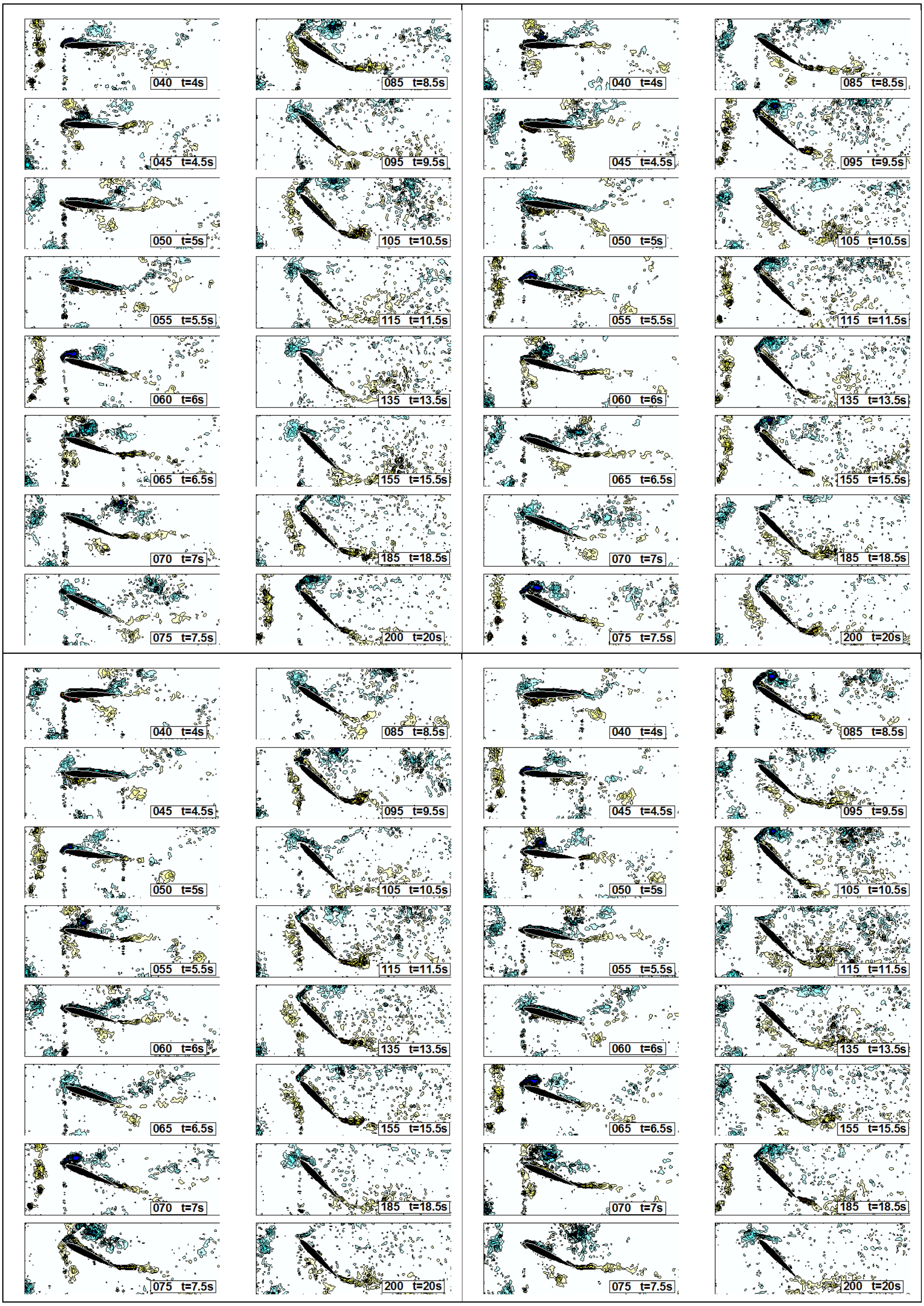

Figure 7: Slow pitch-up motion with Gust No.1 at different encounter times (top left: $\phi = 0°$, top right: $\phi = 90°$, bottom left: $\phi = 180°$, bottom right: $\phi = 270°$)

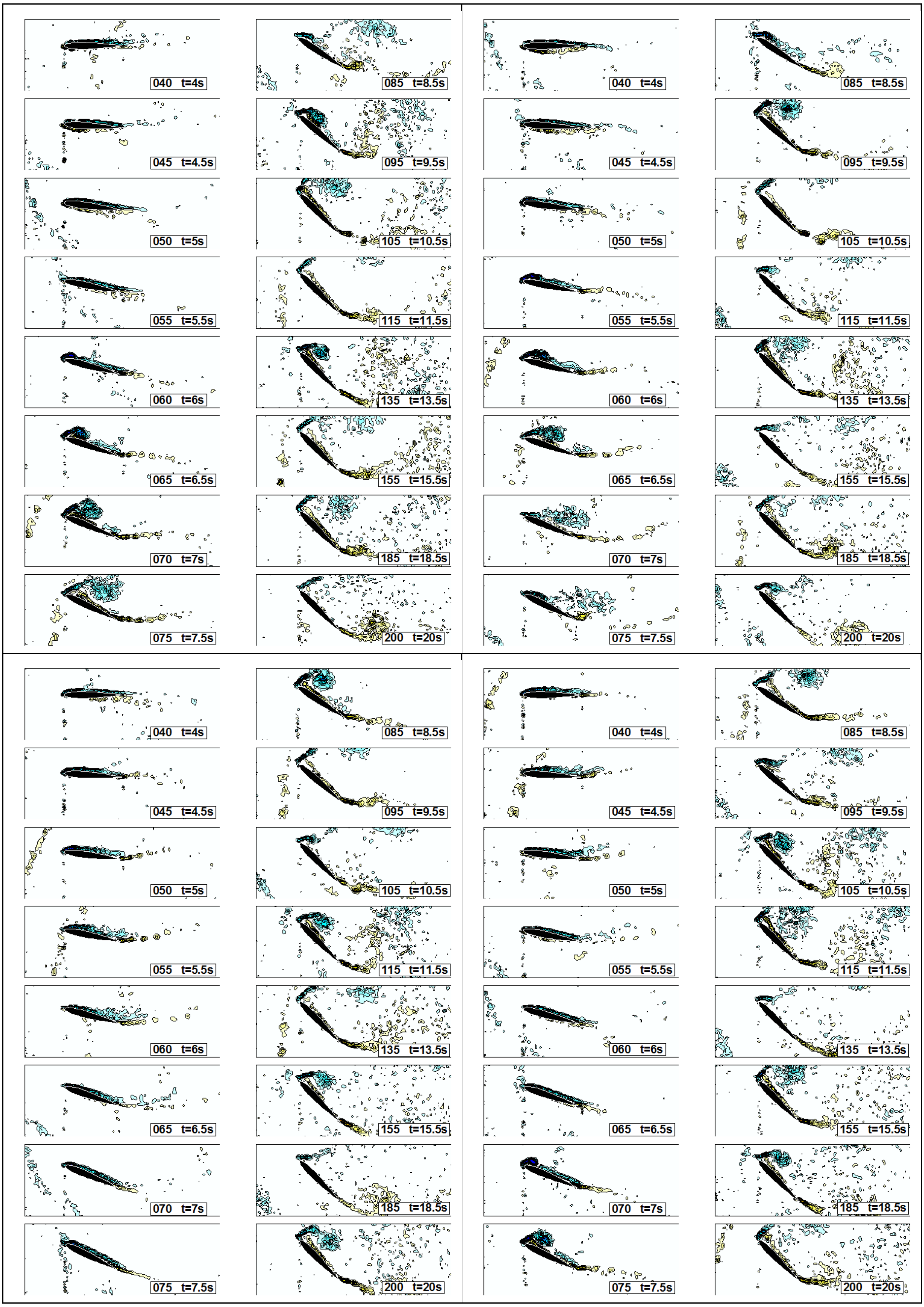

Figure 8: Slow pitch-up motion with Gust No.2 at different encounter times (top left: ϕ = 0°, top right: ϕ = 90°, bottom left: ϕ = 180°, bottom right: ϕ = 270°)

Figure 9: Slow pitch-up motion with Gust No.3 at different encounter times (top left: $\phi = 0°$, top right: $\phi = 90°$, bottom left: $\phi = 180°$, bottom right: $\phi = 270°$)

As the motion duration is longer for the slow pitch-up case, the force variations are observed in more detail and with ease (Figure 9). It is possible to observe lift coefficient values above the static stall limits as the wing is in continuous maneuver with dynamically changing angles of attack. However, when the motion ends both force coefficients decrease drastically. Similar to what is observed for the fast pitch-up case, there is a local increase and decrease after the motion ends. This increase is observed at t=14s for the slow pitch-up case and coincides with the moment when the leading edge and trailing edge vortices are observed together on the suction surface of the wing (Figure 6, t=13.5s).

The flow field images exhibit shear layer separations when the force coefficient variations converges to their static value at around t=20s regardless of the speed of the pitch-up motion.

Figure 10, 11 and 12 show the lift and drag coefficient time histories under the gust effect of Gust No.1, 2 and 3 respectively, in comparison with the case in absence of gust. The first and obvious observation is the sinusoidal fluctuation of the forces in relation with the gust frequencies. This is in accordance with the continuous vortex shedding instead of the shear layer separations after the motion ends. On the other hand, the force fluctuations are shifted according to the phase angle of the case in consideration. This is also in agreement with the shift in time for vortex formations and shedding observed as the phase angle is varied. The local increase and decrease of force coefficients observed after the motion ends is not detectable under gust effect since the fluctuations of forces due to vortex gust have considerably higher amplitude than that of this local force peak.

If a non-dimensional time is defined as:

$$T^* = \frac{gust\ duration}{\frac{c}{U_\infty}}$$

the number of cycles which can be observed in force fluctuations during the motion can be estimated as:

$$\#\ of\ cycles\ of\ C_L\ observed\ during\ the\ motion = \frac{convective\ time\ of\ motion}{T^*}$$

The estimations agree well with the experimental results. It is not possible to observe a complete cycle of C_L for the fast pitch-up motion. However, the slow pitch-up motion exhibits 3 cycles C_L for Gust No. 1, which has a frequency of 0.5 Hz and 1.5 cycle of C_L for both Gust No. 2 and 3, which have a frequency of 0.25Hz.

For the fast pitch-up motion cases where it is not possible to observe a complete cycle of C_L, Gust No. 2 and 3, which have a low frequency of 0.25Hz just shift the force coefficient values in *y*-axis without affecting the force variation characteristics. However, Gust No. 1, which has higher frequency of 0.5Hz, affects the force variation characteristics depending on the gust encounter timing.

CONCLUSION

A NACA0012 wing undergoing ramp-type pitch-up motion in presence of a periodic vortex gust has been investigated experimentally. Force measurements are performed simultaneously with PIV measurements while the wing is pitching at two different rates: fast (1 sec/45 deg) and slow (6 sec/45 deg). Vortex formations during the pitch-up motion and after the motion is completed are obtained and correlated with the force measurements. Then the cases are examined in presence of three different vortex gusts.

The gust affects formation, shedding and timing of the vortices generated by the pitching wing and consequently loading on it, depending on the strength and frequency of the gust, and its encounter time. In summary, when the gust duration is relatively shorter than that of the motion, the characteristics of force variations are not affected, the loading fluctuates around its variation in absence of gust. However, the characteristics of force variations can be considerably changed depending on the encounter timing, if the gust duration is comparable to that of the motion. On the other hand, the frequency of the gust is found to play an important role in vortex structures and loading, while the strength of the gust is secondary.

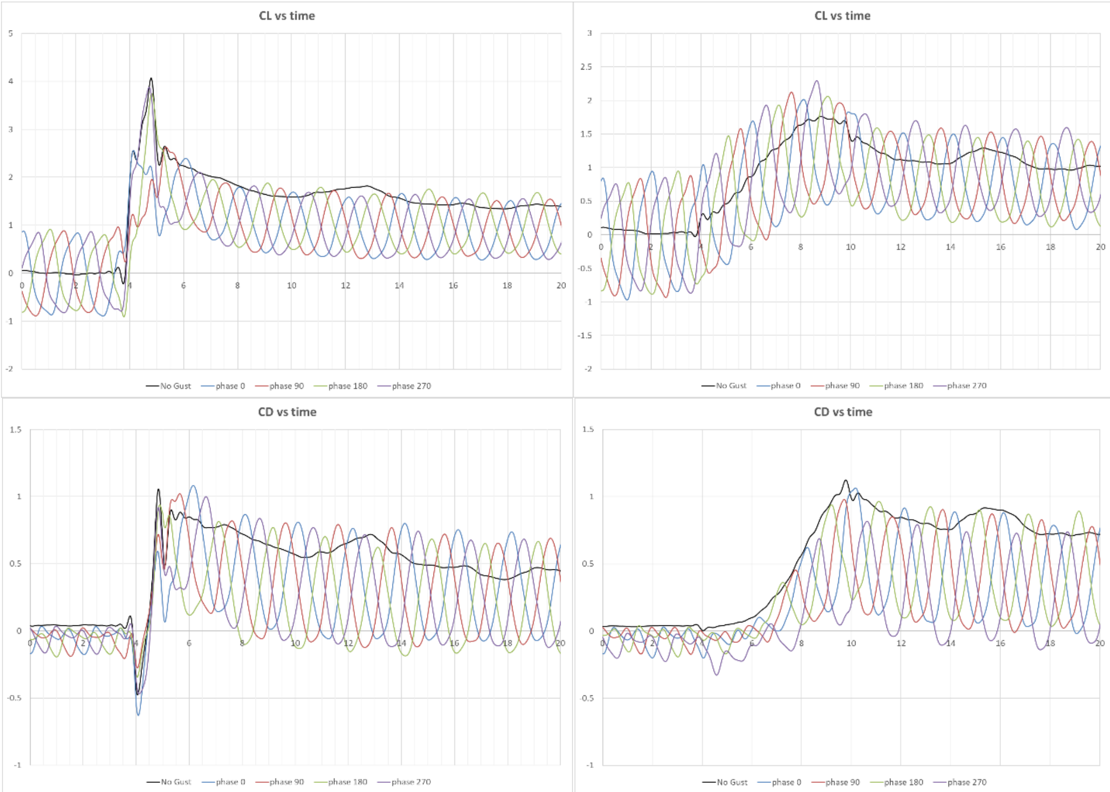

Figure 10: Time histories of lift and drag coefficients for fast (left) and slow (right) pitch-up motions under the effect of Gust No.1

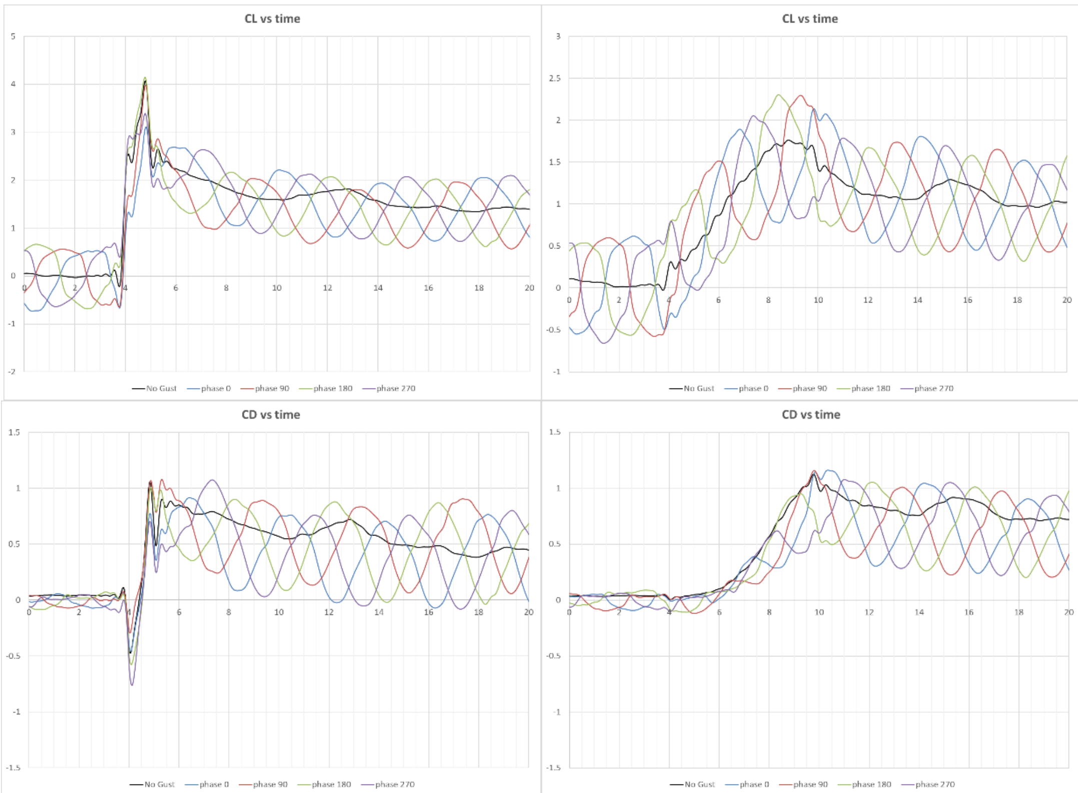

Figure 11: Time histories of lift and drag coefficients for fast (left) and slow (right) pitch-up motions under the effect of Gust No.2

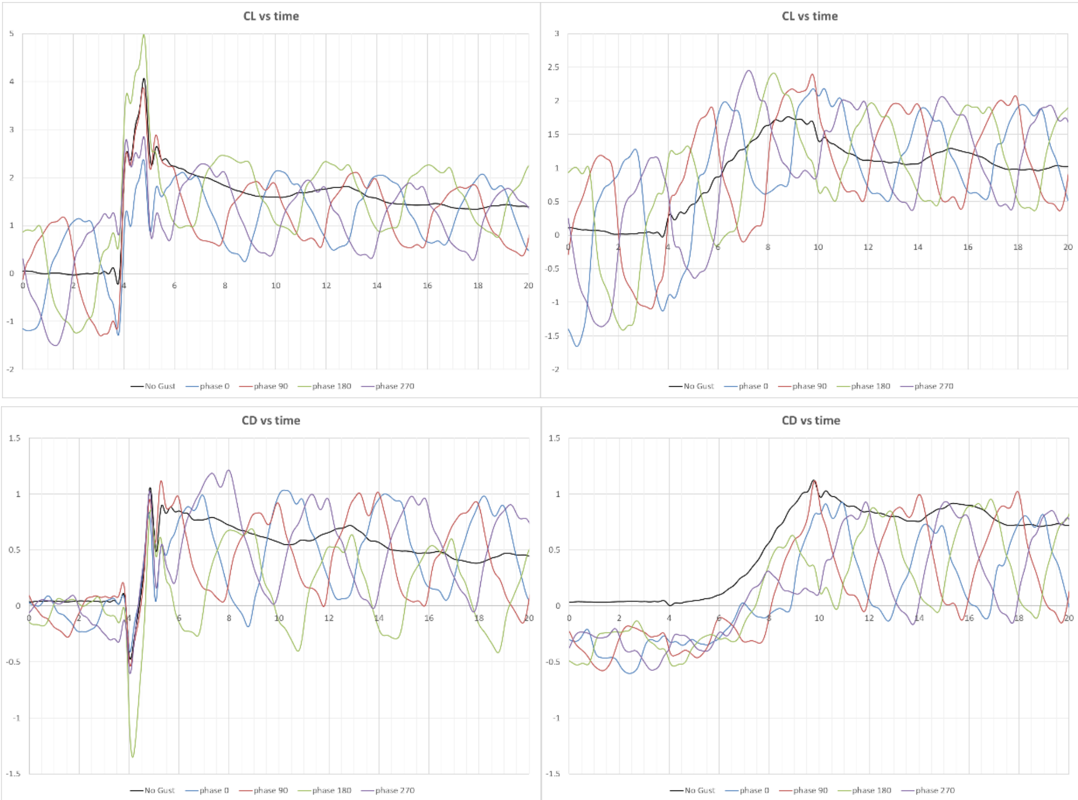

Figure 12: Time histories of lift and drag coefficients for fast (left) and slow (right) pitch-up motions under the effect of Gust No.3

Acknowledgements

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