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Gust Effect on a Plunging Flexible Wing

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Abstract

The performance of a sinusoidally plunging flexible wing under three different gust types is investigated in a free-surface water channel. A flat plate of *AR*=8 is used as a gust generator upstream of the wing in subject and it pitches and plunges in feathering conditions producing a periodic vortex gust where the transverse velocity fluctuations are maximized and streamwise velocity fluctuations are minimized. The gust effect is examined on the wing plunging at 1 Hz at an amplitude of a/c=0.1 in a free-stream of *Re*=10000. Three different materials are used for flexible rectangular flat plate wings of *AR*=4: acetate, lexan and 3D printed polymer based. In addition, the experiments are performed with the rigid flat plate and for all the wings in absence of gust for a full comparison.

1 Introduction

Atmospheric fluctuations that aerial vehicles are subject to, might reach critical rates resulting in control difficulties. Unmanned air vehicles, which are smaller in size and more agile, are expected to be highly effected by those fluctuations (Viswanath and Tafti (2010), Watkins et al. (2006)). These fluctuations or gusts are relatively easier to numerically create and control, yet it is experimentally difficult to create a controlled and uniform gust. In recent years, the flow control under gusts 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)). Recent experiments were carried out by placing two tandem wings in the experimental setup and creating gust on the rear wing by oscillating/flapping the fore wing (Neumann and Mai (2013), Shao et al. (2010)). These studies focused on the applications of fixed wings and performed in wind tunnels. In this study, the gained knowledge from previous experiments on flapping wings (Son and Cetiner (2018), flexible flapping wings (Son and Cetiner (2016)) and gust (Kal et al. (2017)) studies are combined and the gust effect on flapping flexible wings are examined. A pitching and plunging flat plate is used as a gust generator and four different flexible wings are sinusoidally plunged in the wake of the gust generator. Force measurements and PIV images are acquired simultaneously to determine the flow structures and loadings on the wings. Although gust effects on the rigid wing are known to be minimal (Kal et al. (2017)) for higher plunging frequencies compared to gust frequencies, a higher plunging frequency case is deliberately selected to enhance the flexibility effects.

2 Experimental Setup

The experiments are performed in the large scale, free surface water channel located in the Trisonic Laboratory of Istanbul Technical University, Faculty of Aeronautics and Astronautics. A flat plate is used as the gust generator while flexible and rigid flat plate wings are mounted downstream to study the spanwise periodic vortex gusts, all in a cantilevered arrangement inside the water channel. An end plate is used to reduce the free surface effects. The gust generator is mounted from its mid-chord position, the plunging flat plates from their leading edge. The gust generator flat plate has a chord (c) of 10 cm and span (s) of 40 cm, while the wings have c = 10 cm and s = 20 cm. The wings under the effect of gust have a plunging frequency of 1 Hz and plunging amplitude of a/c=0.1. For all cases investigated, the flow speed is set to 0.1 m/s which corresponds to Reynolds number of 10000. Both mounting beams for the gust generator and the test models are connected to pitch motors able to move with linear tables that allow the plunging motion. The experimental arrangement can be seen in Figure 1.

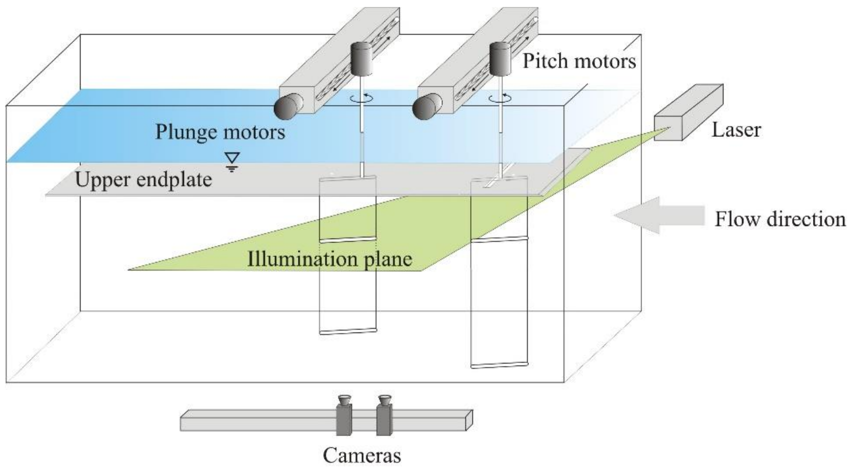

Figure 1: Experimental Setup.

Generated gust characteristics and flapping wing properties are presented in Table 1 and Table 2. All types can be considered as spanwise gusts where the streamwise fluctuations are minimized. DPIV (Digital Particle Image Velocimetry) technique is used to record flow fields around and in the near wake of the plunging airfoil and therefore to analyze the vortical structures and the velocity fields. The flow is illuminated by a dual cavity Nd:Yag laser (max. 120mJ/pulse) and the water is seeded with silver coated glass spheres with a mean diameter of 10 μm. The velocity fields are obtained using two 10-bit cameras with 1600 × 1200 pixels resolution, positioned underneath the water channel. Recorded images are stitched using an in house code and then interrogated using a double frame, cross-correlation technique with a window size of 32 × 32 pixels and 50% overlapping in each direction.

Table 1: Selected gust types and their properties.

Gust Type	**Freestream Average Velocity Before Gust [m/s]**	**Freestream Average Velocity After Gust [m/s]**	**Frequency [Hz]**	**Amplitude v_{ampl} (% of U_∞)**
1	0.100	0.131	0.5	90
2	0.100	0.121	0.25	30
4	0.100	0.097	0.25	90

Force and moments acting on the plunging airfoil are measured using a six-component ATI NANO-17 IP68 Force/Torque (F/T) sensor. The sensor is attached to the vertical cantilevered mounting beam of the test model, oriented with its cylindrical z-axis normal to the pitch-plunge plane. The plunge motion of the model, as well as the feathering of the gust generator plate, are accomplished with Kollmorgen/Danaher Motion servo motors. Motor motion profiles are generated by a signal generator Labview VI (Virtual Instrument) for the given amplitude and frequency. The same VI triggered the PIV system at the beginning of the fifth motion cycle of the gust generator plate and synchronization is achieved using a National Instruments PCI-6601 timer device.

Table 2: Selected wing types and their properties.

Material	**Thickness (mm)**	**Flexural stiffness (EI)**
Rigid	5.00	-
Lexan	0.76	150×10^{-4}
Printed	0.60	61.12×10^{-4}
Acetate	0.15	3.21×10^{-4}

3 Results

Lift and drag coefficient variations for the wings under gust are presented in Figure 2. For all wing types, the lift coefficient amplitudes are affected by the oncoming gust. While Gust 1 and Gust 2 have a decreasing effect on lift coefficient amplitudes, Gust 4 has increased the lift coefficient amplitudes. It should be taken into account that the normalization is made on the average flow velocity after gust and the main reason for amplitude change is the difference in the average velocities given in Table 1. Gust 1 and Gust 2 speed up the freestream value whereas Gust 4 decreases the freestream; consecutively the coefficients are altered accordingly. Force phases do not seem to be affected by the gust.

Drag coefficient variations have similar changes in amplitude with gust compared to the lift coefficient. Drag coefficient have double peaks in one period since drag or thrust is produced twice in a flapping period. For the rigid wing, the periodicity cannot be tracked easily however, on flexible wings the periodicity of the double peaks are evident.

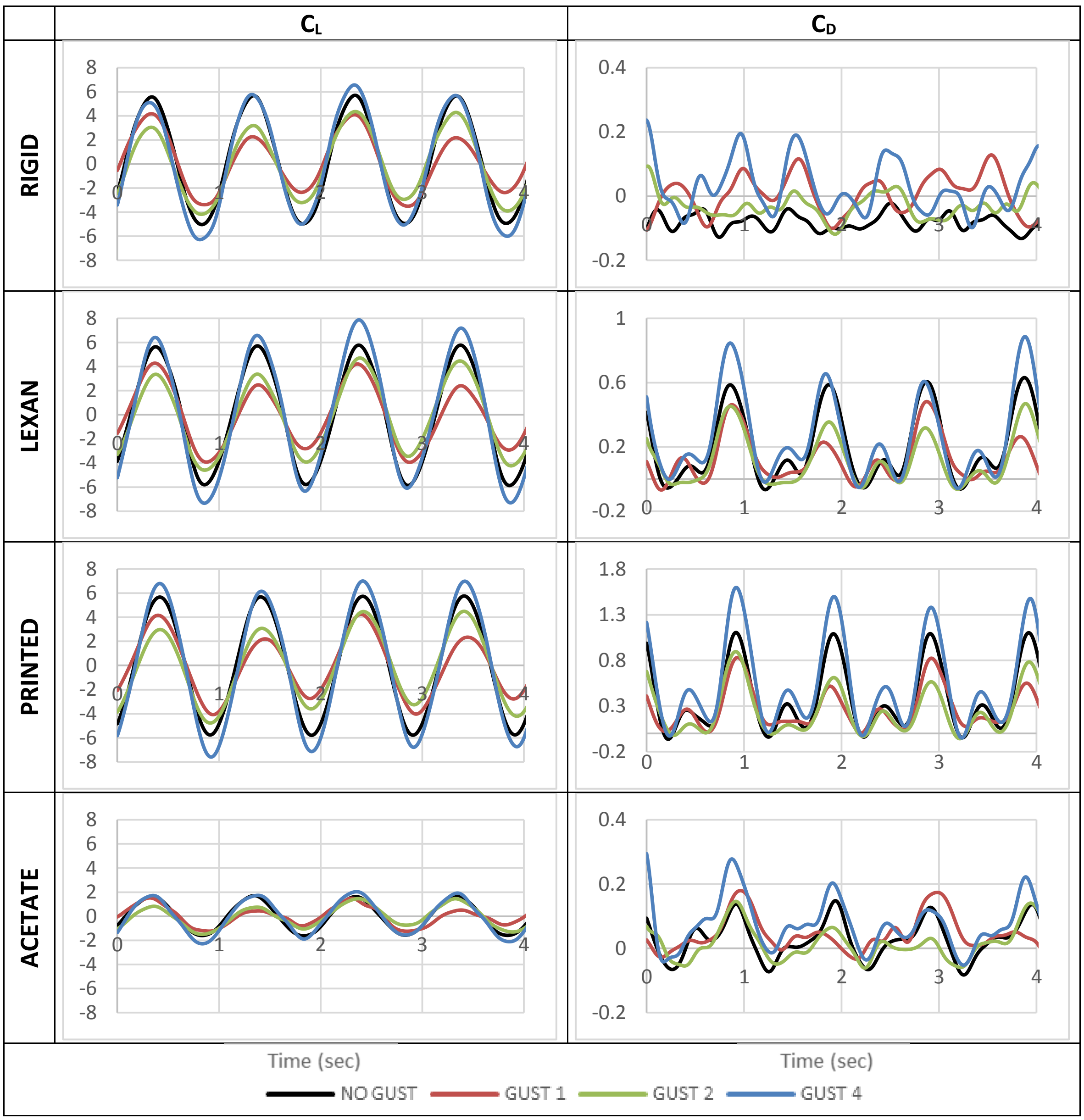

Figure 2: C_L and C_D variations for different wings and gust types.

Time averaged thrust and power input coefficients and efficiencies of different wings under gust are presented in Figure 3. In the absence of gust and in terms of thrust coefficient (C_T), the rigid wing is producing drag, the acetate wing is in the neutral zone and lexan and printed wings are producing thrust. Gust 1 and Gust 2 diminishes the thrust production capability of lexan and printed wings, however Gust 4 results in thrust increase for all flexible wings.

All wing types have similar power input coefficient (C_P) behaviors: C_P values decrease from no gust to Gust 1 cases, slightly increase from Gust 1 to Gust 2 cases and sharply increase from Gust 2 to Gust 4 cases. When the efficiencies are interpreted, printed wing has the highest efficiency values among other wings. In general and average, gusts do not affect the efficiency of the wing except wings under Gust 1, sometimes also under Gust 4 exhibit slightly higher efficiencies.

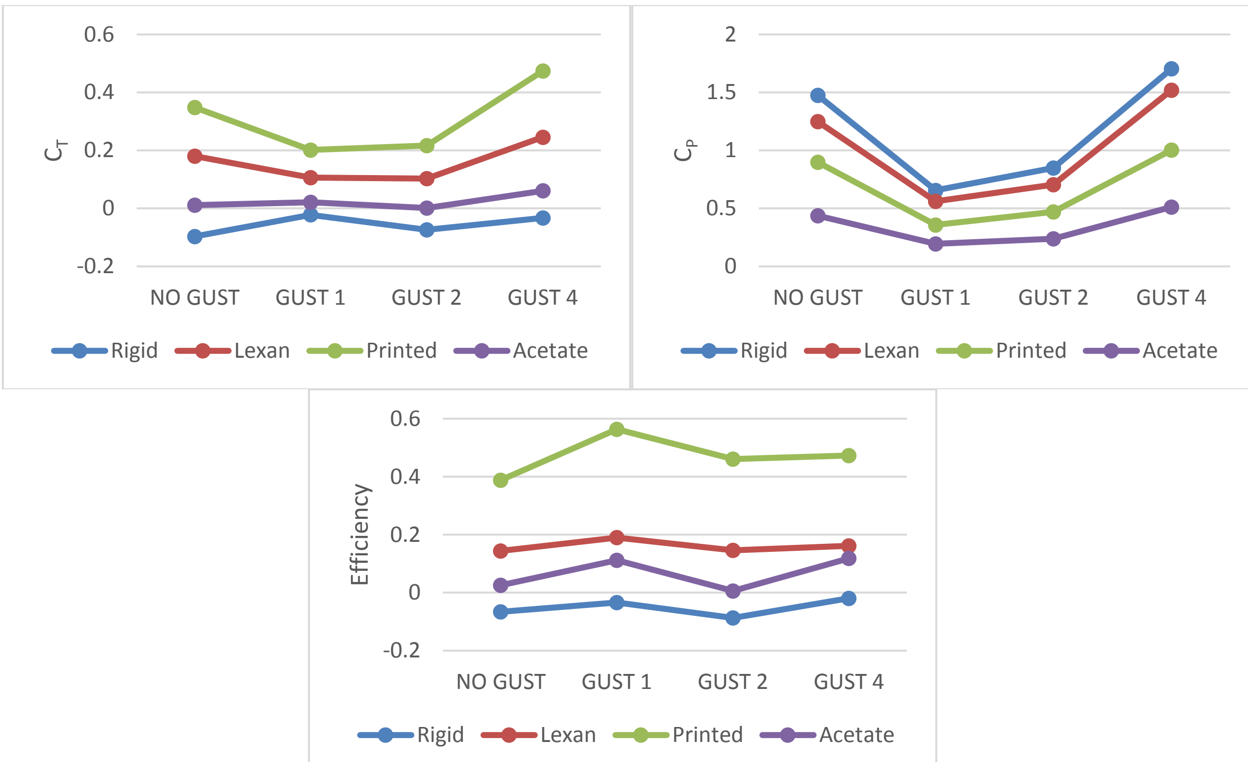

Figure 3: C_T, C_P and efficiency of the wings under different gust types.

Actually, Figure 2 shows four cycles of plunge motion, however a period of gust for types 2 and 4, two periods of gust for type 1 in agreement with the gust frequencies. Although the amplitudes of force coefficients are different for each cycle of motion for Gust 2 and Gust 4, they are repeating twice for Gust 1. This difference will be evident if instantaneous flow structures are studied. Figure 4 shows instantaneous vorticity contours from DPIV images; for the sake of brevity, only third, fourth and fifth images will be compared for the investigation of the effects of either gust encounter and/or flexibility. To begin with the effects of gust encounter, the first 7 rows present the results of the rigid wing in the absence of gust and under the effect of Gust 1 and Gust 4. During the first period of Gust 1, the gust front is evident with positive vorticity contours approaching the flat plate on the first image at t=0.250s and hitting its leading edge on the second image at t=0.375s. The positive vortex suppresses the positive LEV forming at the lower surface of the flat plate and promotes the formation of the negative LEV at the upper surface of the flat plate. Due to the gust, the negative LEV is strengthened when the flat plate is moving downward and is approximately at its mid stroke. On the other hand, during the second period of Gust 1, the gust front is evident with negative vorticity contours approaching the flat plate and hitting its leading edge. As oppose to the first period of Gust 1, the negative vortex enhances the positive LEV formation at the lower surface of the flat plate and forming a layer of negative vorticity at the lower surface, it causes the shedding of a fully developed positive LEV. In the absence of gust, the positive LE formation stops when the plate is at its maximum position and cannot be shed after it moves downward; a positive vorticity layer occupies the whole lower surface of the flat plate during the first half of its downward motion. Formation of the negative

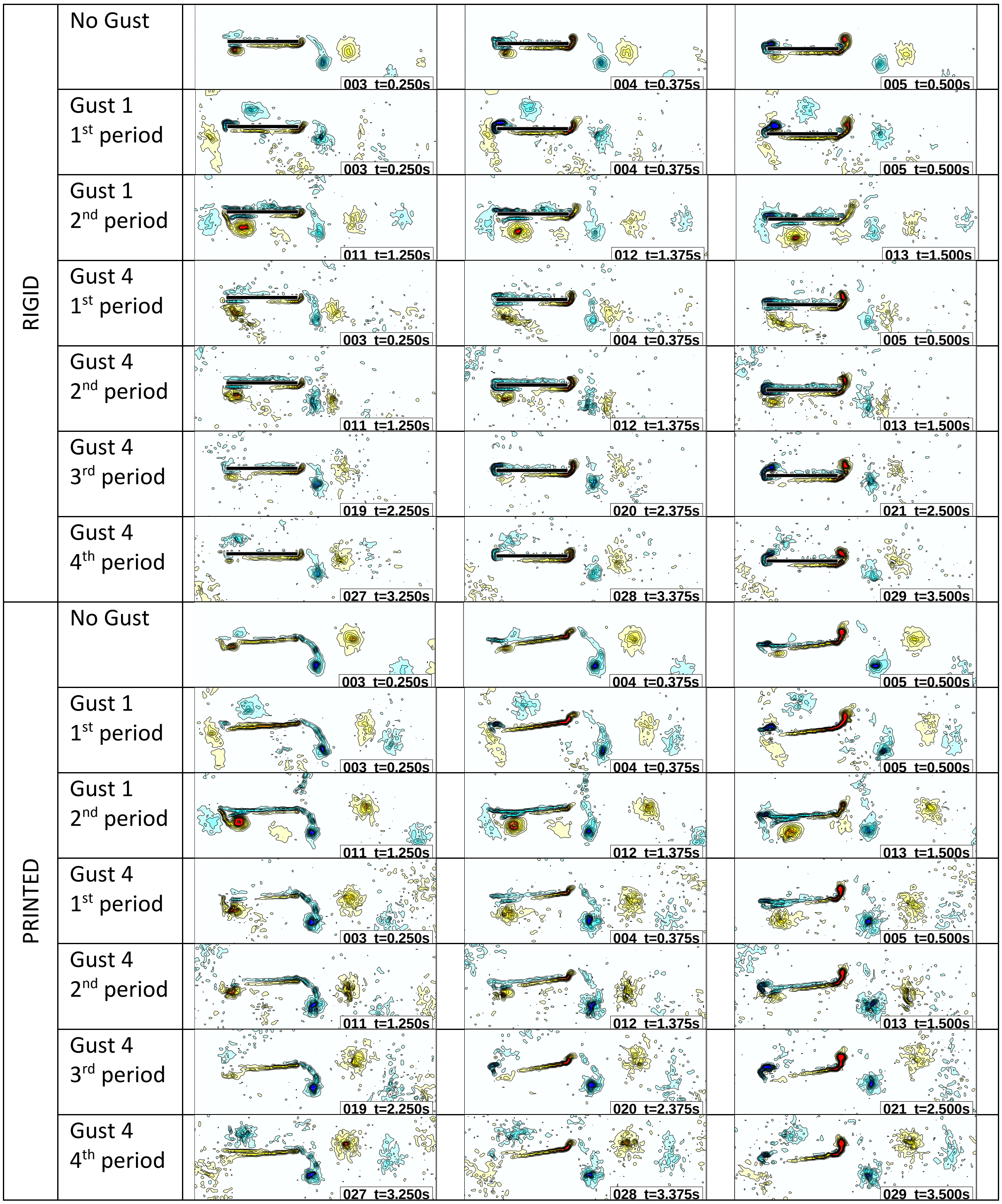

Figure 4: Instantaneous vorticity contours for the rigid and printed wings in absence of gust and under the effect of Gust 1 and 4.

TEV is also suppressed during the second period of the gust; although a counter rotating vortex pair is evident in the near-wake region, the strength of both vortices is diminished compared to the case without gust. In accordance with the force coefficient variations, as oppose to the effects of Gust 1, there are slight differences in vortex formation between different cycles of Gust 4.

The results of the printed wing in the absence of gust and under the effect of Gust 1 and Gust are shown in the last 7 rows of Figure 4. Flow structures occurring at each period of plunge motion during one period of gust, either Gust 1 or Gust 4 are similar for rigid and printed wings. The flexibility effect is pronounced at the TE and as the separating TEV of the flexible printed wing is stronger than that of the rigid wing, gust effect is minimal at the TE compared to the rigid wing.

4 Conclusion

There is a contradiction between the gust and the flexibility effects, large gusts have lower frequencies compared to plunging frequencies and the flexibility is effective when the trailing edge movement is enhanced for high plunging frequencies. Consequently, the effects of flexibility are not changing depending on the presence or the type of investigated gusts and vice versa, the effects of investigated gusts are similar for rigid and flexible wings.

Acknowledgements

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