Aerodynamic interactions in quadcopter configurations with vertical rotor spacing

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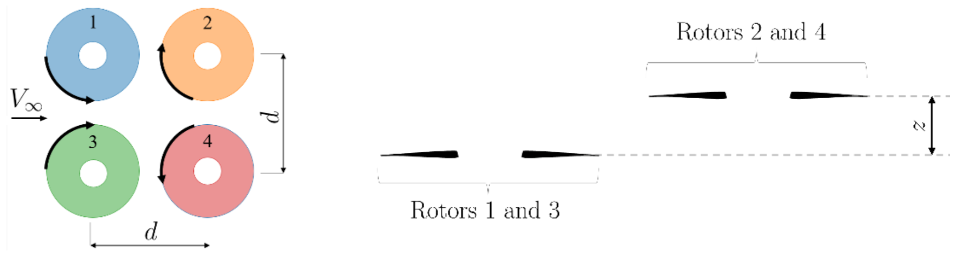
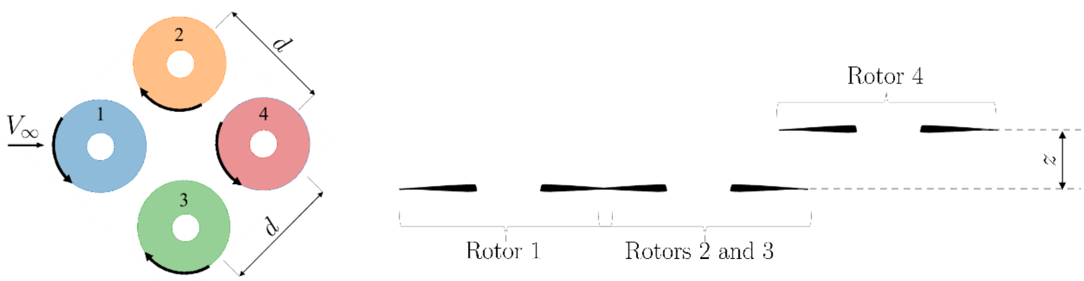
The aerodynamic interactions in a quadcopter have been shown to reduce the efficiency of the back rotor(s) in forward flight [1]. The impact of the wakes from the adjacent rotors is magnified at close rotor spacings and when flying with a nose-up tilt, typical of braking manoeuvres. In order to avoid increasing the vehicle's size, introducing a vertical offset between the front and back rotor(s) can be a practical solution to mitigate the negative interaction effects.

The performance of a quadcopter in square and diamond configuration (Fig. 1) is analysed experimentally as well as numerically using three potential flow solvers (UPM, PUMA and RAMSYS). Forward flight cases with the advance ratio of 0.146 are considered, including variation of vehicle's tilt angle between -10° (nose-down) and +10° (nose-up). The increase of vertical offset *z* is studied in three steps up to 0.38 rotor diameter *D* by raising the two back rotors in the square configuration and the rearmost rotor in the diamond configuration, as shown in Fig. 1. Two horizontal rotor spacings are investigated: *d/D*=1.2 and close rotor positioning of *d/D*=0.96 with overlapping blades.



a) Square configuration

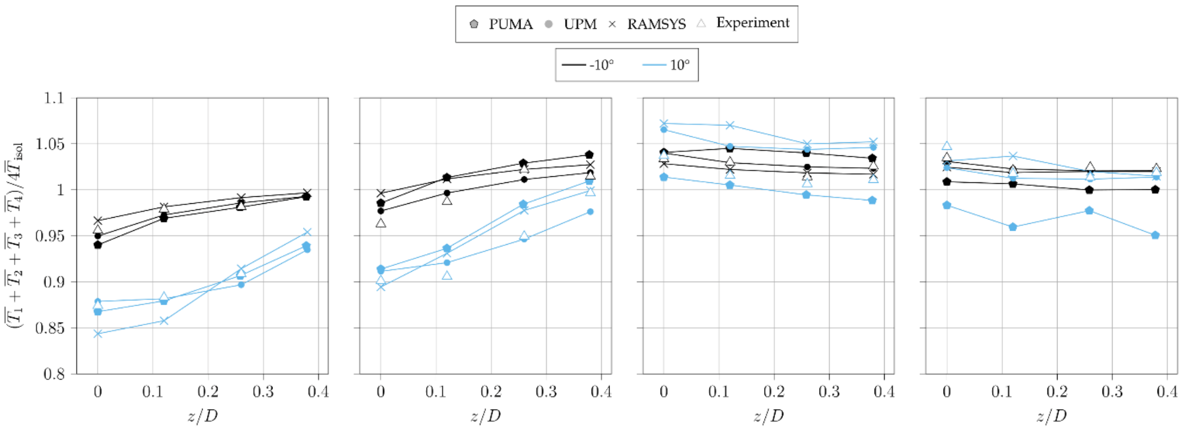


b) Diamond configuration

Figure 1: Definitions of horizontal spacing *d* and vertical spacing *z* in analysed quadcopter configurations

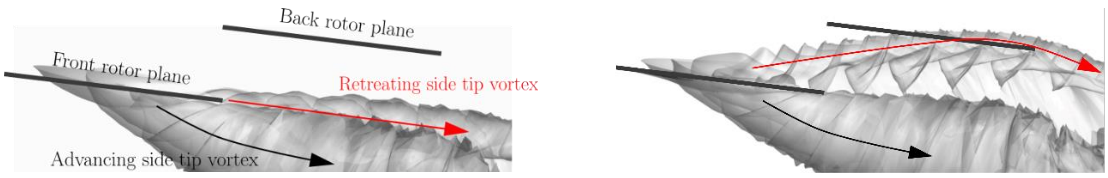
The results show that introducing a vertical offset to the back rotors in the square configuration improves quadcopter's efficiency by up to 5% at -10° tilt angle and 11% at 10° tilt (Fig. 2). The main experimental trends are captured by the applied potential flow solvers. Performance comparable to or higher than four isolated rotors is achieved for the close horizontal rotor spacing *d/D* = 0.96. Prediction of the asymmetric wake propagation of the front rotors is necessary to estimate the required vertical offset. The trajectory of the retreating side vortices is determined by the wake-wake interaction from the bearhug alignment between the front rotors and delays the benefit to a higher vertical spacing (Fig. 3).

In contrast, adding a vertical separation to the back rotor in the diamond configuration has a negative effect on its efficiency. At *z* = 0 inflow conditions around 180° azimuth of the back rotor are comparable to an isolated rotor case due to the upwash produced between the side rotors (Fig. 4). However, the vertically offset back rotor is exposed to the downwash from the wake of rotor 1. A gradual improvement in the rotor performance is expected for vertical separations greater than *z/D* = 0.38.



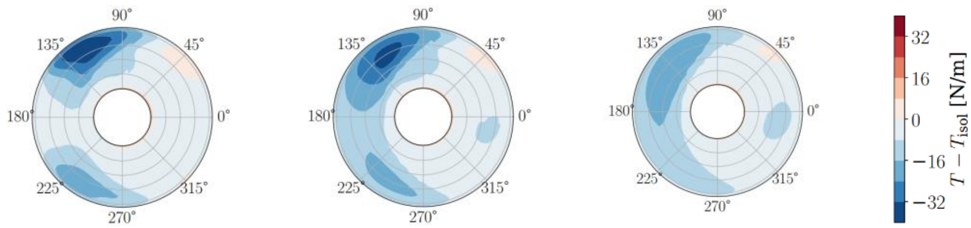
a) Square, *d/D*=1.2 b) Square, *d/D*=0.96 c) Diamond, *d/D*=1.2 d) Diamond, *d/D*=0.96

Figure 2: Change in mean trust of a quadcopter with varying vertical spacing compared to four isolated rotors



a) Wake of a single front rotor b) Wake of both front rotors

Figure 3: Change in the wake trajectory due to interactions between the front rotors



a) *z/D*=0 b) *z/D*=0.12 c) *z/D*=0.38

Figure 4: Change in thrust of rotor 4 in the diamond configuration with tilt -10°, *d/D*=0.96

[1] A. A. Kostek, J. N. Braukmann, F. Lößle, S. Miesner, A. Visingardi, R. Boisard, V. Riziotis, M. Keßler, A. D. Gardner, "Experimental and Computational Investigation of Aerodynamic Interactions in Quadrotor Configurations", *Journal of the American Helicopter Society*, Vol. 69, No. 2, 2024. DOI: 10.4050/JAHS.69.022009