

Computational Study of Wake Interaction and Aeroacoustic Characteristics in Multirotor Configurations

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ABSTRACT

Multirotor configurations such as VTOL and urban air mobility have been focused on today due to the high maneuverability. Aerodynamic and aeroacoustic characteristics of multirotor have much difference to those of a single rotor. In this study, a numerical analysis based on the free wake vortex lattice method is used for identifying the wake interaction effect. In order to compare the various configurations and operating conditions, the effects of the spacing between the rotors in hovering flight and the effects of the advancing ratio and the formation in forward flight are discussed. Aerodynamic and aeroacoustic characteristics are significantly affected by the wake interaction. In the hovering flight, the unsteady loading of multirotor changes periodically and loading fluctuation increases as decreasing the spacing. It causes the variation in unsteady loading noise and the noise directivity pattern. In the forward flight, the difference in loading fluctuation and noise characteristics are observed according to the diamond and square formation of rotors. By comparing with results which obtained by using single rotor analysis for multirotor configurations, multirotor has different directivity pattern according to the location of each rotor. As a result, wake interaction effect becomes a highly important factor for aeroacoustic analysis according to multirotor configurations and operating conditions.

Keywords: Multirotor, Wake interaction, Aeroacoustics **I-INCE Classification of Subject Number**: 13

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1. INTRODUCTION

Multirotor configurations such as VTOL and urban air mobility (UAM) have been focused on today in industrial and commercial applications due to the high maneuverability. The multirotor system is expected to be used in cargo transportation, delivery service, and air mobility system. Unlike a single rotor, a multirotor has a complicated aerodynamic and aeroacoustic characteristics due to the interaction between the rotor and the wake. As noise regulations for aviation system have been strictly regulated, it is necessary to design a noise efficient multirotor system based on the understanding of aeroacoustic characteristics.

Many types of research have been carried out to understand the wake interaction of multirotor. Aerodynamic characteristics of the multirotor were analyzed under various operating conditions using the vortex lattice method (VLM) and CFD^{1,2}. In these studies, it was confirmed that the wake interaction occurs actively even in the hovering flight. Due to the changes in aerodynamic characteristics, the amplitude and the directivity of noise changes during hovering flight³. In the frequency domain, the multirotor has different BPF characteristics with the single rotor and it is necessary to consider the wake interaction effect for analyzing the spectrum⁴. Research on the psychoacoustic features has been actively conducted based on the understanding of noise characteristics through the analysis and experiment of multirotor noise⁵.

However, since there are not enough studies on noise analysis based on the aerodynamic prediction considering the wake interaction of multirotor, this study intends to emphasize the effect of wake interaction on noise. In this study, aerodynamic and aeroacoustic analysis of a multirotor was performed using VLM based solver. Through analysis based on various configurations and operating conditions, wake interaction effect and unsteady loading noise were identified.

2. METHODOLOGY

2.1 Aerodynamic Prediction

2.1.1 Free-Wake Vortex Lattice Method

Assuming that the flow region excluding the boundary of the blade and wake region is an incompressible and irrotational flow, the continuity equation is replaced by the form of the Laplace equation for the velocity potential as Equation 1.

$$\nabla^2 \Phi^* = 0 \tag{1}$$

The general solution of the Laplace equation could be made up of a combination of a source and a doublet potential located at the wake and the blade boundary. The source potential to express the thickness effect is only required on the blade surface boundary, and the potential distribution of the blade surface could be replaced by the doublet potential distribution along the blade camber surface by the thin airfoil theory⁶. The doublet potential of the blade camber boundary and the wake boundary could be



Fig. 1 - Multirotor configurations with coordinate system

expressed as a vortex lattice with the same vortex strength. The total flow field is induced by a velocity component derived from the vortex lattice of the blade and the wake, and the vortex strength Γ at each time step was calculated by the non-penetration condition as Equation 2 and the Kutta condition at the blade surface. V_0 is the free-stream velocity and $\Omega \times r$ is the velocity induced by the rotating motion. For considering the rotor and wake interaction in multirotor configurations, total induced relations which are rotor-rotor, rotor-wake, wake-rotor, and wake-wake were considered in each time step as Figure 1.

$$\left\{\frac{1}{4\pi}\sum_{body}\Gamma\nabla\left[\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right] + \frac{1}{4\pi}\sum_{wake}\Gamma\nabla\left[\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right] + \left(V_0 + \Omega \times r\right)\right\} \bullet n = 0 \quad (2)$$

In addition, the blade loading was calculated by applying the Kutta-Joukowski theorem to the vortex strength along the blade boundary as Equation 3.

$$\vec{F}_i = \rho \vec{V}_i \times \vec{\Gamma}_i \tag{3}$$

Since the vortex lattice method is based on the incompressible and inviscid flow, the compressibility correction was performed using Prandtl-Glauert correction. The viscous effect correction was considered by using the vortex core modeling and viscous vortex model⁷. Also, the CFD-based 2D airfoil aerodynamic coefficients table was used for considering the viscous effect and airfoil camber effect.

2.1.2 Constant Vorticity Contour Wake Model

To model the wake from the trailing edge of the rotor blade, the constant vorticity contour wake model was applied⁸. The constant vorticity contour wake model could simulate the wake effect efficiently compared to a conventional vortex lattice wake model because it is possible to express the distribution of vortex strength on the trailing edge and the strength change with time as a single wake element. In the case of the multirotor

configurations, it is necessary to consider the wake generated in each rotor and its interaction, so that the effect of the wake was efficiently calculated by using the constant vorticity contour wake model.

2.1.3 Curved Vortex Elements

The wake generated from the multirotor configurations is curved shape by the rotation for the blade. Wake modeling with curved vortex elements rather than straight vortex elements is advantageous when calculating the induced velocity by the curved wake⁹. Therefore, wake consisted of a parabolic vortex element and Biot-Savart equation for curved vortex element was applied. By the curved vortex element modeling, complicated wake interaction effects in multirotor could be considered efficiently and accurately.

2.2 Aeroacoustic Prediction

2.2.1 Impermeable Ffowcs-Williams Hawkings Acoustic Analogy

In order to discuss aeroacoustic characteristics of multirotor configurations and wake interaction effect to the noise, the aeroacoustic analysis was implemented by the impermeable surface based Ffowcs-Williams Hawkings (FW-H) acoustic analogy¹⁰. The tip Mach number of multirotor configurations is lower than the transonic region, so the nonlinear quadrupole noise could be neglected. The source surface of the impermeable FW-H was set to the blade surface of the multirotor. Therefore, the pressure of the blade surface which was given by free wake vortex lattice method solver was used for the acoustic analogy. The equations of the impermeable FW-H are as follows in Equations 4 and 5. Each component is thickness and loading noise which are the discrete frequency noise components of the rotor blade. Equation 4 represents the thickness noise which is generated by the flow rate induced by the blade rotating motion, so it is related to the blade shape and the speed of rotation. Equation 5 represents the loading noise which is generated by pressure and time derivative of pressure on the blade surface. It is composed of steady loading noise which is related to the overall thrust and unsteady loading noise. In multirotor configurations, unsteady loading, as well as steady loading occurs in hovering flight because of strong wake interactions.

$$4\pi p_T'(x,t) = \int_{f=0}^{I} \left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2} + \frac{\rho_0 v_n \hat{r} \dot{M}_r}{r(1-M_r)^3} \right]_{ret} ds + \int_{f=0}^{I} \left[\frac{\rho_0 v_n c_0 \left(M_r - M^2\right)}{r^2 \left(1-M_r\right)^3} \right]_{ret} ds$$
(4)

$$4\pi p'_{L}(x,t) = \frac{1}{c_{0}} \int_{f=0}^{f} \left[\frac{\dot{p}\cos\theta}{r(1-M_{r})^{2}} + \frac{\dot{r}\dot{M}_{r}p\cos\theta}{r(1-M_{r})^{3}} \right]_{ret} ds + \int_{f=0}^{f} \left[\frac{p(\cos\theta - M_{i}n_{i})}{r^{2}(1-M_{r})^{2}} + \frac{(M_{r} - M^{2})p\cos\theta}{r^{2}(1-M_{r})^{3}} \right]_{ret} ds$$
(5)

3. RESULTS & DISCUSSIONS

3.1 Verification with Single Rotor Experiment

In this study, DJI 9450 propeller of DJI F450 was set as a reference. The VLM solver was verified using results of the single rotor experiment and the blade element momentum theory (BEMT) analysis. Results for thrust coefficient (C_T) and torque coefficient (C_Q) are summarized in Table 1 and 2. In the case of C_T , the VLM solver predicted more accurately, and the BEMT showed a large error at higher RPM. In all RPM cases, the VLM results showed that the error of C_T is lesser than 6%. C_Q results showed that the VLM has a larger error than the BEMT in low RPM cases. This is because the viscous effect is somewhat weakly considered in the low Reynolds region. For the multirotor analysis, the 5250 RPM fixed condition was used. In this RPM condition, the VLM solver was well verified with the experiment result.

RPM	Experiment	BEMT	VLM	Error-BEMT (%)	Error-VLM (%)
2348	0.0145	0.01541	0.01419	6.28	2.14
2858	0.0142	0.01542	0.01447	8.59	1.90
3495	0.0147	0.01548	0.01460	5.31	0.68
4089	0.0154	0.01557	0.01472	1.10	4.42
4665	0.0157	0.01567	0.01478	0.19	5.86
5250	0.0154	0.01577	0.01489	2.40	3.31
5775	0.0153	0.01587	0.01498	3.73	2.09
6388	0.0151	0.01596	0.01510	5.70	0.00
6968	0.0151	0.01604	0.01515	6.23	0.33
7548	0.0150	0.01611	0.01519	7.40	1.27
8128	0.0149	0.01617	0.01521	8.52	2.08
8707	0.0149	0.01623	0.01519	8.93	1.95

Table 1 – Comparison of thrust coefficient (C_T)

Table 2 – Comparison of torque coefficient (C_0)

RPM	Experiment	BEMT	VLM	Error-BEMT (%)	Error-VLM (%)
2348	0.00238	0.00213	0.002011	10.50	15.50
2858	0.00221	0.00207	0.001953	6.33	11.63
3495	0.00207	0.00203	0.001907	1.93	7.87
4089	0.00204	0.00202	0.001897	0.98	7.01
4665	0.00198	0.00202	0.001894	2.02	4.34
5250	0.00192	0.00202	0.001895	5.21	1.30
5775	0.00191	0.00202	0.001896	5.76	0.73
6388	0.00187	0.00203	0.001898	8.56	1.50
6968	0.00184	0.00203	0.001895	10.33	2.99
7548	0.00182	0.00204	0.001897	12.09	4.23
8128	0.00181	0.00204	0.001897	12.71	4.81
8707	0.00179	0.00204	0.001901	13.97	6.20

3.2 Wake Interaction Effect in Hovering Flight

3.2.1 Aerodynamic Results

DJI F450 was set as a reference and aerodynamic characteristics were confirmed



Fig. 2 - Wake structure of multirotor configurations in hovering flight (a: d/D = 0.1; b: d/D = 0.36; c: d/D = 0.5; d: d/D = 0.8)



Fig. 3 - Sectional effective angle of attack (AOA) in hovering flight (a: d/D = 0.1; b: d/D = 0.36; c: d/D = 0.5; d: d/D = 0.8)

by changing the spacing d/D between rotors. The rotor spacing was set to d/D = 0.1, 0.36(reference), 0.5, 0.8, and the single rotor analysis was performed under same conditions to compare the wake interaction effect. Figure 2 shows hovering wake geometry for four multirotor configurations. It could be seen that the wake geometry in all configurations was greatly affected by the wake of the adjacent rotor at the far-field location where the wake is fully developed. The wake, which greatly affects the rotor aerodynamic and aeroacoustic characteristics, is located adjacent to the rotor. The smaller the spacing between rotors, the stronger the upwash effect was caused by the wake of the

adjacent rotor, and thus the wake was warped toward the rotor. In order to confirm the change of aerodynamic characteristics by the wake interaction, sectional effective angle of attack (AOA) in the rotor in-plane was confirmed. Figure 3 is the results of the rotor 1 of each configuration and comparison with the single rotor result under same conditions.

In all configurations, the effective AOA was increased due to the upwash effect in the vicinity of the other rotor, and the relatively weak inflow occurred in the opposite directions, resulting in a small effective AOA. Compared with a single rotor, the smaller the d/D is, the larger the effective AOA varies with the azimuth angle. It is shown that the multirotor analysis should be performed by considering the wake interaction because the aerodynamic characteristics according to the azimuth angle are significantly varied even in hovering flight.

3.2.2 Aeroacoustic Results

Unsteady loading noise and directivity pattern due to the wake interaction effect were analyzed. Noise analysis was performed for three configurations with d/D = 0.1, 0.36, and 0.8. All four rotors were placed in an in-phase state. Also, a single rotor was placed in the multirotor configuration with d/D = 0.36, and noise analysis was performed by excluding the wake interaction effect. The observer points were located at a distance of 10 times the blade radius with the center of the four rotors as shown in Figure 1. The directivity pattern of the loading noise is shown in Figure 4. The loading noise in the rotor in-plane direction is almost same in all configurations, but in the direction perpendicular to the rotor plane, a large loading noise occurs in a configuration with a small spacing between the rotors. Steady loading noise radiates toward the rotor in-plane direction, and unsteady loading noise radiates in a direction perpendicular to the rotor. That is, as the spacing between rotors becomes shorter, the wake interaction becomes stronger, and the unsteady loading noise is generated intensely. Comparing (b) and (d), (d) has about 15 dB smaller loading noise in the rotor axis direction. This is because the wake interaction effect is totally ignored in the single rotor. In the hovering flight, the multirotor configuration has a strong unsteadiness and asymmetric features of the aerodynamic characteristics, so it is necessary to consider the wake interaction.



Fig. 4 - Loading noise directivity (a: d/D = 0.1; b: d/D = 0.36; c: d/D = 0.8; d: d/D = 0.36 with single rotor)

3.3 Wake Interaction Effect in Forward Flight

3.3.1 Aerodynamic Results



Fig. 5 - Wake structure of multirotor configurations in forward flight (*a*: $\mu = 0.05$; *b*: $\mu = 0.1$; *c*: $\mu = 0.2$; *d*: $\mu = 0.1$ *diamond formation*)



Fig. 6 - Sectional effective AOA in forward flight of square formations (a: $\mu = 0.05$; b: $\mu = 0.1$; c: $\mu = 0.2$; 1: multirotor; 2: single rotor)



Fig. 7 - Sectional effective AOA in forward flight $\mu = 0.1$ of a diamond formation (d1: rear rotor (rotor 1); d2: side rotor1 (rotor 2); d3: side rotor2 (rotor 3))

Wake structure was identified according to the advancing ratio and flight direction. Based on the rotor spacing of the DJI F450, three types of the square formation with the advancing ratio of 0.05, 0.1, and 0.2 and one diamond formation with the advancing ratio of 0.1 were discussed. Figure 5 is the wake structure during the forward flight. Three square formation results show that rear rotors operated under the influence of the front rotors at all advancing ratio. Especially when the advancing ratio is small, many interactions occur between side rotors as well as between front and rear rotors. In the diamond formation, the rear rotor (rotor 1) is influenced by the wake of the others. Each side rotors (rotor 2, 3) are located on the advancing or retreating side of the front rotor, thus exhibiting other interaction effects. Figure 6 shows the effective AOA of the rear rotor (rotor 1) compared with a single rotor of the same advancing ratio in the square formations. In the forward flight of the single rotor, the advancing and retreating side are clearly distinguished by the effective AOA. However, in the rear rotor of the multirotor, the effective AOA of the advancing side is decreased by the wake of the front rotor. The distribution of effective AOA is changed by wake interaction, which causes a large change in amplitude and directivity of the loading noise. Figure 7 shows the effective AOA of the rear and side rotors (rotor 2, 3) in the diamond formation. Comparing (d2), (d3) and (b3) in Figure 6, two side rotors have a large AOA but there are slight differences between two side rotors. In the (d1), the peak of the effective AOA is shifted toward the advancing side of the front rotor, which affects the directivity of the loading noise.





Fig. 8 - *Loading noise directivity at* $\mu = 0.05$ (*a: axis plane; b: rotor plane*)



Fig. 9 - *Loading noise directivity at* $\mu = 0.1$



Fig. 10 - *Loading noise directivity at* $\mu = 0.2$



Fig. 11 - Loading noise directivity at $\mu = 0.1$ of diamond formation

Aeroacoustic analysis was performed for each operating conditions, and characteristics of unsteady loading noise were identified. Noise analysis of multirotor configuration without considering wake interaction using single rotor analysis results was performed to compare the noise directivity of front/rear rotor. The unsteady loading noise due to the wake of the front rotor could be confirmed by comparing the directivity of the front (rotor 4)/rear (rotor 1) and the strength of the unsteady loading could be discussed by comparing with the single rotor. Overall, the difference in single and multirotor in the directivity in the axis plane is remarkable. Especially in rear rotor (rotor 4), unsteady loading noise is generated intensely. Figure 9 (a) shows that the directivity is completely affected by the wake interaction and the unsteady loading noise propagates more in the direction of the rotor axis. In Figure 8, the unsteady loading of the front rotor is intense

when the advancing ratio is low because the front rotor is also affected by the wake of the rear rotor. In the diamond formation (Figure 11), wake interaction is lesser than that of the square formation of the same advancing ratio. The wake interaction occurs in the front rotor (rotor 1) by another front rotor (rotor 2) in the case of square formation. In addition, unsteady loading occurs less in the rear rotor of the diamond formation because it is relatively far from the front rotor.

4. CONCLUSIONS

The aerodynamic and aeroacoustic characteristics of the multirotor configuration under various operating conditions were analyzed using a solver based on the free wake vortex lattice method that was verified by single rotor analysis. Unsteady loading features were apparent in the multirotor due to the wake interaction. In the hovering flight, asymmetric characteristics in the aerodynamics of the rotor were confirmed by the wake structure and effective AOA, while varying the spacing between the rotors, resulting in unsteady loading noise. In the forward flight, the analysis was conducted by changing the advancing ratio and formation. Since the rear rotor is operated under the influence of the wake of the front rotor, aerodynamic and aeroacoustic characteristics were much different from those of the single rotor. Overall, the lower the advancing ratio, the more wake interaction occurred, and front rotor was also affected by the rear and another front rotor.

The aerodynamic analysis was performed considering the wake interaction of the multirotor, and the discrete frequency noise components of the rotor were confirmed. Multirotor analysis was performed with the RPM fixed condition. In the real operating condition, the attitude and flight control of multirotor is performed using the RPM variance condition so that discrete frequency noise components would be varied. In addition, it is important to consider various types of broadband noise such as turbulence ingestion noise, turbulent boundary layer trailing edge noise, and tip vortex formation noise, since the multirotor mainly operates on low Mach number region. There are noise components in broadband noise. Considering these components, it is necessary to perform accurate prediction in the frequency domain. In the future, once accurate spectrum prediction is achieved, it is expected to performing the psychoacoustic analysis and this study would be applied to noise efficient design of the drone and UAM.

5. ACKNOWLEDGEMENTS

This work was conducted at High-Speed Compound Unmanned Rotorcraft (HCUR) research laboratory with the support of Agency for Defense Development (ADD). Also, this work was supported by Advanced Research Center Program (No. 2013073861) through the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIP) contracted through Advanced Space Propulsion Research Center at Seoul National University.

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