Downwash Effect on the Unguided Rocket under Rotor Wake and External Wind

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Downwash effect is the interaction between rotor wake and a launched rocket. Since the effect alters the initial motion of the rocket, a comprehensive analysis of the effect is crucial in predicting the entire trajectory and range of the rocket. In addition, external winds affect the trajectory and range as the winds alter the downwash effect. Because the downwash affected ranges do not appear to be investigated sufficiently, this study aims to reveal the trajectory and range variance characteristics focusing on the downwash effect and external winds. Using an actuator model and six-degrees-of-freedom analysis, trajectories of the rocket due to the downwash effect are described. The range variance characteristics of an un-guided rocket are investigated for a 3,000-lb class helicopter, and the rotor flow field database is analyzed using the CFD method while considering external wind effects. It is concluded that the effective angle of attack of the rocket in the rotor wake region varies along the wind direction, and the final reach range also changes accordingly. In particular, the range increased significantly when the rear wind is blown out. However, the range of the rocket is constant after a specified wind speed due to rocket acceleration.

Key Words: Rotorcraft, Projectiles, Rocket Aiming, Downwash Effect, Trajectory

Nomenclature

\[ C_I: \text{ rolling moment coefficient} \]
\[ C_m: \text{ pitching moment coefficient} \]
\[ C_N: \text{ normal force coefficient} \]
\[ C_Y: \text{ yawing moment coefficient} \]
\[ C_X: \text{ axial force coefficient} \]
\[ C_S: \text{ side force coefficient} \]
\[ C_T: \text{ thrust coefficient of rotor} \]
\[ N_b: \text{ number of blades} \]
\[ \dot{q}: \text{ pitch angular acceleration} \]
\[ q: \text{ pitch angular velocity} \]
\[ R: \text{ rotor radius} \]
\[ \ddot{x}: \text{ additional source from rotor rotation} \]
\[ U_D: \text{ downwash velocity} \]
\[ V: \text{ velocity magnitude of rocket} \]
\[ \alpha: \text{ angle of attack of rocket} \]
\[ \alpha_{eff}: \text{ effective angle of attack of rocket} \]
\[ \beta: \text{ side slip angle} \]
\[ \theta: \text{ pitch angle of rocket} \]
\[ v: \text{ kinematic viscosity} \]
\[ \psi: \text{ azimuth angle of rotor} \]
\[ \Omega: \text{ rotation speed of rotor} \]

Subscripts

MR: main rotor
aero: aerodynamic force on rocket
\[ p: \text{ derivative with respect to roll rate} \]
\[ q: \text{ derivative with respect to pitch rate} \]
\[ r: \text{ derivative with respect to yaw rate} \]

\[ \alpha: \text{ derivative with respect to angle of attack} \]
\[ \beta: \text{ derivative with respect to side slip angle} \]

1. Introduction

Unlike fixed-wing aircraft, unguided rockets launched from rotorcrafts pass through the rotor wake region to reach the final range. As the rockets traverse through the wake region, a downwash effect that changes the motion of the rocket occurs. Because of the downwash effect, it is difficult to predict the range of the rocket desired by the helicopter pilot before launching the rocket. Since unguided rockets have no additional control systems, it is crucial to predict the reach point affected by the downwash in real-time before a rocket is launched. The downwash effect is induced by the rotating rotor of the helicopter and alters the attitude of the rocket immediately after launch. In the rotor downwash region, the effective angle of attack of the rocket is negative and positive pitching moment of the rocket is generated for static pitching stability of the rocket. Since the positive pitching moment increases pitch angle of the rocket, overall range of the rocket is increased. Therefore, the downwash effect needs to be considered in order to predict the trajectory and overall range of the rocket more accurately. In addition, external wind and wind-fuselage interference must also be considered since they affect the trajectory and overall range of the rocket. Under external winds, the downwash effect imposed on the rocket varies because the external wind causes a skewed rotor wake, and the wind can generate wind-fuselage interference as shown in Fig. 1.

The downwash effect has been analyzed using computational simulations due to the restriction on conducting direct target striking experiments. In previous studies, numerical
methods ranging from aerodynamic interference coefficients to full computational fluid dynamics (CFD) have been used to calculate the downwash effect, and six-degrees-of-freedom (6DOF) motion was mainly used to calculate the rocket trajectory. Wei and Gjestvang\(^1\) used the panel method with the vortex wake model to analyze the aerodynamic interference coefficients between a SH-2G helicopter fuselage and a Penguin missile when the missile separated from the fuselage. However, the downwash effect imposed on the overall range was not analyzed. Moreover, it is difficult to grasp a detailed effect of the downwash because they were using coefficients. Lee et al.\(^2\) simulated the initial motion of an unguided rocket launched in the rotor wake region, which was calculated using full CFD with an unstructured overset mesh. They analyzed the pressure distribution on the projectile surface and calculated the pitching-up motion of the rocket under the wake region. The method is appropriate for analyzing the initial motion of a rocket under specific launch conditions. However, the full CFD with the overset grid method is difficult to apply for real-time situations. The full CFD method requires numerous computational resources and extensive calculation time. Gong et al.\(^3\) used the actuator disk model to analyze the downwash inflow from the rotor of a UH-60A helicopter. The downwash effects on a Hydra70 rocket and a Sierra bullet were compared. It showed the entire trajectory and range of the rocket, and the rocket was found to be more influenced by the downwash effect than the bullet. However, it did not consider external wind, which skews the rotor wake and alters the downwash effect, trajectory, and range of the rocket. Kapulu et al.\(^4\) analyzed the trajectory and range of a 2.75-in unguided rocket using the Peters dynamic inflow model in a hovering state. It was concluded that the range increased due to the downwash effect. In addition, the safe separation of the rocket from a UH-60 Black Hawk helicopter was investigated. Using the dynamic inflow model, the trajectory and entire range of a rocket can be calculated in real-time. However, the dynamic inflow method does not consider the viscous effect of air, which is required to analyze the effect of wind-fuselage interference.

Previous studies applied various methodologies to analyze the rotor downwash effect. However, none of them has focused on the downwash effect together with external winds such as skewed rotor wake and wind-fuselage interference, which also change the downwash effect. Additionally, they did not develop a rocket-aiming algorithm that can predict the trajectory and overall range of a rocket in real-time.

To this end, it is crucial to build a database of rotor flow fields analyzed using a Navier-Stokes solver. Furthermore, in order to apply the flow database to real helicopters, the trajectory and overall range of the rocket are required for real-time 6DOF analysis. In addition, the overall range of the rocket is changed because the ambient external wind of the helicopter causes the rotor wake to be skewed and the rocket pitching motion to change. Therefore, it is imperative to investigate the characteristics of rocket range variation with respect to the external wind environment.

This study develops a novel algorithm that can accurately predict the trajectory of the rocket. Our main contribution is that we consider the downwash effect caused by external winds. Using the algorithm, the rocket range variation characteristics are investigated with respect to external wind conditions in the following manner.

1) CFD based on a Navier-Stokes solver was used to calculate the wake region, downwash, and the wind-fuselage interference under various external wind conditions. A database was built based on the results that were obtained. Then, we developed an algorithm to predict the trajectory and range of the rocket using 6DOF analysis. The algorithm can be applied to actual helicopters for real-time rocket range prediction.

2) The variation characteristics of the trajectory and range of the rocket due to the downwash effect, wind-fuselage interference and external wind directions were analyzed. The range variation was also investigated with respect to the velocities of the external wind.

2. Methodology

2.1. Trajectory analysis algorithm

A trajectory analysis algorithm was developed to analyze the downwash effect under external wind and wind-fuselage interference. The algorithm applies rotor downwash data to the aerodynamic force on the rocket. The algorithm consists of two analyses: rotor downwash analysis and rocket motion analysis. After analyzing the rotor downwash of a specific helicopter under various wind conditions, three-dimensional (3-D) velocity vectors of the computational domain are constructed as the rotor downwash data.
The overall algorithm flow is shown in Fig. 2:

1) Set the initial launch condition, external wind condition, projectile data, and aerodynamic coefficients of the rocket.

2) Calculate the Mach number and effective angle of attack of the rocket considering the rotor downwash data at the initial position of the rocket.

3) Calculate the thrust, gravity, and aerodynamic force on the rocket.

4) Calculate the next position of the rocket using the 6DOF equation of motion and the 4th order Runge-Kutta (RK4) time integral.

5) Repeat steps 2–4 until the rocket impacts on the ground.

2.2. Rotor downwash analysis

The rotor downwash data is comprised of the velocity vectors induced by the rotor blades instead of the detailed pressure distribution on the blades under the external wind. For this reason, the actuator model (AM) is the appropriate method to calculate the downwash rather than the full CFD method, which needs excessive computation time for numerical calculations pertaining to various external wind conditions. The AM is a combination of the Blade Element Theory (BET) and Navier-Stokes (NS) equation using virtual rotor blades, applying additional pressure generated by the rotor blades in the NS equation. The AM can efficiently obtain the downwash flow fields under various external wind conditions. The AM is composed of two models: Actuator Disk Model (ADM) and Actuator Surface Model (ASM). The ADM regards the rotor as a virtual disk, and focuses on the pressure average with respect to the rotor azimuth angle. On the other hand, the ASM regards the rotor as virtual blades and considers the pressure in each azimuth angle. The induced velocities in the cell information of the rotor are reflected in the effective angle of attack of the virtual blade section. The pressure induced for both methods is given as a source term for the momentum conservation of the NS equation (Fig. 3).

Kim et al.5) developed an AM solver combined with the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) in the open-source code OpenFOAM. An identical solver was used in this paper. The solver calculated the sectional blade thrust obtained from the BET, as shown in Eq. (1), and the sectional thrust was applied to the pressure source term of the NS equation, as shown in Eq. (2).

\[
\ddot{s} = \frac{dT}{\rho dV} \tag{1}
\]

\[
\frac{\partial U}{\partial t} + \nabla \cdot (\bar{U}U) - \nabla \cdot (\nu \nabla \bar{U}) = \ddot{s} - \nabla p \tag{2}
\]

To validate the rotor downwash analysis, the ADM and ASM analysis results were compared with the results of the experiment of Elliot et al.6) and full CFD of Nam et al. The experiment performed by Elliot et al. measured the inflows induced by four rectangular blades, which have a 0.86-m radius, aspect ratio of 13, root cutout at 0.24R, a NACA 0012 airfoil, and a negative 13-deg linear twist. The inflow was measured at the blade chord length of 1.15 above the rotor with a 0.15 advance ratio, thrust coefficient of 0.0063, and shaft angle of 3-deg with nose down. The fuselage model of the experiment was based on rotor-body interaction (ROBIN). Approximately 11 million unstructured cells were generated for the ADM and ASM simulations (Fig. 4). The rotor wakes generated in the simulations are shown in Fig. 5.

The inflow results of the ASM and ADM were well matched with not only the experimental result, but also the full CFD results validated in previous studies (Figs. 6 and 7). However, the simulation results of the full CFD, ASM, and ADM were different from the experimental results around the center of the rotor, as a detailed rotor hub model was not considered in the simulations. As all of the inflow results were averaged for one rotation of the rotor, the
ADM had the same accuracy of the averaged inflow analysis as the full CFD and ASM.

In addition, Son et al.\(^8\) showed that both ADM and ASM results of pressure distribution on the ROBIN fuselage were almost identical. In addition, the prominent inflow characteristic of the averaged inflow of one rotor rotation should reflect the downwash effect despite the existence of minor inflow variation at a specific azimuth angle. For these reasons, ADM was chosen to analyze the rotor downwash.

### 2.3. Rotor downwash analysis

To analyze the rotor downwash effect, a 3,000-lb helicopter with two stub-wings was generated in the computational domain (Fig. 8). In addition, nearly 5,570,000 unstructured cells were generated including those of fuselage, stub-wings, rotor disk, and the far-field region (Fig. 9).

The boundary conditions were that the fuselage and stub-wings satisfied no-slip conditions, the inlet had the free-stream velocity of the external wind, and the outlet had a zero-pressure gradient. The Spallart-Allmaras model was used as the turbulence model of the NS equation.

As shown in Table 1, the hovering flight of a 3,000-lb LAH with linearly twisted and rectangular blades was used to obtain the downwash flow data.

In order to keep the helicopter stable under the external winds, yawing, rolling, and pitching moment should not be generated. The yawing moment was canceled out by the thrust of the tail rotor. However, the rolling and pitching moments were canceled out by trimming the cyclic and collective pitch angles of the rotor blades. In the rotor downwash analysis, the downwash flow field under the trimmed pitch
angles was analyzed to determine the stable helicopter attitude under the external winds. To analyze the rotor downwash flow field for a stable helicopter attitude, the following were the three convergence criteria of the ADM:

1) The difference between the target thrust coefficient \( C_{T\text{,target}} \) and calculated thrust coefficient \( C_{T\text{,cal}} \) is below 1% for calm wind and all external wind cases.

2) Numerical calculation time is the value over ten rotations of the rotor to consider the fully developed rotor wake.

3) Rolling and pitching moment coefficients\(^9\) are below \(10^{-5}\) to consider the balanced lift distribution under external wind (Eqs. (3), (4), (5), and (6)).

\[
M_x = \frac{N_b}{2\pi} \int_0^{2\pi} \int_0^R y \, dF_z \sin \psi \, d\psi \quad (3)
\]

\[
C_{M_x} = \frac{M_x}{\rho AR(2R)^2} \quad (4)
\]

\[
M_y = \frac{N_b}{2\pi} \int_0^{2\pi} \int_0^R x \, dF_z \cos \psi \, d\psi \quad (5)
\]

\[
C_{M_y} = \frac{M_y}{\rho AR(2R)^2} \quad (6)
\]

All rotor downwash analyses under external wind satisfied the above convergence criteria. The rotor downwash distribution on the view plane, where the rocket is launched during hovering flight under calm wind, is shown in Fig. 10.

2.4. Rocket motion analysis

The unguided rocket performs 6DOF motion using gravity, thrust, and aerodynamic force after launch. To calculate the aerodynamic force, not only the center of gravity, but also the aerodynamic coefficients and center of pressure, which were a function of Mach number, were obtained from the wind tunnel test of Dahlke et al.\(^{10}\).

Aerodynamic coefficients\(^{10}\) were derived by assuming that the rocket was \(90^\circ\) axis-symmetric.

\[
\begin{align*}
C_{n_x} &= C_{m_x} \\
C_{n_y} &= -C_{m_y} \\
C_{y_x} &= C_{N_x} \\
C_X &= \frac{C_D - C_{N_x} \alpha \sin \alpha}{\cos \alpha} \quad (7) \\
C_{m_x} &= \frac{C_{N_x} (X_{CG} - X_{CP})}{L_{\text{ref}}} \\
\end{align*}
\]

The aerodynamic force on the rocket was calculated using the derived aerodynamic coefficients.

\[
\begin{align*}
F_{x\text{,aero}} &= -\frac{1}{2} \rho V^2 A_{\text{ref}} C_X \\
F_{y\text{,aero}} &= -\frac{1}{2} \rho V^2 A_{\text{ref}} C_{Y_x} \beta \\
F_{z\text{,aero}} &= -\frac{1}{2} \rho V^2 A_{\text{ref}} C_{N_x} \alpha \\
L_{\text{aero}} &= \frac{1}{2} \rho V^2 A_{\text{ref}} l_{\text{ref}} \left( C_l + \frac{C_{b,l} l_{\text{ref}}}{2V} \right) \\
M_{\text{aero}} &= \frac{1}{2} \rho V^2 A_{\text{ref}} l_{\text{ref}} \left( C_{m_x} \alpha + \frac{C_{m_x} q l_{\text{ref}}}{2V} \right) \\
N_{\text{aero}} &= \frac{1}{2} \rho V^2 A_{\text{ref}} l_{\text{ref}} \left( C_{n_y} \beta + \frac{C_{n_y} r l_{\text{ref}}}{2V} \right)
\end{align*}
\]

The 6DOF motion was driven by gravity, thrust, and aerodynamic force of the rocket on the body frame.

\[
\begin{align*}
F_x &= m(\dot{u} + g \nu - rv) \\
F_y &= m(\dot{v} + ru - pw) \\
F_z &= m(\dot{w} + pu - qv) \\
L &= I_z \dot{\phi} - I_x \dot{\psi} + qr (I_x - I_z) - I_{xcp} \dot{q} \\
M &= I_z \dot{\phi} + rp (I_x - I_z) + I_{xcp} (p^2 - r^2) \\
N &= I_z \dot{\psi} - I_{xcp} \dot{p} + pq (I_y - I_x) + I_{xcp} \dot{q}
\end{align*}
\]

In the inertia frame, the equation of motion was articulated in Euler angles. Velocities, rotation velocities, and position of the rocket were calculated with the RK4 time integral with a \(10^{-5}\) time step.
used the Peters-He 6-state dynamic inflow model as the rotor downwash analysis, and investigated the trajectory of a 70-mm unguided rocket, which was initially launched at 2-deg nose-up angle and a height of 305 m. Because there was a lack of the detailed aerodynamic coefficients for the rocket in the study, a 2.75-inch rocket with the same diameter as the rocket simulated in the study was used for the trajectory comparison. The wind tunnel test data of Dahlke et al.\textsuperscript{10} was used for the aerodynamic coefficients and thrust of the rocket. The dynamic inflow model results of Kapulu et al.\textsuperscript{4} were the inputs for the trajectory analysis. A comparison of the trajectories is shown in Fig. 12.

The trajectories without the downwash were identical, and the ranges influenced by the downwash had a difference of 2.7%. The error occurred because of the difference in the detailed rocket configuration, which caused dissimilar aerodynamic coefficients. However, the error was in the acceptable range for investigating the downwash effect and variation characteristics of the rocket range. Both simulations showed that the rocket range was increased by the downwash effect. This phenomenon of increase in the range should be physically investigated based on the relationship between rocket aerodynamics and stability.

### 3.2. Investigation of the downwash effect

The increased range of the rocket under the downwash effect can be investigated in the following manner:

1. The rocket was designed to be stable against pitching variation. The pitching moment coefficient derivative with angle of attack $C_{ma}$ was always a negative value for the Mach number range, and the value was quantitatively determined in the wind tunnel test of Dahlke et al.\textsuperscript{10}.

2. Although the rocket was launched horizontally, the negative effective angle of attack of the rocket was induced as a result of the downwash flow.

3. The positive pitching moment (nose-up direction) occurred due to the pitching stability of the rocket.

4. Because of the positive pitching moment, the pitching velocity and pitch angle increased.

---

**Equation (10)**

\[
\begin{align*}
\dot{u} &= \frac{(F_{\text{propulsion}} + F_{\text{aero}})}{m} - g \sin \theta + ru - qw \\
\dot{v} &= \frac{F_{\text{aero}}}{m} + g \cos \theta \sin \phi + pw - ru \\
\dot{w} &= \frac{F_{\text{aero}}}{m} + g \cos \theta \cos \phi + qu - pv \\
\dot{p} &= \frac{L_{\text{aero}}}{I_x} + (I_y - I_z)qr \\
\dot{q} &= \frac{M_{\text{aero}}}{I_y} + (I_z - I_x)rp \\
\dot{r} &= \frac{N_{\text{aero}}}{I_z} + (I_x - I_y)pq
\end{align*}
\]
5) After the pitch angle reached its maximum, it decreased because of the damping pitching moment due to the increased pitch velocity.
6) Rocket thrust was generated during the pitching up motion, which increased the rocket range.

The phenomenon of increased rocket pitch angle due to the downwash was also quantitatively investigated using the trajectory analysis algorithm and the ADM downwash data for hovering flight under calm wind, as shown in Fig. 13.

4. Results and Discussion

The range variation characteristics of the rocket influenced by the downwash effect under external wind should be considered because external wind causes the rotor wake region to become skewed. The downwash effect and range variation were analyzed with respect to the directions and velocities of the wind using the trajectory analysis algorithm and rotor downwash data calculated by the ADM. The 2.75-in rocket, the aerodynamic coefficients and thrust data of which were referenced from Dahlke et al. (10) was chosen as the projectile. The rocket was launched from a height of 440 m at an initial launch velocity of 45 m/s based on referring to the technical data of the MK66 motor.

4.1. Downwash effects with respect to the direction of external wind

Five wind conditions including a no-wind (calm wind) condition were used in the downwash effect analysis, as shown in Fig. 14. The wind velocity in all directions was set at 10 m/s after referring to the wind velocity data from the Korea Meteorological Administration. The downwash data for different wind conditions were shown at the view plane where the rocket was launched (Fig. 15). Although the inflow distribution was symmetrical in the no-wind condition, it was unsymmetrical in the other cases due to the counter-clockwise rotation of the rotor. Under rear wind, the downwash was distributed further ahead in the launch direction than any other wind cases. The downwash near the launch location under left wind was seen to have upward and downward flows, which was because of the wind-fuselage interference. The effective angles of attack of the rocket.
with respect to the rocket range are shown in Fig. 16. The effective angle of attack under rear wind was negative until the 16-m range of the rocket. In the case of left wind, the downwash had a longer effect on the rocket than no wind, and the effective angle of attack fluctuated in the early stage due to interference.

Maximum pitch angles were generated as the negative effective angles of attack caused nose of the rocket to rise (Fig. 16). The resultant total ranges of the wind conditions are shown in Fig. 17. Because the thrust of the rocket was generated at the moment of maximum pitch-up angle, all ranges with the downwash effect were longer than those without the downwash effect. In addition, the negative effective angles of attack had the longest range under rear wind when compared to other wind conditions, as shown in Fig. 15: the maximum pitch-up angle under rear wind was the largest and its corresponding total range was the longest. Except for the cases of rear and left winds, the total range under all other directions of the wind was shorter than the range under no wind. This is because the winds of all other directions caused a skewed wake, which has a smaller influence on the downwash effect.

However, the range under left wind was shorter than the range under no wind even though the negative effective angle of attack occurred in the longer range. The reason for the shorter range was that the pitching-up moment was not generated sufficiently due to the initial fluctuation in the effective angle of attack, which was induced by the wind-fuselage interference.

4.2. Downwash effects with respect to the velocity of external wind

The rear wind had the most influence on range variation. The characteristics of range variation were also investigated with respect to the rear wind velocities of 10, 15, and 20 m/s. As the velocity of the rear wind became higher, the rotor wake was increasingly skewed, as shown in Fig. 18. When the rocket was no longer affected by the downwash, the effective angle of attack of the rocket became zero. Consequently, as the skewness of the wake became larger, the rocket exited the wake at a longer range. At the moment of exit, the pitch velocity and angle of the rocket were increased for the rear winds of 10 m/s and 15 m/s. However, the pitch velocities and angles for the rear winds of 15 m/s and 20 m/s were almost identical.

The maximum pitch-up angle and total range of the rocket increased as the velocity was increased until the velocity of the rear wind reached 15 m/s (Figs. 19 and 20). However, the identical pitch velocities and angles at rear winds of 15 and 20 m/s caused similar maximum pitch-up angles and total ranges. Despite the increased rear wind velocity, the reason for the similar ranges was sufficient acceleration of the rocket caused by fuel combustion. Because of the increased skewness of the wake, the rocket had a long distance to cover before it could exit the downwash. However, the effective angles of attack over the longer distance became smaller due to the acceleration of the forward velocity of the rocket, even in the presence of the downwash (Fig. 21).
5. Conclusion

A novel rocket-aiming algorithm was developed to predict the trajectory and overall range of a rocket exposed to rotor wake and external winds. The algorithm can capture the downwash effect including skewed wake of rotor and the wind-fuselage interference as the result of external winds in a real-time situation. The range variation characteristics of a 2.75-in rocket were investigated using 3,000-lb helicopter specifications, and the rotor flow field database was analyzed using CFD based on Navier-Stokes with respect to external winds.

It was concluded that the range of the rocket increases when the wake is skewed in the forward direction of the rocket because larger pitching-up moment is generated. However, the interference between the wind and fuselage of the helicopter fluctuated the effective angle of attack of the rocket. As a result, the pitch-up angle of the rocket under a left wind was smaller than the angle under a calm wind, even if the rocket under the left wind is in a more influential wake region than under a calm wind. This implies that analysis of the viscous flow field with an external wind is imperative for predicting the range of the rocket. Based on the rear wind in Fig. 17, which was the most influential direction for rocket range, the range increased as the rear wind speed increased. However, the range of the rocket was constant after the speed of the rear wind increased above a specified speed. The reason for this is that as the rear wind speed increases, the wake region increases in the forward direction of the rocket. However, the forward speed of the rocket increases due to the fuel burning, and the effective angle of attack and pitch angle were negligible in rotor downwash.

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