Proceedings of the Eighteenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 10, Paper 9.6
Civil-Comp Press, Edinburgh, United Kingdom, 2025
ISSN: 2753-3239, doi: 10.4203/ccc.10.9.6

CFD Simulation of Multi Rotor-Induced DWOW and Its Effects on Human

Y. Chang[1], Y. Jo[2] and D. Kim[2]

[1]Department of Aeronautical Systems Engineering, Hanseo University, Taean, South Korea
[2]Department of Unmanned Aircraft Systems, Hanseo University, Taean, South Korea

Abstract

When a vertical take-off and landing (VTOL) aircraft employing multiple rotors is operated, the resulting downwash and outwash (DWOW) can critically affect nearby structures, ground facilities, and the stability of adjacent aircraft. Accordingly, for safe urban air mobility (UAM) operations within urban environments, it is essential to identify the range of DWOW effects at vertiports and assess their impact on the human body. In this study, simulations were conducted using the commercial CFD software STAR- CCM+ to investigate the DWOW generated by tandem rotors. By varying the distance between the rotor and a human model, the influence of DWOW was analyzed under various conditions. The results confirmed that the DWOW generated by multi-rotors can pose a practical hazard within certain ranges and should be taken into consideration in vertiport design. Therefore, this work is expected to provide fundamental data for understanding potential hazards that may arise when operating vertiports and to offer a reference for future research and design.

Keywords: urban air mobility, vertical take-off and landing, multi-rotor, downwash and outwash, computational fluid dynamics, unsteady Reynolds-Averaged Navier–Stokes

1 Introduction

Urban Air Mobility (UAM), which has recently garnered attention as an efficient mode of urban transportation, predominantly operates in city centers. Consequently, the frequent low-altitude flights or operations in densely built environments may expose the aircraft to significant aerodynamic interference from the ground and surrounding buildings. If such interference compromises flight stability, it could pose a direct threat to public safety—potentially leading to casualties in populated areas, increased ground traffic congestion, and diminished reliability of UAM as a transportation mode. Therefore, ensuring safe UAM operations within urban environments is of paramount importance.

To address such concerns, the UK Civil Aviation Authority (CAA) has proposed initial perspectives on the downwash effect for safe operation of aircraft and has continued research focusing on passenger and ground crew safety regarding the potential hazards that arise from differences between helicopters and vertical take-off and landing (VTOL) aircraft[1]. Similarly, the U.S. Federal Aviation Administration (FAA) has established design guidelines for public and private air corridors and vertiports, specifically for VTOL aircraft. Among its safety considerations is the need to ensure that downwash and outwash do not adversely affect other aircraft, surrounding infrastructure, or the aerodynamic performance of the VTOL itself[2]. Accordingly, to address safety issues arising from UAM operations in urban areas, predictive simulations and analyses of rotor wake interference near the ground and buildings are required[3,4].

Based on this rationale, this study aims to predict and analyze, via preliminary simulation, the impact of rotor wakes near the ground and around buildings on the human body, with a view to mitigating the safety risks associated with UAM operations in urban environments. By employing the commercial flow analysis software STAR-CCM+, this research characterizes the DWOW generated by multi-rotors and examines its effect on the human body, thereby contributing to the establishment of safety standards in vertiport and urban infrastructure design.

2 Methods

2.1 Numerical Method

2.1.1 Governing Equations

URANS is a turbulence modeling technique that accounts for the temporal variation of fluid flow. By incorporating time-derivative terms into the conventional RANS formulation, it retains the governing equations for the mean flow field while simultaneously reflecting flow unsteadiness. The following equations represent the fundamental governing equations used in URANS. In this study, to account for the unsteady flow behavior over time, the conventional RANS equations are augmented by maintaining the time-derivative term. Furthermore, the Reynolds stress term, which emerges from averaging fluctuating components, is modeled using the SST k-ω turbulence model.

The continuity and momentum equations are given as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \overline{U_j})}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (\rho \overline{U_i})}{\partial t} + \frac{\partial (\rho \overline{U_i U_j})}{\partial x_j} = - \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(\rho \overline{u_i' u_j'}\right) \tag{2}$$

where ρ is the fluid density, and $\overline{U_j}$ denotes the j −component of the time-averaged flow velocity. $\overline{p}$ is the mean pressure, μ is the dynamic viscosity, and $\overline{u_i' u_j'}$ represents the Reynolds stress.

Equation (1) signifies mass conservation. Equation (2) incorporates the Reynolds stress term $\rho \overline{u_i' u_j'}$, which appears in the time-averaging process and can be closed (modeled) using an appropriate turbulence model. Consequently, when performing unsteady flow analysis, the term $\frac{\partial}{\partial t}$ in the above equation is retained, allowing the flow characteristics that vary over time to be captured accurately. Based on these URANS equations, the unsteady flow phenomena around a hovering rotor can be accurately predicted, which is critical for analyzing vortex interactions and wake characteristics in the vicinity of the rotor.

2.1.2 Turbulence Model

The accuracy of turbulent flow analyses strongly depends on the chosen turbulence model, making the selection of a suitable model crucial for specific flow conditions. In this study, the SST k-ω turbulence model was adopted. This model retains the high accuracy of the k-ω model near walls while incorporating the stability of the k-ϵ model in the free stream region, thereby compensating for the strengths and weaknesses of each approach.

2.1.3 Overset Grid Method

Overset grid techniques allow multiple, distinct mesh systems to overlap. By hole-cutting the region of overlap and then independently generating each mesh block, physical quantities on overlapping boundaries are exchanged via interpolation[5]. This approach is beneficial for problems involving complex geometries or moving boundaries, as it can reduce both time and computational costs. Figure 1 shows an example of the mesh generated for this study.

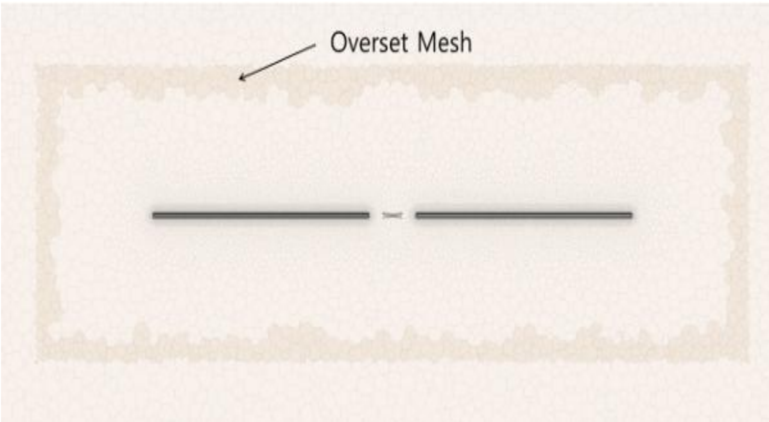


Figure 1 : Overset Mesh

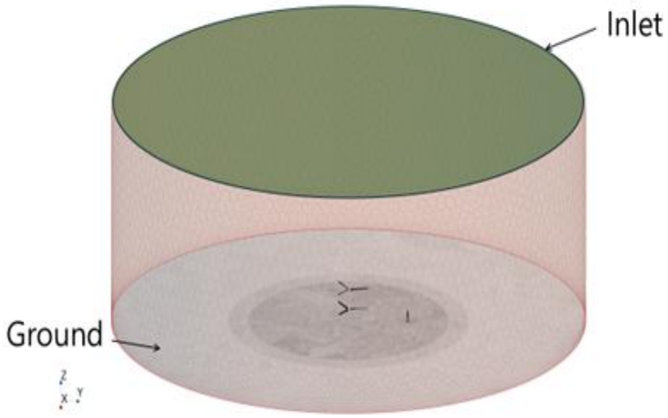


Figure 2 : Mesh for X/R=3

2.1.4 Grid Model and Flow Conditions

In this study, we used version 24.06 of Siemens' STAR-CCM+ for flow analysis. Figure 2 presents the mesh for analyzing flow interference among the rotor, the ground, and the human body. The inlet at the top was set as a Velocity Inlet, and the ground (lower boundary) as a Pressure Outlet. Both the rotor and the ground were defined as No-Slip Walls, and boundary-layer meshes were created to ensure $y^+ \leq 1$. The total number of mesh cells was approximately 35 million, determined through a preliminary grid study that identified a suitable mesh resolution.

2.2 Numerical Validation and Results

2.2.1 Selection of Validation Model

Using the numerical conditions described above, we conducted an unsteady flow analysis to verify our approach. The verification model was the rotor of Bell's XV-15, as shown in Fig. 3[6]; its geometric characteristics are summarized in Table 1. The simulation was performed at full scale with a total aircraft weight of 6,840kg, and the XV-15 was assumed to hover at an altitude of 7.62m above the ground.

Following a U.S. Army technical report, we used experimental and reference location data[7]. As illustrated in Fig. 4, velocities were compared at four points in both the Y[-] and Y[+] directions.

Figure 3 : XV-15

N blade	3
Rotor Radius [m]	3.81
Chord Length [m]	0.3556
Pitch Angle [deg]	15
Twist [deg]	36
Collective Pitch [deg]	2.5
Rotor Speed [RPM]	589
Reynolds Number 75% [-]	1,571,969

Table 1 : Geometric information of rotor model

2.2.2 Validation Results

Figure 5 presents the STAR-CCM+ verification results alongside the experimental data and reference values for the XV-15 rotor. It appears that the CFD URANS simulation correlates more closely with the experimental data than does the reference numerical result. Additionally, the flow behind the aircraft is slightly more pronounced than that in the front. Based on these observations, we conducted further simulations to investigate the effects of DWOW from a multi-rotor aircraft on a human model by positioning the human figure behind the rotor.

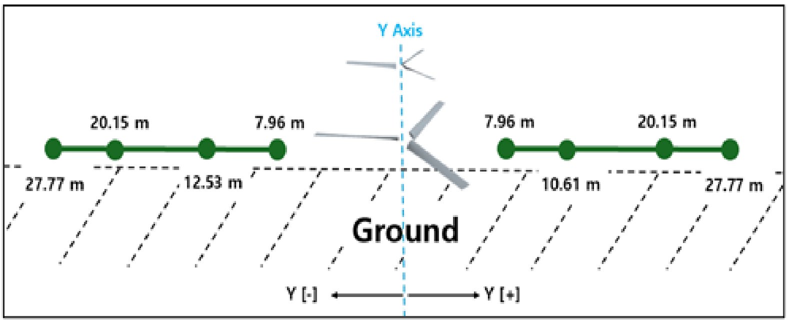


Figure 4 : Full Scale Validation Points

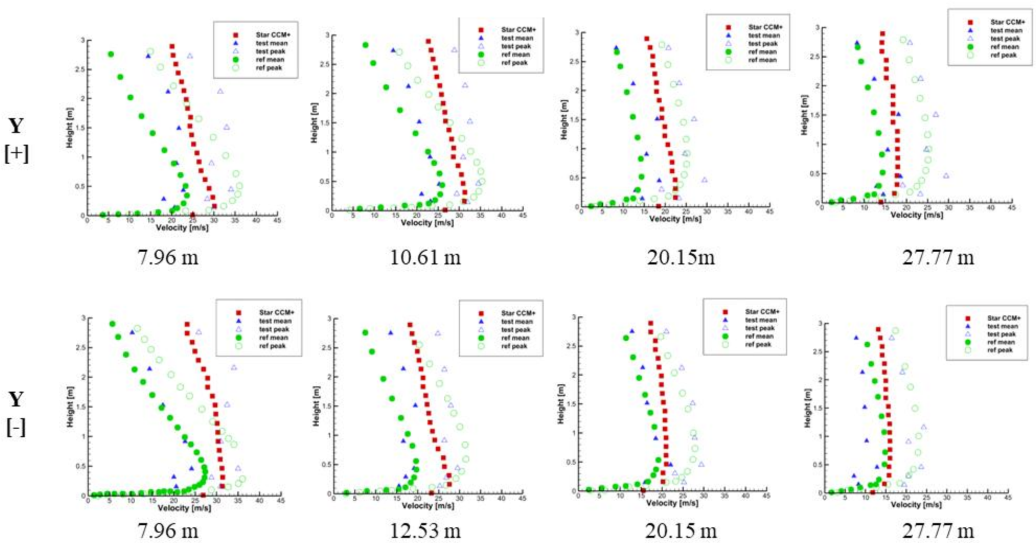


Figure 5 : Full Scale Validation Results

2.3 Human Impact Simulation

2.3.1 Model Selection

The same XV-15 rotor from the earlier verification study was used to investigate the effect of DWOW on the human body. The human model was designed to represent an adult male with a height of 180cm and a Body Mass Index (BMI) of 21, as recommended by the Seoul Citizens Health Portal. The model was created using OpenVSP [8].

2.3.2 Simulation Cases

To examine the effects of DWOW, the distance between the rotor and the human model was varied. As shown in Figure 6, we classified the cases by placing the human model at distances of 1R, 3R, and 5R behind the rotor (i.e., along the -Y axis), where R= 3.8m is the rotor radius.

3 Results

As indicated in the jet flow, substantial variations in flow and velocity were observed both in front of and behind the rotor, as well as along its sides. Consistent with Fig. 5, which shows stronger flow in the rear than in the front, Fig. 5 compares the lateral (side) and rear flows. In particular, the rotor downwash collides with the ground, then rebounds and diffuses rearward, forming a strong jet flow.

To more precisely characterize the effect of DWOW on the human model, Fig. 7 visualizes the velocity and pressure distributions across the model's surface. In the rear region, a sudden increase in velocity and pressure occurs above a height of about 1.0m, suggesting a potential direct impact on the head and upper body.

Specifically, at 1R and 3R behind the rotor, high-speed flow exceeding 25m/s was observed to reach head height. At 1R, the rear DWOW exhibited a maximum speed of 25.19 m/s, an effect comparable to being pushed by a 24.7kg object in 22 m/s wind. It was also found to affect the entire body, indicating that a person closest to the UAM aircraft would be subjected to a very strong wake.

Meanwhile, the maximum speed at 3R reached 25.23m/s, which is slightly higher than at 1R. As shown in Fig. 8, this velocity occurs closer to the ground, suggesting that downwash intensification may account for the higher value compared to 1R.

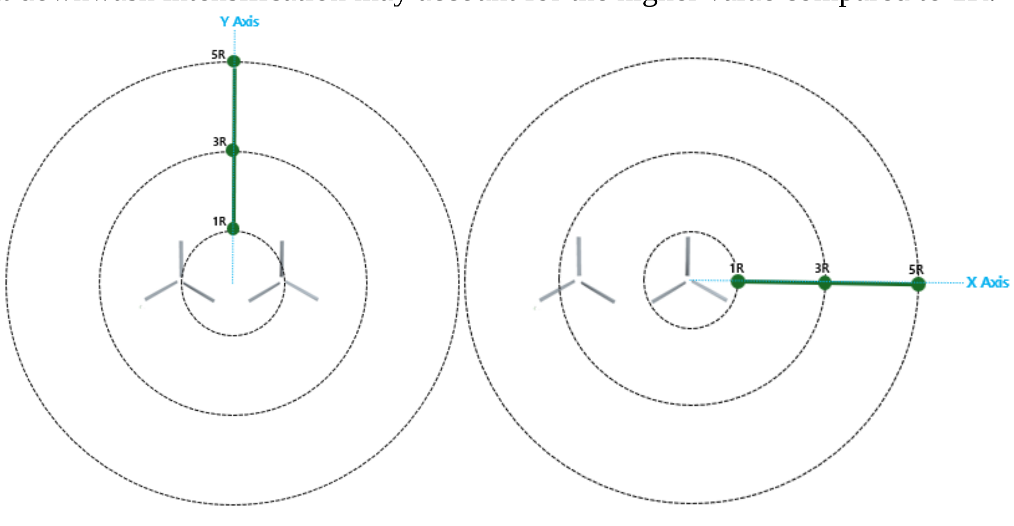
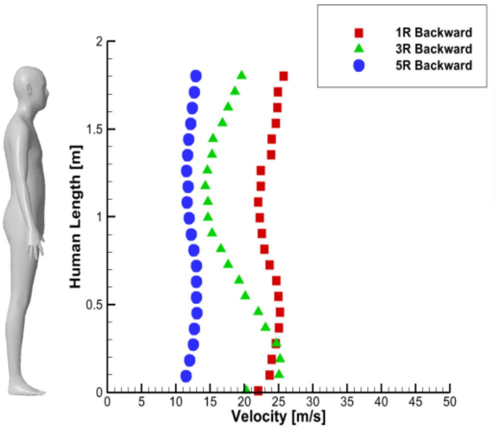
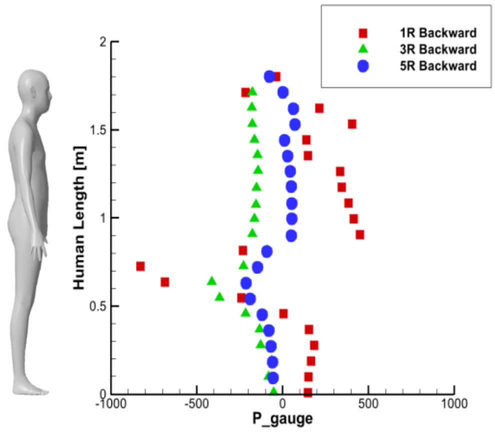


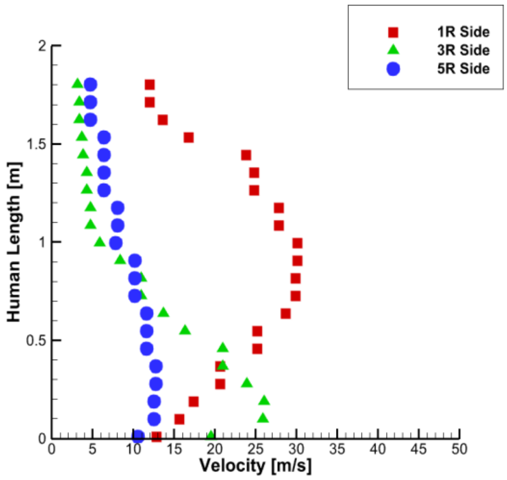
Figure 6 : Point of Each Simulation Case



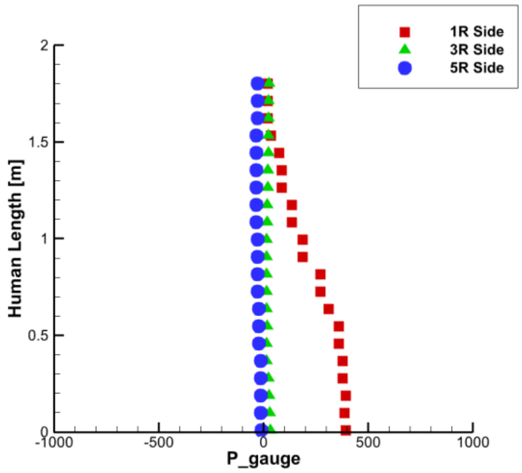
<Backward Velocity Profile>



<Backward p_{gauge} Profile>



<Side Velocity Profile>



<Side p_{gauge} Profile>

Figure 7 : Vector Profile

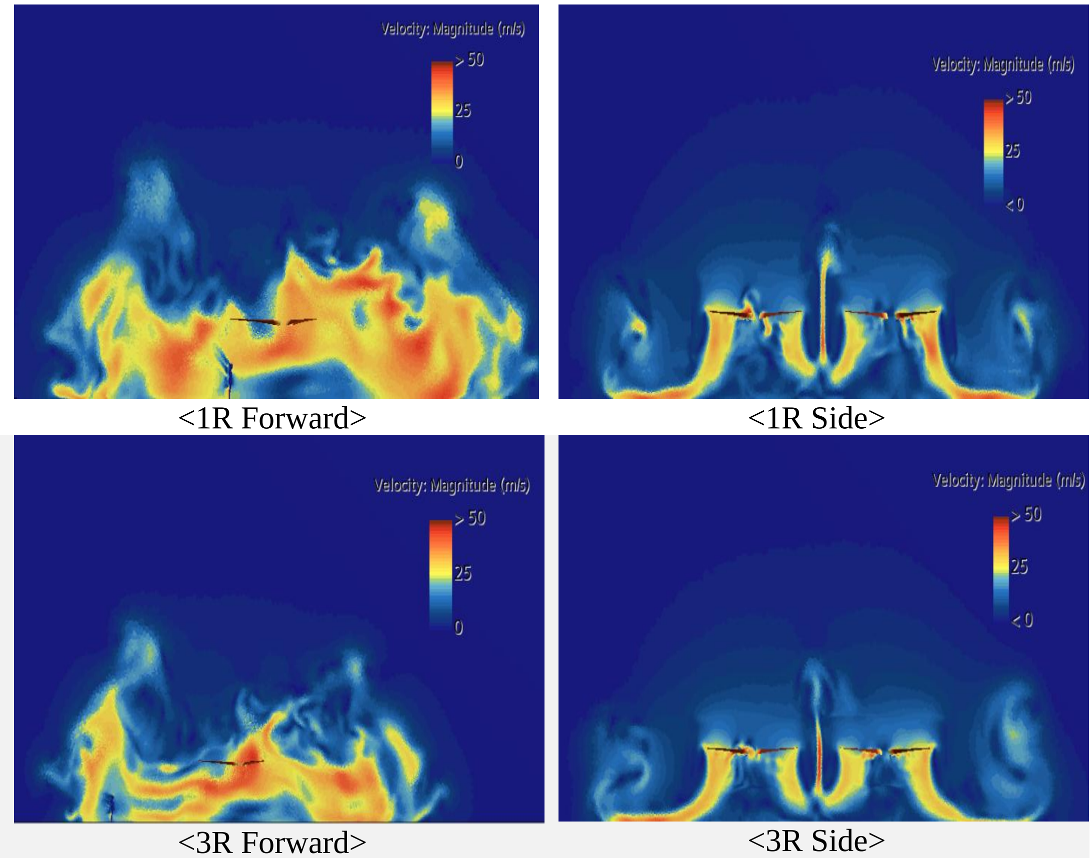


Figure 8 : Velocity Field of Rotorwash

4 Conclusions and Contributions

From the present simulation results, it was confirmed that multi-rotor UAM aircraft can generate strong flow fields extending far in both the fore and aft directions, potentially affecting pedestrians and ground structures either directly or indirectly. Because this jet flow phenomenon involves not only downward motion but also ground reflection and lateral spread, safety standards should be established in a dynamic manner that accounts for actual flow fields, rather than relying solely on fixed safety zones.

According to the simulation findings, if the velocity threshold for human safety is considered, the zone of influence along the Y-axis may extend beyond 5R, whereas rapid velocity decay was observed at approximately 3–5R along the X-axis. Therefore, it is advisable for vertiports to secure a distance of at least 5R in both the fore–aft and lateral directions to protect personnel.

As previously mentioned, at 3R we observed a higher velocity near the ground than at 1R, which we attribute to the influence of downwash. This finding indicates that a more detailed comparison of downwash and outwash at each location is warranted. In future work, we plan to analyze this phenomenon more thoroughly.

By presenting CFD-based DWOW impact assessments on the human body, this study underscores the need for dynamic safety zones instead of the fixed ranges recommended by current FAA and CAA guidelines. These findings are expected to serve as valuable foundational data for future UAM infrastructure design and for establishing operational guidelines for UAM in urban settings.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government(MSIT)(No.NRF-2021R1A5A1031868).

References

[1] 2023, Published by the Civil Aviation Authority, "Understanding the downwash/outwash characteristics of eVTOL aircraft".

[2] 2024, Michael, A.P. Meyers, P.E. Manager, Airport Engineering Division, AAS-100. "Engineering Brief No. 105A, Vertiport Design".

[3] 2017, Giulia, C., Damuen, S., Luigi, V. and George, N.B., "Numerical modelling of the aerodynamic interference between helicopter and ground obstacles".

[4] 2018, Prothin, S., Fernandez Escudero, C., Doue, N. and Jardin, T., Aerodynamics of MAV rotors in ground and corner effect," IMAV.

[5] christoffer Johansson, "Overset mesh in Simcenter STAR-CCM+", https://volupe.com/simcenter-star-ccm/overset-mesh-in-simcenter-star-ccm/, 8 October 202

[6] Bell,"XV-15", https://web.archive.org/web/20050411052448/http://www.space.com/imageoftheday/image_of_day_030917.html

[7] Preston, J. R.; Troutman, S.; Keen, E.; Silva, M.; Whitman, N., "Rotorwash Operational Footprint Modeling", Technical Report, 2014

[8] Seoul Citizens Health Portal, https://health.seoulmc.or.kr/healthCareInfo/myBMIPopup.do"