DEVELOPMENT OF UNSTEADINESS IN A ROTOR WAKE IN GROUND EFFECT

Saijo, T., Ganesh, B., Huang, A., §, Komerath, N.M. †
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

ABSTRACT
The flow field around the rotor in ground effect has been studied using flow visualization and hot-wire anemometry. Two distinctive flow phenomena, recirculation and ground vortex, are observed in the flow visualization. Hot-wire measurement results indicates high intensity of unsteadiness of the flow field with long time scale. The evolution of the ground vortex is better understood from the experimental results. Three different types of velocity fluctuations are observed around the ground vortex.

INTRODUCTION
Rotorcraft designers must deal with a variety of handling problems which the craft encounters during operation close to the ground. The ground alters the behavior of rotor wake and causes a significant perturbation to the flow near the blades. While steady ground effect appears to be well understood, the occurrence of unexpected unsteady loads and moments is unexplained; discrepancies are also seen between cases of ambient wind, and motion in still air.

This paper reports results on a project whose objective is to develop physically-based models for rotor wake behavior in ground effect, with unsteadiness due to maneuvers or gusts. Detailed studies of the rotor wake and ground vortex are being performed with an isolated model rotor above a static ground plane at low advance ratio, and various ground heights. This experiment is being used to quantify time scales of unsteadiness using flow visualization and hot-wire anemometry, and these are being correlated with vortex interactions, feedback of vortices to the inflow, and other observed phenomena. This is a companion paper to Ref. 1, which used laser sheet flow visualization to prove that a steady wake could be obtained at low advance ratio out of ground effect, and that ground proximity increased the unsteadiness. Regimes of flow structure were identified. Calculations using a vortex method also showed indications of unsteadiness due to vortex interactions.

Several aspects of in-ground-effect (IGE) operation are known. The proximity of the ground to a hovering rotor reduces the induced velocity at the rotor and increases the rotor thrust at a given power. Ground effect is generally considered to be negligible when the rotor is more than one diameter above the ground, or for flight speeds above twice the inflow speed, roughly corresponding to an advance ratio (\(\mu\)) of 0.15. In low-speed forward flight (or cross-wind), where the wake is swept behind the rotor, the effect of ground diminishes rapidly as the forward speed increases.

Ground proximity has complex effects on handling qualities. Ref. 2 divides IGE phenomena into two distinct flow regimes: recirculation of the rotor wake at very low advance ratio, and a ground vortex formed as advance ratio increases. Other studies of quasi-steady ground effects on helicopters are discussed in Ref. 1. At low advance ratio, a small region of flow recirculation is formed upstream of the rotor near the ground, increasing the inflow through the forward part of the rotor disk. This increases the induced power requirement. The effect of the ground vortex is to increase the down flow through the front part of the rotor disc, making the flow more uniform and reducing the requirement for left stick. After the ground vortex is overrun, left stick is required suddenly. Periodic fluctuation of the interference flow between downwash and upwash due to flow re-circulation has been reported as the cause of the unsteady phenomena. In Ref. 2, the flow field was found to fluctuate at a rather low frequency. Ref. 3 has studied tail rotor IGE operation. When the forward stagnation line dividing the main rotor downwash and the free stream flow, reached the leading edge of the rotor disc, large-scale unsteadiness was observed, with the ground vortex switching intermittently between two positions.

In this paper, the objective is to isolate and quantify long-time scale unsteadiness in the flow field of an isolated rotor operating in ground effect at low speed. The experiments of Ref. 1 are extended, using hot-wire data, and quantitative measures of unsteadiness are derived.

§: Graduate Student, Student Member, AIAA
†: Professor, Associate Fellow, AIAA
EXPERIMENT

Facility and Equipment
The experiments were conducted in John J. Harper Low Speed Wind Tunnel of Georgia Institute of Technology. This facility is a closed-circuit wind tunnel with a 7ft × 9ft test section. The rotor installation in the test section and the coordinate system are shown in Figure 1, and rotor specifications and test conditions are shown in Table 1. A DC motor is used to drive the rotor shaft at speeds between 0 and 2100 rpm. A ground plate was installed in the test section. For flow visualization the laser sheet optics (New Wave Research Gemini 30Hz) was placed downstream of the test section as shown in Figure 2. The flow images were captured by a SONY DV camera or a SONY CCD camera placed perpendicular to the plane of the laser sheet. Flow seeding was generated by fog machines placed upstream of the rotor. Time histories of velocity and frequency spectra were obtained using hot-wire probes (TSI 1201–20) in the flow field. The data were recorded in the personal computer through a Labview board. The hot-wire measurement setup is also shown in Figure 2. These conditions in Table 1 are roughly equivalent, for instance, to those of a UH–1B helicopter hovering at a skid altitude of 4ft, and headwind varying from 0 to 38 knots.

Table 1 Rotor specifications and test conditions

| Radius r (in) | 18 |
| Chord length (in) | 3.37 |
| Airfoil | NACA0015 |
| Number of blades | 2 |
| Collective pitch angle (deg) | 10 (fixed) |
| Twisted angle (deg) | 0 |
| Rotor shaft tilt angle (deg) | 6 |
| Solidity | 0.1193 |
| Advance ratio μ | 0.03, 0.04, 0.05, 0.06, 0.07, 0.08 |
| Rotor speed (rpm) | 2100 |
| Ground clearance h/r, IGE | 0.72 |
| Ground clearance h/r, OGE | 2.77 |
| Laser sheet location: y/r | 0, −1/3, −2/3 |

RESULTS AND DISCUSSION

Flow Visualization (IGE)
IGE flow visualization results are detailed in Ref. 1, and selected images are shown at the tops of Figures 3–5. At low advance ratio the rotor tip vortices were moving forward and upward and recirculating through the rotor disk. This recirculation phenomenon was observed in the range of 0.03 ≤ μ ≤ 0.04. In the circulation, 7 or 8 vortices were observed in the loop. In this experiment the rotor was rotating at 2100rpm and the number of blade was 2. Therefore, it is expected that the timescale of recirculation is in the scale of 0.11secs (approximately 9Hz) in this case. At higher advance ratio, recirculation disappeared and a large vortex occurred near the ground. This ground vortex phenomenon is a strong function of advance ratio. At μ=0.05 flow separation was occurring intermittently, but no ground vortex could be observed unambiguously. At μ=0.06 the ground vortex was clearly formed. At μ=0.07 the ground vortex could be still seen. However it moved downstream and its diameter decreased. At μ=0.08 the ground vortex moved downstream and its diameter decreased further. OGE flow visualization results were also shown in Ref. 1. Compared to that of IGE, the flow state around the rotor was quite stable throughout the entire range of advanced ratio.

Hot-wire Measurement (IGE)
To obtain quantitative data on flow unsteadiness, hot-wire measurements were performed along the centerline of the ground plate (y/r = 0). The hot-wire probe was placed 1in above the ground plate. The results for μ=0.05–0.08 are shown in Figures 3–5. Velocity plots and power spectra at 5 selected points are shown. The locations corresponding to these are shown in Figure 6, where the frequency content of the fluctuations is also classified.

μ=0.05 (Figure 3)
At point (a), a velocity fluctuation at low frequency (2~4Hz) occurred. It should be noted that since hot-wire anemometry was used, velocity measurements taken are absolute values and do not give information about flow direction. This intermittent nature of the data here is attributed to movement of the flow separation point moves around point (a), and the flow direction is presumed to be reversing intermittently as well. At both points (c) and (e), the frequency of the velocity fluctuation became relatively broad-band (0~50Hz). From the flow visualization results it can be judged that the flows at these points were directed upstream. The mean flow velocities at these points were higher than free stream speed, which is approximately 16.5fps at μ = 0.05. At point (g), a low frequency velocity fluctuation occurred. The flow direction at this point did not fluctuate, unlike point (a). In this regard the velocity fluctuation at point (g) is different from that at point (a).

μ=0.06 (Figure 4)
At point (c), which was near the front edge of the ground vortex, the flow showed occasional large-
amplitude fluctuations with a long time scale. This velocity fluctuation resembles the one seen at point (a) for $\mu = 0.05$ case, but is much less frequent. This type of fluctuation is categorized as LFF (Low Frequency Fluctuation) here. At point (f), which was located in the ground vortex, the velocity fluctuated with broad band (0~50Hz) frequency and extremely high amplitude fluctuations with 1P or 2P (1 or 2 per revolution: 35Hz or 70Hz) frequency and extremely high amplitude occurred. Similar velocity fluctuations were observed for $\mu=0.05$ to 0.08. This type of fluctuation is categorized as HFF (High Frequency Fluctuation).

$\mu=0.07$ (Figure 5)

At point (e), a low frequency velocity fluctuation occurred. The amplitude of the largest spikes is however less than half of the corresponding values at (c) for the $\mu = 0.06$ case. It is expected that the flow separation point at $\mu = 0.07$ is steadier. BFF appeared at point (f) and its region moved further downstream than $\mu=0.06$ case. At (h) and (i), HFF occurred. Similar results were seen (no figure shown) at $\mu=0.08$, though shifted downstream as expected.

Formation of the Ground Vortex

The location distribution for the types of fluctuations for seen in the range $\mu=0.05$ to 0.08 is presented in Figure 6. Characteristics of these three types are as follows:

- **LFF**
  - Low frequency (2~4Hz)
  - Observed at separation point at $\mu = 0.05$ to 0.06
  - Not observed for $\mu = 0.07$ to 0.08
  - Altering flow direction
  - Caused by the oscillating separation point

- **BFF**
  - Broad band frequency (0~50Hz)
  - Observed at $\mu = 0.05$ to 0.08 at the core of the ground vortex
  - Flow going upstream

- **HFF**
  - 1P/2P frequency (35Hz/70Hz)
  - Observed at the rear edge of the ground vortex at $\mu = 0.06$ to 0.08
  - Caused by the rotor wake
  - Extremely high amplitude

The evolution of the ground vortex is better understood from flow visualization and hot-wires measurement results. The process is summarized in Figures 7 to 10.

At $\mu = 0.05$ (Figure 7), the rotor wake collides with the free stream and the flow separation occurs at upstream of the rotor. The separation point oscillates back and forth. The free stream velocity is too low to permit formation of a ground vortex. At $\mu = 0.06$ (Figure 8), the rotor wake collides with the free stream and the flow separation occurs upstream of the rotor similarly. The separation point is still unstable. The separated flow rolls up and forms a ground vortex between the rotor and the ground plate. At $\mu = 0.07$ to 0.08 (Figures 9 and 10), the ground vortex is formed in a similar manner to $\mu = 0.06$. However the diameter of the ground vortex shrinks and it moves downstream. The separation point is almost fixed in contrast to that for $\mu = 0.06$.

Hot-wire Measurement Comparison (IGE/OGE)

Time histories of velocity measurements between IGE and OGE are compared in Figure 11. A high level of unsteadiness with long time scale was seen for the IGE case, while the flow field for OGE was much steadier. To quantify the time intervals of unsteadiness observed for IGE case, the following procedure was used: Amplitude limits were set successively at 1, 2 and 3 standard deviations of the velocity data. The intervals between successive peaks exceeding the limit in each case, were measured, and sorted into histograms, as shown in Figure 12. The results are shown in Figures 13 to 15 for the case of advance ratio 0.06. In these histograms the number of time intervals at each range of fluctuations for 10 seconds are shown. The average flow velocity is 16.3fps and the standard deviation ($\sigma$) is 7.4fps here. At the range of $+1 \sigma \sim +2 \sigma$ (Figure 13), short time scales, less than 0.05 seconds, are dominant. At the range of $+2 \sigma \sim +3 \sigma$ (Figure 14), time scales of 0.05 to 0.3 seconds are seen comparatively frequently. At the range of $+3 \sigma$ (Figure 15), while only small number of fluctuations is seen here, long time scales, more than 0.5 seconds, are observed with relatively high probability of occurrence. It is expected that these high amplitude fluctuations with long time scales are due to large flow structure, associated with the oscillation of the ground vortex (or, in other words, the separation point between the upstream flow and the wake-generated flow). These oscillations appear to occur due to complex interactions between the rotor tip vortices as they roll into the ground vortex.

These long time-scale, large-amplitude fluctuations are significant. Translating this to typical full-scale helicopter values gives a time scale on the order of 5 to 10 seconds.
CONCLUSIONS
The major conclusions from this study are as follows:

1) Two distinctive phenomena, recirculation and ground vortex, were observed in the flow around the rotor in ground effect.
2) A high level of unsteadiness with large time scale was observed for IGE, but not for OGE.
3) Three distinctive types of velocity fluctuations, LFF and BFF, HFF, were observed around the ground vortex.
4) Large-amplitude oscillations of the ground vortex are observed to occur with a long time-scale, corresponding to full-scale rotorcraft time-scales of the order of 5 to 10 seconds.

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REFERENCES

Figure 1 Test rotor with ground plate and coordinate system

Figure 2 Flow visualization and hot-wire setup
Figure 3 Velocity plots and power spectra (IGE, $y/r = 0, \mu=0.05$)
Figure 4 Velocity plots and power spectra (IGE, $y/r = 0, \mu=0.06$)
Figure 5 Velocity plots and power spectra (IGE, $y/r = 0, \mu=0.07$)
Figure 6 Location distribution of LFF and BFF, HFF (IGE, y/r = 0, $\mu=0.05$~0.08)

Figure 7 Evolution of the ground vortex ($\mu=0.05$)

Figure 8 Evolution of the ground vortex ($\mu=0.06$)

Figure 9 Evolution of the ground vortex ($\mu=0.07$)

Figure 10 Evolution of the ground vortex ($\mu=0.08$)
Figure 11 Velocity time history (OGE/IGE, y/r = 0, µ=0.06)

Figure 12 Example of a time interval

Figure 13 Time interval histogram (IGE, µ=0.06, +1 σ ~+2 σ)

Figure 14 Time interval histogram (IGE, µ=0.06, +2 σ ~+3 σ)

Figure 15 Time interval histogram (IGE, µ=0.06, +3 σ ~)