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PERFORMANCE ANALYSIS OF A MICRO-SCALE MODEL HELICOPTER ROTOR IN HOVER FLIGHT

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ABSTRACT

This experimental study contains the design, production, test and evaluation of the test processes of a Micro-Scale Rotor Test-Rig. For the study, NACA 0012 airfoil section is selected as a rotor blade without a twist and a taper ratio. The tests cover the thrust and the torque relation with different blade pitch angles and RPM values.

Keywords: Model Helicopter Rotor, NACA 0012, Hover Flight, and Rotor Test-Rig

INTRODUCTION

Helicopter rotor test rig is a system that consists of rotor blades and a rotating mechanism such as electrical or fuel powered engines etc. The rotor test rigs are mostly used for the rotor thrust/torque performance analysis, rotor downwash flow field study, blade tip vortex research, ground effect investigation, CFD simulations validations etc.

Rotor test rigs may be found either as a model scale or a full scale. Model scale test rigs are less expensive and give beneficial insight about the full-scale rotor systems. The main objective of this work is the establishment and development of a rotor test-rig starting from micro scale to a larger scale in order to provide insight to the rotor aerodynamics. For this purpose, this work may be considered as a preliminary study of larger future scale. Following test systems are significant examples in the literature.

Caradonna and Tung constructed a rotor test system with two NACA 0012 blades. Their work was about the blade pressure measurements and tip vortex research. Besides, it is a comprehensive benchmark for CFD validation since it includes a wide range of cases such as different RPM values [Caradonna and Tung, 1981]. Knight and Hefner [Knight and Hefner, 1941] conducted a ground effect research with the help of three different helicopter rotors mounted to their test rig. Leishman and his team [Rauleder and Leishman, 2012; Rauleder and Leishman, 2013; Sydney and Leishman,2013; Sydney and Leishman,2014] set up a micro rotor test system in order to investigate the rotor aerodynamics, ground effect, brownout effects and fuselage - rotor interaction. For better investigation, rotor downwash and blade tip vortices are examined with both PIV (Particle Image Velocimetry) method and particle tracking velocimetry technique. The work of Lee [Kalra, Lakshminarayan and Baeder,2010; Lee, Leishman and Ramasamy,2008; Thomas, Amiraux and

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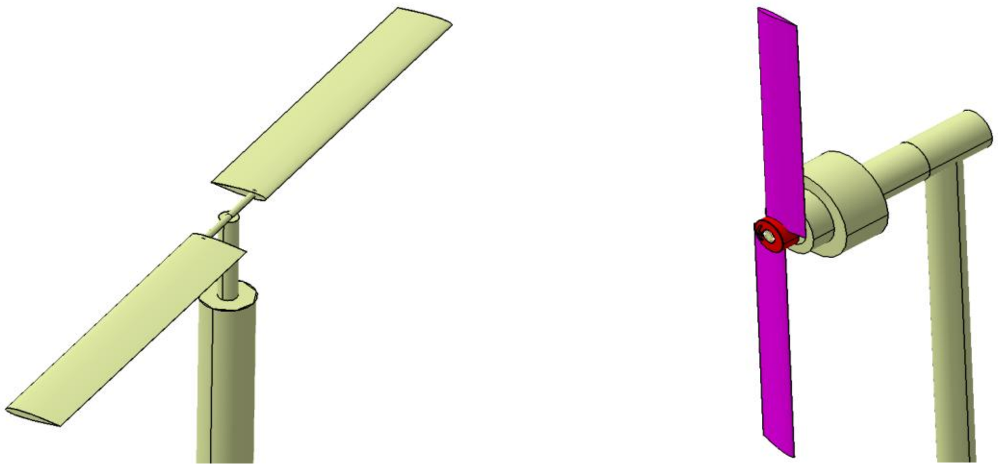
Baeder,2013] is almost similar to Leishman's test setup in terms of size. In addition, this setup is used for some CFD validations to measure the capabilities of the CFD codes used for ground wake interactions, thrust and torque measurements and tip vortex flow field predictions.
In the study of Iboshi et al.[Iboshi, Itoga, Prasad and Sankar, 2014], an experimental investigation into the effects of confined area geometry on the aerodynamic performance of a hovering rotor was performed. The confined area was represented by a vertical single plate or a pair of parallel plates on the ground effect plate. For the work, a model rotor test rig was used.

The work of Hanker and Smith [Hanker and Smith 1985] depicts an experimental investigation on a model rotor test rig in the Boeing Vertol 2041 by 2041 V/STOL wind tunnel to develop further insights into the parameters that affect helicopter interactional aerodynamics in ground effect which affects helicopter handling qualities. Balch et al. [Balch, Sacullo and Sheehy, 1983] established a rotor test rig to observe main rotor/tail rotor/ airframe interaction. Model scale hover tests were carried out in the Sikorsky Aircraft Model Rotor Facility. The work is a comprehensive benchmark for CFD validation since it contains many main rotor cases such as in- out of ground effect, different rpm values, with/without tail rotor etc. The research of Curtiss et al. [Curtiss, Sun, Putman and Hanker, 1984] describes the results of an experimental investigation of the aerodynamic characteristics of an isolated rotor operating at low advance ratios close to the ground. The study includes flow visualization in addition to measurement of the forces and moments of the rotor as a function of collective pitch, advance ratio, and rotor height above the ground-to-diameter ratio. The experiments were conducted in the Princeton Dynamic Model Track Test Rig using a model moving over the ground. The work of Light [Light, 1993] has a main target of tip vortex monitoring in/out of ground effect via model tail rotor test rig. Tip vortices visualization of a hovering rotor was conducted in ground effect. The tip vortex geometry and performance data from the tests are compared with the tip vortex geometry and performance data were predicted using a free wake hover performance analysis and several computational methods. Ganesh and Komerath [Ganesh and Komerath, 2004] carried out a work that is basically the aerodynamic characteristics of rotor close to the ground by means of the model test rig. Flow visualization was applied to assess the flow characteristics in ground effect, and compare it with the out of ground effect case. Force measurements were realized to measure the loads at various advance ratios and yaw angles. Gilad et al. [Gilad, Chopra and Rand, 2011] studied ground effect on hovering rotor performance both experimentally and theoretically. The experimental cases are done with a rotor test system. Encouraged by the Sikorsky Human Powered Helicopter Challenge (HPH), an attempt to further study about extreme ground effect on a hovering rotor of highly elastic blades has been researched. Experimental results are used to validate a new computational tool that couples blade element method and structural finite element analysis for the prediction of elastic blade behavior in ground effect. Iboshi et al. [Iboshi, Itoga, Hayata and Prasad, 2002; Iboshi, Itoga, Hayata and Prasad, 2003] used a model rotor test system in order to observe the effects of ground effect with/without ground inclination. The blade flapping motion of a rotor in ground effect is inspected. Fradenburgh [Fradenburgh, 1960] observed the ground effect with performance effects and hover flow characteristics by utilizing a model rotor test setup. Sloped surface, power during transition to forward flight issues were examined. Yeager et al. [Yeager, Young and Mantay, 1974] performed an investigation about the directional control and performance helicopter rotor- tail-fin configuration in ground effect in Langley Full-Scale Tunnel.

For the current study, a similar and minimized version of the work of Caradonna and Tung [Caradonna and Tung, 1981] is used with the same aspect ratio, and the same airfoil (NACA 0012) but with a horizontally mounted system. Figure 1 shows the technical drawing of the setups of Caradonna and Tung and current study.



a) Setup of Caradonna and Tung [1] b) Setup of the Current Study

Figure 1: Test Setups for Rotor Performance Analysis

METHODOLOGY

The rotor blade was tested for two different rotational speeds and four different pitch angles as seen in Table 1. The RPM values and pitch angles were selected according to the sensor limitations, structural restrictions and safety reasons.

Table 1: Test Cases

Cases	RPM	Pitch Angle
1	4000	3°, 6°, 9 °, 12°
2	5000	3°, 6°, 9 °, 12°

The propeller test-rig available in SCALAB of Aerospace Engineering Department of METU was modified to achieve the purpose of this study. The experimental setup consists of a rotor with two blades and hub connection part, PC, Power Supply Unit, DAQ Hardware, F/T Sensor, RPM Sensor with a controller, Electronic Speed Controller.

The two rotor configurations were implemented as Baseline I and II. Figure 2 gives the Baseline I configuration after installation for the test.

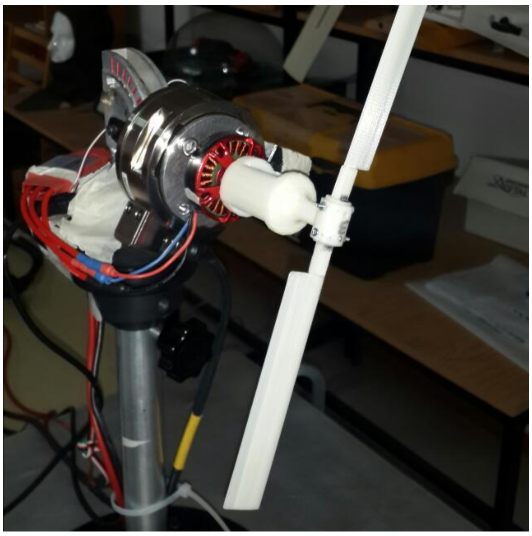
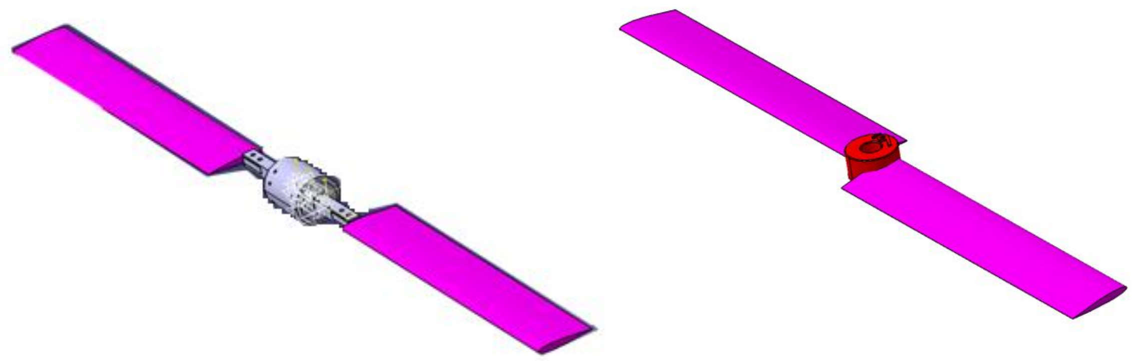


Figure 2: Experimental Setup with Baseline I Rotor

Figure 3 shows the technical drawings of these two Baseline cases.



a) Baseline I b) Baseline II (6° Pitch Angle)

Figure 3. Rotor Configurations

The radius, area and solidity values of the rotor of Baseline ll configuration are given in Table 2. Solidity is basically the ratio of the total blade area to rotor disk area.

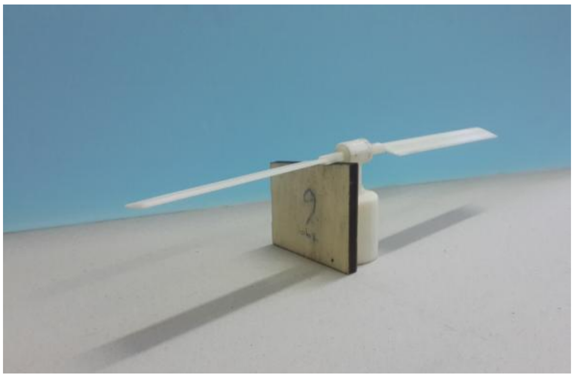
Table 2: Rotor Parameters of Baseline II

	Current Study	Test stand of Balch UH-60 [11]
r[m]	0.115	1.428
Area [m2]	0.042	6.406
Solidity (σ)	0.053	0.082

Manufacturing and Test Setup

Baseline I configuration, which consists of a hub connection part and blades, was produced by a 3D printer as two sets, one as a spare part. During the design process of Baseline I, it was planned to use manual adjustment of the blade pitch angles by means of pins. For this reason, some pinholes were drawn on the hub. However, after the manufacture of Baseline I, it was realized that the pinholes were not large enough to place the pins. Therefore, reopening process was performed on the hub and at the blades' roots for the usage of tiny bolt/nut connection. But this process caused to use both rotor sets 3 and 9-degree on one rotor set, 6 and 12-degree on the other. To carry out the process, the blades angles were fixed by means of 3, 6, 9, 12 degree-angled trapezoid wooden parts. Figure 4 shows the preparation stage of the Baseline I for the experiments.

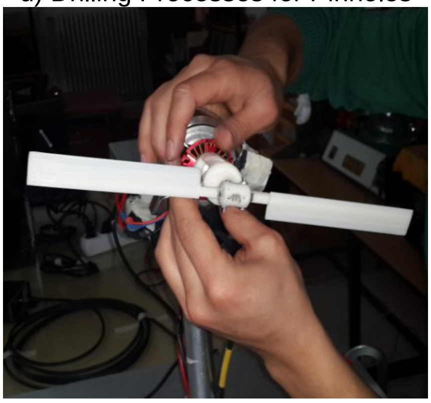
a) Manufactured Parts for the Baseline I b) Finishing Process



c) Angular Stabilization of Blades

d) Drilling Processes for Pinholes

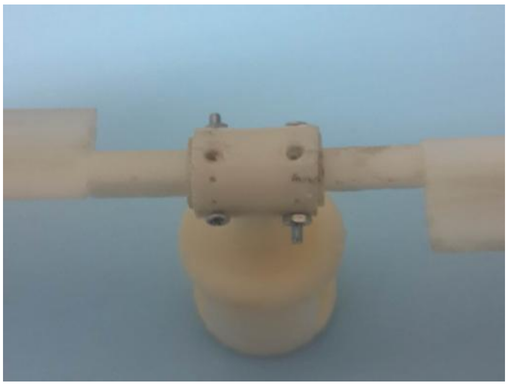
e) Baseline I Rotor



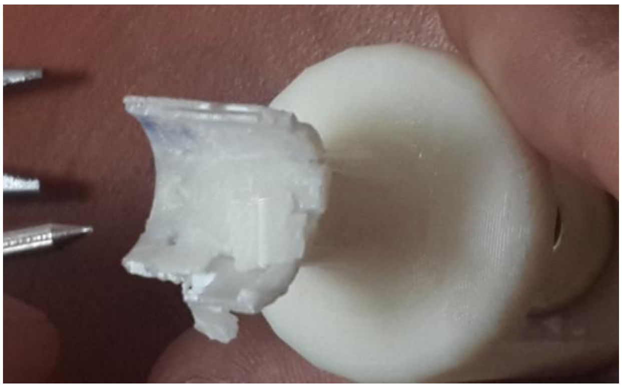
f) Mounting the Rotor

Figure 4: Preparation of Baseline I Rotor Configuration

During the trial runs, some cracks on the rotor hub section were observed and one of the rotors set got damaged during an experiment. Potential reasons may be the manufacturing failure, quality of material and/or larger holes on the hub. Figure 5 shows the cracks on the hub before/after the damage.



a) Cracks before the damage



b) Cracks after the damage

Figure 5: Cracks on the Hub for Baseline I

Thereafter, it was decided to draw and produce another rotor set as one-piece in order to reduce the structural restrictions lead by bolt connections, material properties and so on. This one-piece rotor system is called as “Baseline II” in the current study.

For the Baseline II, it was decided to reduce the diameter of the rotor to 23 cm and the rotor blade root was drift into the hub as 1 cm, due to the production limitations which caused the effective rotor wing half span to be as 10.5 cm and hinge offset length as 1 cm. Besides, the problems encountered in Baseline I are resolved by using this new configuration. Figure 6 gives the different-degree pitch-angled for Baseline II configuration.

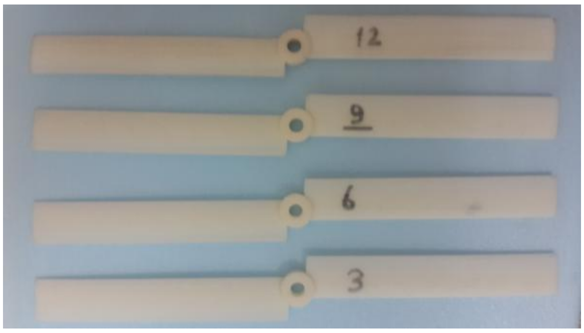


Figure 6. Baseline II Rotors

Data Collection Procedure

With ATI GAMMA F/T sensor [ATI, 2015], force and torque values were obtained with a frequency of 20 Hz. LabVIEW Software is used to monitor the data.

In LabVIEW Software,

- 3 to 5 runs per one case were carried out.
- Average value was estimated among the mean values of all runs.
- Mean thrust and torque values were obtained.
- Data collection was performed for 10 seconds per one run.

In addition, an Eagle Tree RPM Sensor and its software were used to adjust the RPM values and the voltage was fixed to 14.8 V on the Power Supply Unit.

During the experiment, the following errors were observed:

- The interference effect of the ATI GAMMA sensor in rotor wake.
- Manufacturing errors: Actual blades do not correctly meet the real NACA 0012 sections, due to the small dimensions. Tolerance errors were observed. Finishing process was carried out to reduce those errors.

Stabilization of an RPM is such a challenging procedure. To take values in low RPMs (800-1000) were impossible due to the sensitivity of the Eagle Tree RPM sensor and the control unit knob. To apply high RPM values (7000-8000) was considered to be as dangerous because of the structural concerns and safety reasons. Hence, data collection in 4000 and 5000 RPMs seems reasonable.

RESULTS

The thrust (T) and torque (Q) values obtained from the tests are shown in Table 3 for 2 different RPM values.

Table 3: Test Results

	@4000RPM		@5000 RPM	
Pitch Angle [°]	**T [N]**	**Q [Nm]**	**T [N]**	**Q [Nm]**
3	0.006	0.26	0.0094	0.31
6	0.0075	0.41	0.0125	0.65
9	0.0127	0.82	0.0185	1.275
12	0.019	1.255	0.03	1.86

These torque and force results were converted into dimensionless parameters by using Eq. 1 and Eq. 2 [Leishman, 2002].

$$C_T = \frac{T}{\rho A(\Omega R)^2} \quad \text{(Eq.1)}$$

$$C_Q = \frac{Q}{\rho A R(\Omega R)^2} \quad \text{(Eq.2)}$$

Figure 7 shows the C_Q/σ versus C_T/σ values for two different rotational speeds and shows the expected trend that C_q/σ increases when C_t/σ increases. The results of Balch [Balch, Sacullo and Sheehy, 1983] are also shown in Figure 7.

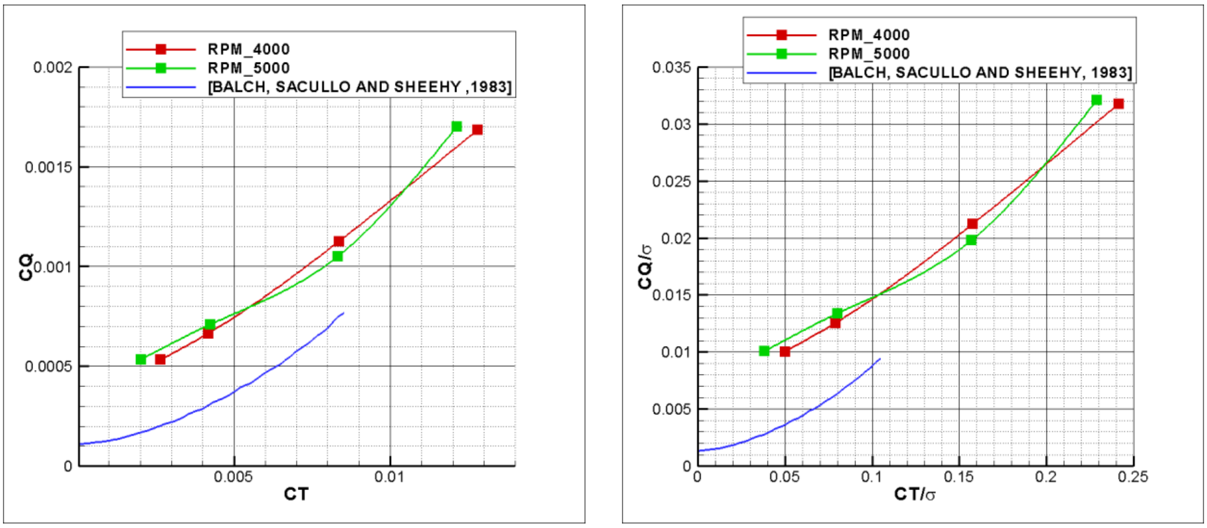


Figure 7: C_Q versus C_T curves and C_q/σ versus C_t/σ curves

In Figure 7, the blue curve depicts the UH-60 model rotor test from Balch [Balch, Sacullo and Sheehy, 1983], which has a similar trend with the tests of the current work but a shifted difference is observed due to the solidity and size difference.

This work proves that the actual rotor test rig is suitable to test micro-scale rotor performance experiments since curve trend is similar to literature data. And it is ready for improvements such as larger rotor tests, PIV, ground effect implementation etc.

CONCLUSION and FUTURE WORK

It is considered that for such a small-scale rotor design, a united design is better made for an easy manufacturing process. This consumes much more material, yet it provides much more structural integrity as well. Additionally, adjusting the angles manually is quite hard to achieve in such a small-scale model and fastening the bolts tightly often brings an undesired flapping angle. Hence, Baseline I has been recovered from those errors.

As a future work, in/out of ground effect tests and rotor tip vortex detection via PIV is considered with higher rotor diameter (up to 40 cm). Further, a computer simulation (panel code or CFD) is intended to imply in order to endorse this experiment. This work is clearly the preliminary study for the further applications of micro hovering rotor for the insight to the massive rotorcraft systems. Such micro rotor systems, as declared before, are available in Lee et al. [Kalra, Lakshminarayan, Baeder, 2010; Lee, Leishman, Ramasamy, 2008; Thomas, Amiraux, Baeder, 2013] and Rauleder and Leishman [Rauleder and Leishman, 2012; Rauleder and Leishman, 2013; Sydney and Leishman, 2013; Sydney and Leishman, 2014].

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References

ATI (2015), “http://www.ati-ia.com/products/ft/ft_models.aspx?id=Gamma”, April 2015.

Balch D.T., Sacullo A., Sheehy T.W.(1983) ‘’Experimental Study of Main Rotor/Tail Rotor/Airframe Interactions in Hover -Volume1’’NASA Contractor Report 166485, June 1983.

Caradonna, F.X., Tung, C. (1981) Experimental and Analytical Studies of a Model Helicopter Rotor in Hover, NASA Ames Research Center, Sep 1981.

Curtiss, Jr. H.C., Sun, M., Putman, W. F., Hanker, Jr. E.J. (1984) “Rotor Aerodynamics in Ground Effect at Low Advance Ratios’’, Journal of the American Helicopter Society, January 1984.

Fradenburgh, E.A. (1960) “The Helicopter and the Ground Effect Machine’’ Sikorsky Aircraft Division. Stratford. Connecticut, Journal of the American Helicopter Society, Volume 5, Number 4, 1 October 1960, pp. 24-33(10)

Ganesh, B., Komerath, N. (2004) “Unsteady Aerodynamics of Rotorcraft in Ground Effect’’. AIAA Paper 1004-2431 Fluid Dynamics Meeting Portland. OR. June 2004.

Gilad, M., Chopra, I., Rand, O. (2011) “Performance Evaluation of a Flexible Rotor in Extreme Ground Effect” Alfred Gessow Rotorcraft Center, Department of Aerospace Engineering Maryland USA, 37th European Rotorcraft Forum, Milan, Italy, 2011.

Hanker, Jr. E.J., Smith, R.P. (1985) “Parameters Affecting Helicopter Interactional Aerodynamics in Ground Effect’’, Journal of the American Helicopter Society, January 1985.

Iboshi, N., Itoga, N., Hayata, Y., Prasad, J.V.R. (2002) “Ground Effect and Blade Flapping Motion of a Rotor Hovering above Finite Inclined Ground Plane” Journal of the Japan Society for Aeronautical and Space Sciences,2002.

Iboshi, N., Itoga, N., Hayata, Y., Prasad, J.V.R. (2003) “Hovering Performance of a Rotor in an Inclined and Partial Ground Effect’’ Journal of the Japan Society for Aeronautical and Space Sciences, Volume 51, Issue 595, pp. 433-440, 2003.

Iboshi, N., Itoga, N., Prasad, J.V.R., Sankar, L.M. (2014) “Ground Effect of a Rotor Hovering above a Confined Area” FAE Journal, Frontiers in Aerospace Engineering Volume 2 Issue 1, February 2014.

Kalra, T.S., Lakshminarayan, V. K., Baeder J.D. (2010) “CFD Validation of Micro Hovering Rotor in Ground Effect’’. Alfred Gessow Rotorcraft Center. University of Maryland, 66th Annual Forum and Technology Display of the American Helicopter Society International, Phoenix, Arizona, May 11–May 13, 2010

Knight M., Hefner R.A. (1941) “Analysis of a Ground Effect on the Lifting Airscrew” Daniel Guggenheim School of Aeronautics , Georgia School of Technology, Washington December 1941.

Lee, T. E., and Leishman, J. G. and Ramasamy, M. (2008), “Fluid Dynamics of Interacting Blade Tip Vortices With a Ground Plane,” American Helicopter Society 64th Annual Forum Proceedings, Montreal, Canada, April 29–May 1, 2008.

Leishman, J.G. (2002) “Principles of Helicopter Aerodynamics” Cambridge University Press, 2002.

Light, J.S. (1993) ‘’Tip Vortex Geometry of a Hovering Helicopter Rotor in Ground Effect’’ NASA Ames Research Center. Moffett Field. CA. Journal of the American Helicopter Society. April 1993.

Rauleder, J., Leishman, J.G. (2012) “Measurements of Organized Turbulence it the Dual-Phase Flow Below a Rotor’’. Department of Aerospace Engineering., ERF 2012.

Rauleder, J., Leishman, J.G., (2013) “Turbulence Modifications and Phase Couplingsin Ground Effect under Simulated Brownout Conditions’’ Department of AEE University of Maryland, American Helicopter Society 2013.

Sydney, A., Leishman, J.G. (2013) “Measurements of Rotor/Airframe Interactions in Ground Effect Over a Sediment Bed’’ Department of AEE. American Helicopter Society, 2013.

Sydney, A., Leishman, J.G. (2014) “Measurements of the Plume-Like Three Dimensionality of Rotor Induced Dust Fields’’ Department of Aerospace Engineering, American Helicopter Society 2014.

Thomas S., Amiraux M., Baeder J.D. (2013) “GPU-accelerated FVM – RANS Hybrid Solver for Simulating Two-phase Flow beneath a Hovering Rotor” AHS 2013.

Yeager, W.T. Jr., Young, W.H. Jr., Mantay, W.R. (1974) “A Wind Tunnel Investigation of Parameters Affecting Helicopter Directional Control at Low Speeds In Ground Effect’’. NASA Technical Note D-7694 Washington D.C. November 1974.