SIMULATION OF HELICOPTER DURATION MODELS

Research and Development Report

Prepared for: **NARAM-54**
Muskegon, Michigan
July 30-August 3, 2012

Submitted by: **Chris Flanigan**
NAR 17540 L1
C Division

ABSTRACT

An Excel spreadsheet was developed for use in simulating the performance of Helicopter Duration (HD) models. The spreadsheet performs a transient analysis to simulate the spin-up and steady state portions of HD descent. The spreadsheet has several assumptions and limitation, but results seem reasonable and have moderately good agreement to a sample model.

The spreadsheet was used to perform sensitivity studies of blade angle (for a flat blade) and the optimum curvature for a curved blade. The spreadsheet can be used for many future tasks including:

- Simulation of point designs
- Trade studies of weight, blade span, and many other parameters.

The spreadsheet has been uploaded to ContestRoc for use by the competition community.

Prepared by:

_____

Christopher C. Flanigan

NAR 17540 L1

TABLE OF CONTENTS

NOMENCLATURE

ω	Angular position
Δt	Time step
F	Force
I	Mass moment of inertia
m	Meter
M	Mass
U	Displacement
s	Second
T	Torque

ACRONYMS

AOA	Angle of attack
HD	Helicopter Duration
PCF	Pounds per cubic foot
RPS	Rotations per second

1 INTRODUCTION

Helicopter Duration (HD) models can be very unique and elegant when they work well. An example of a high performance helicopter duration model is shown in Figure 1-1.
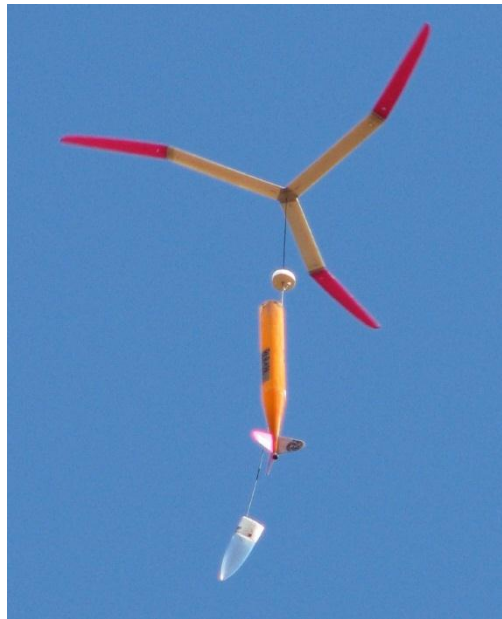

Figure 1-1. Helicopter Duration models have unique design challenges.

Prior work has been done to study HD model performance [1, 2, 3, 4, 5]. However, there are few software tools that can be used to help design and optimize HD models. Professor Mark Drela at MIT has developed some innovative software tools (XROTOR, QMILL, and QPROP) for rotary aerodynamic systems [6]. Unfortunately, XROTOR is not generally available. QMILL and QPROP require significant expertise and do not directly address the transient spin-up phase of an HD model. Therefore, the development of most HD models is done by trial-and-error.

The purpose of this R&D project was to develop a software tool that can be used to address important topics for HD models including:

- How much blade twist is needed to achieve successful spin-up?
- What is the trade-off between rapid spin-up versus steady state descent rate?
- What is the performance improvement from an optimally twisted blade?

2 OBJECTIVE AND APPROACH

2.1 OBJECTIVE

The objective of this project was to develop a software tool to simulate the spin-up and steady state performance of Helicopter Duration models. The HD tool could then be used to assess effects of design parameters such as blade geometry and vehicle weight.

2.2 TECHNICAL APPROACH

The technical approach for this project included the following tasks:

- **Software Development**. Develop a spreadsheet to simulate HD spin-up and steady state performance.

- **Verification**. Use the HD tool to simulate the performance of a known vehicle and compare predicted performance versus flight results.

- **Sensitivity Studies**. Use the HD tool to assess the effects of selected design parameters such as blade twist and vehicle weight.

These tasks are described in the following sections.

3 HELICOPTER DURATION SIMULATION

3.1 HD AERODYNAMICS

Helicopter aerodynamics is an extremely complex subject. Typical books on helicopter aerodynamics [7] discuss a wide variety of flight conditions including take-off, hover, acceleration, cruise, and maneuver conditions.

Fortunately, model rocket HD models need to assess only two conditions:

- Spin-up after blade deployment
- Steady-state descent

A detailed simulation of these two conditions can still be complex. See the XROTOR, QMILL, and QPROP programs [6] for further details.

For this project, a simplified approach called "Strip Theory" aerodynamics was used to simulate the rotor blade. Strip Theory has been used in the aircraft industry for many years for simplified/preliminary design [8]. Strip Theory divides an aerodynamic surface (such as a wing or a rotor blade) into a number of span-wise strips as shown in Figure 3.1-1. The aerodynamic performance (lift and
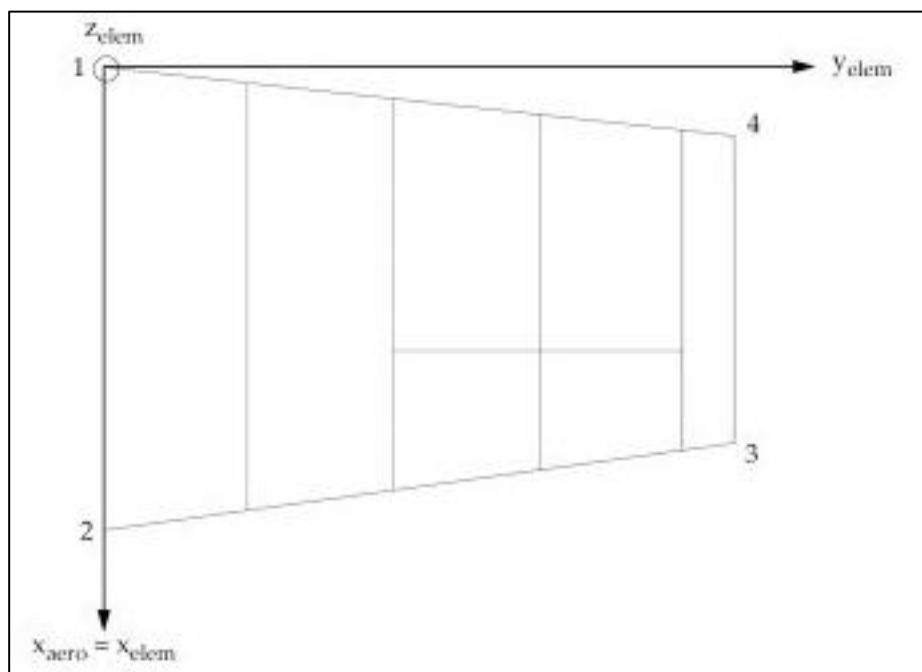

Figure 3.1-1. Strip theory divides an aerodynamic surface into spanwise strips.

drag) of each strip is calculated based on the aerodynamic conditions of the strip as shown in Figure 3.1-2. Each strip is independent; i.e., an individual strip does not consider the aerodynamic performance of adjacent strips or any other strip. Strip theory has been shown [8] to be reasonably accurate for analysis of high aspect ratio surfaces (such as a typical HD rotor blade). Strip theory is not as accurate for low aspect ratio surfaces.
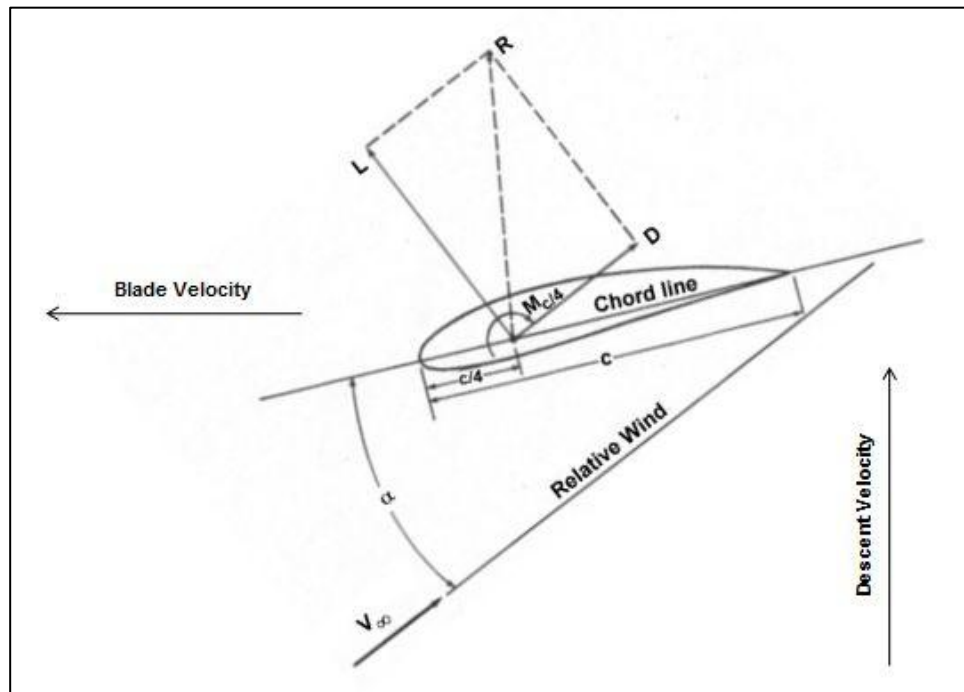

Figure 3.1-2. The lift and drag of each strip are based solely on the aerodynamic conditions of the strip.

The other aerodynamic challenge for helicopter duration models is that the blade sections experience a wide range of angle of attack (AOA). After blade deployment, the blades are fully stalled at an angle close to 90 degrees. However, as the blades spin-up, the local AOA drops until the blade section starts operating in the more efficient pre-stall low AOA range. To handle this wide range of AOA conditions, this project made two assumptions. First, low AOA aerodynamic data (below stall) can be obtained from XFOIL [9] or references on airfoil performance [10]. Second, for angles of attack above stall, flat plate surface aerodynamics from Hoerner [11] was used. Some arbitrary fitting was done to merge the low AOA and high AOA data. The aerodynamic coefficients used in this simulation are shown in Figure 3.1-3.
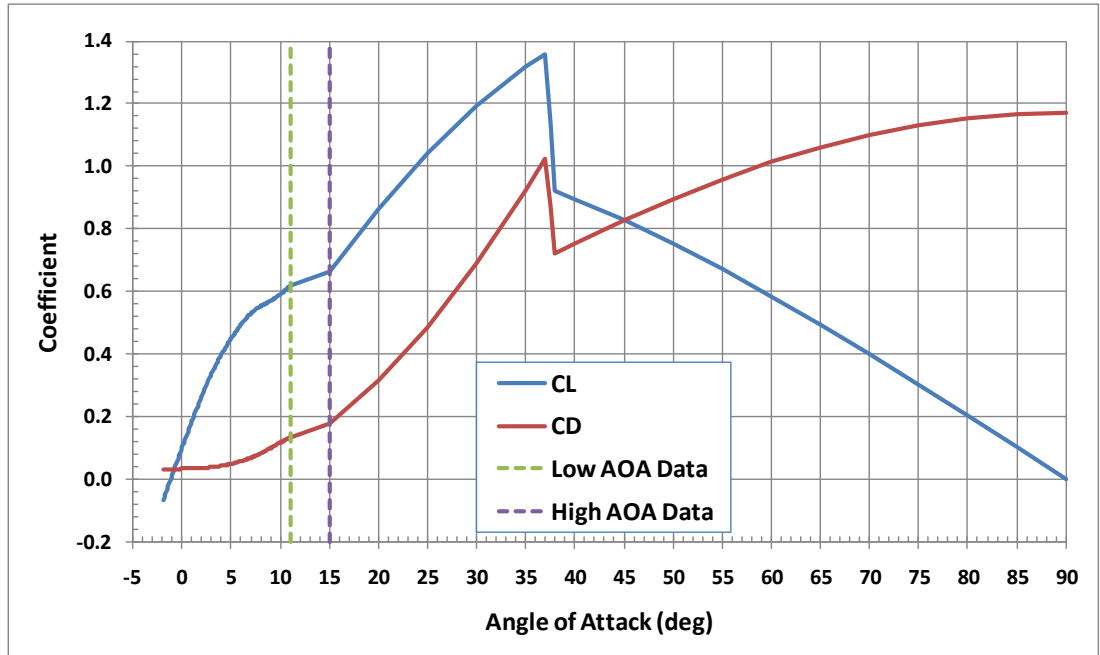
Figure 3.1-3. Aerodynamic coefficients for a wide range of angle of attack were assembled from low AOA and high AOA data.

3.2 EQUATIONS OF MOTION

The HD simulation performs a transient solution of rotor blade spin-up and steady state performance. The simulation starts with the blade deployed, axis of rotation vertical, zero initial descent velocity, and zero rotor rotation speed.

At each time step, the following calculations are performed:

- Calculate lift and drag in each blade strip based on local aero conditions of the current step.
- Resolve lift and drag into vertical force and torque
- Sum the vertical force and torque from all strips
- Calculate vertical acceleration given the vertical force from the blade and the gravity force on the overall vehicle
- Calculate rotor rotational acceleration given the torque and the moment of inertia of the rotor/blade assembly
- Calculate vertical and rotational velocities and displacements at the end of the step
- Continue performing time steps until the vehicle reaches stead state conditions.

The numerical integration equations for vertical motion are as follows:

$$\ddot{U} = \frac{F_{vertical} + F_{gravity}}{M}$$

$$\dot{U}_{n+1} = \dot{U}_n + \ddot{U} \, \Delta t$$

$$U_{n+1} = U_n + \dot{U}_n \, \Delta t + \ddot{U} \, \Delta t^2$$

The numerical integration equations for rotational motion are as follows:

$$\ddot{\omega} = \frac{T}{I}$$

$$\dot{\omega}_{n+1} = \dot{\omega}_n + \ddot{\omega} \, \Delta t$$

$$\omega_{n+1} = \omega_n + \dot{\omega}_n \, \Delta t + \ddot{\omega} \, \Delta t^2$$

3.3   HD SPREADSHEET

The HD simulation was implemented in an Excel spreadsheet. The spreadsheet starts with an "Input and Results" worksheet. This sheet defines the HD model including blade geometry, number of blades, and mass of the model. This worksheet also includes charts of selected output versus time. Charts include rotor speed, descent rate, and aero strip performance including lift, drag, vertical force, and torque. A screen snapshot of this worksheet is shown in Figure 3.3-1.
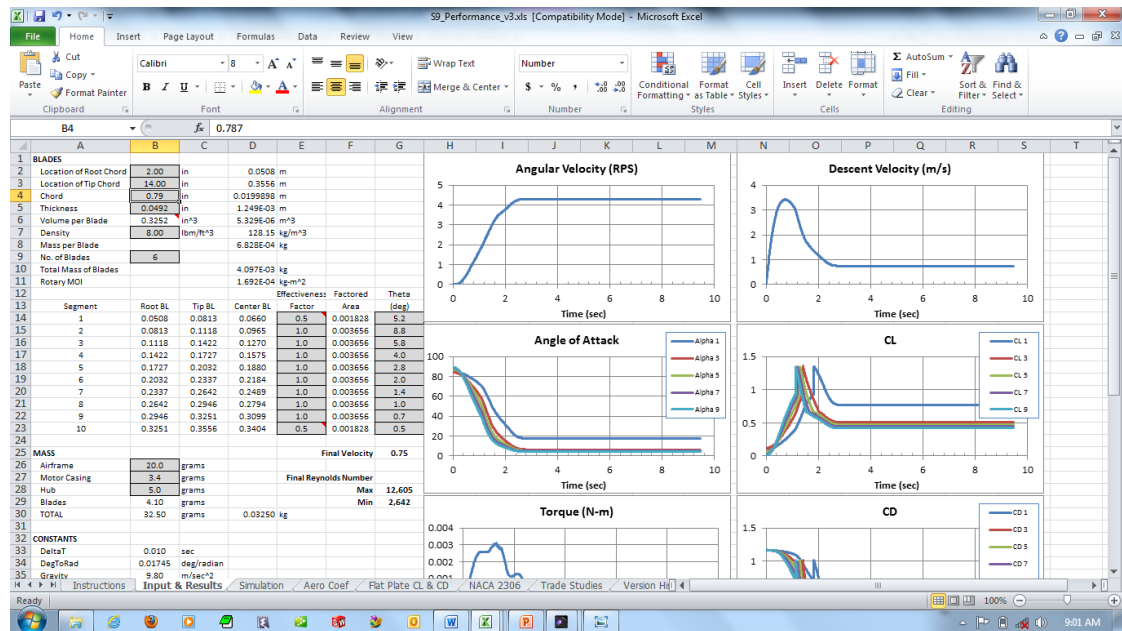

Figure 3.3-1. The "Input & Results" worksheet includes model definition and selected results.

The transient solution is performed in the "Solution" worksheet. This sheet includes groups of columns to calculate the lift, drag, vertical force, and torque of each strip. Other columns sum the vertical force and torque from the strips to calculate the net loads on the vehicle. Each row represents one time step of the timewise numerical integration.

Note that Excel includes the "Solver" function with is a powerful nonlinear optimization algorithm. The "Solver" can be used to vary selected model design parameters (such as blade twist angle) to achieve an optimum result (such as minimum descent rate).

3.4 LIMITATIONS

The HD simulation has several limitations that may affect the results. Significant limitations include:

- The strip theory model is divided into ten strips. More strips might provide improved resolution of the results but would require more detail in the spreadsheet.
- Strip theory aerodynamics neglects strip-to-strip interaction.
- Strip theory aerodynamics neglects tip losses (i.e., the loss of aerodynamic effectiveness that occurs near the inboard and outboard tips). Note that the "Input and Results" worksheet includes cells where the user can manually set the effectiveness of each strip to approximate tip losses.
- Strip theory ignores blade-to-blade interaction.
- The airfoil lift and drag coefficients are currently set based on a typical airfoil section (NACA 2306) as calculated by XFOIL for Reynolds Number = 10,000. These coefficients may need to be updated based on the blade chord, airfoil section, and Reynolds Number of the blade.
- The spreadsheet neglects friction of the hub and any aerodynamic effects of the rocket body/fins.
- The spreadsheet assumes that the rotor disk is horizontal and steady (no precessing, oscillations, etc.). Any effects of blade dihedral are neglected.
- The spreadsheet neglects the effects of the Betz limit (the theoretical limit on the amount of energy that can be extracted from a given amount of fluid flow) [12]. The spreadsheet results may be valid for rotor performance below the Betz limit. The results will be invalid for performance approaching or exceeding the Betz limit.

4 FLIGHT COMPARISON

The HD spreadsheet was used to predict the behavior of an HD model design for international completion (S9A event). The model had the following features:

- Blade angle = constant 3 degrees (flat blade)
- Blade span = 12" (inboard edge at radius 2", blade tip at radius 14")
- Blade chord = 1"
- Blade thickness = 0.0625"
- Number of blades = 4
- Blade material = 8 PCF balsa
- Mass of rest of vehicle (body, rotor, and motor casing) = 28 grams

The predicted rotational velocity (in revolutions per second) of the rotor is shown in Figure 4-1. Note that the blade angular speed starts at zero and reaches a steady state condition in approximately three seconds. The blade rotational velocity of six rotations per second (RPS) seems fairly fast. However, the blade rotor for the sample model is mounted on a low friction axle, and blade speed observed during flight descent is very high (although no attempts have been successfully made to measure it).
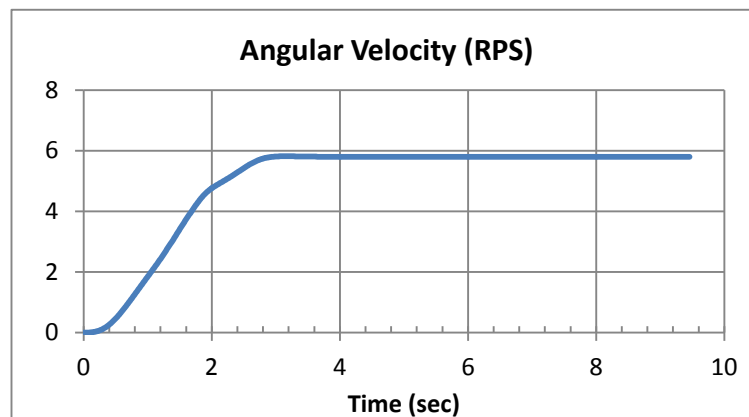

Figure 4-1. The rotor of the sample model spins up to steady state conditions in approximately three seconds.

The predicted descent velocity is shown in Figure 4-2. The descent velocity reaches nearly four meters/sec before the rotor spins up. At steady state, the descent velocity is approximately 1 m/sec.
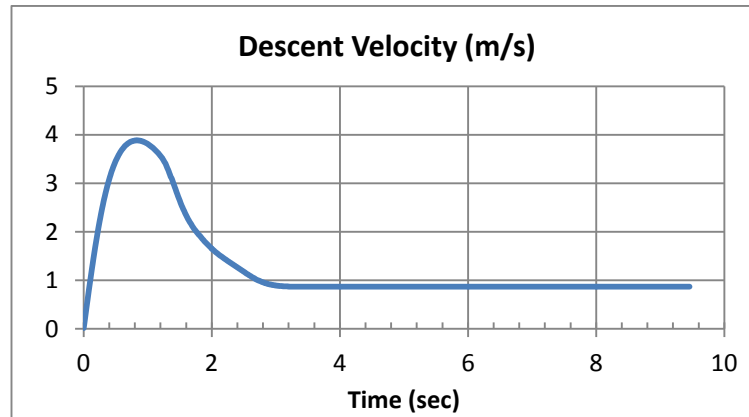
Figure 4-2. The steady-state descent velocity is approximately 1 m/sec.

Torque versus time is shown in Figure 4-3 for strips 1, 3, 5, 7, and 9. [Results for the other strips are available in the "Results" worksheet but are not plotted in the summary chart to avoid clutter.] Note that strip 3 provides the highest torque during spin-up, while strip 5 provides the most torque during steady-state descent. Strip 9 (near the tip) causes negative torque. The sum of the torque from all strips will be zero for steady state operation.
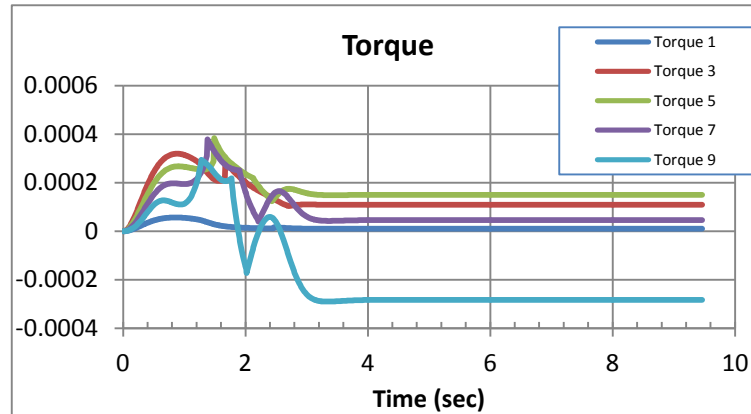

Figure 4-3. The torque from the segments varies from spin-up to steady state.

Vertical force versus time is shown in Figure 4-4. The outboard strips provide the most vertical force, initially operating as a flat plate but then transitioning to operate at the more efficient low angles of attack.
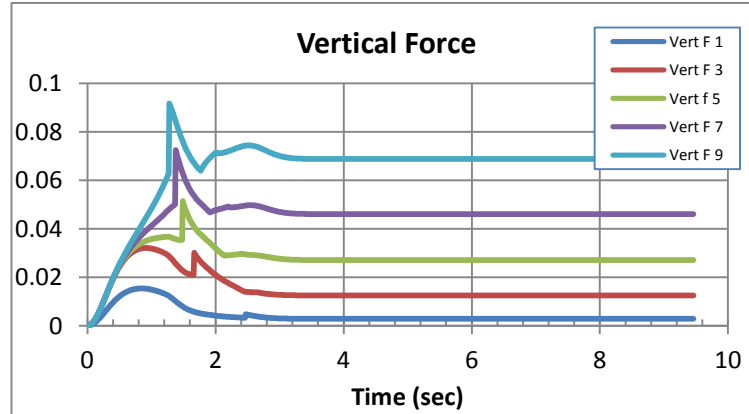
Figure 4-4. The outboard region of the blade provides the most vertical force.

The sample model was flown six times at two contests. Flight times are listed in Table 4-1. The average time was approximately 50 seconds.

Table 4-1. Flight times of the example S9A model.

Contest	Flight	Time
2011 Capitol Cup	#1	52
	#2	47
	#3	39
2012 Great Lakes Cup	#1	73
	#2	42
	#3	48
Average		50.2

Using Rocksim, the predicted altitude of the flight was approximately 67 meters (220 feet) depending on assumed drag coefficient. The model should have lost approximately 7 meters during the ~2 second spin-up phase (the integral under the curve in Figure 4-2.) The remaining altitude was 60 meters, and the steady state descent velocity was approximately 1 m/sec. Therefore, the flight time should have been two seconds (spin-up) + (60 meters) / (1 m/sec) = 62 seconds. This compares reasonably well with the actual times of ~50 seconds. Better correlation might be achieved if the altitude was measured during ascent and descent with an altimeter.

In summary, the results from the spreadsheet look reasonable, and the predicted flight duration was "in the ballpark" for one example vehicle. Many more comparisons of predicted duration to flight results would be highly desirable.

5 SENSITIVITY STUDIES

The HD analysis spreadsheet was used to perform sensitivity studies on two parameters:

- Blade angle vs. descent rate for flat blades
- Optimally twisted blade vs. flat blade

5.1 FLAT BLADE ANGLE

The example model described in Section 4 was used to perform a sensitivity study of blade angle. For all cases, the blade was assumed to be flat. Analyses were performed with the initial blade angle varied from 1° to 10°.

The results of the flat blade variations are shown in Figure 5.1-1. The lowest descent rate was achieved using an initial blade angle of 2°. However, the spin-up behavior of a 2° blade was fairly slow. A good blend of low descent rate and reliable spin-up behavior would be achieved using an initial angle of 3-4°.
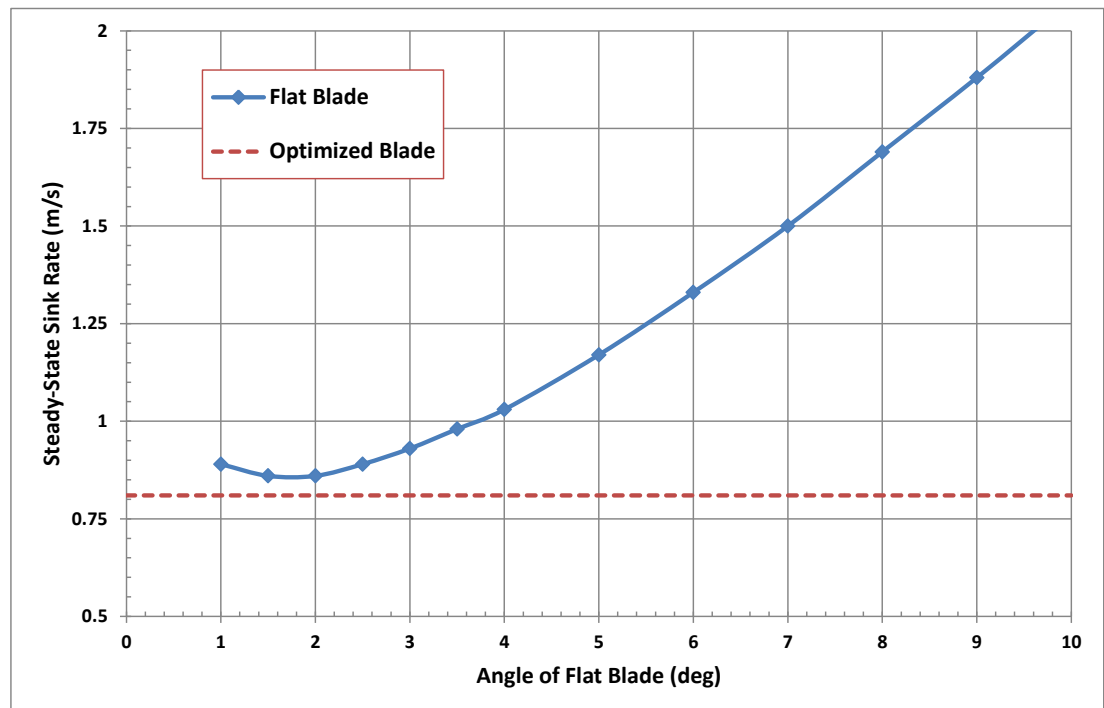

Figure 5.1-1. The minimum descent velocity using a flat blade was obtained by setting the initial blade angle to 2°.

It is somewhat interesting that the flat blade at an optimum angle had a descent rate nearly as low as an optimally curved blade (see Section 5.2).

5.2 OPTIMUM TWIST BLADE

The "Solver" feature in Excel was used to develop an optimized blade. For the Solver optimization, the design variables were the initial angle of each blade strip. The optimization goal was to minimize the sink rate.

As shown in Figure 5.2-1, two solutions were obtained by Excel depending on the initial geometry of the blade. In one case, the optimum angle followed a continuous curvature, as expected. However, in the other case, the blade angles of the inboard section decreased. This indicates that the behavior of the inboard blade is not a major driver of descent rate. Either blade design would provide essentially the same descent rate.
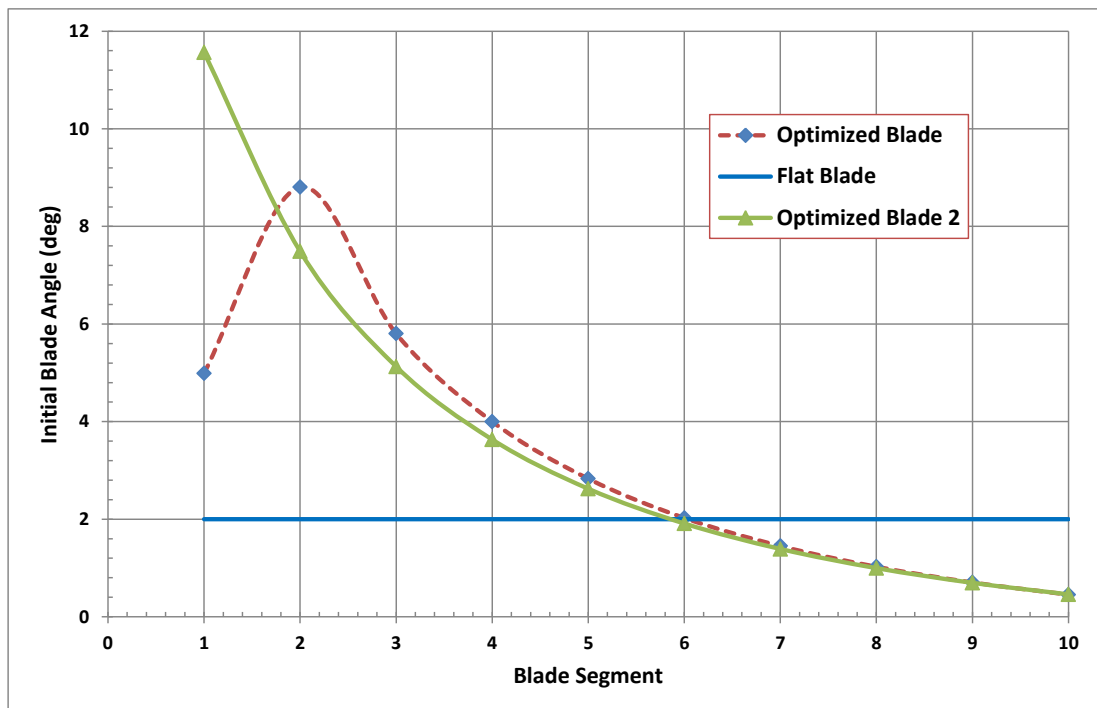
6 CONCLUSIONS AND RECOMMENDATIONS

An Excel spreadsheet was developed for use in simulating the performance of Helicopter Duration models. The spreadsheet performs a transient analysis to simulate the spin-up and steady state portions of HD descent. The spreadsheet has several assumptions and limitation, but results seem reasonable and had moderately good agreement to a sample model.

The spreadsheet was used to perform sensitivity studies of blade angle (for a flat blade) and the optimum curvature for a curved blade. The spreadsheet can be used for many future tasks including:

- Simulation of point designs
- Trade studies of weight, blade span, and many other parameters.

The spreadsheet has been uploaded to ContestRoc for use by the competition community.

7 EQUIPMENT, FACILITIES, AND BUDGET

7.1 EQUIPMENT

- Laptop computer, provided by Quartus Engineering Incorporated
  (www.quartus.com)

7.2 BUDGET

The budget for this project was essentially zero. The laptop computer had
Microsoft Excel installed, so no additional software or special tools were needed.
Flight data was used from prior contests, so no flight testing was needed.

REFERENCES

1. Barber, Trip, "Model Rocket Helicopter (Gyrocopter) Duration," http://www.nar.org/competition/plans/pdf/Helicopter%20Duration%20Presentation%20%28Barber%29.pdf.

2. Zunofark Team (Gassaway, Steele, and McCarthy), "Rotor Twist on Rotaroc Models," NARAM-25 R&D report, 1983.

3. Van Milligan, Tim, "Calculating the Rate of Descent of a Helicopter Duration Rocket," NARAM-33 R&D report, 1991.

4. Langford, Ellis, "Rotation! Optimization of Rotor Design for the Helicopter Duration Event", NARAM 43 R&D entry, 2001.

5. Pacific Flying Machines Team (Parks and Coleman), "Helicopter Duration Model Descent Stability", NARAM-53 R&D report, 2011.

6. MIL and QPROP programs by Prof. Mark Drela (MIT) for design of windmills and propellers, http://web.mit.edu/drela/Public/web/qprop/.

7. John Seddon and Dr. Simon Newman, Basic Helicopter Aerodynamics, Third Edition, AIAA Education Series, 2011, 264 pages, hardback, ISBN 978-1-60086-861-0.

8. "NX Nastran Aeroelastic Analysis User's Guide," UGS Corporation, 2007.

9. XFOIL program by Prof. Mark Drela and Harold Youngren (MIT) for design and analysis of airfoils, http://web.mit.edu/drela/Public/web/xfoil/.

10. Ira H. Abbott and A. E. von Doenhoff, Theory of Wing Sections: Including a Summary of Airfoil Data, Dover Books on Aeronautical Engineering, 1959, ISBN 0486605868.

11. Dr.-Ing S.F. Hoerner, Fluid-Dynamic Drag, 1965.

12. Betz limit (http://en.wikipedia.org/wiki/Betz'_law)