Helicopter Rotor Aerodynamics and Modeling

Course Development, Part II

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ENE506 Content, Assessment, and Pedagogy

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I. Introduction

This document describes an introductory helicopter aerodynamics and design engineering course for undergraduates in aeronautical or aerospace engineering. The three major sections of this document are Content, Assessment, and Pedagogy. These sections have been developed according to Engineering Education research principles and findings, such that the three sections are aligned with one another. The course's foundation is to provide authentic practice for meaningful learning.

The course emphasizes understanding of pilot controls of the hardware of a rotor, mathematical modeling of theoretical performance models, and design of a rotor to meet a defined mission. The assessment strategies are based on the types of learning in this course, where project-based learning and design thinking employ higher levels of thinking and therefore need the matched assessment strategy of a rubric. Pedagogy is primarily based on Perkins' *Making Learning Whole*, where certain elements for the student are emphasized: distributed, deliberate practice; intrinsic motivation and choice; working on the hard parts with feedback and assessment; participation in a community of practice; and metacognition.

A. Setting

I expect that the institutional setting will be an ABET-accredited engineering college that offers aerospace engineering at the bachelors level. ASEE reports 67 schools that award bachelors aerospace engineering degrees, paling in comparison to the 283 schools that award mechanical engineering degrees and to the 256 that award electrical engineering degrees (American Society for Engineering Education, 2011). For example, the rotorcraft centers of excellence are Georgia Tech, University of Maryland, and Penn State (Schweitzer, 2014). Kansas University offers a professional short course for helicopters. Purdue University and

Arizona State seem to have offered a helicopter course as recently as 2012. These institutions have developed plans of study to support a complex subject such as helicopter aerodynamics.

I assume that the students who would pursue this course have an eager interest in helicopters as it seems to be a rare topic even among aerospace schools. I may encounter students who are airplane pilots, as the minimum age for a private pilot is 16. The knowledge base of private pilots is correct but incomplete because the emphasis for a pilot is on operation instead of on design. I will expect to compare new information to prior airplane knowledge. In a rarer case of having a helicopter pilot as a student, I expect such a person to be older than typical bachelor's level students, as helicopter training is expensive enough to be a skill usually acquired in the military.

I expect to offer the course to undergraduates who have fulfilled key mechanical and aerospace prerequisites. The prerequisites include: introduction to kinematics, machine elements, introduction to dynamic systems and controls, introduction to fluid mechanics, and introduction to aerodynamics. These prerequisites have their own prerequisites, such as physics, calculus, and mechanics of solids. These subjects will have introduced the concepts: a rotational axis system, aerodynamic forces and moments in the translational axis system, time-dependency of forces and moments, and functions of common helicopter parts. These prerequisites are necessary for design.

B. Motivation for this Curriculum

Nothing about helicopters is easy and that is why it is satisfying to demonstrate mastery of the subject. I spent seven years in the helicopter business, in the aerodynamics department specifically, working on military and civilian tiltrotors. I had the opportunity to participate in KU's short course designed for professionals to understand helicopter aerodynamics and handling qualities; it was a 40 hour lecture. There does not exist a civilian tiltrotor pilot license, so I pursued both fixed wing (airplane) and rotary wing (helicopter) pilot licenses in order to gain a more comprehensive understanding of the pilots, the rules, the machines, and the emergencies. I logged 62 hours (@ $150/hour) of airplane training and 46 hours (@ $325/hour) of helicopter training, numbers large enough to qualify but miniscule compared to career pilots. Because of exorbitant cost of flight training, this marvel of technology is becoming more difficult to access for mere mortals either as a career or as a hobby. My hope is to bring the subject back to forefront of attainability for undergraduates in engineering, with a renewed emphasis on making the technology more affordable through sound engineering design.

II. Content

The content of this course is arranged according to the principles of Backward Design (Wiggins & McTighe, 2005). The concepts are arranged according to enduring understandings or Enduring Understandings, items that are Important-to-Know, and items that are Good-to-be-Familiar-With. I show here existing helicopter course descriptions from other prominent universities for comparison to my proposed content and assessment. I describe in the next section the concepts that fit into these three categories. In the Concept Map section below, I describe how I converged upon these categories for these concepts.

I considered what other universities might offer as described in course descriptions, syllabi, and required texts. Three stand apart as helicopter centers of excellence: Georgia Institute of Technology, Pennsylvania State University, and University of Maryland College Park. A fourth institution that deserves mention is the University of Kansas because of the textbook author, Ray Prouty, who joined the American Helicopter Society in 1952 (American Helicopter Society, 2014), a mere eight years after the Bell 47 was the first helicopter certified for civilian use (Bell Helicopter Textron Inc, 2014). Georgia Tech and Arizona State provide senior level courses and Georgia Tech offers two semesters of specialization. Penn State offers undergraduate and graduate level courses. The University of Maryland, Purdue, and KU only provide masters level courses, but my original goal is undergraduate level.

Georgia Tech's course AE4358 uses Prouty's text and have five course objectives: "Identify and explain the purpose of key elements of a rotorcraft configuration; Utilize actuator disk theory to analyze rotor system performance; Utilize rotor blade element theory to analyze rotor system performance; Predict rotorcraft performance such as maximum speed, maximum rate of climb, endurance, etc; Use the Rf design process to size a rotorcraft configuration against a given mission" (Costello, 2014). I assume the Rf design process refers to a balance between what is *required* and what is *feasible*; this is not mentioned in helicopter textbooks. These five course objectives are very similar to my Enduring Understandings and my learning objectives listed in the next sections.

Arizona State offers a Rotary Wing Aerodynamics and Performance class, which is described as "Introduces helicopter and propeller analysis techniques. Momentum and blade-element, helicopter trim. Hover and forward flight. Ground effect, autorotation and compressibility effects" (Arizona State Universiy, 2014). The required textbook is *Principles of Helicopter Aerodynamics* by Gordon Leishman of the University of Maryland. The course description is thin here I cannot infer much about the alignment of assessment or emphasis of the content.

One interesting thing to note from these descriptions of other universities' classes is that the undergraduate level courses (GIT and ASU) draw from textbooks written by individuals whose schools only offer graduate level courses (KU and UMD). I wonder why the graduate-level-only universities have arranged their plans of study this way. Another interesting thing to note is how few authoritative sources there are, such that different universities frequently reference each other's work; this gives the impression of a tight-knit community.

A. Enduring Understandings

Helicopters are unique because of the rotor at the top that does most of the work, second to that of the pilot. How the pilot interacts with the helicopter is of paramount importance in design. The rotor is typically made of many moving parts, the largest and most noticeable of which are the blades, the hub, and the swashplate, all of which operate in rotation as a function of time. The pilot commands the forces generated by the rotor through the controls in order to accomplish a mission, whether it be hover, forward flight, or some combination of both. Therefore, Enduring Understanding 1 is: The student will be able to describe the rotor and blade motions in a rotational reference axis system and the student will be able to identify rotor designs and the allowable controls between the pilot and the rotor. This is shown best in Figure 2 and Figure 3 for the pilot controls to the main rotor.

A rotor designer is different from a pilot in that a designer can make a prediction of rotor performance, given a particular shape or configuration, whereas a pilot plans a mission around known performance capabilities. (Performance has multiple definitions in helicopters; performance of the rotor considers thrust generated and power required; performance of the total aircraft considers maximum attainable altitude, speed, gross weight, and range on a tank of fuel.) There are four common theoretical models of increasing fidelity to the physical geometry of the rotor, and therefore increasing mathematical complexity. The student will be able to construct mathematical representations of different theoretical models that predict rotor lift, drag, thrust, and power required. Therefore, Enduring Understanding 2 is: The student will be able to calculate performance using theoretical mathematical models of a rotor, and list the assumptions and limitations of each of the theoretical models. This is shown best in Figure 4**Error! Reference source not found.**.

A rotor designer is also different from a pilot in that a designer can design an optimum configuration to satisfy a given mission. The engineering student should practice substantiating and defending all their claims and decisions with sound engineering data. Therefore, Enduring Understanding 3 is: The student will draw upon a broad knowledge base of mission maneuvers, performance prediction tools, and rotor designs to create and select an optimum configuration to meet or exceed a defined mission. This is shown best in Figure 4.

Expressing the differences between design engineers and pilots highlights the fact that engineers think in a particular way and behave accordingly. One mode of behavior among engineers is to distribute cognition among specialists, which necessitates particular vocabulary for efficient communication. Another aspect of engineering thinking is to test large prototypes by first applying calculations where possible and by devising a rigorous test through careful planning. Therefore, Enduring Understanding 4 is: To develop design engineering thinking and technical communication. I note, however, that this Understanding is really an Outcome, is more difficult to measure, and is beyond the scope of this course for assessing. These will be practiced, however, in the various assignments of the course.

B. Important-to-Know

Overlapping micro-concepts that are Important-to-Know are shown in blue in Figure 1. There are six clusters of micro-concepts, starting from bottom left of Figure 1 and moving clockwise.

- Lift distribution from four effects on the rotor in forward flight.
- Motions of the blade from three possible hinges. Motions are a result of aerodynamic forces.
- Hub configurations based on which motions are allowed and constrained by the hinges at the hub. Because the blades are subject to large aerodynamic forces, the blades themselves may still flap (out-of-plane), feather (twist in-plane), or experience lead-lag (translation in-plane).
- Angular effects of RPM, rotor coning, and the Coriolis effect.
- Four controls available to the pilot. Collective and cyclic (longitudinal and lateral) control the main rotor. Anti-torque pedals control the tail rotor (a tail rotor can be

designed just as the main rotor at the top of the helicopter is designed; if the student knows the main rotor, the instructor assumes that the student can design the tail rotor).

- Four common mathematical models of the rotor. It is possible to combine the momentum theory and blade element theory models. There also exists vortex theory. Momentum theory, blade element theory, and vortex theory are completely abandoned if the designer uses computational fluid dynamics (CFD).

There are macro-concepts built from the above micro-concepts. These are shown in Figure 1 in blue, closer to the purple Enduring Understandings. Descriptions below start from the center left of the Figure.

- Forward flight. One of the main interests in this class is the performance of the rotor in forward flight. However, for total mission performance, the student must know lift, drag, and pitching moment of the fuselage, which knowledge may have been gained in a prerequisite course.
- Hover, which is the main virtue of helicopters and merits the most study. When a rotor is attached to a fuselage, the fuselage may experience pendular action, which is of interest to a pilot for the purpose of controlling it.
- The rotor wake, as a consequence of the blade shape. The wake structure will change as a function of aircraft velocity. The wake can also be affected by its proximity to the ground (ground effect).
- Rotor blades, which will be the primary focus of optimizing performance for a mission.
- Hub, which has historical and manufacturer-specific significance. Understanding this invites a student into the helicopter community of practice.

- Mission, which is the deciding element of sizing a rotor and fuselage. Analyzing a mission for its most demanding segments will have been explored in a prerequisite course, at least for fixed wing solutions. There will be some exploration in this course about analyzing a mission for hover segments.
- Flight Test. It is important to know that there is such a thing as flight test. Since no theoretical model is complete, the rotor designer should know that a logical next step after design is to build and to test the configuration. Planning flight test is a component of engineering thinking within Enduring Outcome 4. Planning for flight test includes identifying critical input parameters, critical output parameters, and permutations of the key inputs that produce a safe-to-risky ordering of test points. I have listed flight test as Important-to-Know because I will not include practice in this course for planning flight test points according to risk.

C. Good-to-Be-Familiar-With

In Figure 2, I show in green some items that a rotor designer would need to be familiar with from a design perspective. The overlapping circles indicate micro-concepts whereas the independent circles represent macro-concepts.

- Twist, chord, airfoils, planform, and tip shape are facets of the blade’s aerodynamic shape. Chord and airfoils are concepts covered in prerequisite aerodynamics courses. Twist, planform, and tip shape are rotor-specific concepts.
- The swashplate is a unique helicopter part that links pilot control stick movement to rotor movement, manifested mostly in collective pitch of the blades and the tip path plane of the whole rotor. Its function is in Enduring Understanding 1; its form is good-to-be-familiar-with.

- The pilot has control of the entire aircraft, with control sticks in particular governing the rotor. The pilot also has training in mission planning, normal operations and maneuvers, and emergency operations and maneuvers.
- Downwash is the resulting deflected airflow as the blades generate a pressure difference. Its distribution is dependent upon the blade shape, the collective pitch of the blades (requiring power from the engine to maintain normal RPM), and the velocity of the entire aircraft.
- Tip vortex is a nontrivial contributor to overall rotor performance in hover because most of the useful work of the rotor occurs between 75% radius and the tip. The tip vortex shed by one rotor blade may impede the performance of the advancing blade behind it as the blades rotate about the hub.

In Figure 3, I show the governing principle of the Conservation of Angular Momentum, but I expect that the concept will have been seen before in a kinematics prerequisite course. Also in Figure 3, blade inertia is a factor in Conservation of Momentum, but inertia concerns the materials and inner structure of the blade, which is beyond the scope of this course. Suffice it to say that these inertial forces cannot be ignored but will not be included in this exercise of optimization of rotor aerodynamic performance of thrust and power required.

Another list of items that a rotor designer should be familiar with is housed in the table of contents of the FAA’s Rotorcraft Flying Handbook (Flight Standards Service, 2000). This is the book that all helicopter pilots are supposed to read as part of their initial training. The chapters include: aerodynamics, flight controls, helicopter systems, the owners’ manual, weight and balance, performance, maneuvers, emergencies, instruments in the cockpit, night operations, and decision-making. The designer and the pilot need to have common vocabulary and concepts if a design is going to be successful. This links back to technical communication as part of Enduring Understanding/Outcome 4.

D. Concept Map

I drew upon several sources at several different times in order to develop a list of concepts. My first iteration included micro-concepts that I sorted into macro-concepts, all drawn from my memories of employment and flight training. My second iteration of concepts was a list of the functional groups within the Flight Technology department of Engineering at my former employment, a more systems thinking approach. My third iteration was generated from a list of memos that I wrote while I was employed as an aerodynamicist, as I was searching for the topics I wrote about the most. My fourth iteration was a revisiting of the first iteration with an emphasis on rotor wake that I had forgotten before. My fifth iteration was the chapter headings from the FAA Rotorcraft Handbook.

There are other concepts that must be noted as beyond the scope of this course but within the scope of designing an entire helicopter. Aspects of blade design (from my second iteration of my concept map) include handling qualities, vibrations (or dynamics), loads fatigue, materials, and structures. These concepts do not appear in the FAA Rotorcraft Handbook since they are matters of engineering design that the pilot does not have the power to change. Engine propulsion is a significant aspect of designing well, as it involves power delivered to the rotor for a certain cost in weight and fuel consumption. In the case of this course, the rotor designer will determine what amount of rotor power is required but not what amount of engine power is required. It may be my future effort to develop a second course of Helicopter Design with these concepts, where Rotor Design would become an Important-to-Know understanding.

Therefore, my sixth iteration, presented here in Figure 1, Figure 2, Figure 3, and Figure 4, draws heavily from the Rotorcraft Handbook topics and adds micro-concepts from my fourth iteration that support detailed design of a rotor. Helicopter rotor concepts are so interactive that I must represent the concept map in several figures for clarity and readability. Enduring Understandings are colored in purple. Important-to-Know items are colored in blue. Good-to-be-Familiar-With items are colored in green. Micro-concepts are indicated by their bubbles slightly overlaying each other as a cluster. Not surprisingly, the rotor has the most connections.

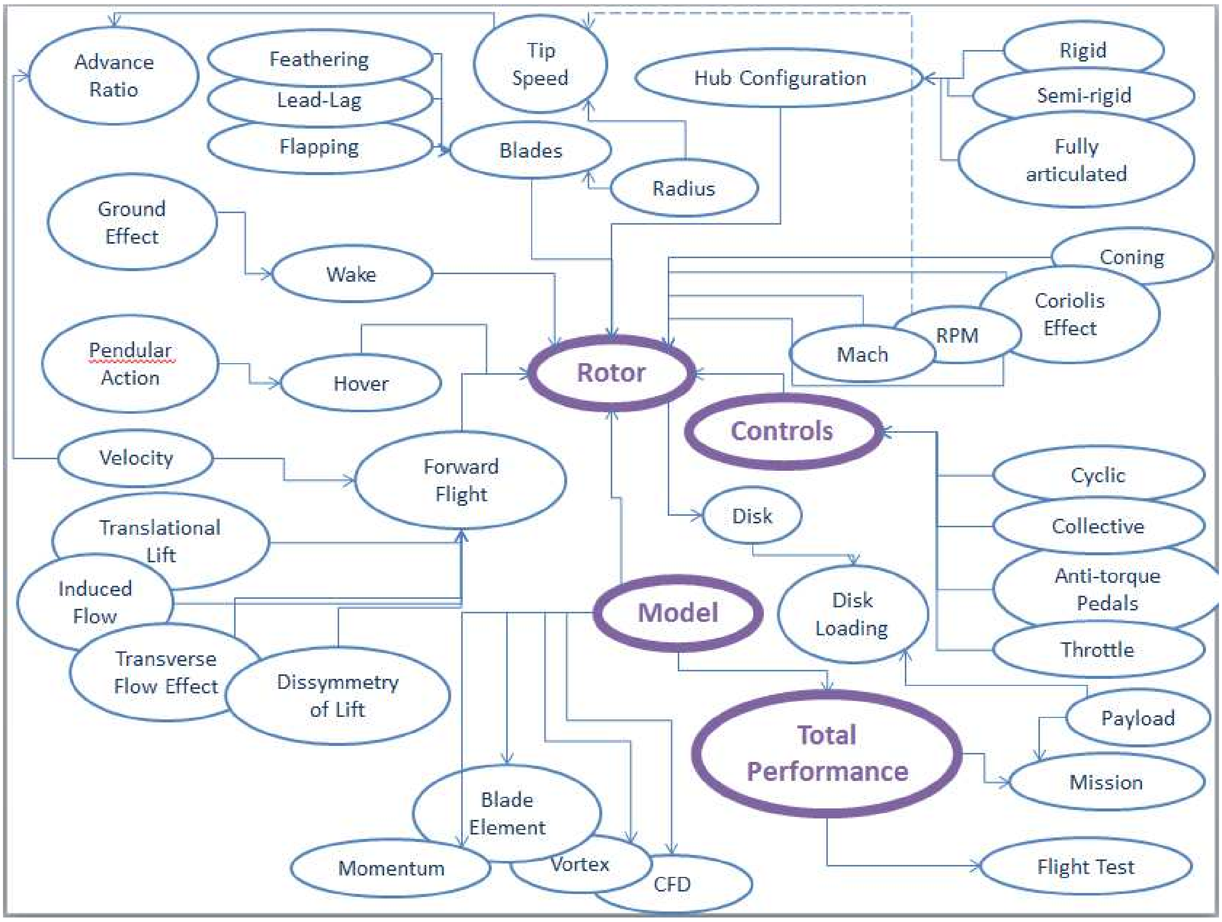

Figure 1. Simple concept map for Enduring Understandings and Important-to-Know items.

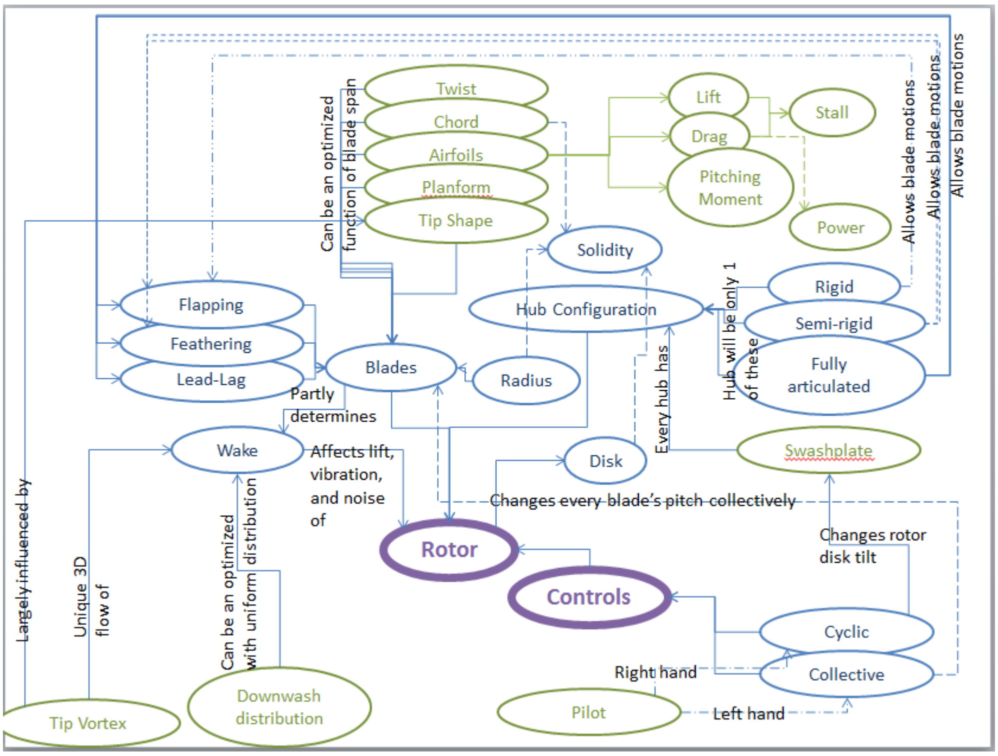

Figure 2. Detailed concept map for rotor, blades, hub, and controls.

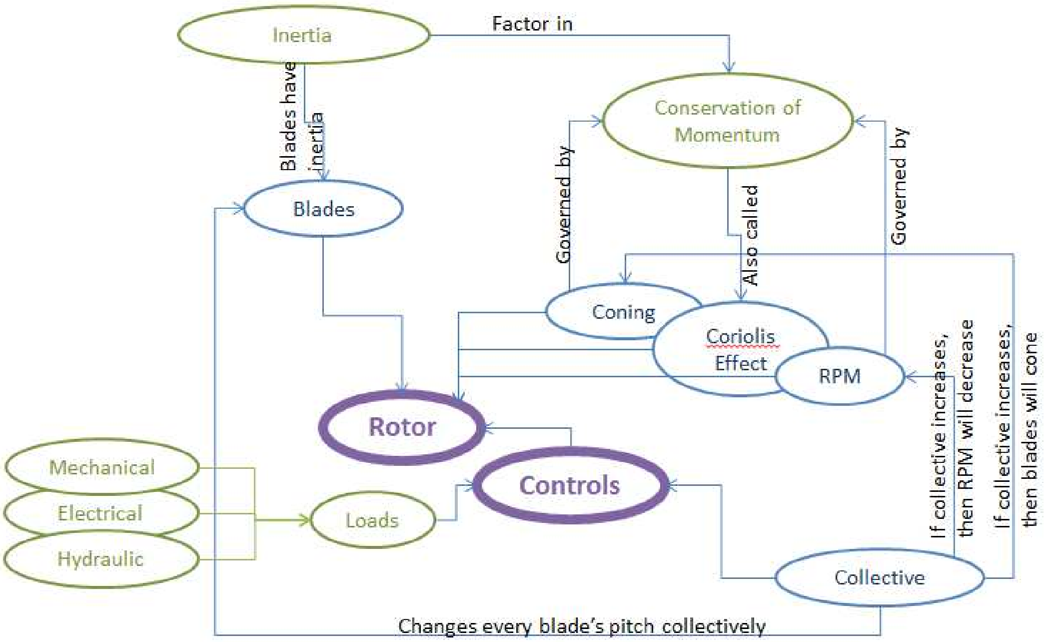

Figure 3. Detailed concept map of rotor with Good-to-be-Familiar-With Conservation of Angular Momentum and Control Loads.

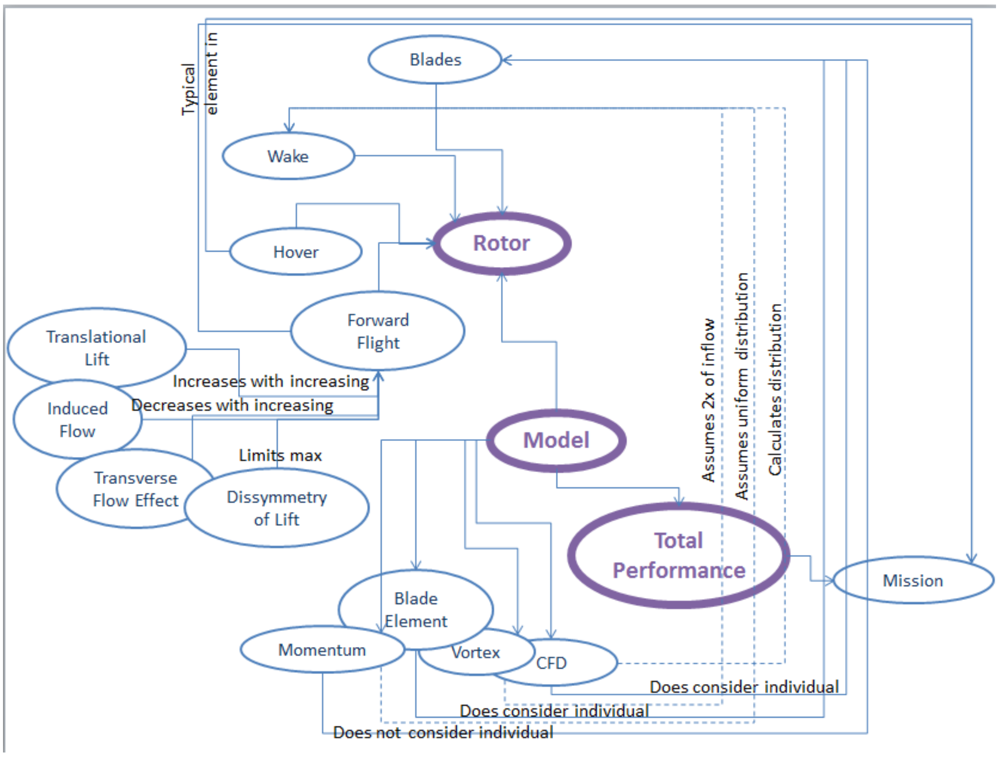

Figure 4. Detailed concept map for Enduring Understandings of Modeling the Rotor and calculating Total Performance for a mission.

E. Difficult Concepts and Misconceptions

Perkins outlines eight attributes of conceptually difficult knowledge (Perkins, 2009). Helicopter rotors have seven of the eight. See Table 1 below for concepts and micro-concepts that have these attributes. He also advocates working on the hard parts, so the course will uncover these concepts repeatedly and in various ways.

Table 1. Conceptually difficult knowledge for helicopters.

Attribute	Helicopter or Aerodynamic Concept or Micro-concept
Abstract	Airflow over airfoil; rotor wake; pressure distributions; mathematical representations
Continuous	Input controls; airflow; power required
Dynamic	Cyclic controls; total rotor motion; total aircraft motion
Simultaneous	Forces and moments; blade motions and rotor motions
Organicism	N/A, unless the selected materials include wood, or air counts as organic
Interactiveness	Forces and moments; rotor performance to total aircraft performance; control

	inputs to rotor and fuselage responses
Conditionality	Rotor hub designs or configurations on mission parameters; velocity, rotor blade shape on wake structure
Nonlinearity	Forces and moments of airfoils; rotational reference system; mathematical representations

A keyword search for “teaching aerodynamics” using the Purdue e-library system produced 17 results, two of which I discuss here as being significantly related to my course. A search for “teaching helicopters” produced no related results. A short paper in the *Journal of Engineering Education* proposed six experiments to demonstrate aerodynamics principles visually, but the authors provided only anecdotal evidence aimed at increasing the students’ enthusiasm for the subject (Pols, Rogers, & Miaoulis, 1994). Another paper presents a new tool, a packaged code whereby a student may experiment with an airfoil shape and compute its aerodynamic properties, but the authors do not present any evidence that this tool has an impact on a student’s understanding of the subject (Zuppardi & Napolitano, 1987). The data here suggest that this area needs more rigorous research.

The two aerodynamics papers above bring up the point that engineering thinking is often skewed toward visual and spatial representations instead of verbal representations only. An author presents trends of research for learning science, with a conclusion that learning abstract concepts and dynamic concepts can be supported with “3D models, diagrams, gestures, and other visual-spatial modes” in addition to language-based methods (Ramadas, 2009). The difficult concepts here are things that are dynamic or are non-visible, attributes that are confirmed by Perkins above.

A keyword search for “difficult engineering concepts” produced four results. One author, in his thesis, specifically conducted a literature review for difficult concepts; he highlighted cognitive load theory and related it to problem-based learning (Mayer, 2013). In this work, he highlights that measurement variation, which uses probability and statistics, is the difficult concept targeted in his research. He concluded the effectiveness of scaffolding with worksheets in a laboratory setting instead of lectures and textbooks in problem-based learning in order to teach difficult engineering concepts.

Other researchers, in proving the usefulness of simulations for teaching, highlighted typical problems that students encounter. In broad categories, students have difficulty with generating hypotheses, with designing experiments, with interpreting data, and with planning and self-monitoring (de Jong & van Joolingen, 1998). Related researchers identify these problems not as concepts, but as learning processes (Njoo & de Jong, 1993). It is important to note that these are difficult for students because these are included within the Enduring Understandings of my course.

F. Progression to Expertise

The most comprehensive Enduring Understanding is for a student to create and select an optimum configuration for a given mission. This implies design thinking, for which there has been considerable research. There are patterns of behavior (Crismond & Adams, 2012) that have value here as students practice design. While all the patterns of behavior identified are valuable, I will highlight a few informed designer behaviors here that I will expressly expect students to exercise, though, as noted above, these are difficult.

Pattern D, Deep Drawing and Modeling, as a means of representing ideas will be emphasized. This includes modeling, creating artifacts, and sketching. Pattern E, Balance Benefits and Tradeoffs, as a means of weighing options and making decisions, will be emphasized. This includes giving explanations for design choices. Pattern F, Valid Tests and Experiments, as a means of conducting experiments, will be emphasized in order to optimize performance. These patterns are in contrast to beginner design behaviors that ignore tradeoffs or have poorly planned experiments. I expect that upper-class undergraduates have made progress toward informed designer behaviors through other classes.

G. Cognitive Theory of Learning

Svinicki summarizes the best theories for learning, with cognitive theory described by Piaget at the top (Svinicki, 2004). Firstly in cognitive theory, a learner receives new information by paying attention to it with his senses. Secondly, the information moves to working memory or short-term memory and is compared to existing memory. Thirdly, if the information is found to be meaningful in working memory, it moves to long-term memory by being encoded in a network of organized associations. Svinicki also describes concept learning theory as long term memory being made of “schemata all interconnected in an organized manner”. Svinicki then describes constructivist theory as a learner having schemata that are “a very complex and unique world view peculiar to each individual, having been constructed out of all the learner’s prior experiences”. These theories, if incorporated into teaching and learning, have the implication that the student must have deliberate and distributed practice with the content in order to learn. Learning here means encoding information into long-term memory.

III. Assessment

This section presents several tools that help align assessment strategies with course content as presented in the previous section. Firstly, I map the Content of the Section II to Bloom's Taxonomy. Secondly, I develop assessment strategies for the Enduring Understandings of this course through Assessment Triangles and Assessment Worksheets. Thirdly, I show a rubric for the most comprehensive Enduring Understanding, shown as an authentic task.

A. Learning Objectives for the Entire Course

The revised Bloom's Taxonomy recommends the construction of learning objectives with one noun (as a direct object) and one verb as a cognitive process (Anderson, Krathwohl, & Bloom, 2001). I use the concepts in Figure 1 as the nouns; therefore, I am highlighting in the list below only Enduring Understandings and Important-to-Know items. I find that, through my own development, these Learning Objectives in the list below emulate the objectives as written by Georgia Tech.

1. The student shall recall the motions of a blade and of a rotor.
2. The student shall describe the rotational reference axis system of a rotor.
3. The student shall identify the controls of a rotor blade.
4. The student shall describe the wake structure of a rotor.
5. The student shall contrast in-ground effect to the out-of-ground effect on the wake.
6. The student shall model or draw the balance of forces of a rotor in hover.
7. The student shall subdivide the effects of forward flight on a rotor.
8. The student shall construct a model of performance for the rotor, using Momentum Theory, Blade Element Theory, or Vortex Theory.
9. The student shall compare and contrast the performance models.

10. The student shall calculate total mission performance of a rotor in hover and in forward flight.
11. The student shall select an optimum configuration of a helicopter for a given mission.
12. The student shall plan for flight test of total performance of a helicopter.
13. The student shall measure performance of a helicopter in a flight test.

B. Mapping the Learning Objectives to Bloom's Taxonomy

The front cover of the revised Bloom's Taxonomy provides a table in which to map the learning objectives of a course so as to assist in crafting appropriate teaching and assessment strategies. I use the numbers in the above list and the abbreviations EU, IMP, and FAM to represent Enduring Understanding, Important-to-Know, and Good-to-be-Familiar-With concepts. Table 2 below shows the concepts in the revised Bloom's Taxonomy. I show here four Enduring Understandings as my concept map listed, while the remaining Important-to-Know items are summarized versions of the items in the concept map.

I did not represent any of the concepts here as factual knowledge because of Hansen's list of attributes of concepts, such as timelessness, universality, abstractness and breadth, and representation in 1 or 2 words (Hansen, 2011). Also, Bloom defines fact as "the basic elements students must know to be acquainted with a discipline or solve problems in it", whereas concept is defined as "the interrelationships among the basic elements within a larger structure that enable them to function together" (Anderson, Krathwohl, & Bloom, 2001). None of the 13 learning objectives proposed here is a basic element, but rather at least two elements interrelated. I did not represent any of the learning objectives here as metacognitive knowledge but I do expect that students will engage in reflection, noted in the syllabus in Section IV.A below.

Table 2. Learning Objectives mapped to the revised Bloom's Taxonomy.

	Remember	Understand	Apply	Analyze	Evaluate	Create
Factual						
Conceptual	1 – IMP	2 – IMP 6 – IMP	***3 – EU*** 4 – IMP	5 – IMP 7 – IMP 9 – IMP		
Procedural				10 – EU	***11 – EU***	***8 – EU*** 12 – IMP 13 – IMP
Metacognitive						

C. Assessment Triangles

For this assignment, I develop here assessment triangles for the three most important Learning Objectives, identified in Table **2** as 3, 8, and 11 Enduring Understandings. Cognition, Observation, and Interpretation corners constitute the assessment triangle (Pellegrino, Chudowsky, & Glaser, 2001), where the Cognition corner should be developed first. For all the Learning Objectives, I take the cognitive perspective as described by Pellegrino, where students actively construct knowledge by trying to connect new information to prior knowledge. The preferred method of cognition is the strong method, which is to learn a domain-specific algorithm. I believe that this course should be at the junior or senior level, so students will be encouraged to connect new helicopter information to previously-gained engineering knowledge.

To answer the question about how students will learn the Enduring Understandings of this course, this course will employ equal parts mental simulation, project-based learning, and design thinking, with some expectation of rote memorization. These learning activities will be shown in the assessment triangles below.

1. Enduring Understanding 1 – Learning Objectives 1, 2, 3, 4

The student will be able to describe the rotor and blade motions in a rotational reference axis system and the student will be able to identify rotor designs and the allowable controls between the pilot and the rotor.

Cognition Corner – Mechanical reasoning by mental simulation will require a student to construct a mental model of a dynamic system; the student will probably follow the system piecewise (Hegarty, 2004). The student can develop a mental model by articulating inputs and reactions of a dynamic system with many moving parts. Rote memorization plays a small role in this course because of unique names given to helicopter-specific parts, such as a blade, a hub, and a swashplate. Supporting memorization requires prior experiences (Jonassen, 2011), which I suppose means exposure and repetition.

Observation Corner – The student will be provided an exploded view and an assembly view of an existing helicopter rotor system without any parts labeled. In the images, the student will label the components of the rotor, such as the rotor shaft, the hub, the swashplate, the flap hinge, the lead-lag hinge, and the pitch link. Alternatively, the student may be provided or may construct a physical model of a rotor system out of simple prototyping materials, Legos, or K'nex type materials.

The student may choose to draw motions of a rotor blade, where the blade is rigid in the chordwise direction and that the slender beam can have bending and rotating motions (this is an application of engineering beam theory). The student will identify out-of-plane motion of the blade from the flap hinge. The student will identify in-plane motion of the blade from the lead-lag hinge. The student will identify feathering motion from the pitch links.

The student may choose to draw swashplate pictures showing a tilt change from neutral position, or an elevation from neutral position, as indicators of cyclic inputs or collective pitch inputs. The student may draw before-after pictures of blade coning, blade flapping, and blade feathering. The student may draw pictures of lift distribution and Mach number distribution across the span of the rotor blade in hover. The student may write equations for the conservation of momentum, with the Coriolis Effect and rotor speed or RPM.

Alternatively, the student may choose to use a physical model of an articulated rotor with a swashplate to describe verbally and demonstrate physically inputs and reactions. The student may move parts statically to describe the resulting blade motion. The student will identify lateral cyclic and longitudinal cyclic inputs from the swashplate. The student may spin the rotor and move parts to describe the resulting blade motion. Alternatively, the student may move the pilot control sticks and verbally describe the resulting motions in the rotor system.

Interpretation Corner –Complete descriptions of the components and the possible motions are available in chapter seven of the classic textbook by Gessow (Gessow & Myers Jr, 1999) and in chapter five of the helicopter text from Boeing Philadelphia that is used by Purdue (Stepniewski & Keys, 1984). The instructor will compare the student’s labels and drawings to the textbook illustrations. With the alternative observation of the student manipulating a physical model, the instructor will compare the student’s movement of rotor parts, coupled with verbal descriptions, to the textbook illustrations.

2. Enduring Understanding 2 – Learning Objectives 8 and 9

The student will be able to calculate performance using theoretical mathematical models of a rotor, and list the assumptions and limitations of each of the theoretical models.

Cognition Corner – Project-based learning takes place in an authentic task (Dym, Agogino, Eris, Frey, & Liefer, 2005); an authentic task may be a student building his own math model, based on a helicopter theory, to compare with textbook equations and results. The student will develop the project by applying computer programming skills to create a compiled code or create a spreadsheet with equations central to the theory being modeled. The student will make conjectures on the impact of included and excluded physical phenomena for each of the theories.

Observation Corner – There are four commonly-used domain-specific algorithms for modeling the performance of a helicopter rotor, listed here in increasing complexity (and therefore, accuracy and computational time required): momentum theory, blade element theory, vortex theory, and CFD. (CFD modeling of helicopters is still being developed in peer-reviewed research journals, with some frameworks available (Steijl, Barakos, & Badcock, 2006) and will therefore not be emphasized, but at least mentioned.) The student will create a spreadsheet or compiled program for each of the first three listed math models, identifying key inputs and key outputs available in the different models.

The student will calibrate his spreadsheets or codes of the three models by using parameters of an existing helicopter and its accompanying performance as documented in the flight manual. The student will create plots of blade performance for key input and output parameters as a function of blade span, or total rotor performance as the model allows. The student will create plots of thrust versus power required for hover and forward flight.

Interpretation Corner – Complete descriptions of the first three theories are available in chapters 2, 3, and 4 of Stepniewski's book. The instructor will compare codes or spreadsheets input to the textbook equations for the three models. The instructor will compare outputs to his own constructed math models. The instructor could compare outputs of the math models to performance charts of existing products, with the caveat that the models are incomplete such that the analytical and flight-test-measured results will not match within 3% accuracy.

3. Enduring Understanding 3 – Learning Objectives 10 and 11

The student will draw upon a broad knowledge base of mission maneuvers, performance prediction tools, and rotor designs to create and select an optimum configuration to meet or exceed a defined mission.

Cognition Corner – Design thinking can be learned by doing, by iterating and receiving feedback, and by dialoguing with artifacts and other people (Crismond & Adams, 2012), as in working in a team, with a professor, to design a helicopter to meet a particular mission. The designer predicts range, maximum speed, payload, fuel required and cost of a rotor configuration. The designer then compared results to mission specifications and iterates until mission specifications are met. The designer must also compare results to the limits of reasonable design, such as disk loading, advance ratio, drag and compressibility as a function of Mach number, solidity, airfoil stall, and control loads. The novice designer should take care not to exceed these limits. The student should compare his calculations to those presented in class.

Observation Corner – There does not appear to be a concise method for optimizing a helicopter rotor because each parameter is a tradeoff to another; rather, there exists an energy balance method for analyzing the mission for power required, fuel, and payload. Staying within the above-mentioned limits allows a designer to select tip speed, twist, planform, number of blades, and airfoil sections. A mission will be defined by the instructor. The student will complete the following steps:

- translate the mission legs into helicopter rotor parameters (defined in the cognition corner)

- determine the most demanding mission segments as the design point
- outline reasonable limits for each of the rotor parameters
- identify trade-offs between rotor parameters
- select airfoil, tip speed, rotor radius, chord, twist, number of blades, and number of rotors
- calculate hover and forward flight performance of the given selection
- iterate until a solution is found to meet the mission; plots will be created

Interpretation Corner – Suggestions and hints to optimization of a rotor design can be found in the previously mentioned texts, such as all of second half of Stepniewski's book and chapter seven of Johnson's book (1980). The instructor will check the work for the above seven steps. The instructor will confirm that the design stayed within reasonable limits. The instructor will check plots created, if any, for validity and comprehensiveness. The instructor will check that the final proposed configuration and performance predictions at least appear to meet the mission.

D. Assessment Worksheets

I show here assessment worksheets for the top three learning objectives for which I developed assessment triangles. The assessment worksheet shows the claim, the task, and the evidence for the learning objective.

1. Enduring Understanding 1 – Learning Objectives 1, 2, 3, 4

The student will be able to describe the rotor and blade motions in a rotational reference axis system and the student will be able to identify rotor designs and the allowable controls between the pilot and the rotor.

General – The student will be provided an exploded view and an assembly view of an existing helicopter rotor system without any parts labeled. The student will be instructed to label hardware of a rotor. The student will be instructed to draw and label allowable motions of the rotor blade. The student will be instructed to describe pilot input controls and resulting rotor motions.

Claim – The student will be able to draw and name aerodynamic and inertial forces and moments of a rotor in a rotational axis system. The student will be able to draw and name blade motions in a rotational axis system. The student will be able to show cause and effect of control inputs on individual rotor blade motions.

Task – The student will label images and diagrams of the hardware of a rotor. The student will draw vectors of forces and moments on the rotor blades and assign the proper names of the forces, moments, and motions. The student will make a model of a rotor with a spinning disk on a mast to narrate gyroscopic motion.

Evidence – The student will have written labels on images of hardware of a rotor. The student will label flapping, feathering, and lead-lag motions with vectors and arrows. The student will label lift, centrifugal force, drag, and pitching moment with vectors and arrows. The student will show that a force input on a spinning disk has its full effect 90 degrees later. The student will describe pilot control inputs' effects on rotor motions.

2. Enduring Understanding 2 – Learning Objectives 8 and 9

The student will be able to calculate performance using theoretical mathematical models of a rotor, and list the assumptions and limitations of each of the theoretical models.

General – The student will be instructed to build his own mathematical models in a spreadsheet or compiled code of his choice. The student will be instructed to show results of the models compared to existing helicopters.

Claim – The student will identify key assumptions for each mathematical model for rotor and blade performance. The student will identify sources of information required for each model. The student will build a mathematical model of each model.

Task – The student will list assumptions for each model, expressed mathematically where possible. The student will identify key output parameters when using the models. The student will draw pictures of the unit of calculation for each theory (momentum theory analyzes a disk, regardless of blades; blade element theory analyzes a blade within a rotor; vortex theory analyzes the rotor wake). The student will show governing mathematical equations and operationalized calculations. The student will list possible output variables in each model. The student will input key parameters of an existing helicopter and plot the outputs of the three models to the performance data of the existing helicopter.

Evidence – The student will have a spreadsheet or code in electronic form. The student will have a list of inputs and outputs for each mathematical model. The student will have a list of governing equations for each model. The student will have a list of assumptions for each model. The student will have graphs of hover and forward flight performance data from each of the models and from an existing helicopter.

3. Enduring Understanding 3 – Learning Objectives 10 and 11

The student will draw upon a broad knowledge base of mission maneuvers, performance prediction tools, and rotor designs to create and select an optimum configuration to meet or exceed a defined mission.

General – The student will be instructed to make an argument that a particular configuration of a helicopter meets the given mission. The student will substantiate the argument with data generated from the mission description and from at least one mathematical model from Enduring Understanding 2.

Claim – The student will be able to calculate hover and forward flight performance, predict mission range from performance calculations, and match to a defined mission.

Task – The student will itemize key mission specifications. The student will model hover and forward flight performance using theoretical mathematical models of a rotor. The student will calculate mission fuel required and mission range achieved.

Evidence – The student will create a table or a mission diagram. The student will create and use a spreadsheet or a compiled code of the mathematical model. The student will create graphs of mathematical model inputs and outputs as compared to mission thresholds.

E. Authentic Tasks

Hansen outlines six characteristics of authentic tasks in which students will gain an understanding and an appreciation for the subject (Hansen, 2011). I argue here that the Enduring Understanding 3 of designing a helicopter to meet a mission has five of the six characteristics. The characteristics are:

- realistically contextualized
- require judgment and innovation
- ask student to “do” the subject
- replicate key challenging situations in which professionals are truly “tested” in their field
- assess student’s ability to use a repertoire of knowledge and skill
- allow opportunities to rehearse, practice, and get feedback

A typical military contractor such as Bell Helicopter Textron Inc, Boeing Helicopters, or Sikorsky Aircraft Corporation, may answer a Request For Proposal (Federal Business Opportunities, 2014). The RFP will define a mission or series of missions that the vehicle is expected to complete and will define any other constraints or requirements, such as the use of parts already in inventory or compliance with other existing systems such as GPS. The contractors are typically given 90 to 120 days to make a proposal and submit a bid. The proposal process is the context of the rotor design process, where the engineers analyze the missions, size the vehicle, review their historical data for cost, weight and performance, and propose development time and testing time required. I do not intend to emphasize financial aspects in this course, but I do intend to emphasize vehicle design and comparison to publicly available historical data. Emulating this RFP process emphasizes five of the six authentic task characteristics.

The sixth characteristic of providing opportunity for practice and feedback shall be incorporated into the course that I am developing for the benefit of the students. The details of this are provided in Section IV.A below.

F. Rubric

Hansen proposes that a rubric to assess a student's performance of a task should contain three aspects: dimensions of quality, level of mastery attained, and commentary (Hansen, 2011). The dimensions of quality should be criteria from theories of critical thinking and be specific to the discipline. The levels of mastery should have a label for which a point value can be attached, and the number of levels should be dependent on the complexity of the task. The commentary should indicate a student's strengths and weaknesses on the performance of the task. The rubric in general should be provided to students beforehand in order for them to practice self-assessment. The rubric also communicates key criteria of the discipline to students.

For this course, I develop a rubric for one Enduring Understanding 3, the most comprehensive and most authentic one in this course. This Enduring Understanding is computationally intense, so I will center the rubric on careful mathematical modeling. Table 3 below shows the rubric for three levels of mastery on four dimensions of quality.

Table 3. Rubric for Enduring Understanding 3: design configuration for a given mission.

Dimension of quality	Exemplary	Satisfactory	Unsatisfactory
Statement of design specifications	-Shows design points of mission, translated to helicopter parameters -Identifies most demanding mission segment	-Identifies most demanding mission segment	-Does not consider given mission
Create mathematical model	-States assumptions, uses mathematical formulas and expressions where possible -States related equations -States unit system and consistently uses it	-States related equations	-Identifies model only by name or does not identify model at all
Use data sources	-Uses data sources correctly -Uses several sources, properly cited -Identifies reputable sources	-Uses several sources, properly cited	-Does not identify sources or uses secondhand sources of questionable reputation
Make recommendation of configuration	-Creates relevant graphs and drawings, well labeled -Identifies limits on plots -Identifies threshold values from mission specs -Meets mission	-Creates relevant graphs and drawings, well labeled -Recommended configuration meets mission	-Does not create relevant graphs or drawings -Configuration does not meet mission

IV. Pedagogy

This section outlines the printed material that will be provided to the student at the beginning of the course. The foundation of this part of the course is the inclusion of the seven principles of *Making Learning Whole* (Perkins, 2009) in order to outline to the student *how* and *why* the content will be taught in this course. Perkins' principles, from an extended sports analogy, are explained with some details in the list and Table 4 below:

- Play the whole game – To find a problem; To get better at something; Deliberate rehearsal; reflection
- Make the game worth playing – Intrinsic motivation; Give students a choice; Make the most of the student's imagination
- Work on the hard parts – Identify troublesome knowledge; Deliberate practice of deconstructing and reconstructing difficult part so that they are executed in new and better ways; Ongoing assessment and feedback from instructor
- Play out of town – Transfer of knowledge; Learning by doing
- Uncover the hidden game – Learning strategies, causal thinking, systems phenomena; Uncover tacit messages that people send by their conduct
- Learn from the team – Peer problem solving; Community of practice; Mentors
- Learn the game of learning – Cognitive apprenticeship; Reflection

Table 4. Perkins' *Making Learning Whole* principles incorporated into this course.

Principle	**Example in this course**	**Details**
Play the whole game	Designing a rotor in response to a Request for Proposal; Incorporating previously acquired engineering knowledge about forces, moments, kinematics, machine elements, airfoils, and mission modeling	Section III.E Section III.D.3
Make the game worth playing	A generative topic with disciplinary and societal significance	Section III.E
Work on the	Deconstruction of theoretical mathematical models of rotor	Section II.E

hard parts	performance in order to reconstruct for the purpose of optimization and design of a new rotor	
Play out of town	Going back and forth between theory and examples; Calibration and comparison of theoretical mathematical models to the measured performance of an existing helicopter product; Make broad generalizations of the theoretical models through reflective thinking	Table 5, Table 6, Table 7, Table 8 helpful resources columns
Uncover the hidden game	Students have difficulty with generating hypotheses, designing experiments, and planning	Section II.E
Learn from the team	Enduring Understandings 1, 2 and 3 shall be team efforts because of the broad and detailed scope of each; there shall be resource interdependence in-class; students shall rotate through 4 teams during the course	Table 5, Table 6, Table 7, Table 8 in-class activity columns
Learn the game of learning	Iterating efficiently in design (using elements in Uncover the hidden game) and shall be scaffolded by the instructor with in-class tasks, accompanying worksheets (Mayer, 2013), rubrics provided beforehand, and coaching by the instructor	Table 5, Table 6, Table 7, Table 8 assignments due columns; Section III.F

A. Syllabus

Course Goals, Objectives, and Expectations

This course is designed to introduce undergraduate aeronautical engineering students to helicopter rotor aerodynamics, with an emphasis on theoretical mathematical modeling of rotor performance for designing a rotor to meet a defined mission composed of hover and forward flight.

By the end of the course, the student should be able to:

- name and describe helicopter rotor hardware
- understand the helicopter pilot perspective of control of the rotor
- understand aerodynamic forces and moments in the rotor
- describe three theoretical mathematical models for rotor performance, including their assumptions and limitations

- apply these mathematical models to the design of a new rotor for a given mission
- engage in general engineering design practices, such as design notebooks and reflection
- be conversant with engineers who know other aspects of helicopter design, such as handling qualities, loads and fatigue, and propulsion

Criteria for Grading and Grading Standards

The student shall be graded on the quality of the worksheets and reports generated for each assignment. Upper-class undergraduates are expected to use engineering vocabulary and knowledge from prerequisite courses and this course in order to write professional technical reports. Teamwork is an element of each assignment and the student shall also be graded on participation and distribution of workload in the team as reported by their teammates.

The reports shall be clear and detailed on project definition, assumptions, data sources, operationalization of theoretical models, and results of those models. The recommendations of the reports shall be clearly stated and shall be numerically precise.

Specific Criteria for Each Graded Assignment

Each graded assignment will have a rubric. The student shall be provided the rubric before the assignment is due so that the student may check his own work before submitting for a grade. Certain assignments will have closed-form numerical solutions as criteria in the rubric, such as the building of a mathematical model for comparison to an existing helicopter product. Certain assignments will have open-ended responses, such as the design of a new rotor to meet a new mission.

Description of Class, Including Description of and Rationale for Teaching Method

The three credit hour course shall meet once a week in a three hour session with the instructor. This class will follow the flipped classroom model, where text reading and lecture will occur before class on a student's own time and class meeting time will be spent on working through examples and class assignments in small teams. Additionally, the in-class sessions will include multiple laboratory-like opportunities for visualization of and experimentation with aerodynamic phenomena, where worksheets will be provided to guide students' own inquiry. In class, the students will have access to physical models of helicopter rotors for hands-on exploration and discovery.

How Students Prepare for and Behave During Class Session

The flipped classroom model employs pre-recorded lectures for students to listen to or view before class on their own time. The instructor shall make these videos and accompanying slides (visual content) available to the students a week before each in-class session. The student is expected to take notes in a design notebook so that the student may refer to and employ the content during in-class sessions. Reflection notes along with lecture notes are highly encouraged so that the student reminds himself to ask the instructor about confusing content in the next in-class session.

During the in-class sessions, the student is expected to bring his own design notebook. The student may also bring his own computer as the course moves to mathematical modeling and design. The student will participate actively in worked examples and team assignments and will contribute equal labor to the team assignments. DO NOT simply copy others' work or notes and expect that you will understand it.

What Students Can Expect from Instructor

The instructor shall be prompt in providing a schedule of activities and relevant material at least one week in advance. The instructor shall provide rubrics as assignments are given and shall abide by the standards in the rubrics for grade determination. The instructor shall provide feedback on draft reports one week before reports are due. The instructor shall return graded assignments one week after student submission.

The instructor shall make frequent use of the student's prior knowledge of fixed wing aerodynamics. The instructor shall coach students in self-guided inquiry. The instructor shall model engineering and design thinking as was practiced in private industry. The instructor shall model helicopter pilot thinking. The instructor shall provide weekly office hours (TBD) for consultation for the assignments or for anything else that might be on the student's mind.

Advice on How to Read/Approach Materials

Helicopters are a complex culmination of multiple disciplines of engineering, so materials attempting to explain helicopters thoroughly will be short and complicated, or very long and simplified. Also, engineers and pilots together still do not know everything about how helicopters really work, so there will be unanswered questions and unexplained phenomena. Do the work so that you will develop a "gut feeling"; this will prepare you to answer the unanswered questions when you enter the workforce.

The student should be prepared to commit significant time (possibly years) understanding how all the hardware moves and how all the air flows. Some of what you already know from previous fixed wing classes will be applicable to this course. Skip to the pictures in the textbooks, but be clear that pictures do not convey rotating parts and aerodynamic phenomena very well. Do watch the lecture videos for moving parts and airflow visualization.

Take advantage of powerful computing capacity because there will be many parameters and variables to consider. Refresh yourself on programming (C, MatLab or other familiar code) or using spreadsheets (Excel) because of the intense focus on calculations in this course. Make notes in your code or spreadsheet to remind yourself of the names, uses and units of the different variables. Maintain a naming convention for your files and your experiments because there will likely be many files building upon each other.

Schedule of Material Each Time Students Meet

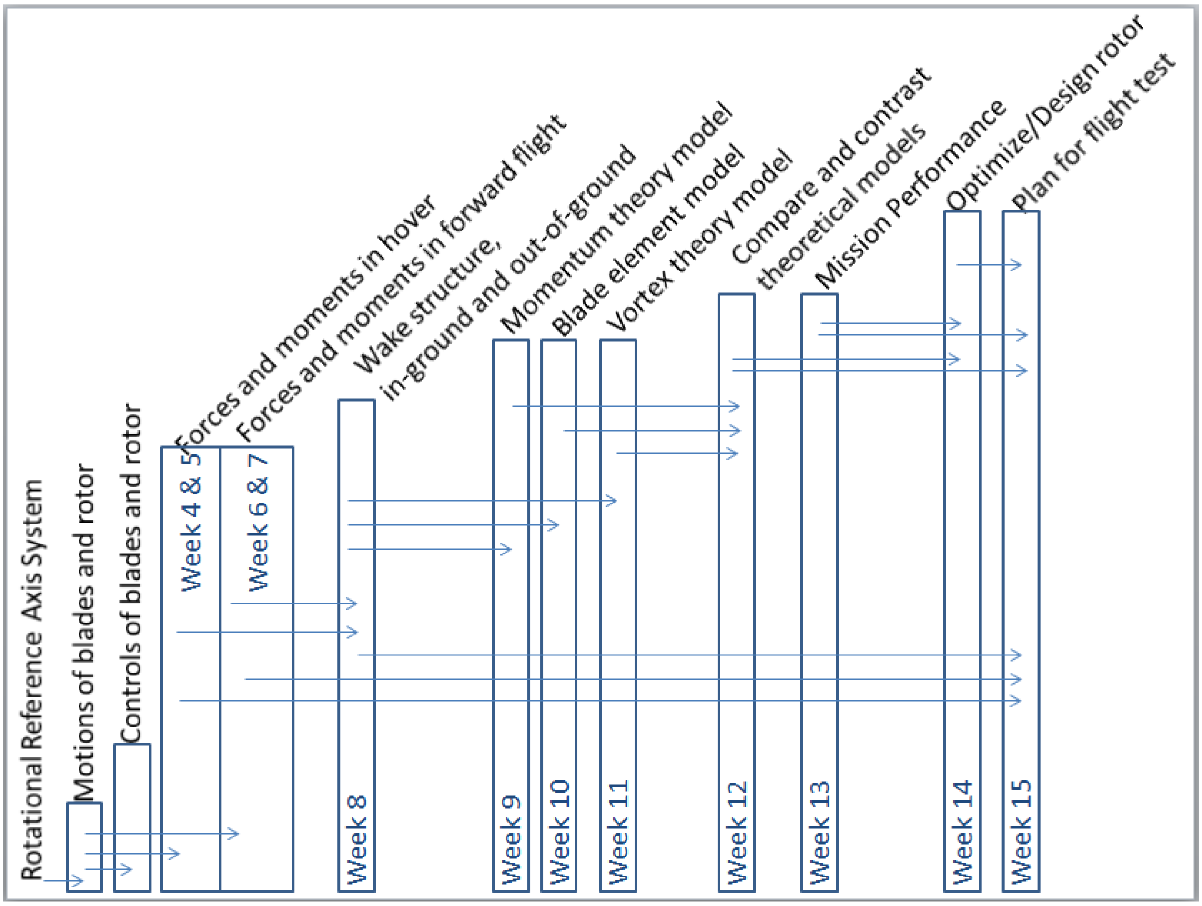

Figure 5. Sequence of content for 15 week helicopter aerodynamics course.

Figure 5 above was developed from Fink's (2003) template of lesson plans for structuring the sequence of content in a course. The first step is to list the learning goals from Section III.A into Fink's Worksheet 1 for designing a course, and to address 1) ways of assessing this kind of learning 2) actual teaching-learning activities and 3) helpful resources for each learning goal. I show the results of Worksheet 1 in Table 5, Table 6, Table 7, and Table 8 in the next section. Secondly, the learning goals should be introduced, as in Figure 5 above, such that the subsequent topic includes the previous topic. I show arrows between topics in order to show inclusion of previous topics into new topics from left to right. As noted in the Content Section II of this paper, it is possible that we may not get to the Learning Objectives 12 and 13 of planning flight test, but it is better to plan for more content in a course than less, in case the students demonstrate heightened aptitude and interest in the subject.

B. Lesson Plan

A high quality lesson plan contains the following elements: General Objectives; Specific Objectives; List of Activities and Timeline; Concepts in The Lesson; Outline of How Concepts Will Be Taught; Description of Learning Activity; How Learning Will Be Assessed. I show below in the following tables, grouped according to Enduring Understandings and Important-to-Know items, the lesson plan for this 15 week course with the above elements itemized. To be consistent in Table 5, Table 6, Table 7, and Table 8 I use the truncated descriptions in Figure 5, which are built from the list in Section III.A. Much larger descriptions of the ways of assessing are described in Assessment Section III above.

Table 5. Lesson plan for Enduring Understanding 1.

Week	Learning Goal	Ways of Assessing	Teaching-Learning Activities	Helpful Resources	Out-of-Class Activity Before	In-Class Activity	Assignment due
1	Rotational reference axis system	Comparing labeled images to textbook;	Lecture with sketches;	Textbooks;	Obtain bound notebook	Intro to class, individual pre-test for prior knowledge	Labeled worksheets
2	Motions of blades and rotors	Comparing labeled images to textbook	Review 2-d schematics of many rotors; constructing and manipulating 3-D models	Prototype materials; scale model or remote control helicopter	Video lecture with demos	Prototyping models with Team1	Labeled worksheets
3	Controls of blades and rotors	Comparing verbal descriptions of inputs and rotor responses to textbook	Review 2-d schematics of many rotors; constructing and manipulating 3-D models	Heli-chair (2014) and remote control model helicopter	Video lecture with real flight manual images	Build and fly Heli-chair and RC model with Team1	Labeled worksheets

Table 6. Lesson plan for Important-to-Know forces in hover, forward flight; wake structure.

Week	Learning Goal	Ways of Assessing	Teaching-Learning Activities	Helpful Resources	Out-of-Class Activity Before	In-Class Activity	Assignment due
4	Forces and moments in hover	Comparing labeled images to textbook	Lecture with sketches; rapid experiments	Textbooks; wind tunnel simulation tool	Video lecture with worked examples of calculations	Simulations, with worksheets to guide experiments with Team2	Labeled worksheets of images, completed experiment worksheets
5	Forces and moments in hover	Comparing labeled images to	Lecture with sketches; rapid	Textbooks; wind tunnel simulation	Video lecture with worked examples of	Simulations, with worksheets to guide	Labeled worksheets of images, completed

		textbook	experiments	tool	calculations	experiments with Team2	experiment worksheets
6	Forces and moments in forward flight	Comparing labeled images to textbook	Lecture with sketches; rapid experiments	Textbooks; wind tunnel simulation tool	Video lecture with worked examples of calculations	Simulations, with worksheets to guide experiments with Team2	Labeled worksheets of images, completed experiment worksheets
7	Forces and moments in forward flight	Comparing labeled images to textbook	Lecture with sketches; rapid experiments	Textbooks; wind tunnel simulation tool	Video lecture with worked examples of calculations	Simulations, with worksheets to guide experiments with Team2	Labeled worksheets of images, completed experiment worksheets
8	Wake structure	Comparing labeled images to textbook	Flow visualization experiments	Textbooks; lab equipment: pressure gauges, smoke, scale model of rotor	Video lecture with real flight test videos, wind tunnel videos	Physical experiment, with worksheets to guide experiments with Team2	Lab report with pictures, test points, input parameter sweeps, outputs measured

Table 7. Lesson plan for Enduring Understanding 2.

Week	**Learning Goal**	**Ways of Assessing**	**Teaching-Learning Activities**	**Helpful Resources**	**Out-of-Class Activity Before**	**In-Class Activity**	**Assignment due**
9	Momentum theory model	Rubric III.F Table 3 rows: math model, data sources;	Programming, run simulations, report results	Textbooks, computers, plotting software	Lecture with slides of equations	Build model in spreadsheet or compiled code with Team3	Small report with general equations and exact program code;
10	Blade element theory model	Rubric III.F Table 3 rows: math model, data sources;	Programming, run simulations, report results	Textbooks, computers, plotting software	Lecture with slides of equations	Build model in spreadsheet or compiled code with Team3	Small report with general equations and exact program code;
11	Vortex theory	Rubric III.F Table 3	Programming, run	Textbooks, computers,	Lecture with slides of	Build model in	Small report with general

	model	rows: math model, data sources;	simulations, report results	plotting software	equations	spreadsheet or compiled code with Team3	equations and exact program code;
12	Compare and contrast models	Rubric III.F Table 3 rows: math model, data sources;	Report results, read existing flight manual performance charts	Textbooks, computers, plotting software, flight manuals	Video lecture of reading charts in performance manuals	Discuss physical phenomena sources of mismatch between models and real data; Short presentation on CFD model	Big report of all three models with real product data comparison;

Table 8. Lesson plan for Enduring Understanding 3, Good-to-be-Familiar-With flight test.

Week	**Learning Goal**	**Ways of Assessing**	**Teaching-Learning Activities**	**Helpful Resources**	**Out-of-Class Activity Before**	**In-Class Activity**	**Assignment due**
13	Mission performance	Compare student's equations to Energy Balance Method; Section III.D.3	Lecture with sketches; limits from existing performance charts	Textbooks; prior class resources	Video lecture of Energy balance method	Lecture on matching rotor parameters to mission parameters; build model with Team4	Mission diagram
14	Design rotor	All of Table 3 rubric in Section III.F	Update programs; Run simulations, report results	computers, plotting software	Video lecture on trade-offs in performance between rotor parameters	Plan for rigorous parameter sweep for producing data to support selection of optimal rotor with Team4	
15	Plan flight test	Compare proposed	Lecture with sample test	Sample test plan	Video lecture on	Develop test plan for new	Big report for new rotor

		test plan points to test goals, inputs that can be controlled or measured, outputs that can be measured	plan; learning to assess risk		risk assessment and flight test disasters	rotor with Team4; Individual Post-test for new knowledge, compare to Week 1 pre-test	design following rubric outline in Section III.F

Certain elements in the lesson plan tables above bear further discussion and substantiation because these elements must be prepared by the instructor because they are not simply chapters out of a textbook. Firstly, the audio-tutorial method is detailed in *Teaching Engineering* chapter 8 (Wankat & Oreovicz, 1993) where lectures and accompanying printed materials are provided to the student outside of class; this is colloquially referred to as the flipped classroom (Lindenlaub, 1993). This method is enhanced here in this course by video lecture to include demonstration of moving parts. Additionally, the instructor must prepare a number of different worksheets to guide student's inquiry for the content: rotor hardware, rotor motions, rotor controls, rotor forces and moments in hover, rotor forces and moments in forward flight, experiments with a wind tunnel simulation tool, and a flight test plan. This document does not develop any of these items specifically.

Certain elements in the lesson plan at least need to be located for the students before class. Firstly, the instructor needs to find a wind tunnel or a wind tunnel simulation in order for the students to examine a rotor wake. It might be best if the simulation tool were based upon Computational Fluid Dynamics, as this theoretical model is more likely to capture more physical phenomena than the three models explored in this course. The nature of CFD software is such that one can query macro-level and micro-level elements, such as a summed force on a rotor blade or a certain location around a rotor blade. Secondly, the instructor needs to provide performance charts from existing helicopter flight manuals for the students to read and use for comparisons to their theoretical mathematical models. I am not yet certain about a fast and inexpensive CFD wind tunnel model for helicopter rotors. I am certain that performance charts are readily available in flight manuals that all helicopter pilots must have; the flight manuals also provide descriptions of the rotor, such that key parameters can be extracted and applied to the theoretical mathematical models for calibration.

C. General Synthesis of Overall Alignment of Content, Assessment, and Pedagogy

The content of this course is intended to emphasize a student's ability to think like an aerodynamicist, a design engineer and a helicopter pilot. The assessment strategies of this course are intended to measure the student's ability to think like an aerodynamicist and a design engineer, especially where the answers are not known beforehand and the engineer must show a logical process in finding at least one acceptable solution. The pedagogy is driven by research results and recommendations from several disciplines. Lastly, the day-to-day course activities are developed "downstream" of the content, the assessment strategies, and the pedagogy, instead of simply following the chapter order of a respected textbook.

The content reflects the commonly held understandings that multiple leading universities document in their course descriptions. The assessment strategies reflect the varied results that students may generate with higher level thinking. The pedagogy reflects the established trend of cooperative learning as the "best" form of active, student-centered learning, where the instructor scaffolds the student's learning process and develops the student's ability to pursue self-guided inquiry, which is the highest goal of teaching.

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