EA429 Course Objectives

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August 2, 2007

1 EA429 Course Description

This course applies the fundamentals of fluid mechanics and thermodynamics to the study of air-breathing and rocket propulsion systems. A review of the fundamentals covered in the prerequisite courses (EA305, EA332, and EM319) is essential for success in this course. For understanding the principles of propulsion, the sources of propulsive forces will be considered. Fundamental performance parameters for air breathing propulsion systems and rockets will be explored. The aerodynamics of propellers and their propulsive characteristics are studied early in the course for the groundwork for the Applied Aerodynamics course (EA401) and Special Aircraft Design (EA439) taken simultaneously by the students. A practical propeller laboratory exercise is completed to reinforce these concepts. A review and extension of cycle analysis studied in thermodynamics is completed in order to understand the design point for maximum thrust and thermal efficiency.

As an initiation to the understanding of more complicated propulsive devices, the simplest of all jet engines, the ideal ramjet, will be studied next followed by the performance analyses of actual jet, turbofan, and turboprop engines. On design parametric analyses will be emphasized using hand calculations, Matlab and GasTurb10. These concepts are reinforced using the SR-30 Turbojet in the USNA Propulsion Laboratory (R035). Elements of rocket propulsion will conclude this course; effects of staging also will be considered. Some discussion of turbomachinery (axial compressors and turbines), inlets, gas turbine combustors, and nozzles as well environmental impacts will be presented. Many of these topics will be covered in more detail in a follow-up elective course (EA430, Propulsion II). High temperature effects, materials selection, review of current inventory, and development of new devices will be covered during various segments of the course. See table 1 below for the class syllabus and schedule.

2 EA429 Summary Course Objectives

By the end of this course midshipmen are expected to:

2.1 Understand:

1. how propulsive forces are generated
2. basic characteristics of different propulsive devices
3. range of performance of current devices
4. component types and performance
5. introductory turbomachinery
6. introductory combustion concepts including emissions concerns
7. basic processes for engine selection

2.2 Perform:

1. basic propeller performance calculations
2. parametric jet engine performance analysis
3. basic turbomachinery calculations
4. basic combustion calculations
5. on-design engine selection using parametric analyses
6. basic rocket performance calculations

These objectives should serve the more global objectives of:

- Prepare the student for Aircraft Design by providing a foundation by which to select aircraft propellers and engines for various applications.
- Prepare the junior engineer and Naval Officer by providing a basis for understanding aerospace systems in general based on propulsion classification.
- Prepare the junior engineer for follow-on studies in the field of aerospace propulsion.

3 EA429 Detailed Course Objectives

3.1 Weeks 1-2

3.1.1 Aerospace Engine Overview

- Get exposure to all the major types of flight propulsion, turbojets, turbofans, turboprops/shafts and rockets. Be able to cite examples of all major types and some historically significant engines.

- Present an engine of your choosing describing its operation, application, technology and any technological advances it represents. This presentation should include details about components, weight, key parameters such as thrust, compression ratio, single of split-shaft, liquid of solid propellant etc.

3.1.2 Propulsive Forces

- Derive the net thrust equation from first principles using the Reynolds Transport Theorem.
- Understand the signicance of and be able to calculate additive drag.
- Calculate thrust for the air-breather and the rocket.
- Manipulate thrust equation to obtain effective exhaust velocity, C.
- Understand the meaning of net and gross thrust as well as ram drag.
- Be able to calculate the thrust of a turbofan with separate exhaust streams and mixed exhaust streams.

3.1.3 Efficiencies

- Understand various forms of the Brequet Range Equation in terms of efficiencies and other metrics listed below.
- Be able to write down the meaning of overall, thermal and propulsive efficiencies both in words and equation form(s).
- Explain the meaning of propulsive efficiency using the definition, specific thrust and comparative examples say between the turbojet and turbofan (see figure 1-7 in Hunecke).
- Be able to discuss the effect of a turbofan on propulsive efficiency.

3.1.4 Other Metrics

- Define the fuel-air ratio. Use it's definition to simplify the thrust equation and expressions for thermal and propulsive efficiency.
- Define Thrust Specific Fuel Consumption (TSFC) making sure to understand units in the both the English engineering system and the International System (SI).
- Define Specific Impulse (Isp) and contrast with TSFC in terms of the respective definitions and uses common to industry.
- Understand how effective velocity, Isp and the rocket equation are related.

3.2 Weeks 2-4

3.2.1 Propeller Momentum Theory and Introduction

- Use the momentum theory if propellers as a first approximation to determining required propeller performance and design
- Extend the momentum theory to basic helicopter flight regimes including climb, hover and autorotate.
- Examine basic propeller velocity and force vector diagrams. Use this diagram to understand propeller geometry and propeller design fundamentals. How does this geometry explain blade pitch, β, at the hub and at the tip?

3.2.2 Real Propellers

- Be able to use propeller dimensionless groups to perform basic propeller design/selection using functional relationships, equations and charts. Specifically, be able to use the definitions of J, C_T, C_P, C_S and η combined with propeller charts to complete preliminary propeller design.
- Perform a laboratory examination of no less than three propellers of identical diameter with increasing pitch angle. Map all dimensionless parameters as a function of advance ratio and examine the effect of increasing β and flight velocity.

3.2.3 Blade Element Theory

- Use the blade element theory combined with the items above to establish a propeller design based on given propeller airfoil characteristics and aircraft/flight parameters.
- Specifically, for a given blade section, pitch distribution, $\beta(r)$ and cord, $c(r)$, calculate the differetial thrust and torque coefficients, integrate these quantities to get C_T and C_Q and ultimately determine shaft power required and propeller efficiency.
- Complete a blade element theory propeller design project.

3.3 Weeks 4-6

3.3.1 Thermodynamics Review

- Review the first and second laws of thermodynamics. In particular, understand the first law of thermodynamics for a steady one-dimensional process. Also, review the first law of thermodynamics for a cycle.
- Review the polytropic processes for perfects gases including isobaric, isothermal, isentropic and isometric.

- Review the forms of the first law when assuming the working substance is a perfect gas. Be able to calculate heat and work for constant pressure and isentropic processes respectively. How would you determine the entropy change for the constant pressure process?
- Review the Carnot cycle. Be able to calculate the Carnot cycle efficiency for any cycle.
- Familiarize yourself with the h-s (T-s) and P-v diagrams for the Carnot cycle. What is the area inside these diagrams represent?
- Review the assumptions for "air standard" cycle analysis and "cold air standard" cycle analysis. Please see your thermodynamics text for details.

3.3.2 Ideal Brayton Cycle and Optimum Ideal Brayton Cycle

- What is the history of the Brayton cycle?
- Understand the major components of the Brayton cycle including the isentropic compression work, isobaric heat addition, isentropic expansion work and the constant pressure heat release.
- Be able to draw the T-s and P-v diagram of this cycle and properly identify each process.
- For a set of given cycle parameters be able to calculate the work or heat derived from all processes and the thermal efficiency.
- Understand that for the ideal cycle the thermal efficiency, η_{th}, is only a function of pressure ratio and the ratio of specific heats, γ.
- Be able to plot the dimensionless net work, $\overline{w}$, as a function of T_c or Pr and be able to identify the T_c and/or Pr value at which $\overline{w}$ is a maximum and minumum for a given $\overline{T}$ where $\overline{T} = \frac{T_{max}}{T_{min}} = \frac{Tt3}{Tt1}$.
- Be able to show or explain how one arrives at this maximum value of net work.
- Finally, be able to calculate work, heat and cycle efficiency as well as optimum cycle parameters (e.g. T_c*, $\overline{w}$*, η* etc.)

3.3.3 Practical (Non-Ideal) Brayton Cycle, Optimum Cycle Work and Efficiency

- Be able to list the losses associated with the non-ideal compression and expansion processes.
- Be able to draw the h-s (T-s) diagram for the non-ideal cycle
- Be able to define the isentropic compression and expansion efficiencies.
- Use the definitions of the isentropic efficiencies to estimate non-ideal compression and expansion work.
- Recall the pressure ratio is defined as $Pr = \frac{Pt2}{Pt1}$ and now we write $T_c = \frac{Tt2s}{Tt1}$.
- Also recognize the non-ideal $\eta_t h$ is not strictly a function of pressure ratio and the fundamental definition must be used, that is $\eta_{th} = \frac{w_{net}}{q_{in}}$.

- As above, be able to obtain the minimum and maximum net work and plot the net work as a function of T_c and Pr.
- Be able to calculate the net work and efficiency for maximum work.
- Be able to plot efficiency as a function of T_c and Pr for the practical Brayton cycle.
- Be able to calculate the work and efficiency for maximum efficiency.
- Finally, be able to calculate work, heat and cycle efficiency as well as optimum cycle parameters (e.g. T_c*, T_c**, $\overline{w}$*, η*, $\overline{w}$**, η** etc.).
- Be able to explain the fundamental limitations of the Brayton cycle and why the optimum cycle, whether for optimum efficiency or work, is critical to understanding the turbojet.

3.4 Weeks 6-9

3.4.1 The Turbojet

- Name the major components of a Turbojet and define component parameters and work/heat interactions. These include inlet efficiency and pressure loss (η_d, π_d), compressor work, pressure ratio and efficiency (w_c, π_c, η_c), combustion efficiency and pressure loss as well as fuel heating value (η_b, π_b, LHV), turbine work, pressure ratio and efficiency (w_t, π_t, η_t) and finally nozzle pressure ratio and efficiency (π_n and η_n).
- Understand the combustor heat rate balance, associated assumptions and be able to estimate temperatures and fuel flow rates in a model combustor system. Note this heat rate balance can be used to analyze and afterburner system.
- Understand the turbojet power balance in that the core turbine must drive the compressor and all associated accessory drives. The basic statement of the power balance is $\dot{W}_{acc} + \dot{W}_c \equiv \eta_{mech}\dot{W}_t$. Note the turbine is hampered by less than unity mechanical efficiency, but also non-ideal compressor performance and effects of bleed air used for onboard cooling and offboard aircraft functions.
- Using the parameters and energy relations above estimate the specific thrust, net thrust, TSFC, thermal, propulsive and overall efficiency for the turbojet cycle. It should be possible to examine the cycle as a function of pressure ratio, burner exit temperature, altitude and Mach number using a student derived code for the turbojet or GASTURB10.
- Understand the modifications to the basic turbojet cycle including the afterburning turbojet, the turbofan and turboshaft. In the case of the turbofan, and additional turbine is added to drive the fan in which case the power balance above applies as well as a balance between the fan turbine and fan itself ($\dot{W}_F \equiv \eta_{mech}\dot{W}_{FT}$). For the turboshaft, the power turbine transmits power via shafting, a gear box and other mechanical linkages to a propeller or a generator. The power balance might look like $T_{net}V_{\inf} = \eta_{propeller}\eta_{mech}\eta_{gearbox}\dot{W}_{PT}$ or $P_{elec} = \eta_{elec}\eta_{mech}\eta_{gearbox}\dot{W}_{PT}$

- Be able to analyze actual turbojet data taken from the SR-30 small turbojet. This analysis will involve making estimates of thermodynamic parameters not available in the SR-30 to estimate net thrust and TSFC for comparison with actual outputs from the SR-30, particularly thrust. Further analysis of the SR-30 will be completed using GASTURB10.
- Be able to use GASTURB10 to perform basic turbojet and derivative cycle parametric analysis as detailed in homework and laboratory assignments.
- For all cycles discussed above you must be able to DRAW the T-S diagram including accounting for non-ideal engine components!

3.5 Weeks 10-12

3.5.1 Turbomachinery Introduction

- Understand the different types of turbomachines by purpose and type such as the turbine, pump, compressor, blower and fan. Also be able to differentiate between an axial flow machine and a radial or centrifugal machine.
- Be able to list the important parameters associated with turbomachines and how these parameters are combined to form non-dimensional groups such as the capacity, flow and power coefficients. Recognize that these dimensionless groups are the result of dimensional analyses using the Buckingham-pi theorem.
- Be able to write down the FILL IN equation and label the important parts of this equation. Recognize it as source of the Euler turbine equation and write down the assumptions inherent in the Euler equation and specialize this equation to axial flow machines.

3.5.2 Axial Flow Compressors and Turbines

- Be able to state clearly the assumptions associated with the mean line and repeating stage analyses of axial machines.
- Be able to draw the velocity triangles and use them to determine unknown velocities and absolute and relative flow angles.
- Define the turbine or compressor stage work equations in terms of those angles for both axial flow compressors and turbines.
- Define the stage work in terms of enthalpy and with the perfect gas assumption in terms of temperature.
- Define the thermodynamic process across the stator (where total enthalpy is constant) and rotor (where relative energy is constant).
- Be able to define the stage reaction in terms of enthalpy and velocity and calculate the reaction in terms of blade angles.

- Be able to define and apply the polytropic efficiency and the isentropic efficiency to compressor turbomachinery design.
- Understand the difference between total-to-total and total-to-static turbine efficiency.
- Given some turbomachine design parameters such as wheel speed and diameter, be able to determine the blade angles from the work rate and visa versa.

3.6 Weeks 13-15

3.6.1 Introduction to Rockets

- Be able to describe the basic thermodynamic processes occurring in a typical chemical rocket including constant pressure heat addition and expansion (isentropic or otherwise) in the nozzle.
- Be able to determine the exit velocity, mass flow and thrust of a rocket given the chamber pressure,P_c and temperature, T_c and nozzle exit conditions (either area ratio, $\frac{A_e}{A*}$ exit to chamber pressure ratio, $\frac{P_e}{P_c}$ and atmospheric pressure, P_{atm}).
- Be able to define specific impulse in terms total impulse. Use I_{sp} to compare rocket performance and to determine the effective exhaust velocity.
- Noting that I_{sp} and $Vexit$ and thus C are closely related, be sure to understand what factors contribute to high V_{exit}
- The characteristic velocity is a rocket parameter used to evaluate the relative quality of the chamber combustion process. Define the characteristic velocity, C* in terms of P_c, A* and $\dot{m}$ as well as gas constant, chamber temperature, T_c and the expression for $\Gamma(\gamma)$.
- Be able to show how c* relates to V_{max}.
- The thrust coefficient, C_T, is a rocket parameter used to evaluate the quality of nozzle expansion process. Define C_T in terms of thrust, P_c and A*. Be able to calculate C_T in terms of $\frac{P_e}{P_c}$ and γ.
- The concepts of C* and C_T are unified by the fact that the product of C* and C_T is the effective exhaust velocity.

3.6.2 Introduction to Solid Rockets

- Be able to sketch and explain the mass balance inside a solid rocket. In the steady state the mass added to the system is from the burning of solid rocket fuel and the mass leaving the system is described by the chamber conditions T_c and P_c as well as A*.
- The rate of burning for many propellants can be described by St. Robert's Law which states the burn rate is $r_b = a{P_c}^n$ where a is the burn rate coefficient and n is the burn rate exponent. The mass flow from the surface of the propellant grain can be determined from the propellant density, ρ_b, and burn area, A_b as follows: $\dot{m} = \rho_b r_b A_b$.

- Based on the above, the pressure history and thus thrust history of a solid rocket will depend on the burn rate exponent, n and the burn area, A_b.
- Rocket thrust history can be regressive, neutral or progressive depending on how A_b is configured. Some common types are end-burning (neutral), cylindrical (progessive) and star pattern (neutral).