Brief Tutorial on Aircraft Propulsion

GMU SYST 460/560
Fall semester, Nov. 5, 2012
Prof. George Donohue
Overview

• One of the most sophisticated of modern engineering designs

• Requires an understanding of Thermodynamics, Heat Transfer, Fluid Mechanics, Mechanics of Materials

• Designs have evolved from Prop to Jet, to Turbojet, Turboprop, High Bypass Ratio Fan Jet engines
Archimedes of Syracuse  
(c.287-212 BCE)

• Sum of the Forces $F = 0$
• Sum of the Moments $(F \times L) = 0$
• Buoyancy force = weight of displaced fluid
• First Description of the Screw Propeller
• Foundation for Lighter than Air Flight in 18th cent.
• Pi: “The ratio of the circumference of any circle to its diameter is less than 3 1/7 but greater than 3 10/71.” – calculus like derivation
• Great Mathematician and Military Engineer killed in 2nd Punic War
Leonardo da Vinci
(c. 1452-1519 CE)

- Self Educated
- Continuity Equation
  \[- A_1v_1 = A_2v_2.\]
- Precursor to “Conservation of Mass” and Bernoulli Equation in the 18\textsuperscript{th} century
- Artist and Military Engineer
- Designs poorly documented
- Art works better known
- Conceptual Designs of Winged Gliders
Robert Boyle (1627-1691 CE)

- $pV = \text{constant}$
- addition of temperature ($T$) in Charles's law
  - $pV/T = \text{constant}$ (Gas Law)
- Thermodynamic Equation of State
  - Used in Mechanical, Aerospace and Chemical Engineering
- Fundamental to understanding Brayton Cycle
- Foundation for Lighter than Air flight in 18th century
Isaac Newton (1642-1727 CE)

- Great Mathematician, Physicist
  - Vector Calculus
- Law of Gravity
- Vector Relationships
- Conservation of Momentum
- $m\vec{v} =$ constant
- $\sum \vec{F} = ma = d(m\vec{v})/dt$
- Sigma $\vec{F} = 0$
- “If I have seen further, it is by standing on the shoulders of Giants”
Gottfried Wilhelm Leibniz
(1646-1716 CE)

- Great Statesman, Mathematician, Physicist
  - Calculus
- Altitude + Vis Viva \((mv^2)\) = Constant
- Today, we state this as the:
  - “Law of Conservation of Energy” for solid bodies:
    - Potential Energy + Kinetic Energy = Constant
Daniel Bernoulli (1700-1782 CE)

• Recognized Leibniz *vis vita* applied to fluid motion as well
• Medical experimentalist and Mathematician

**Pressure** + \(\rho \cdot \nu^2\) = Constant

– Where \(\rho\) is the fluid density and \(\nu\) is the fluid velocity magnitude (along a streamline).

• Simple Equation to calculate both Airfoil Lift and Propeller/Fan Thrust
Rudolf Julius Emanuel Clausius (1822-1888)

- The net change in the total energy of the universe is zero – 1st Law of Thermodynamics
- For a thermodynamic cycle, the net heat supplied to the system equals the net work done by the system.
- Carnot efficiency = 1 – Low Absolute Temperature/High Absolute Temperature <100%
- The net change in the total entropy of the universe is always greater than zero – 2nd Law of Thermodynamics
  - Temperature is a Measure of Entropy in a Heat Engine
  - \( d(Q) = T \, d(S) \)
- Perpetual Motion Machine is impossible and the Universe is running down, Information order decays
John Barber (1734-1801)
George Brayton (1830-1892)
Frank Whittle (1907-1996)

• John Barber - UK pat. No. 1833 gas turbine engine
  – Materials inadequate to construction & operation

• George Brayton – US pat. (1872) constant pressure combustion thermodynamic cycle
  – Lost ground trans. Competition to Otto Cycle

• Air Commodore Sir Frank Whittle (RAF)
  – pat. (1930) Turbojet engine
  – Ranked by BBC poll #42 of 100 Greatest Britons
Fundamental Attributes of All Aircraft Designs

• Aero 101:
  – If it Fly’s, It weights TOO MUCH!

• Wright Bros Major Accomplishment:
  – Designed a System with Adequate Thrust to Drag ratio, Low weight with Adequate Structural Strength, Wings with Adequate Lift to Weight ratio and a Stable Flight Control system
## Some Energy Density Comps

<table>
<thead>
<tr>
<th>Energy Storage Medium</th>
<th>Energy Density (KW-Hr/Lb)</th>
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<tbody>
<tr>
<td>Lead-acid Auto Battery</td>
<td>0.016</td>
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<tr>
<td>CNG (CH4)</td>
<td>1.3</td>
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<tr>
<td>Gasoline (C8H18)</td>
<td>5.3</td>
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<tr>
<td>Diesel (Kerosene or JetA) (C12H26)</td>
<td>5.8</td>
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\[
\text{TNT} = 0.34 \\
\text{Natural Gas} = \text{CH4} \quad \text{can be chained as} \quad (\text{CnH2n+2}) \\
2 \text{C8H18} + 25 \text{O2} = 18 \text{H2O} + 16 \text{CO2} + \text{ENERGY}
\]
Prediction: Renewables grow rapidly, but under current policies fossil fuels still provide 78% of U.S. energy use in 2035.
Shale gas offsets declines in other U.S. supply to meet consumption growth and lower import needs

U.S. dry gas trillion cubic feet per year

History | 2009 | Projections

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Source: EIA, Annual Energy Outlook 2011
Oil prices in the *AEO2011* Report Reference Case rise steadily

annual average price of low sulfur crude oil
real 2009 dollars per barrel

Source: EIA, *Annual Energy Outlook 2011*
Turbo Jet Fundamental Operating Principles

• **Suck** - Air Intake
• **Squeeze** - Cool Axial Compression (Work In)
• **Bang** - Fuel + Combustion (Heat In)
• **Blow** - Hot Turbine to Extract (work Out)

• Thrust = \( \frac{d(my)}{dt} \)
Basic Axial Flow Turbo Jet Engine

- Low Mass Flow, High Exit velocity (~3:1)
- Low Efficiency
Brayton Cycle Thermodynamics

Actual Brayton cycle:
- adiabatic process - compression.
- isobaric process - heat addition.
- adiabatic process - expansion.
- isobaric process - heat rejection.

Idealized Brayton cycle
Carnot Eff. = $1 - \frac{T_{\text{low}}}{T_{\text{high}}}$
Fan/Prop. Thrust & Power

- Conservation of Energy – Bernoulli Equ. To find Pressure and Velocity Before & After Prop or Fan
- Thrust Force = $\frac{d(m\vec{v})}{dt}$
- Useful Power = $F_{\text{Thrust}} \times \text{Velocity} = \frac{d(m\vec{v})}{dt} \times \vec{v}$
- Power Input = $\frac{dm}{dt} \times \vec{v} \times d\vec{v} \left[ 1 - \frac{d\vec{v}}{2\vec{v}} \right]$

Pressure

Fuel + Heat = Work + Waste Heat
Est. of Max efficiency

- Brayton Cycle Thermal (Carnot) Efficiency
  \[ 1 - \frac{T_{\text{low}}}{T_{\text{high}}} = 1 - \frac{300K(80F)}{1500K(2240F)} \approx 80\% \text{ max} \]
  - Increase Turbine Inlet Temp to Increase efficiency
  - Material Properties Limitation

- Fan (Prop) Propulsive Efficiency = Power Out/Power In
  \[ = 1 - \frac{dv}{2\nu} \approx 80\% \text{ max} \]
  - Where Advance ratio (J) = \( \frac{\nu}{nD} \) \approx 0.9
  - D = Prop Disc Diameter
  - Bernoulli Equation (const. energy analysis along an accel. streamline)

  - Max Thrust at High \( dv \)
  - Max Efficiency at LOW \( dv \)

- Increase Mass Flow at Minimum \( dv \) to Increase Thrust @ min.

- Wake Loss

  \[ \approx 0.8 \times 0.8 \approx 0.64 \text{ MAX} \]
Constraints

• Prop/Fan Diameter
  – Tip Speed less than M1.0 (Noise/Drag)

• Advance Ratio (J)
  – Too High leads to Compressor Blade Stall

• Turbine Inlet Temperature
  – Too high leads to loss of Blade material strength
    • Active Cooling, Titanium, Ceramics
Specific fuel Consumption
Lb Fuel/Hr/ Lb. Thrust

• Turboprop = SFC ~ 0.5 * \( \sqrt[2]{V/550} \) * prop. Eff (per shp)
  – Prop. Eff. ~ 0.8
  – \( V \) (ft/sec)
  – \( d\sqrt{V} \sim 1.5:1 \)
  – SFC @ 550 ft/sec ~ 0.40 / Hr. @~M0.7

• Jets @ cruise = SFC ~ 0.9e^{(-0.05BPR)} : 0 <BPR<6.0
  – Turbojet (d\sqrt{V}~3:1) ~ 0.9 lb fuel/hr / lb Thrust
  – LBPR Turbofan (BPR ~6)~ 0.67 lb fuel/hr / lb Thrust
  – HBPR Turbofan (~BPR 9:1) ~ 0.57 lb fuel/hr/ lb Thrust

• Max Combustion Efficiency @ “stoichiometric”
  – Air/fuel 15:1 Turbine Inlet Temp TOO HIGH for Material strength
  – Air/fuel @ 60:1 Turbine Inlet temps (2,000 to 2,500 deg. F)
Turbo Prop Vel <M0.75 with Controllable Pitch Propellers
## Some Typ. Turboprops

<table>
<thead>
<tr>
<th>A/C</th>
<th>Engine</th>
<th>TO rating (KW)</th>
<th>Weight (Kg)</th>
<th>Power/Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATR-72-200</td>
<td>PW 127</td>
<td>2,051</td>
<td>481</td>
<td>4.3</td>
</tr>
<tr>
<td>C-130J</td>
<td>RR AE 2100</td>
<td>3,424</td>
<td>702</td>
<td>4.9</td>
</tr>
<tr>
<td>Dash 8 (Q400)</td>
<td>PW 150A</td>
<td>3,781</td>
<td>690</td>
<td>5.5</td>
</tr>
<tr>
<td>Airbus A400M</td>
<td>EU TP-400-D6</td>
<td>8,203</td>
<td>1,900</td>
<td>4.4</td>
</tr>
<tr>
<td>TU-95 Bear</td>
<td>NK-12MV</td>
<td>11,033</td>
<td>1,900</td>
<td>5.8</td>
</tr>
</tbody>
</table>

- First applications in 1948
Tu-95 w/ NK-12MV & (2) AV-6H CR
Controllable Pitch Props
TU-95 Bear Bomber (1952-present)

• Max Speed = 470 Kn
• Cruise Speed = 415 Kn
• Range = 3,300 nm
• Cruise Altitude = 26,000 ft.
• Service Ceiling = 39,000 ft.
• High Reliability
• 224 PAX
• Pwr/Wt = 5.8 Kw/Kg
• Contra-Rotation Prop ~ 10% increased Efficiency
• 4 X 4 Props Noisy (5X3 Scimitar would be a better combination)
Dash 8 (Q400)

- Bombardier Aerospace
- Production (1983-pres)
- 1,054 (Oct. 2011)
- $27M price
- PW 150A engines
- Pwr/Wt = 5.5 Kw/Kg
- 78 PAX
- 360 Knot Cruise
- 27,000 Max Alt.
- 1,500 nmi. Range
- Active Noise& Vibration Reduction (ANVS)
GE-Dowty R391, Prop (Q400)

- P&W150A
- 3,781 KW Take Off Pwr
- Carbon Fiber
- 6 Blade
- Controllable pitch
- Scimitar Propellers
Antonov An-70
Progress D-27 Propfan w/ SV27 Contra-Rotation Scimitar Propellers

- Dev. ~ 1992 - 1994
- 14,000 shp
- Prop. Dia. 4.2m (165 in.)
- Wt. 1,650 Kg (3,600 lb.)
- Pwr/Wt = 6.3 Kw/Kg
- Never entered production
- Competitor to A400M
- High efficiency
- Noise Concerns
A400M

- IOC ~ 2012?
- TP400-D6
- CR 8 Bld composite props
- Composite Wings & Emp
- Cruise M0.72 (300Kt)
- Ceiling > 37,000 ft.
- Range ~ 3000 nmi.
TP-400-D6

- 11,000 shp (8,200 Kw)
- 1,900 Kg
- $TIT = 1500K$
- 8 Bld CP composite prop
- Scimitar Propellers
- $SFC = 0.4 \text{ lb/shp-hr}$
- $Pwr/Wt = 4.4 \text{ Kw/Kg}$
- FADEC to Civil specs
- FOC 2009

FADEC= Full Authority Digital Engine (or Electronic) Control
Basic Turbofan Engine
High BPR increases Thrust Efficiency
Large Air flow Mass at Low $dv$

Modern, fuel-efficient engines called turbofans blow air around the main part of the engine as well as through it. This decreases noise and increases the amount of airflow, which in turn increases power.
High-bypass Turbofan
GE CF6-6
### Some Typ. Long Range Turbo Fan Jets

<table>
<thead>
<tr>
<th>A/C</th>
<th>Engine</th>
<th>Thrust (KN)</th>
<th>Weight (Kg)</th>
<th>BPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 737-500/A320,A340</td>
<td>CFM 56</td>
<td>100</td>
<td>1,950</td>
<td>6:1</td>
</tr>
<tr>
<td>B 777-200LR</td>
<td>GE 90</td>
<td>417</td>
<td>7,550</td>
<td>9:1</td>
</tr>
<tr>
<td>B 787,B747-8</td>
<td>GEnx</td>
<td>300</td>
<td>5,816</td>
<td>9.5:1</td>
</tr>
<tr>
<td>B787</td>
<td>RR Trent 1000</td>
<td>330</td>
<td>5,765</td>
<td>11:1</td>
</tr>
<tr>
<td>B747-400,767,A300,A310</td>
<td>CF6-80C2</td>
<td>280</td>
<td>4,100</td>
<td>5.2</td>
</tr>
</tbody>
</table>

- GE90 has a 128 inch fan diameter
# Fanjet Commuter Aircraft

<table>
<thead>
<tr>
<th>A/C</th>
<th>Engine</th>
<th>Thrust (KN)</th>
<th>Weight (Kg)</th>
<th>BPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A318</td>
<td>PW6000</td>
<td>100</td>
<td>2,289</td>
<td>5:1</td>
</tr>
<tr>
<td>CRJ100/440</td>
<td>GE CF 34-3</td>
<td>41</td>
<td>760</td>
<td>6.2:1</td>
</tr>
<tr>
<td>E190/195,ARJ21</td>
<td>GE CF34-10</td>
<td>89</td>
<td>1,700</td>
<td>5.1:1</td>
</tr>
<tr>
<td>B717-200</td>
<td>BR 715</td>
<td>83-95</td>
<td>2,800</td>
<td>4:1?</td>
</tr>
<tr>
<td>G V</td>
<td>BR 710</td>
<td>66</td>
<td>2,100</td>
<td>?</td>
</tr>
</tbody>
</table>

- BR 715 has a 58 inch fan diameter
- GE CF34-10 has a 57 inch total diameter
Some Final Thoughts

- BPR on Commuter Jets have been ~ 4 to 6:1
- Long Range, high efficiency engines have moved BPR ~ 9 to 11:1
- Q400 may be the future of Hub feeder routes
- Jet A fuel can be replaced by Synfuel at a cost of over ~$60/bl
- Electric Propulsion is not in the future due to low energy density of source and high weight of engines