Propulsion System Models for Rotorcraft Conceptual Design

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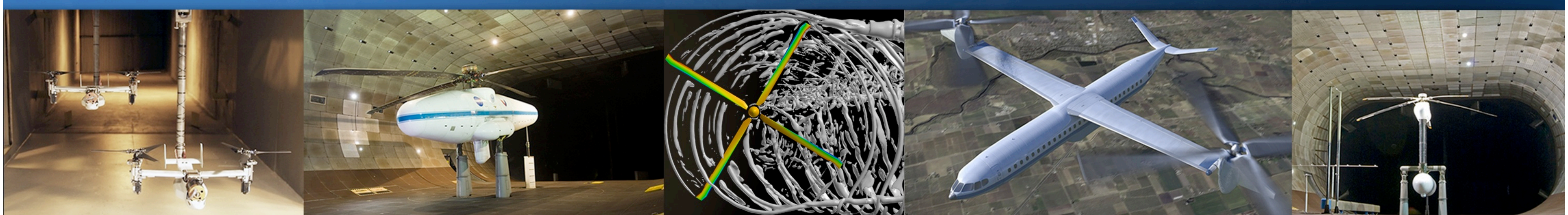


Aeromechanics Branch - NASA Ames Research Center

Outline

- Background
  - Rotorcraft design
  - NASA Design and Analysis of Rotorcraft (NDARC)
- Objectives
- Original NDARC Propulsion Representation
- Extended NDARC Propulsion Representation
  - Organization of components
  - Component models
- Examples of NDARC propulsion configurations
- Conclusions
- Future work

Rotorcraft Design

- **Design capability is required to support research in a government laboratory**
  - **Technology impact assessments**
    - **Show how technology will affect future systems**
  - **System level context for research**
    - **Support level of investment for technology maturation**
  - **Concept exploration, decision, and refinement**

- **Quantitative evaluation and independent synthesis of wide array of aircraft configurations and concepts**

NDARC
NASA Design and Analysis of Rotorcraft

- **Conceptual/preliminary design and analysis computer program for rotorcraft**
  - **Design task sizes rotorcraft for set of design conditions and missions**
  - **Analysis task for off-design missions and point operating conditions**

- **Initially implemented to model conventional rotorcraft propulsion systems**
  - **Turboshaft engines burning jet fuel**
  - **Connected to one or more rotors**
  - **Through mechanical transmission**

Objectives

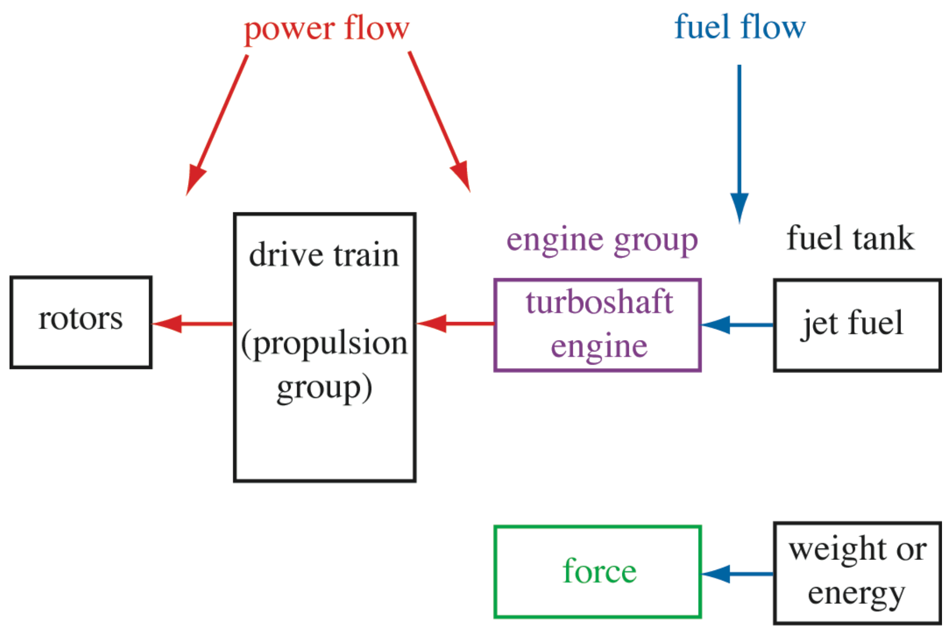
- Support development and assessment of environmentally-friendly rotorcraft designs
  - For example, aircraft utilizing electric motors, or electrical energy storage, or hydrogen-burning engines

- Extend NDARC propulsion system representation to cover additional propulsion concepts
  - Develop framework for theory and code
  - Implement models for new propulsion components

- Identify requirements for improved performance and weight models of new propulsion system components

Original NDARC Propulsion Representation

- Mechanical drive train, connecting engine groups and rotors
- Engine group, consisting of one or more turboshaft engines
  - Referred Parameter Turboshaft Engine Model
- Fuel tank system (main and aux tanks)
  - Weight changes as fuel used, fuel is measured in weight
- Force generation by simple model
  - Fuel used is measured as weight or energy



Extended NDARC Propulsion Representation

- Turboshaft engine

- Motor
- Generator
- Generator-Motor
- Fuel cell
- Solar cell
- Battery
- Flywheel
- Capacitor

Components needed to support development and assessment of environmentally-friendly rotorcraft designs

Extended NDARC Propulsion Representation

- Turboshaft engine

- Motor
- Generator
- Generator-Motor
- Fuel cell
- Solar cell
- Battery
- Flywheel
- Capacitor

Components needed to support development and assessment of environmentally-friendly rotorcraft designs

- Reciprocating engine
- Turbojet / turbofan
- Compressor
- Reaction drive

Additional air-breathing components

Extended NDARC Propulsion Representation

Engine Group
Turboshaft engine
Reciprocating engine
Compressor
Motor
Generator
Generator-Motor

Jet Group
Turbojet / turbofan
Reaction drive
Simple force

Charge Group
Fuel cell
Solar cell

Fuel Tank
Weight
- jet fuel
- gasoline
- diesel
- hydrogen

Energy
- battery
- flywheel
- capacitor

Engine Group:

Transfers power by shaft torque

Connected to drive train

Propulsion group includes rotors

Jet Group:

Produces force on aircraft

Charge Group:

Generates energy for aircraft

Fuel Tank:

Associated with components that use fuel

Extended NDARC Propulsion Representation

Engine Group

Turboshaft engine
- convertible — jet
- convertible — reaction

Reciprocating engine
Compressor
Compressor-reaction
Motor
Motor + fuel cell
Generator
Generator-Motor

Transfers power by shaft torque

Connected to drive train

Propulsion group includes rotors

Jet Group

Turbojet / turbofan
- convertible — reaction

Reaction drive
Simple force

Produces force on aircraft

Charge Group

Fuel cell
Solar cell

Generates energy for aircraft

Fuel Tank

Weight
- jet fuel
- gasoline
- diesel
- hydrogen

Energy
- battery
- flywheel
- capacitor

Associated with components that use fuel

Propulsion Configurations in NDARC

Original Propulsion Models

New Configurations with New Models

Features of Engine, Jet, Charge Groups

- Size can be adjusted
  - Engine power, jet thrust, charger power

- Geometry
  - Location on aircraft
  - Direction of force, orientation of shape

- Control
  - Amplitude (engine power, jet thrust, charger power)
  - Mode (convertible engines, generator-motor)

- Aerodynamic drag

Fuel Tank Systems

- Each system consists of main tank(s) and auxiliary tank(s)
  - Engines, jets, chargers associated with a fuel tank system
  - Fuel container has weight
  - Fuel quantity stored and burned is measured in weight or energy

- Weight changes as fuel used
  - Jet fuel, gasoline, diesel, hydrogen
  - Characteristics: density (lb/gal or kg/liter), specific energy (MJ/kg), tank weight

- Energy changes as fuel used, weight does not change
  - Battery, flywheel, capacitor
  - Characteristics: tank density (MJ/liter), tank specific energy (MJ/kg)

- Battery model
  - Characteristics: efficiency (varies with power, state-of-charge), power density (kW/kg)

Engine Group and Drive Train

- **Power balance of propulsion group:**

$$P_{avail} = P_{req} = P_{\mathrm{comp}} + P_{\mathrm{xmsn}} + P_{\mathrm{acc}}$$

Turboshaft engine

Rotors (shaft torque)

Engine Group and Drive Train

- **Power balance of propulsion group:**

$$P_{avail} = P_{req} = P_{comp} + P_{xmsn} + P_{acc}$$

Turboshaft engine
Reciprocating engine
Motor
Motor + fuel cell
Generator-Motor

Rotors (shaft torque)
Compressor
Compressor-reaction
Generator
Generator-Motor

Component Models

- Engine group, jet group, and charge group provide general framework for theory and code

- Performance and weight evaluated using engine, jet, or charger model
  - Typically need power or thrust available, mass flow, fuel flow, jet force
  - Functions of independent parameters (power or thrust, atmosphere, speed, etc.)

- Need parameterized, surrogate representation of component performance and weight
  - Applicable to wide range of operating conditions and component size

Component Models Implemented for NDARC

- Engine group models
  - Referred Parameter Turboshaft Engine Model (RPTEM)
  - compressor
  - motor/generator

- Jet group models
  - Referred Parameter Jet Engine Model (RPJEM)
  - simple force

- Charge group models
  - fuel cell
  - solar cell

- Battery model for fuel tanks

Referred Parameter Turboshaft Engine Model

- **Power available**

power $\quad \dfrac{P_a}{\delta\sqrt{\theta}} = P_0\, g_p(\theta, M, n)$

- **Performance at power required**

mass flow $\quad \dfrac{\dot{m}_{req}}{\delta/\sqrt{\theta}} = \dot{m}_{0C}\, g_m(q, \theta, M, n)$

fuel flow $\quad \dfrac{\dot{w}_{req}}{\delta\sqrt{\theta}} = \dot{w}_{0C}\, g_w(q, \theta, M, n)$

gross thrust $\quad \dfrac{F_g}{\delta} = F_{g0C}\, g_f(q, \theta, M, n)$

- **Scale with pressure ($\delta = p/p_0$) and temperature ($\theta = T/T_0$)**
- **Functions of power required ($q = P_q/(P_{0C}\delta\sqrt{\theta})$), temperature ratio, Mach number, turbine speed ($n = N/\sqrt{\theta}$)**

Referred Parameter Turboshaft Engine Model

- **Power available**

$$\text{power} \quad \frac{P_a}{\delta\sqrt{\theta}} = P_0\, g_p(\theta, M, n)$$

g_p from constants that are piecewise linear functions of θ

- **Performance at power required**

$$\text{mass flow} \quad \frac{\dot{m}_{req}}{\delta/\sqrt{\theta}} = \dot{m}_{0C}\, g_m(q, \theta, M, n)$$

$$\text{fuel flow} \quad \frac{\dot{w}_{req}}{\delta\sqrt{\theta}} = \dot{w}_{0C}\, g_w(q, \theta, M, n)$$

$$\text{gross thrust} \quad \frac{F_g}{\delta} = F_{g0C}\, g_f(q, \theta, M, n)$$

g_m, g_w, g_f proportional to cubic polynomials in q

Good representation for design code NDARC

- **Scale with pressure ($\delta = p/p_0$) and temperature ($\theta = T/T_0$)**
- **Functions of power required ($q = P_q/(P_{0C}\delta\sqrt{\theta})$), temperature ratio, Mach number, turbine speed ($n = N/\sqrt{\theta}$)**

New Models for Propulsion Components

- Air-breathing propulsion components
  - Reciprocating engine, compressor, turbojet / turbofan
    - Following turboshaft model, implemented simple dependence on atmospheric conditions and flight speed
  - Reaction drive, convertible engines

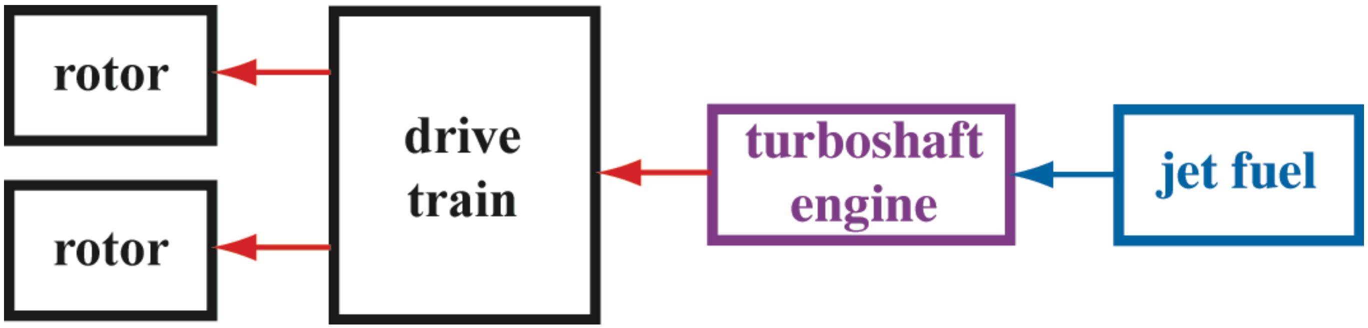
- Electrical propulsion components
  - Motor, generator, fuel cell, solar cell
    - Implemented models for losses and efficiencies

Examples of NDARC Propulsion Configurations

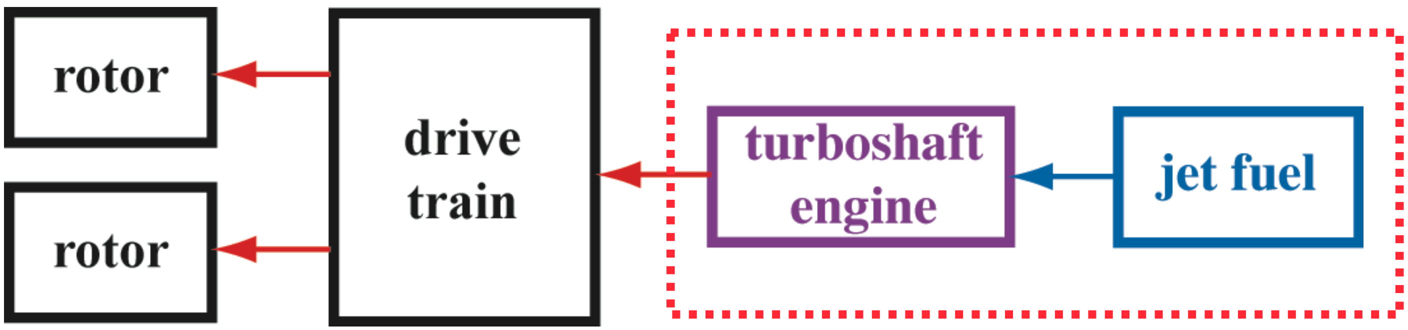
Original Propulsion Models

New Configurations with New Models

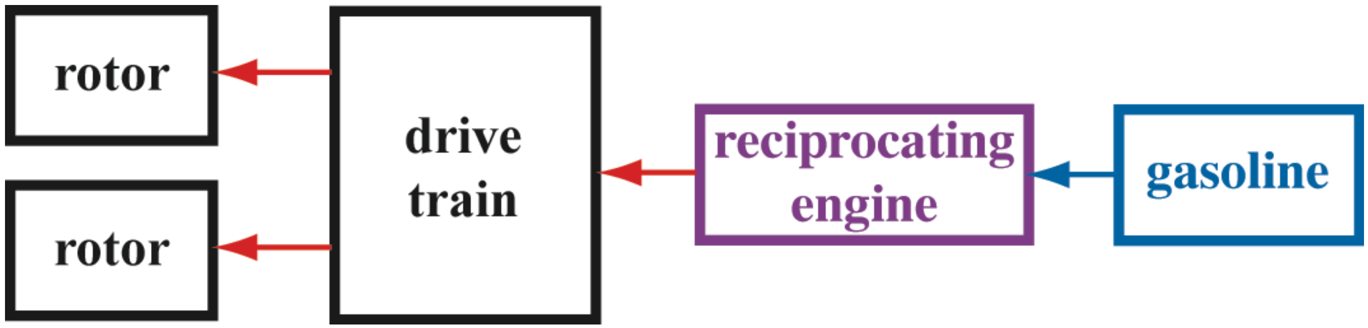
Turboshaft Helicopters



Examples of NDARC Propulsion Configurations
Turboshaft Helicopters

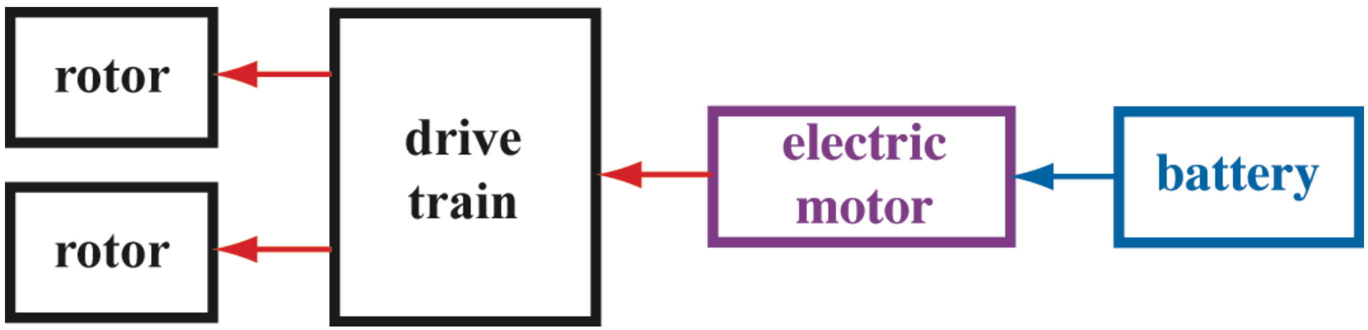


Helicopter — Reciprocating Engine



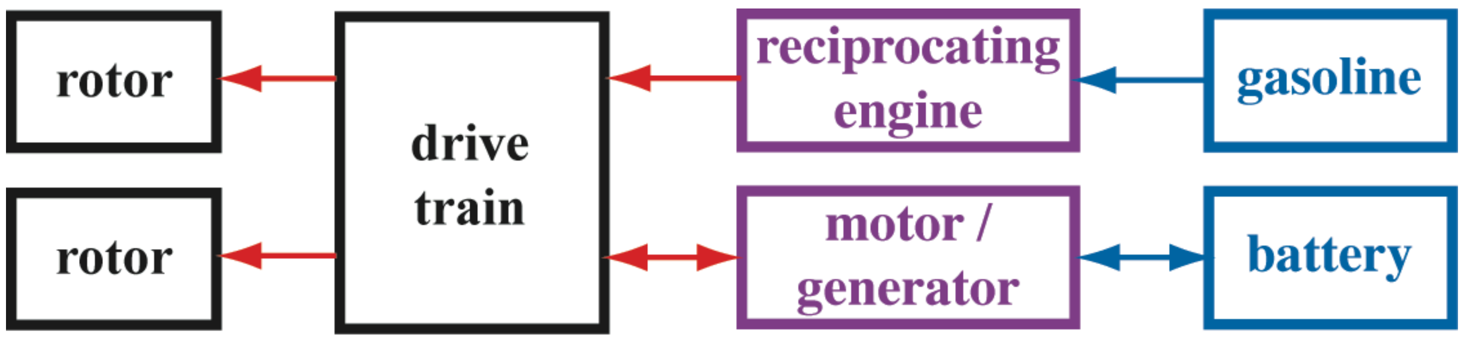
Hughes 300C

Helicopter — Electric Motor

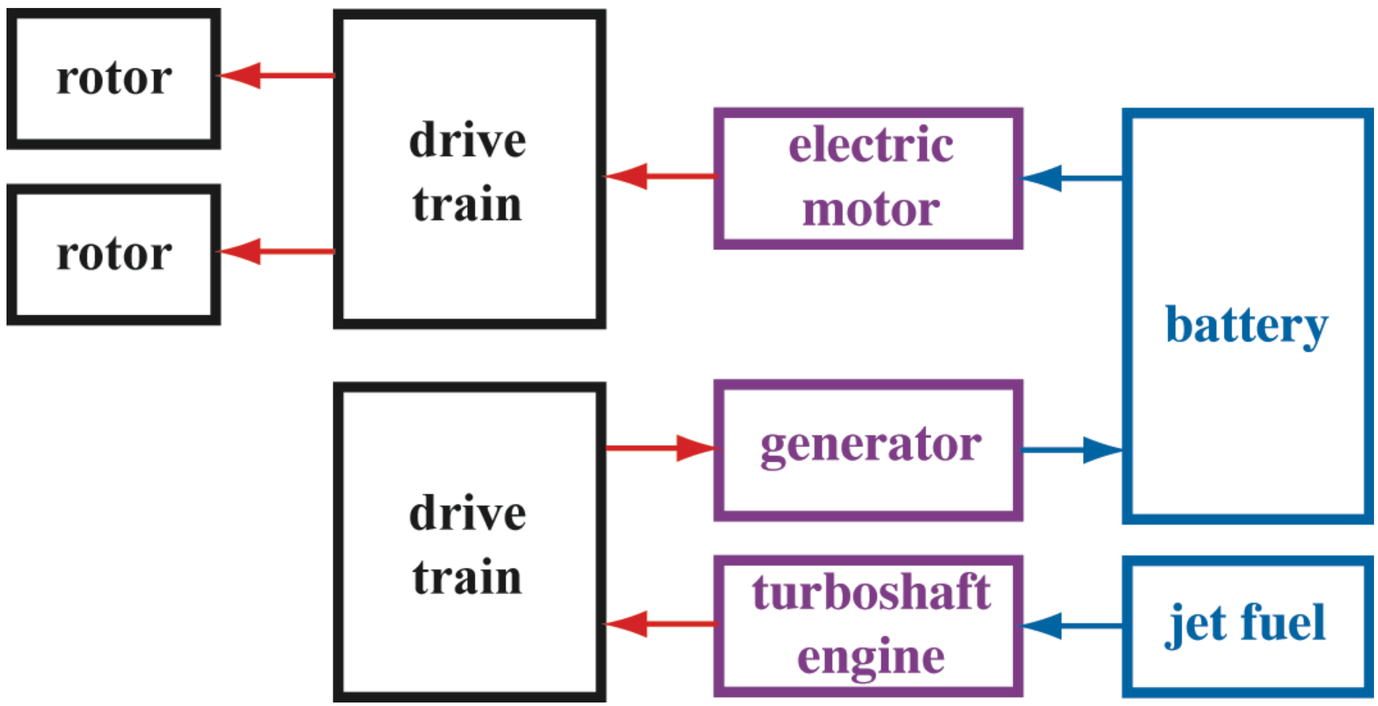


Sikorsky FireFly

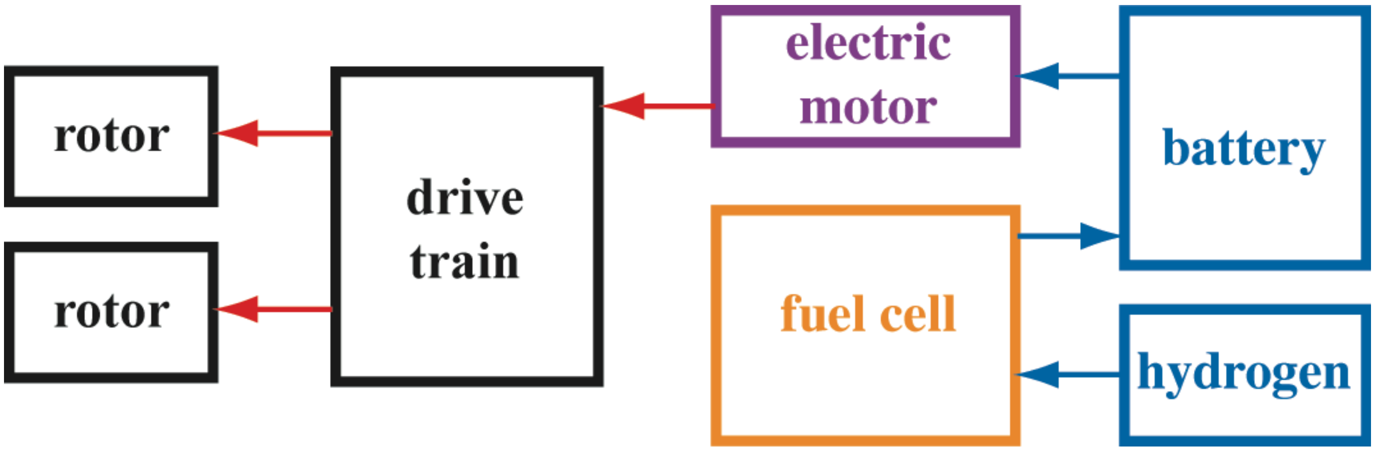
Helicopter — Hybrid



Helicopter — Turbo-Electric



Helicopter — Fuel Cell

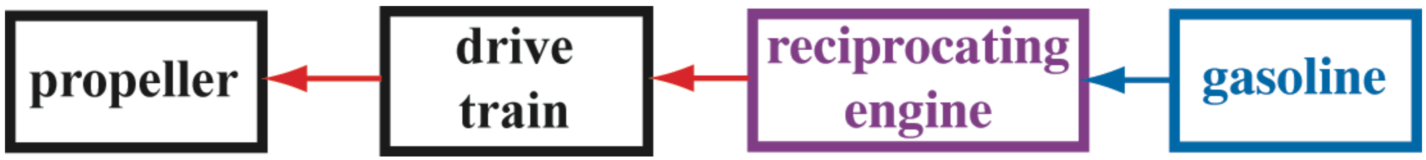


Airplane — Jet

turbofan engine ← jet fuel

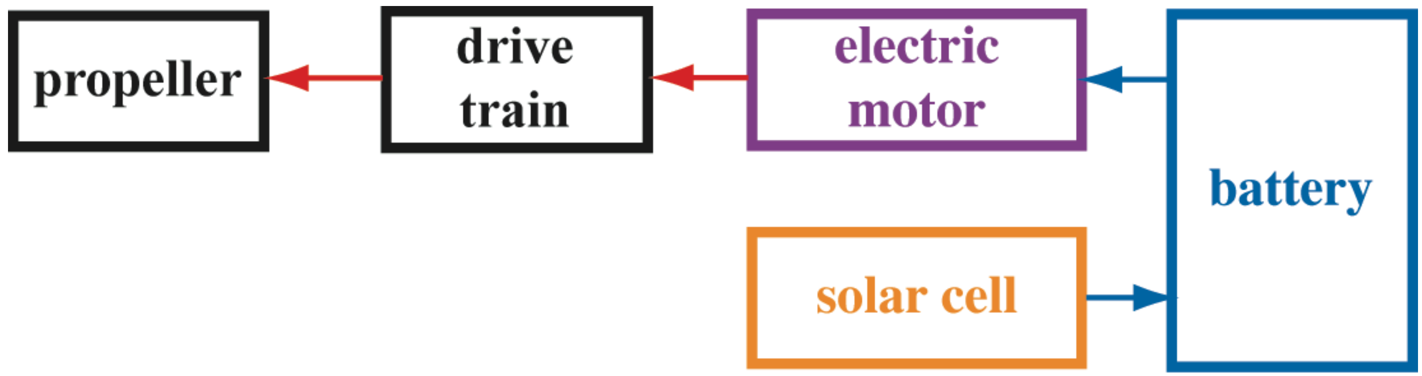
Cessna Citation

Airplane — Reciprocating Engine



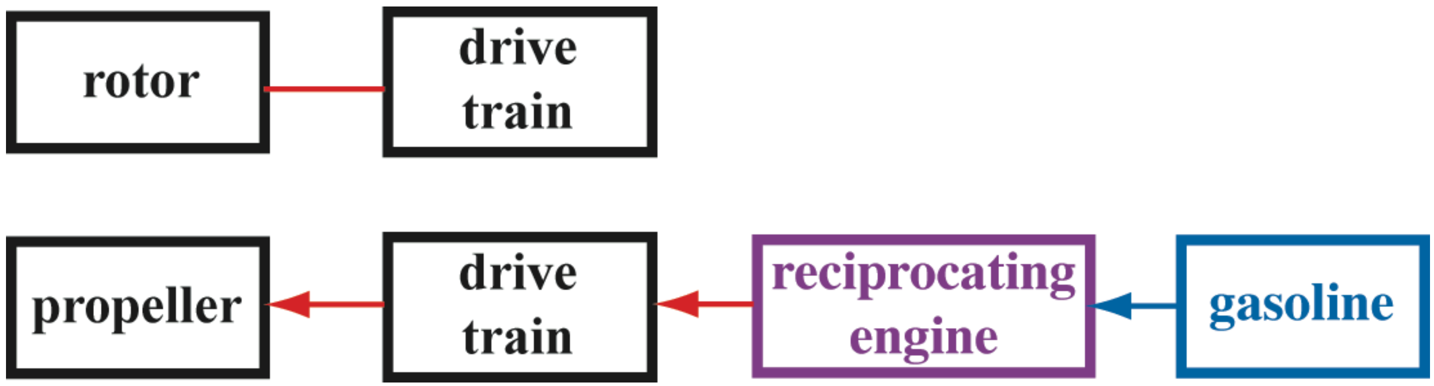
Beechcraft Bonanza

Airplane — Solar Cell



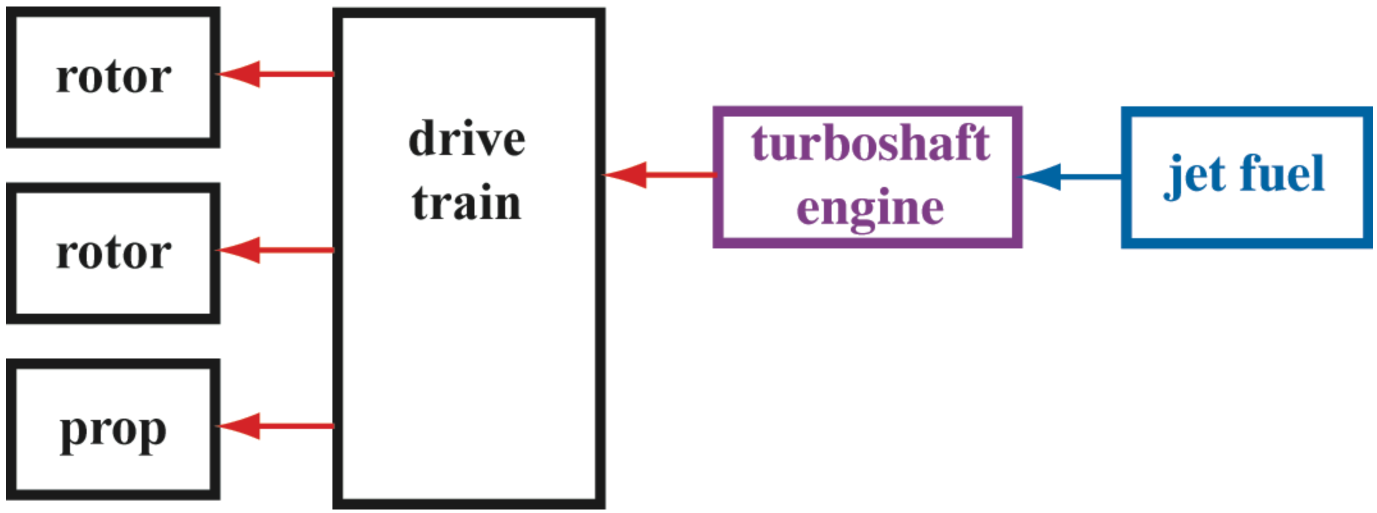
Solar Impulse

Autogyro



Pitcairn PCA2

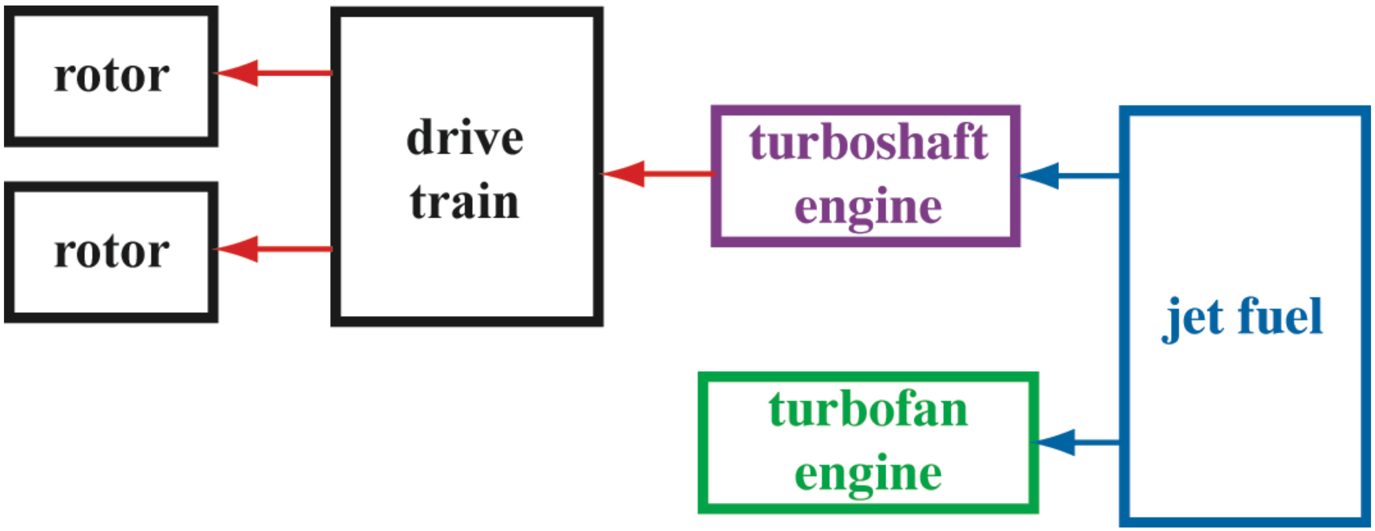
Compound Helicopter



Lockheed Cheyenne

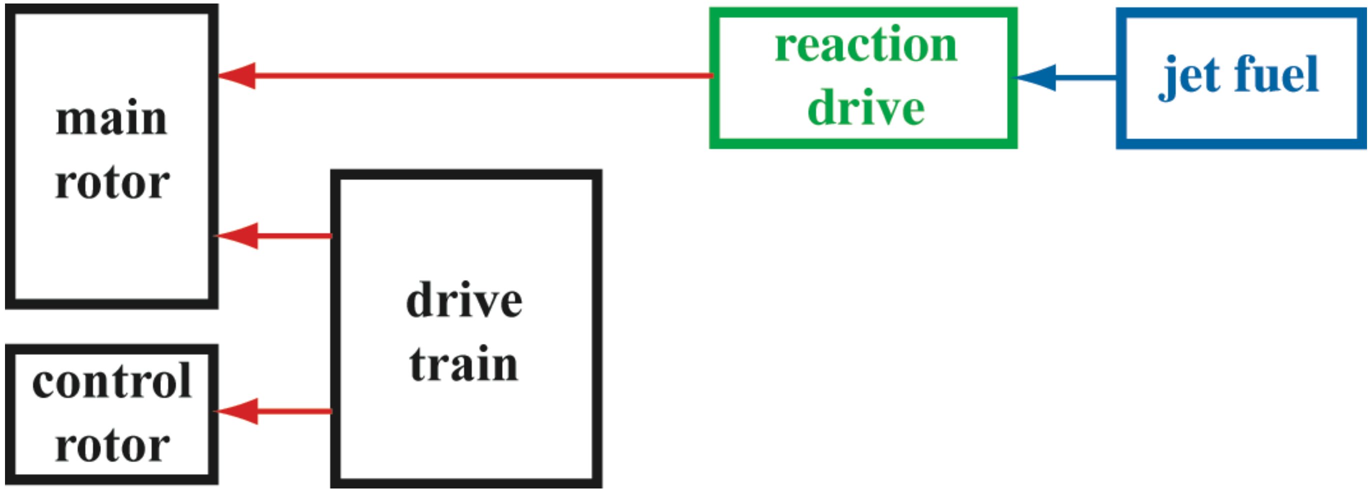
Eurocopter X^3

Compound — Jet



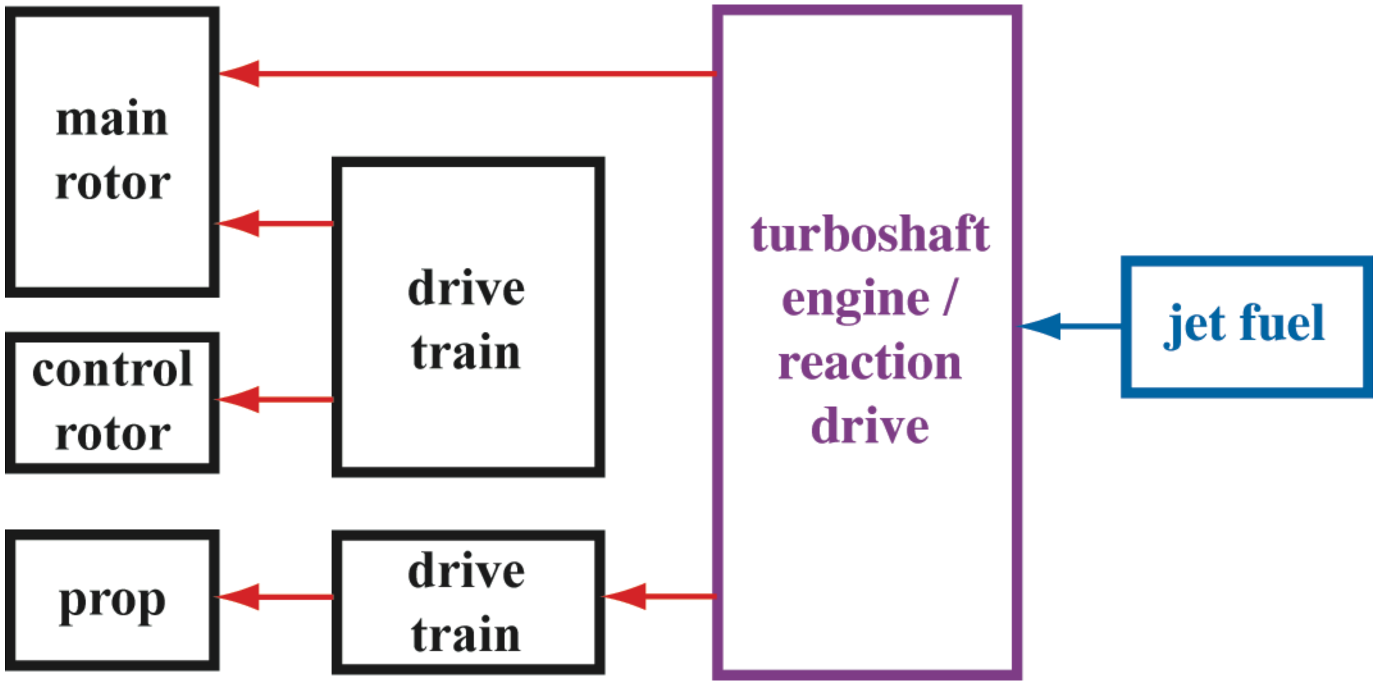
Sikorsky XH-59A

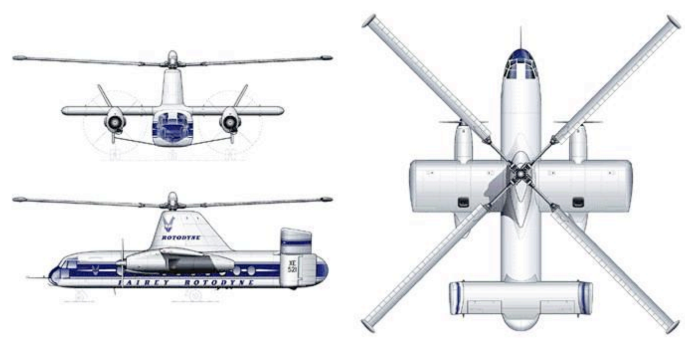
Reaction Drive



Hughes XV-9A

Reaction Drive — Compound





Fairey Rotodyne

Conclusions

- Extended propulsion system representation in the rotorcraft conceptual design code NDARC
  - Engine groups, jet groups, and charge groups provide general framework for theory and code
  - Implemented engine / jet / charger models for new propulsion components
    - Sufficient to starting designing rotorcraft and airplanes

- Enables development of environmentally-friendly rotorcraft designs
  - For example, aircraft utilizing electric motors, or electrical energy storage, or hydrogen-burning engines

Future Work

- More work required on models for new propulsion components
  - Air-breathing
    - Reciprocating engine, compressor, turbojet / turbofan
      - Anticipate need more elaborate models to cover full range of operating conditions
    - Reaction drive, convertible engines
      - Likely introduce additional complexities
  - Electrical
    - Motor, generator, fuel cell, solar cell
      - Need database of performance characteristics

Future Work

- Need database to support development of parametric weight models
- Need characterization of influence of scale and technology on performance and weights

- Separate tools will be used to design propulsion components

- Calibration and Validation

- Application to new rotorcraft concepts