Concepts for Multi-Speed Rotorcraft Drive System - Status of Design and Testing at NASA GRC

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Objective

Overview the Status of Three Drive Designs from an earlier concept study:

1. Design/testing of two *multi-speed drives*.
   Highlight some positive/negative aspects and future development areas.

2. Update to the design of *third concept*.
   *Variable-speed gear drive* based on a dual-input planetary differential.
Background

Future advances in rotorcraft propulsion systems require increased efficiency, power, and enhanced capabilities.

Studies show that *variable rotor speed* is required for:

- Reduction in noise
- Increased performance
- Enhanced capabilities (speed - capacity - range)

*Advances are contingent upon *varying rotor speeds* 50%.

*Present Limitations* ~15% (via engine control).
Future Rotorcraft Propulsion System Configuration
V/M-S Gearbox Application

Hover Ratio 131.4 : 1    Forward Flight Ratio 243.6 : 1
Test Article Design Requirements

- 250 HP nominal (200 HP facility capacity)
- Inline configuration (input-output shafts)
- Input Speed 15,000 rpm
- Output Speeds 15,000 rpm (hover), 7,500 rpm (cruise)
- Employ straight spur gear geometry (budget consideration)
- Drive should fail safe to the high-speed (hover) mode
- Lubricant: DOD-PRF-85734A, synthetic ester-based oil
  - 40C 104F 23.0 cSt
  - 100C 212F 4.90-5.40 cSt
  - -54C -65F pour point
- a Provide high-speed positive drive element
- b Light-weight rotating components (flight like)
- c Housing design (modular, possibility of windage shrouds)

a requirement dropped due to complexity and budget
b requirement dropped due to scope and budget
c not an original requirement
Modules: Gear & Clutch

1:1 Direct Drive (Vertical Flight)
Main Clutch Engaged

2:1 Reduction Drive (Cruise)
Main Clutch Disengaged

2x Gear Modules
2x Clutch Modules

Forward Bearing
Low-Speed Shaft
Aft Bearing
Hydraulic Feed-Through

Input Shaft
Gear Train
Clutch (Main)
Sprag
Output Shaft
Baseplate/Supports/Housing

- Fwd Brg Support
- Intermediate Brg Support
- Aft Brg Support
- Rotating Feed-Through Support

Fixity - Main Rotating Ass’y
Fixity - Offset Cluster Gear
Floating
Two-Speed Drive Test Configurations

Configuration 1:
OCG / Dry-Clutch (Tested)

Configuration 2:
DSI / Dry-Clutch (Tested)

Configuration 3:
OCG / Wet-Clutch (In assembly)
Gear Module 1: (OCG) - Offset-Compound Gear

Sun Gear
Ring Gear

Sun Gear
Ring Gear

Cluster Gear (OCG)

Offset Axis

Mesh 1 Oil Jets

Mesh 2 Oil Jets

2:1

1:1
Balancing the OCG Cluster Assembly

Input Shaft 1

OCG Cluster Ass’y

OCG Offset C/L

Drive Belt System
Shaft 1 Support
OCG Cluster Supports
Shaft 1 Support
Gear Module 2: (DSI) - Dual Star-Idler Planetary

- Star Gear
- Idler Gear
- Input Shaft
- Sun Gear
- Ring Gear
- Carrier (Fixed)

Gear ratios:
- 2:1
- 1:1
DSI Planetary Gear Design

- Ring
- Star
- Sun
- Idler
- Oil In (Typ)
- Spacer Sleeve
- Planet Gear Assembly
- Oil-In Plane
- 3-Plate Carrier
- Carrier Ass’y

Bearing Loads vs. Rotational Direction

- CW In
- CCW In
- CW Out
- CCW Out
- Load CW
- Load CCW

φ = 20°
Gear Parameters - OCG vs. DSI

**OCG Gear Train**
Material: 9310, Backlash: 0.006-0.011 inch, 
Width: 0.375 inch, Contact Angle 20º

<table>
<thead>
<tr>
<th>Gear</th>
<th>Pitch</th>
<th>Pitch Dia (inch)</th>
<th>N&lt;sub&gt;teeth&lt;/sub&gt;</th>
<th>Rpm</th>
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<tbody>
<tr>
<td>Input</td>
<td>8.727</td>
<td>2.865</td>
<td>25</td>
<td>15,000</td>
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<tr>
<td>2</td>
<td>8.727</td>
<td>4.240</td>
<td>37</td>
<td>10,135</td>
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<td>3</td>
<td>8.0</td>
<td>3.875</td>
<td>31</td>
<td>10,135</td>
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<tr>
<td>Ring</td>
<td>8.0</td>
<td>5.250</td>
<td>42</td>
<td>7,481</td>
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</table>

**DSI Gear Train**
Material: 9310, Backlash: 0.010-0.015 inch, 
Width: 0.600 inch, Contact Angle 20º

<table>
<thead>
<tr>
<th>Gear</th>
<th>Pitch</th>
<th>Pitch Dia (inch)</th>
<th>N&lt;sub&gt;teeth&lt;/sub&gt;</th>
<th>Rpm</th>
</tr>
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<tbody>
<tr>
<td>Sun</td>
<td>12</td>
<td>4.1667</td>
<td>50</td>
<td>15,000</td>
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<tr>
<td>Star</td>
<td>12</td>
<td>1.5833</td>
<td>19</td>
<td>39,474</td>
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<tr>
<td>Idler</td>
<td>12</td>
<td>1.6667</td>
<td>20</td>
<td>37,500</td>
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<tr>
<td>Ring</td>
<td>12</td>
<td>8.4167</td>
<td>101</td>
<td>7,426</td>
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</table>

Observations: DSI planet gears spin at 4x the speed of the OCG cluster gear.
### OCG Bearing Parameters.

<table>
<thead>
<tr>
<th>Site</th>
<th>Rpm</th>
<th>Size</th>
<th>D_{brg}</th>
<th>d_{brg}</th>
<th>dN factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>15,000</td>
<td>206</td>
<td>62</td>
<td>30</td>
<td>450,000</td>
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<tr>
<td>2</td>
<td>10,135</td>
<td>1822</td>
<td>140</td>
<td>110</td>
<td>1,114,850</td>
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<tr>
<td>3</td>
<td>10,135</td>
<td>1822</td>
<td>140</td>
<td>110</td>
<td>1,114,850</td>
</tr>
<tr>
<td>Ring</td>
<td>7,481</td>
<td>210</td>
<td>90</td>
<td>50</td>
<td>374,050</td>
</tr>
</tbody>
</table>

### DSI Bearing Parameters.

<table>
<thead>
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<th>Site</th>
<th>Rpm</th>
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<td>35</td>
<td>15</td>
<td>592,110</td>
</tr>
<tr>
<td>Idler</td>
<td>37,500</td>
<td>202</td>
<td>35</td>
<td>15</td>
<td>562,500</td>
</tr>
<tr>
<td>Ring</td>
<td>7,426</td>
<td>210</td>
<td>90</td>
<td>50</td>
<td>371,300</td>
</tr>
</tbody>
</table>

(Bearing diameters in millimeters)

Observations: Bearing dN are higher for OCG despite high speeds of the DSI planet bearings.
Observations – Gear Trains

High planet gear speed is an inherent aspect of a single stage planetary gear train with a 2:1 output since the ratio is defined by the ratio of pitch diameters of the ring and sun gears.

For a basic 2:1 Planetary: Ø5.0 sun & Ø10.0 ring yields the following intermediate gear speeds for an input speed of 15,000 rpm

<table>
<thead>
<tr>
<th>Gear Train</th>
<th>Intermediate Speed (rpm)</th>
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</thead>
<tbody>
<tr>
<td>Basic Planetary</td>
<td>30,000</td>
</tr>
<tr>
<td>DSI (idler addition)</td>
<td>37,500 +25% speed increase due to reduced diameter planets</td>
</tr>
<tr>
<td>OCG</td>
<td>10,000</td>
</tr>
</tbody>
</table>

The OCG is simpler to lubricate due to reduced number of gear meshes and bearings.
Clutch Module: (DC) DRY-CLUTCH

- Dry-Clutch
- Low-Speed Shaft
- Intermediate Shaft
- Sprag
- Output Shaft
- Clutch Hub
- Release Bearing Ass’y
- Rotating Feed-Through

* Unique hardware necessary to meet the inline design requirement
Dry-Clutch Design

- Clutch Hub
- Clutch
- Piston (Release Bearing Ass’y)
- Input Flange
- Pre-Load Springs
- Intermediate Output Shaft
- Output Shaft
- Hydraulic Signal

1:1
Clutch Module: (WC) Wet-Clutch

- Low-Speed Shaft
- Release Piston
- Sprag
- Output Shaft
- Drive Plates
- Drive Springs
- Rotating Feed-Through

2:1
1:1
Wet-Clutch Design

- Drive Plates
- Release Piston
- Drive Springs
- Hydraulic Signal
- Output Shaft
- Orifice Bleed
- Polygon Drive
- Input Flange

1:1
Output Shaft Hydraulic / Lubrication Passages (Wet-Clutch)
Clutch Release Closed-Loop Load Path

Closed-Loop Load Path (Dry-Clutch)

Closed-Loop Load Path (Wet-Clutch)
Rotating Hydraulic/Lubricant Feed-Through

- 15,000 rpm
- Ring Seals – DuPont Vespel
- Significant drag

Lube Oil A, B, C
Ring Seals
O-Rings
Lube Inlets A, B, C

Rotating Feed-Through
Main Housing Aft Wall
Sprag (Overrunning Clutch)

- Sprag Hub
- Sprag Races
- Low-Speed Shaft
- Lube Inlet (Shaft)
- Lube Drain (Hub)
- Straddle Support Duplex Bearings

Sprag:
- 16-element
- 4-lube inlets

Races:
- 4-drive pins

Revisions:
- Addition of aft-sprag bearing forming straddle duplex bearing support
Future Design (Concept 3)

Variable-Speed Drive
Dual-Input Planetary Differential

• Concept Variable-Speed Drive leveraged from the DSI Planetary Gear Train & Lubrication Design
  – Sun Gear - Input
  – Carrier - Control (Second Input)
  – Ring Gear – Output

• Direct Point Bearing and Gear Lubrication

Second Input Is Not Within Current Scope
DUAL-INPUT PLANETARY DIFFERENTIAL

1 - Primary Input (Fixed)

2 - Carrier Input (Variable A or B)

A

B

Planet Bearing Oil Jets

Carrier Bearing Oil Jets

Output (Variable)

Mesh Oil Shaft-Fed

Drains (Rotational)

Rotating Feed Through
CONCLUDING REMARKS

• Presented an overview of designs and current status of two-speed drive concepts developed at NASA GRC.

• Identified a few areas for future development.  
  
  Many more are discussed in detail in the paper.

• Presented an updated concept for a variable-speed gear drive based on a dual-input planetary differential.
Questions?