TECHNOLOGY INNOVATION OF POWER TRANSMISSION GEARING IN AVIATION

by

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Overview

An overview of rotary wing evolution and innovations over the last 20 years was presented. This overview is provided from a drive system perspective. Examples of technology innovations that have changed and advanced drive systems of rotary wing vehicles will be provided. These innovations include full 6-axis CNC gear manufacture, face gear development to aerospace standards, health and usage monitoring, and gear geometry and bearing improvements. Also, an overview of current state-of-the-art activities being conducted at NASA Glenn is presented with a short look to fixed and rotary wing aircraft and systems needed for the future.
Technology Innovation of Power Transmission Gearing in Aviation

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Drive Systems:
The Necessary Evil or they can’t succeed without us!
Topics

• Fixed and rotating wing aircraft evolution / innovation
  – Types of aircraft
  – Engines
  – Drive system
• Technology innovation - drive system perspective
• Current NASA / GRC research
  – Structures and Materials Division
  – Tribology & Mechanical Components Branch
• Future, what is next ?????
• Questions?
NASA Glenn Research Center
**Propulsion and Power System Components**

- Aeroshells
- TPS; Cooled strls.
- Cryogenic tanks
- Nacelles
- Combustors
- Engine fan system
- Mechanisms
- Oil-Free engines
- Injectors
- High-power motors
- Space lubricants
- Protective Coatings
- Sensors
- Thermoelectrics
- Surface mobility systems
- Nozzles
- In-space & on-surface modules
- Rotor discs and systems
- Turbine vanes
- Energy absorbing systems
- Mechanical drive systems
- Human health systems
- Thrusters
- Bearings and flywheels
- Solid oxide fuel cells, batteries
- High temp. and cryogenic seals
- Porous membranes
- BN nanotubes

**Core R&T Capabilities**

- Probabilistic methods
- Mechanical power transfer
- Impact dynamics
- Structural mechanics
- Material modeling
- Material characterization
- Functional materials
- Metallic alloys
- Computational materials
- Surface science
- Materials science
- Matl. and strl. Concepts
- Health prognostics
- Blast mechanics
- Structural dynamics
- Joining technology
- Failure and damage growth
- Processing technologies
- Shape memory alloys
- Protective coatings
- Extreme environment effects
- High temperature chemistry
- Design technology
- Experimental methods
- Measurement technology
- Aeroelasticity
- Durability and life
- Fatigue and fracture
- High temp. and cryo seals
- Ceramic materials
- Multifunctional Materials
- Lubricant chemistry
- Friction and wear
Technical Innovation

- Airplane / rotorcraft evolution
- Engines (piston to gas turbine to .....)
- Drive systems
Civil Aircraft Evolution

- Douglas DC-3
- Boeing 707
- Boeing 737, 747
Civil Aircraft Evolution

- Airbus 380
- Boeing 787
Helicopter Evolution

• Piston engine RC’s (1950’s)
• Turbo – shaft powered RC’s (Huey, OH-58…)
• Multi-engine RC’s CH-46, UH-60,…
• Civilian use for medivac, border patrol, law enforcement, television news, sightseeing…….
Helicopter Evolution
Tiltrotor Evolution
Engine Innovation

- Piston engines (radial)
- Turbo-jet engine
- Turbo-fan / turbo-shaft engines
Engine Innovation

• High By-pass Turbofan engines
• Geared turbo-fan…
Drive “System” Evolution

• Higher speed engines
• Multi-engine main drive systems
• Advanced concepts
  – Non-traditional arrangements & gear types
  – Split torque – multipath
  – Advanced manufacture
  – Advanced analysis
  – Advanced testing
Example Rotorcraft Transmission
Drive System Stress Analysis

- Beam models
- AGMA, ISO, DIN and other methods
- FEA – assumed loading, single gear mesh
- FEA – tooth contact, multi-component contact, …..

Leads to better understanding of what is found in practice.
• Simple dynamic models – rigid body – lumped mass
• Profile modification effects, helical effects,…
• More complex – multi-element analysis
• Shafting – bearings – damping
• Complete end-to-end dynamic simulation
• Involute gear geometry
• Extrapolation to other non-involute gearing
• Computer kinematic manufacture process for surface geometry – details of surface only graphical
• Gear geometry analysis – Dr. Faydor Litvin, kinematics of manufacture, equation of meshing, principal surface orientation, exact surface information
• Techniques applied to many types of gear systems
Gear Manufacturing

- Manual machine tools
- Gear geometry
- Coordinate measuring machinery
- Combination of gear measurement – manufacture machine tool settings
- Full CNC manufacture with feedback from manufactured parts
Gear Performance

- Gear meshing efficiency – sliding & rolling losses: NASA - Anderson & Lowenthal models
- High speed gearing requirements
- Gear windage – empirical models
- Gear windage – CFD analysis & high speed experimental capability
Examples of Technology Innovation of Power Transmission Gearing in Aviation
Spiral Bevel Gear Manufacturing

Spiral Bevel Gear Grinding

Gleason Works
463 Machine
Manual

Gleason Works
463 CNC Machine
Partial CNC

Gleason Works
Phoenix
Full CNC
Technology Innovation – Face Gears

Advanced Rotorcraft Transmission Program

Face Gear Geometry Development

Face Gear Grinding Development

Face Gear Testing - Fatigue

Face Gear – Aircraft Application
Face Gears

MDHS/Lucas Face-Gear, Split-Torque Configuration Concept

- 40-percent weight reduction
- 9.6 dB noise reduction
- 6270 hours MTBR
Face Gears

Face Gear Development for Rotorcraft Drives
5000-hp Demonstrator Transmission

Conventional baseline configuration (Apache-type)

Split-torque, face-gear configuration
40% weight reduction
Condition Based Maintenance

Lubricant Analysis

Chip Detectors

Metallic Debris Monitors

Vibration Sensing

Vibration Algorithms

Fuzzy Logic & Data Fusion used for Improved condition determination
Vibration Algorithm Development

[Images of vibration patterns and a graph showing time/cycles and NA4 readings with labeled peaks a), b), and c).]
Data Fusion Applied to Spiral Bevel Gear Bearings

Unanticipated bearing failure reinforces importance of data fusion
Spiral Bevel Gear Development

Gleason Works
Geometry – Machine Settings

Improved Contact Conditions,
Fillet Geometry with
Litvin Machine Tool Settings

Lower Cost Formate Design
with
Low Noise and Stress
Results: Decreased noise, vibration, stresses
Gear Performance - Superfinishing

1. Surface Finish Improved
   - ground
   - superfinished
   - 1 µm
   - 100 µm

2. Power Loss Reduced
   
   ![Graph showing power loss vs. speed (rpm)]
   - ground
   - superfinished

3. Scoring Load Increased
   
   ![Graph showing scoring load vs. sliding speed (m/s)]
   - ground
   - superfinished

4. Surface Fatigue Life Increased
   
   ![Graph showing percent specimens failed vs. millions of stress cycles)]
   - ground
   - superfinished
   - suspended
   - (x3)
   - (x7)
Technology Innovation has resulted in the transmission system design power going from 300 hp to over 600 hp.
Current Activities of Tribology and Mechanical Components Branch at NASA Glenn Research Center in Support of Future Innovation
Branch Organization:

- Oil-Free Turbomachinery - Air Bearings for Aeronautic and Space Applications
- Space Mechanisms & Lubrication – Basic Research for Space Applications
- Aerospace Seals – Seals for turbine engine and aerospace / space structures
- Aero Drive Systems – Power Transfer (Gears, Bearings, etc.) for Aeronautic & Space Applications
Tribology & Mechanical Components Branch

**Oil-Free Turbomachinery**
- Aero / Space application
- World-leading bearing experts
- Advanced modeling methods
- Foil bearing predictive design

**Aerospace Seals Research**
- Space habitat seals for extreme environments
- Structural / thermal protection seals
- Non-contacting turbine seals

**Space Mechanisms & Lubrication**
- Accelerated space lubricant life testing under vacuum
- New mechanism concepts for planetary environment
- New space lubricant development
- Terramechanics modeling & testing for efficient wheels

**Aero Drive Systems**
- Gear fatigue research
- High speed gear lubrication
- Drive system diagnostics
- Fatigue crack modeling
- Dynamic mechanical components
- Rotorcraft transmission systems
- Advanced rolling element and wave bearing technologies

**From basic research to application**
Oil-Free Turbomachinery

For cryogenic to 800°C sliding contacts

PM304 bushings for industrial furnaces and valves

TGIR Award for Level I Milestone: “Core Hot Bearing Tests” (OFTET)
Space Tribology & Materials

SPIRAL ORBIT TRIBOMETER
Accelerated Lubricant Life Testing Under Realistic Conditions

VACUUM 4-BALL
Accelerated Bulk Property Testing of Lubricants

BEARING RIG
Full Scale Bearing Tests

Other Facilities:
• Vapor Pressure of Fluids
• Radiation Damage of Polymers
NASA GRC Seal Research:

- Shuttle main landing gear door environmental seals
- Thermal barrier (braided carbon fiber rope) for nozzle joints of Shuttle and Atlas V SRM’s
Seal Test Facilities

Exploration Systems Seals Lab (B5, C-9/SE-14)

Structural Seals Lab (B5, SW-17)
- Actuator
- Load frame
- 3000 °F furnace
- Laser extensometer
- Test fixturing
- Load cells & alignment fixture
Drive Systems Team

Current Research Activities

(Future Innovation)
Drive System Analytical Capabilities

- Finite Element Based Structural - Thermal
- Planetary Gear Dynamics
- Fracture Mechanics - BEM
High Speed Gearing - Windage

\[ P_{Windage} = C_3 C' \rho N^{2.85} D^{4.7} v^{0.15} \lambda \]
Condition Based Maintenance

Objectives: Increase reliability and decrease false alarms for mechanical component diagnostics. Demonstrate integration of oil debris and vibration based damage detection techniques results in improved capability.

Approach:
Instrument and monitor all GRC gear fatigue test facilities and work with other govt. agencies, university, and industry
Condition Based Maintenance

Vibration Techniques (FM4, NA4) and Oil Debris

Output of Fuzzy Logic Model

Model Output

- Normal
- Inspect
- Damage

Reading Number

0 500 1000 1500 2000 2500 3000 3500
Wave Bearing Technology

Bearing Concept

- Improved stability and cooling
- Ability to tailor stiffness and damping
- Use of hard sleeves

Test Facility
# Advanced Gear Material

## Surface Fatigue Results

<table>
<thead>
<tr>
<th>Gear Material</th>
<th>Number of failures</th>
<th>Number of tests completed</th>
<th>Median life (million cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS 6308B [Ref. 10]</td>
<td>15</td>
<td>21</td>
<td>134</td>
</tr>
<tr>
<td>AISI 9310 [Ref. 13]</td>
<td>25</td>
<td>33</td>
<td>200</td>
</tr>
<tr>
<td>Ferrium® C69 [present study]</td>
<td>5</td>
<td>10</td>
<td>361</td>
</tr>
</tbody>
</table>

## Fracture Toughness

- Ferrium® C69
- AISI 9310
  - Excellent Contact Fatigue
  - Poor Fracture Toughness
Space Mechanism Wear

Dither Damage Assessment
Low Cycle Bending Fatigue

![Low Cycle Bending Fatigue Experiment](image1.png)

![Bending Stress vs Cycles](image2.png)

![Finite Element Analysis](image3.png)

![Material Fatiguefracture](image4.png)
Where are we headed in aviation?

(Still need drive system technology to make configurations possible)
Future Aircraft
Tri-Fan Configuration

Blended Wing Propulsion Schematic
Civil Tiltrotor Drive System Configuration

Hover Ratio 131.4 : 1     Forward Flight Ratio 243.6 : 1

To Mid-Wing Gearbox

Variable / Multi-Speed Gearbox

Tilt Axis Gearbox

Combiner Gearbox

Rotor

Reduction Gearbox
In-Line Two Speed Drive System

High Speed Operation: Wet / Dry Clutch engaged, Over-Running Clutch over-running
Low Speed Operation: Wet / Dry Clutch disengaged, Over-Running Clutch driving
What’s Next?

Drive system R&D – still much to be done

Full System modeling & simulation

On-condition maintenance

Improved efficiency of drive systems
Questions?

Thanks for your attention!