TECHNOLOGY INNOVATION OF POWER TRANSMISSION GEARING IN AVIATION

by

Dr. Robert F. Handschuh

Army Research Laboratory, NASA Glenn Research Center
Cleveland, Ohio, USA

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

Dr. Robert F. Handschuh
U. S. Army Research Laboratory
Vehicle Technology Directorate
NASA Glenn Research Center
Cleveland, Ohio, U.S.A.
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?
Materials and Structures Division

Propulsion and Power System Components

Aeroshells
TPS; Cooled strs.
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
Gear Geometry

- 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

Gleason Works
463 Machine
Manual

Gleason Works
463 CNC Machine
Partial CNC

Gleason Works
Phoenix
Full CNC
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

- Output to rotor
- Planetary mesh
- Combiner gear mesh
- Input from engine 2
- Input from engine 1
- Torque-splitting face-gear mesh

- 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
Condition Based Experiment

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: 1 μm
   - Superfinished: 100 μm

2. Power Loss Reduced
   - Graph showing power loss (W) vs. speed (rpm)
     - Ground
     - Superfinished

3. Scoring Load Increased
   - Graph showing scoring load (N) vs. sliding speed (m/s)
     - Ground
     - Superfinished

4. Surface Fatigue Life Increased
   - Graph showing percent specimens failed vs. millions of stress cycles
     - Ground
     - Superfinished
     - Ground (x3)
     - Superfinished (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

**Heat Shield Interface Seal**

- Docking Seal

**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
Oil-Free Turbomachinery

Foil air bearings

PS304
For cryogenic to 800°C sliding contacts

Oil-Free enabling technologies

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 Test Facilities

- Spur Gear Fatigue Test Rigs
- Spiral Bevel / Face Gear Test Facilities
- Gear Noise / Dynamics Test Facility
- Split Torque Test Facility
- OH-58 Transmission Test Facility
- High Speed Helical Gear Train Facility
Drive System Analytical Capabilities

Finite Element Based Structural - Thermal

Planetary Gear Dynamics

Fracture Mechanics - BEM
High Speed Gearing - Windage

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

- Damage
- Inspect
- Normal

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

- Excellent Contact Fatigue
- Poor Fracture Toughness
Space Mechanism Wear

Dither Damage Assessment
Low Cycle Bending Fatigue

![Machine Experiment](image1.png)

**Graph:**
- **X-axis:** Cycles (1e+0 to 1e+5)
- **Y-axis:** Bending Stress (ksi) (200 to 650)

- **Legend:** Bending Stress Index (ksi)

![Graph Image](image2.png)

![Material Test](image3.png)
Where are we headed in aviation?

(Still need drive system technology to make configurations possible)
Tri-Fan Configuration
Civil Tiltrotor Drive System Configuration

Hover Ratio 131.4 : 1     Forward Flight Ratio 243.6 : 1
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!