Plenary Presentation at the Motion and Power Transmission Conference (MPT2009), Matsushima, Japan, May 2009

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 Aeronautics Centers

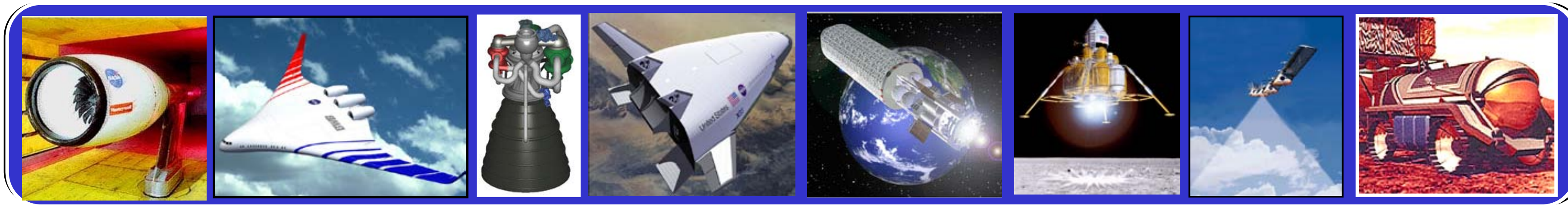
Glenn Research Center

Ames Research Center

Langley Research Center

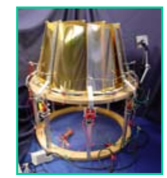
NASA Glenn Research Center

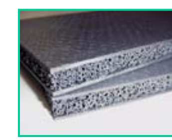
Materials and Structures Division

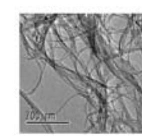


Propulsion and Power System Components

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







Core R&T Capabilities

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

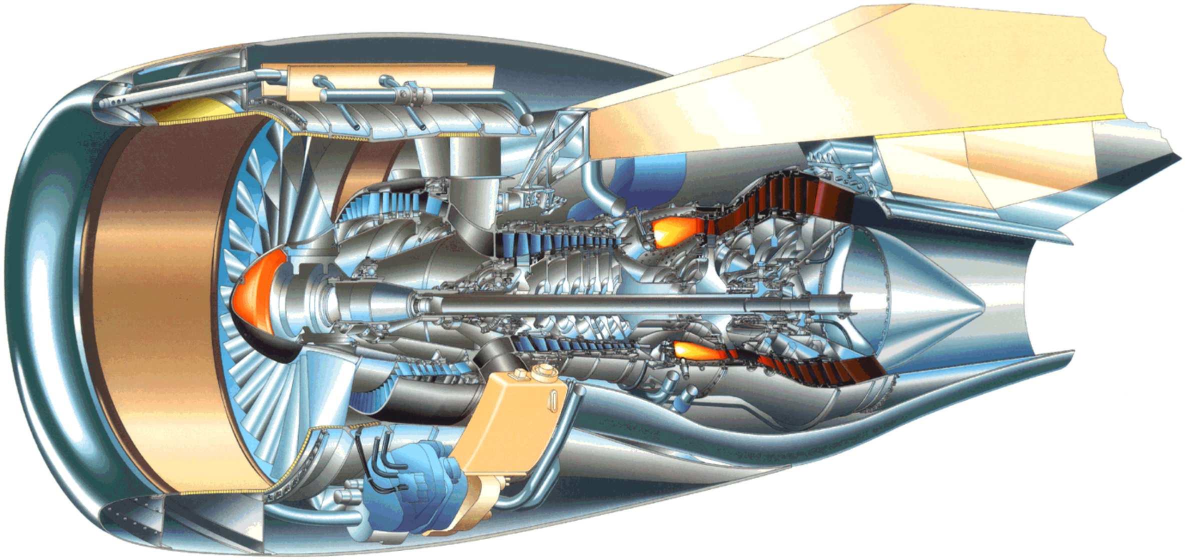
Helicopter Evolution

Helicopter Evolution

Tiltrotor Evolution

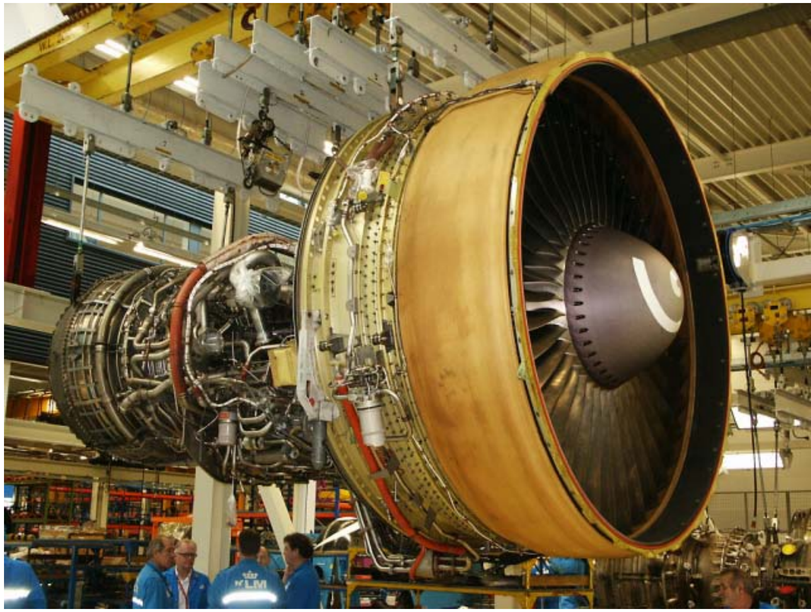
Engine Innovation

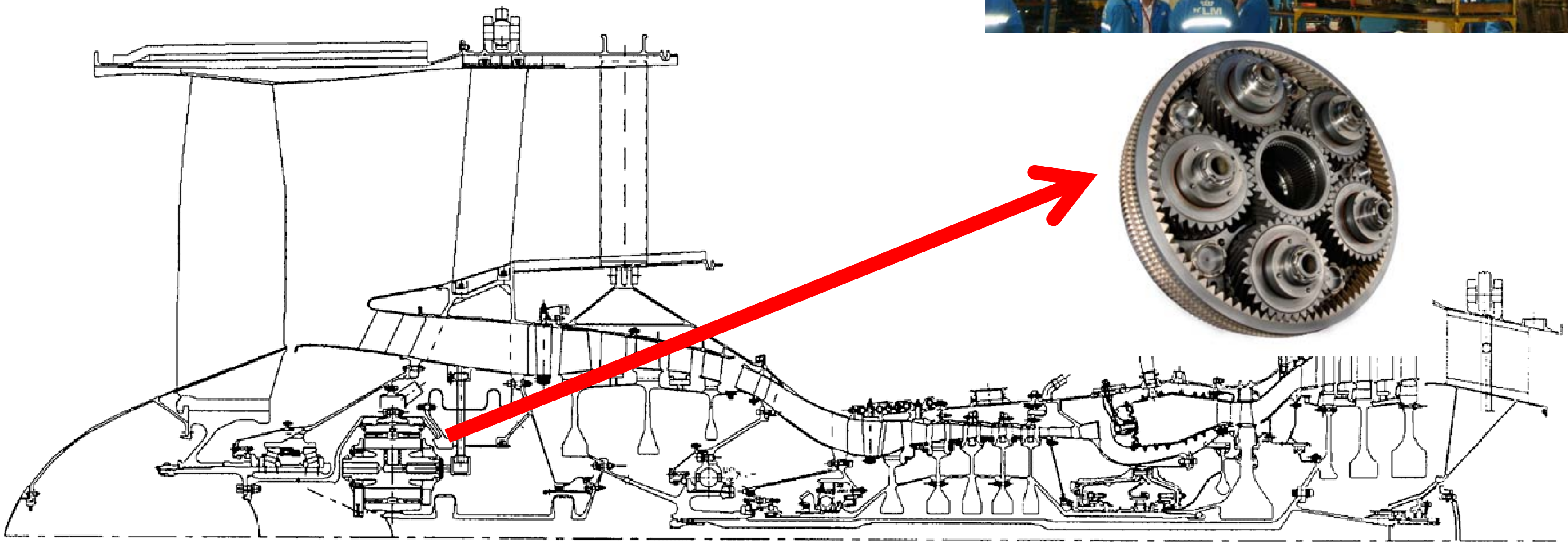
- Piston engines (radial)
- Turbo-jet engine
- Turbo-fan / turbo-shaft engines



Engine Innovation

- High By-pass Turbofan engines
- Geared turbo-fan…

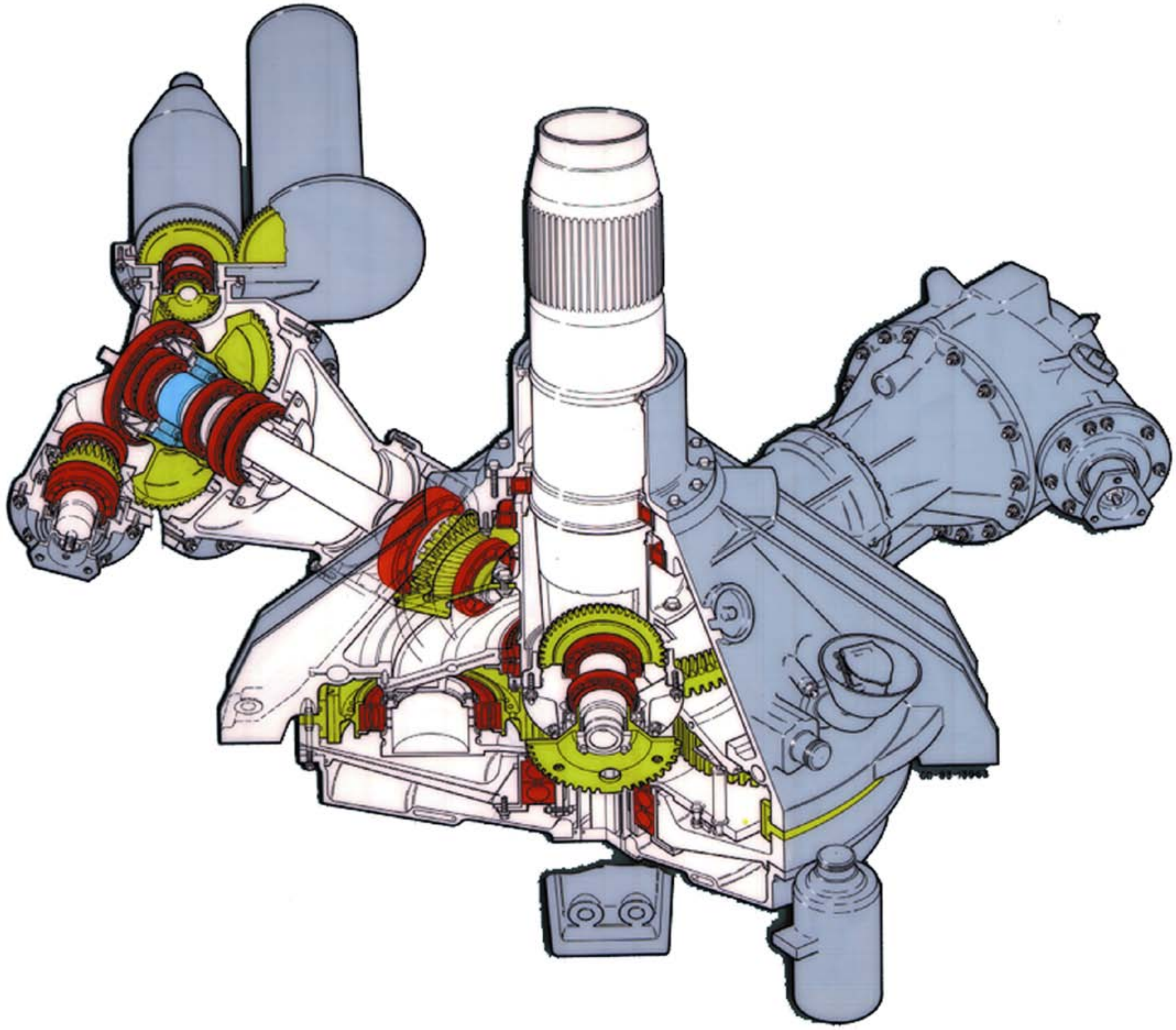




Drive "System" Evolution

- Higher speed engines
- Multi-engine main drive systems
- Advanced concepts
  - – Non-traditional arrangements & gear types
  - – Split torque – multipath
  - – Advanced manufacture
  - – Advanced analysis
  - – Advanced testing

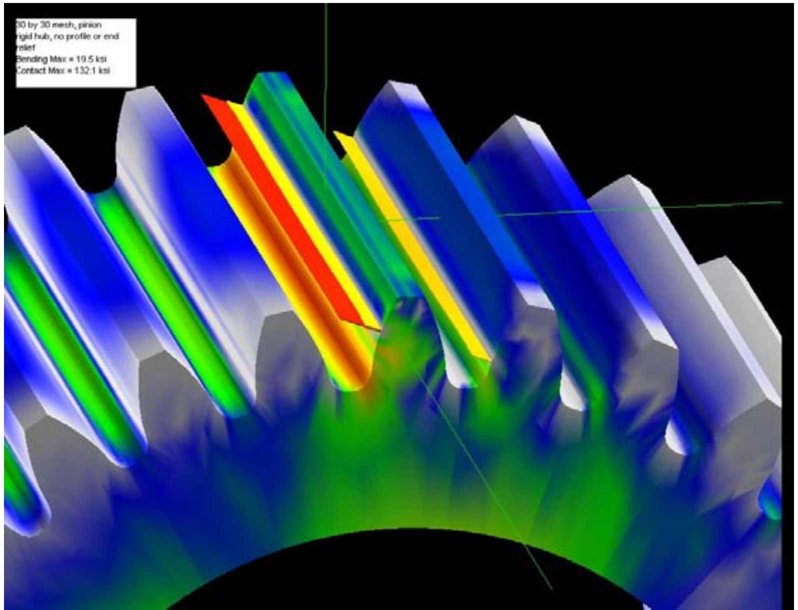
Example Rotorcraft Transmission

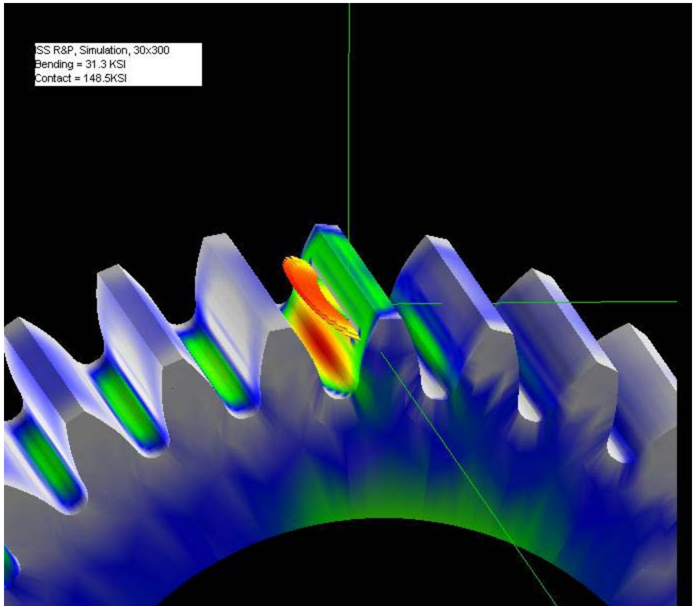


Drive System Stress Analysis

- **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.





Drive System Vibration / Noise

- 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

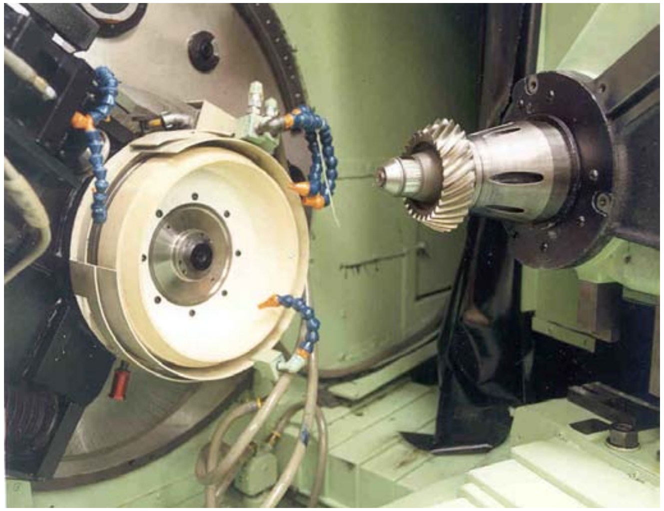
Examples of Technology Innovation of Power Transmission Gearing in Aviation

Spiral Bevel Gear 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

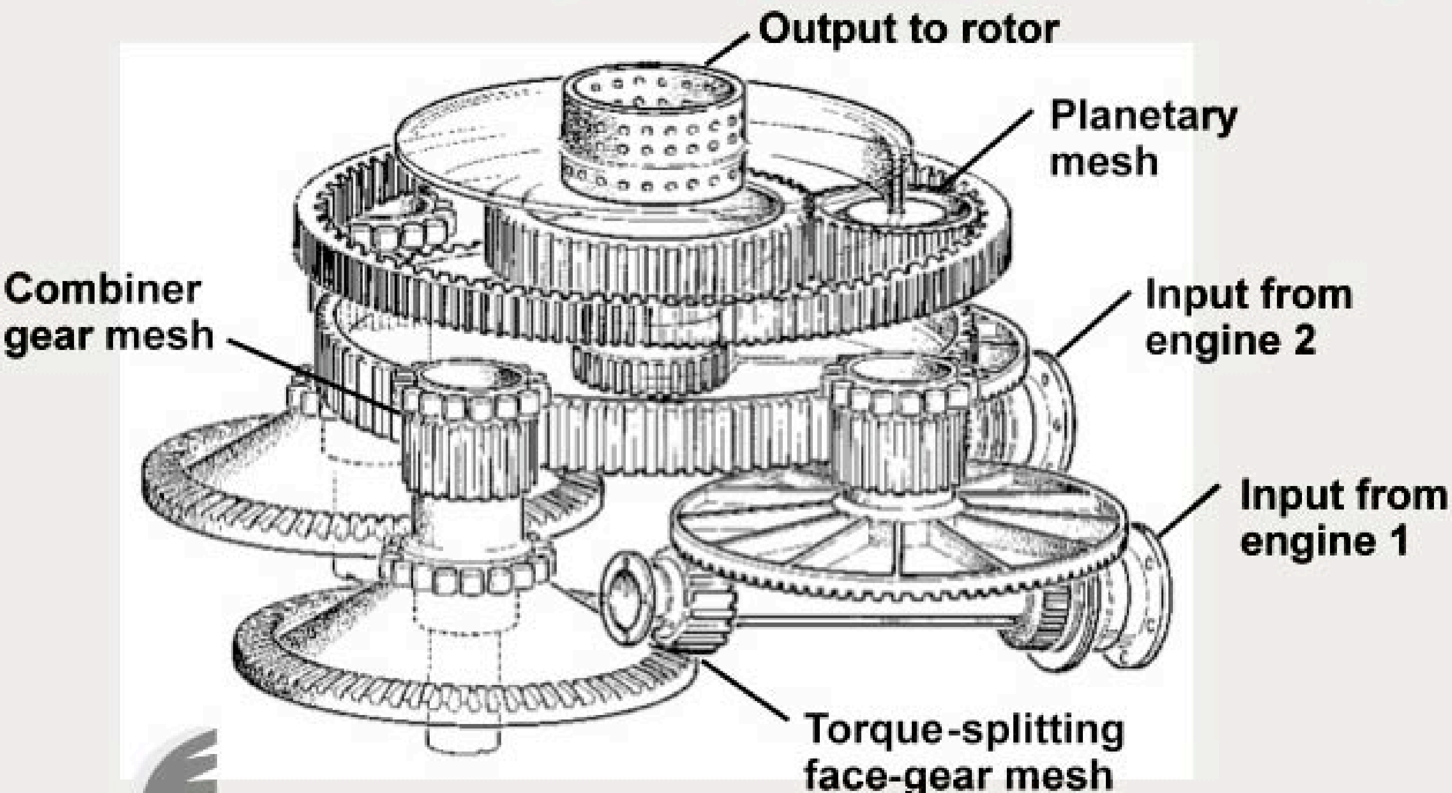
Face Gear Grinding Development

Face Gear Testing - Fatigue

Face Gear – Aircraft Application

Face Gears

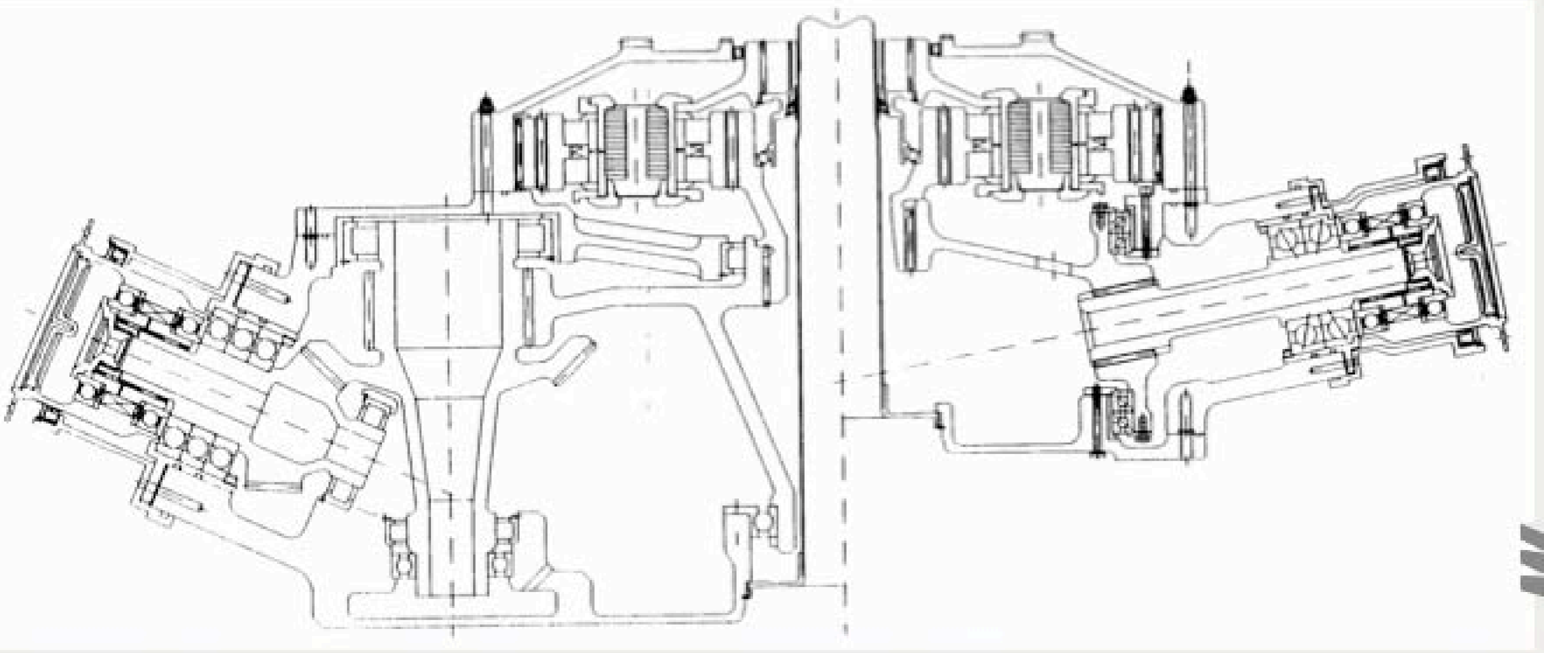
MDHS/Lucas Face-Gear, Split-Torque Configuration Concept



- 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

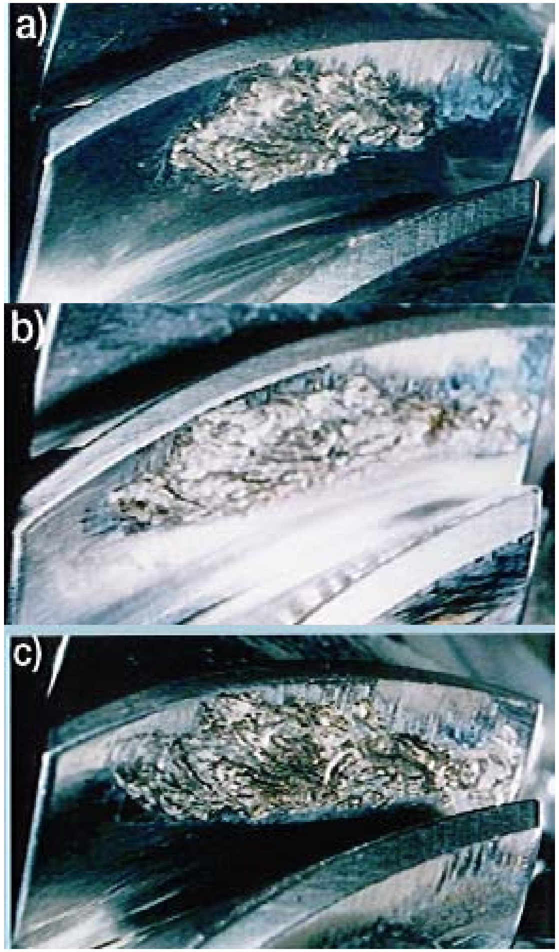
Metallic Debris Monitors

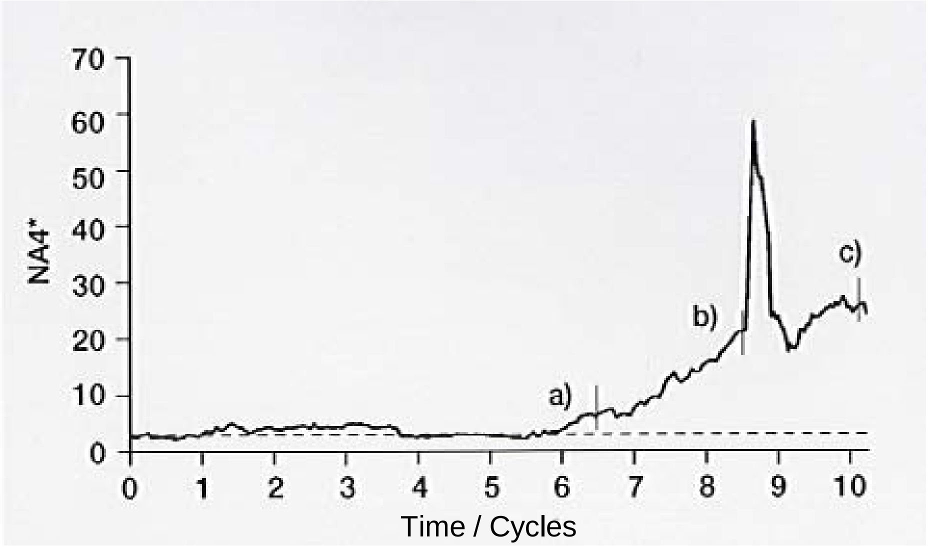
Vibration Sensing

Vibration Algorithms

Fuzzy Logic &
Data Fusion used for
Improved condition
determination

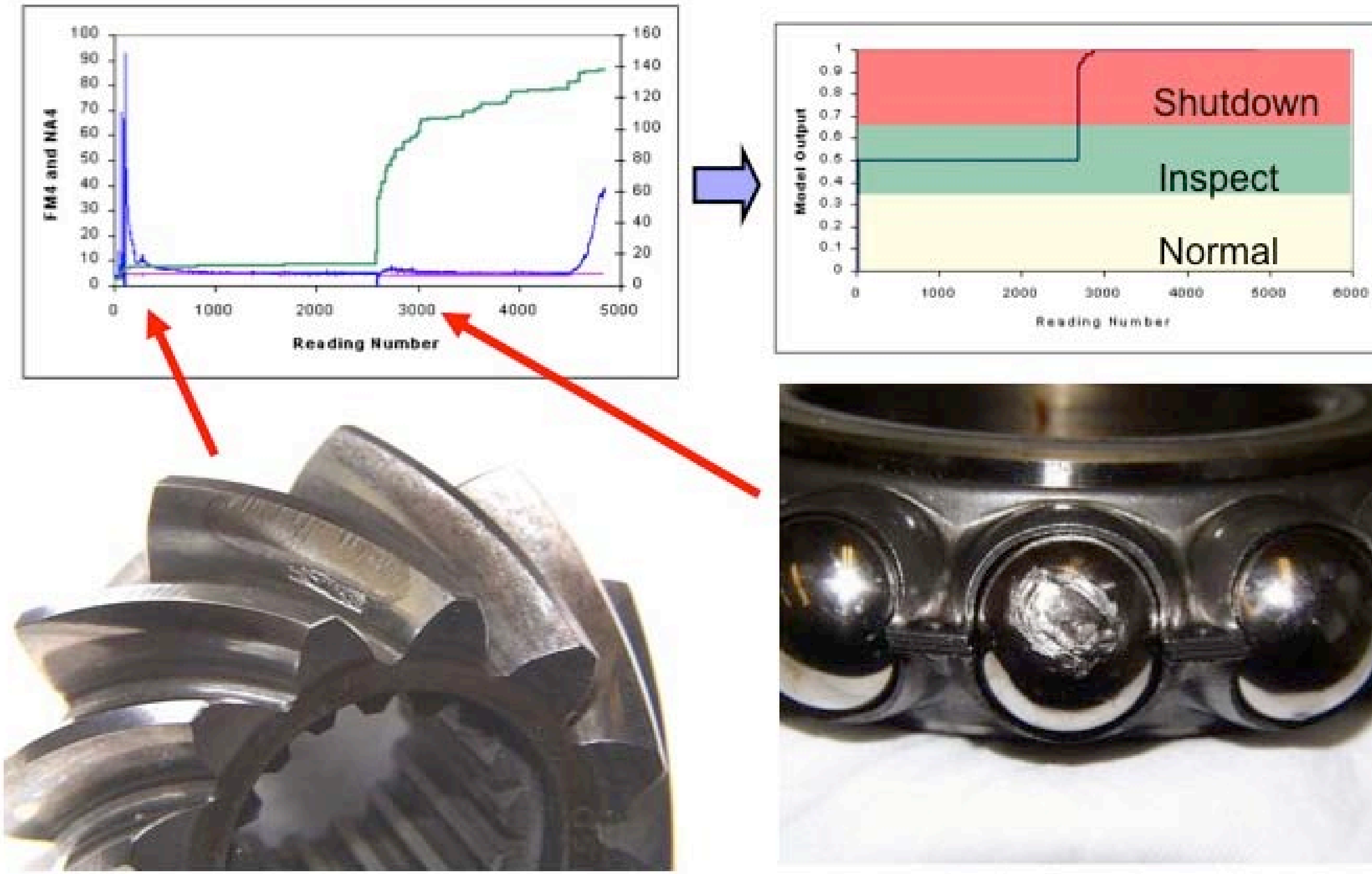
Vibration Algorithm Development





Condition Based Experiment

Data Fusion Applied to Spiral Bevel Gear Bearings



Unanticipated bearing failure reinforces importance of data fusion

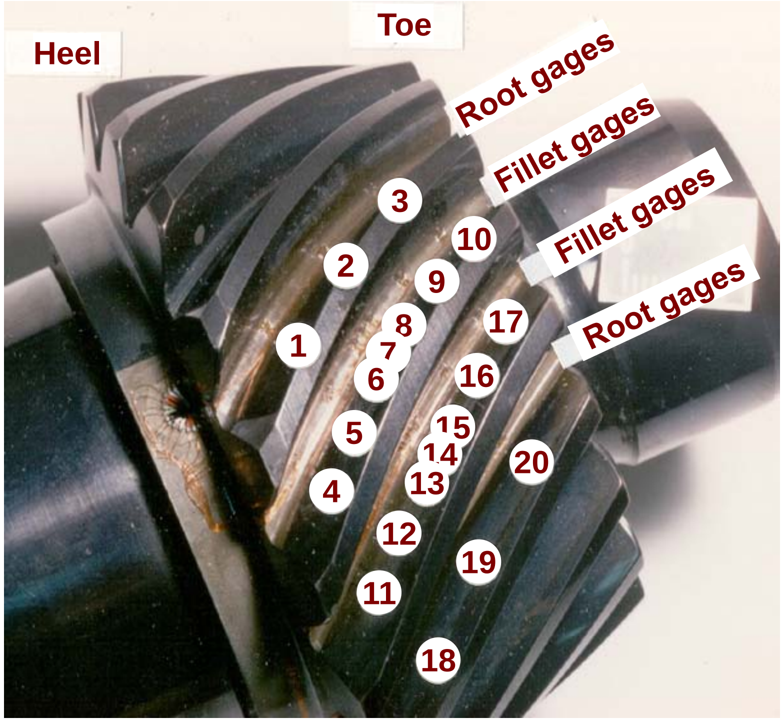
Spiral Bevel Gear Development

Gleason Works
Geometry – Machine Settings

Improved Contact Conditions,
Fillet Geometry with
Litvin Machine Tool Settings

Lower Cost Formate Design
with
Low Noise and Stress

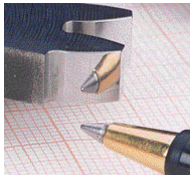
Low-Noise Formate Spiral-Bevel Gears

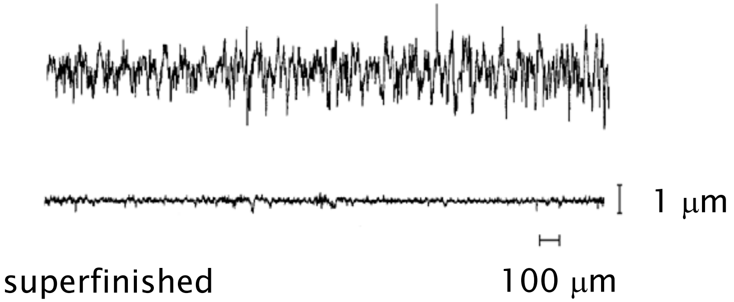


<u>Results:</u> **Decreased noise, vibration, stresses**

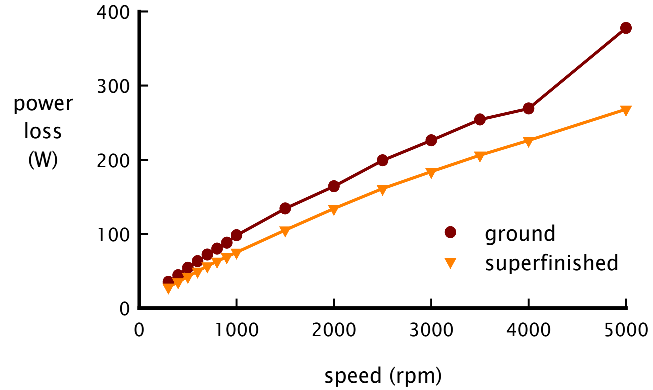
Gear Performance - Superfinishing

1 Surface Finish Improved

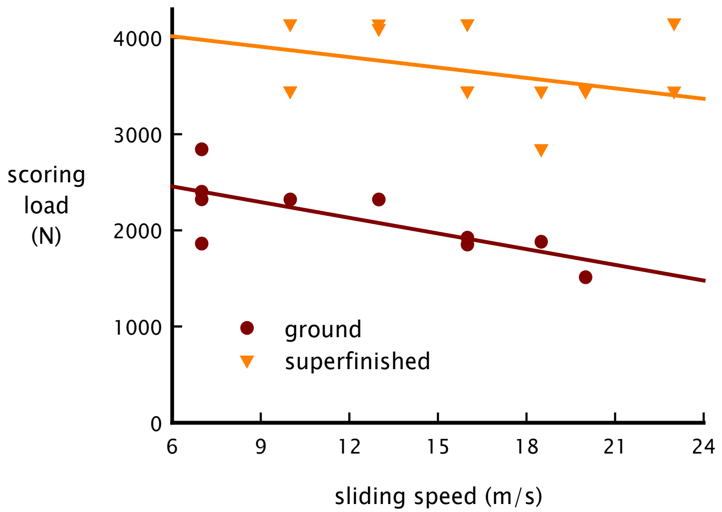




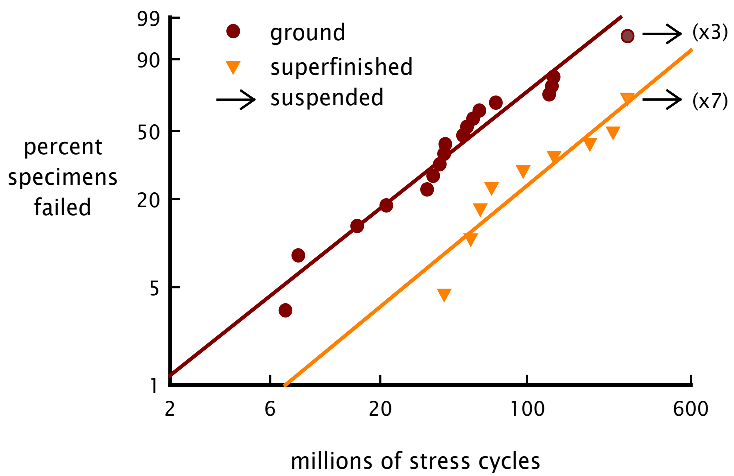
2 Power Loss Reduced



3 Scoring Load Increased

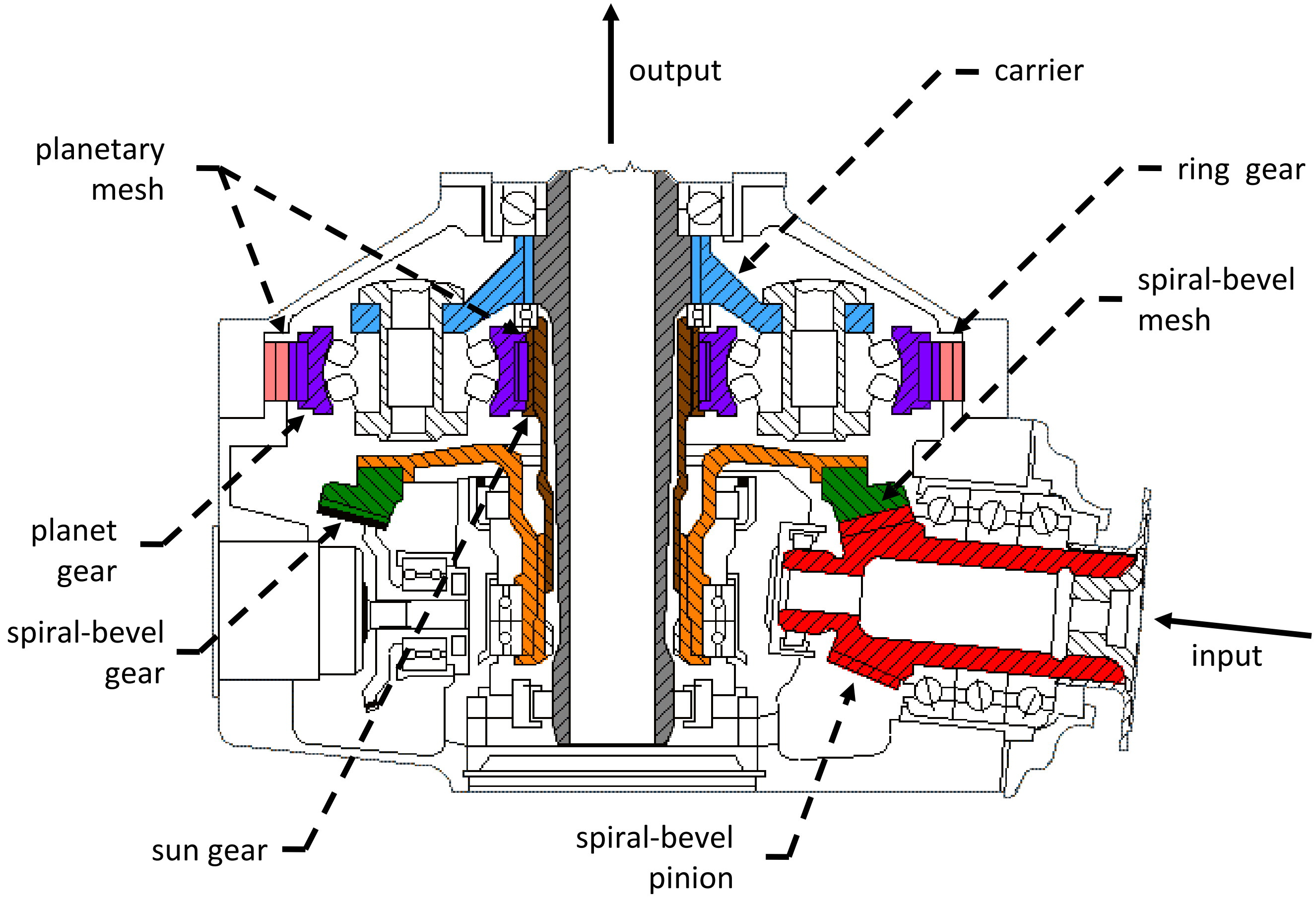


4 Surface Fatigue Life Increased



Transmission System

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

From basic research to application

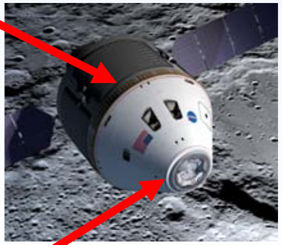
- Aero / Space application
- World-leading bearing experts
- Advanced modeling methods
- Foil bearing predictive design

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

Aerospace Seals Research

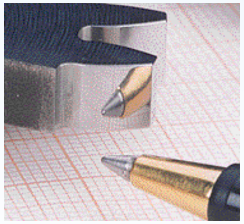
Heat Shield Interface Seal

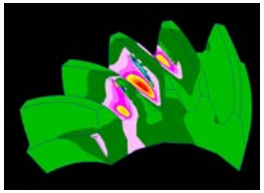


Docking Seal

- Space habitat seals for extreme environments
- Structural / thermal protection seals
- Non-contacting turbine seals

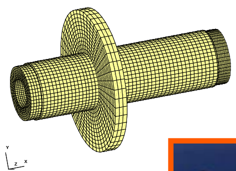
Aero Drive Systems



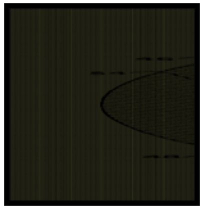


- Gear fatigue research
- High speed gear lubrication
- Drive system diagnostics
- Fatigue crack modeling
- Dynamic mechanical components
- Rotorcraft transmission systems
- Advanced rolling element and wave bearing technologies

Oil-Free Turbomachinery

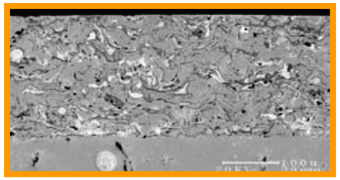


CAD



Foil air bearings

PS304



For cryogenic to 800C sliding contacts

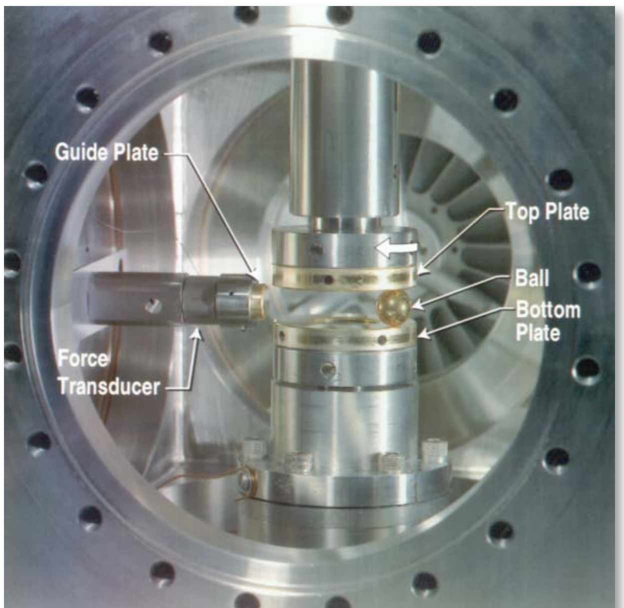
Oil-Free enabling technologies

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

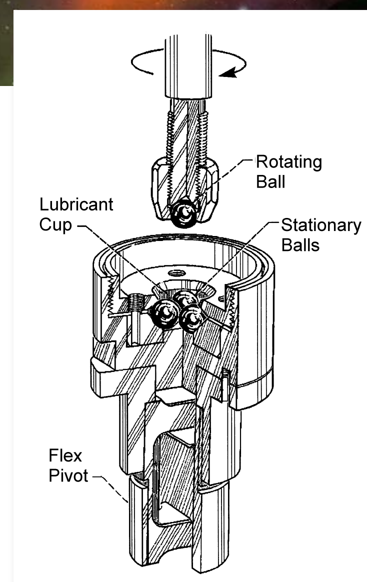
?

PM304 bushings for industrial furnaces and valves

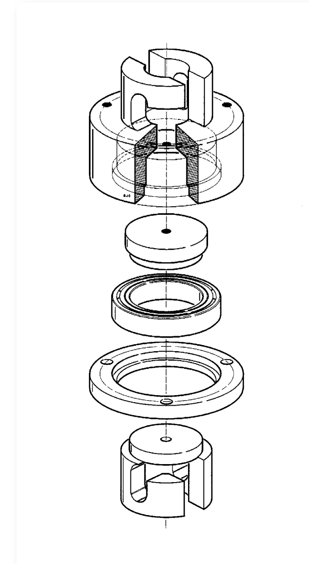
Space Tribology & Materials



SPIRAL ORBIT TRIBOMETER
Accelerated Lubricant Life Testing Under Realistic Conditions



VACUUM 4-BALL
Accelerated Bulk Property Testing of Lubricants



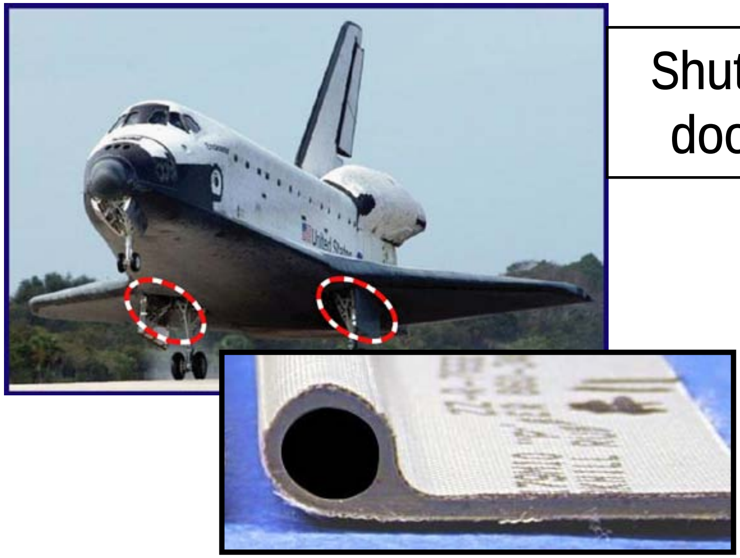
BEARING RIG
Full Scale Bearing Tests

Other Facilities:
- Vapor Pressure of Fluids
- Radiation Damage of Polymers

NASA GRC Seal Research

NASA GRC Seal Research:

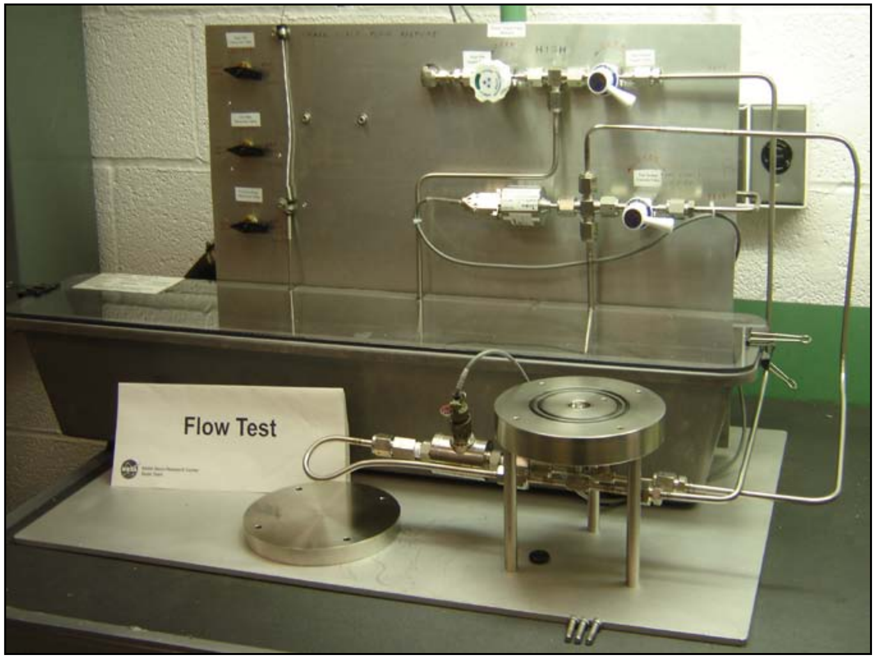
- Shuttle main landing gear door environmental seals
- Thermal barrier (braided carbon fiber rope) for nozzle joints of Shuttle and Atlas V SRM’s



Shuttle MLG door seals

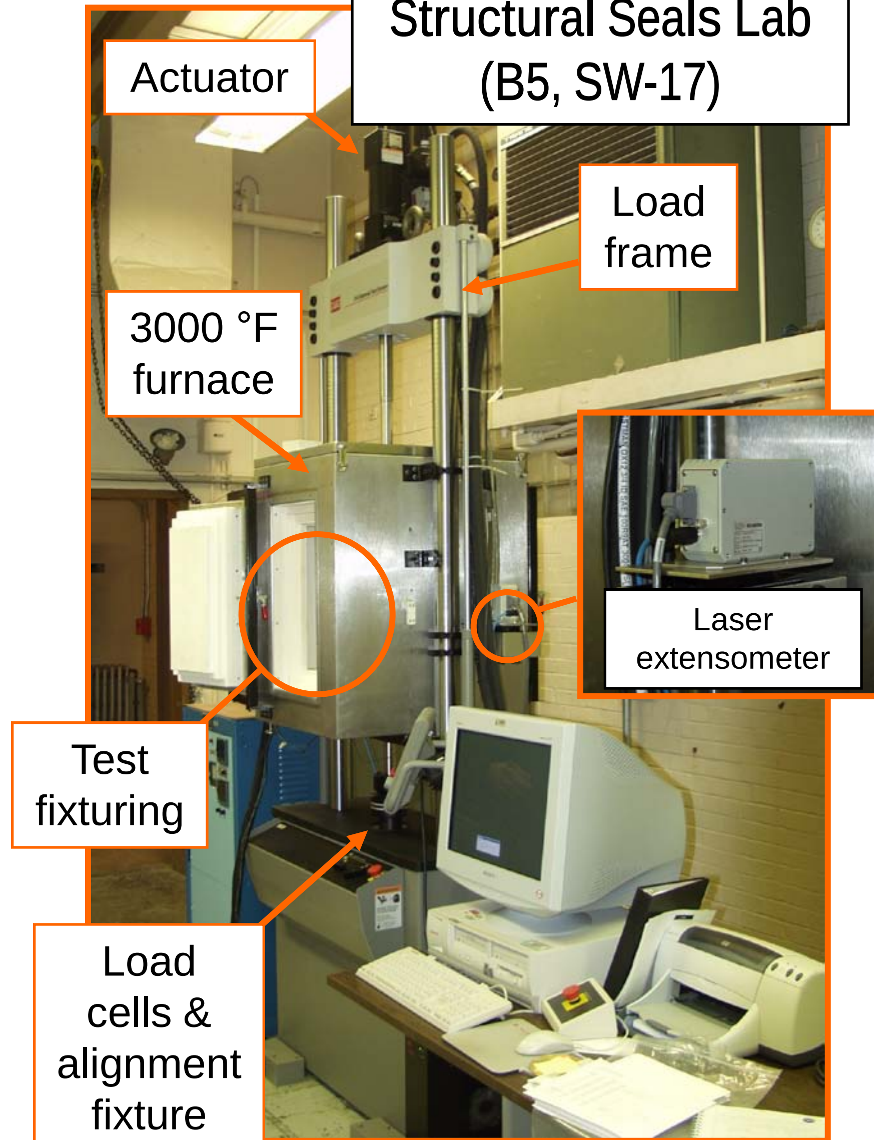
Thermal barrier for Shuttle and Atlas V SRM nozzle joints

Seal Test Facilities



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

Structural Seals Lab
(B5, SW-17)



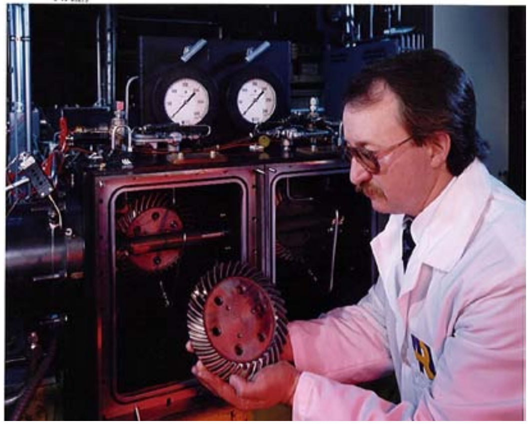
Drive Systems Team

Current Research Activities

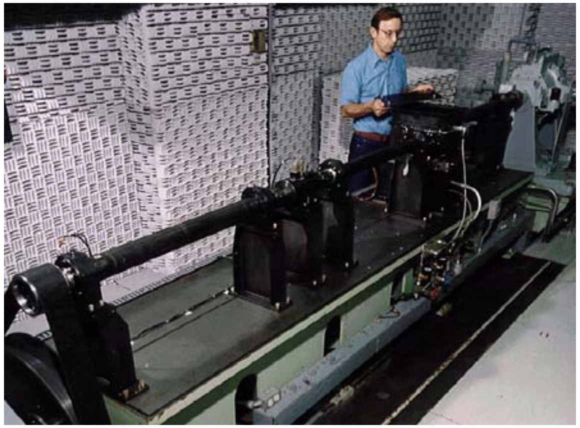
(Future Innovation)

Drive System Test Facilities

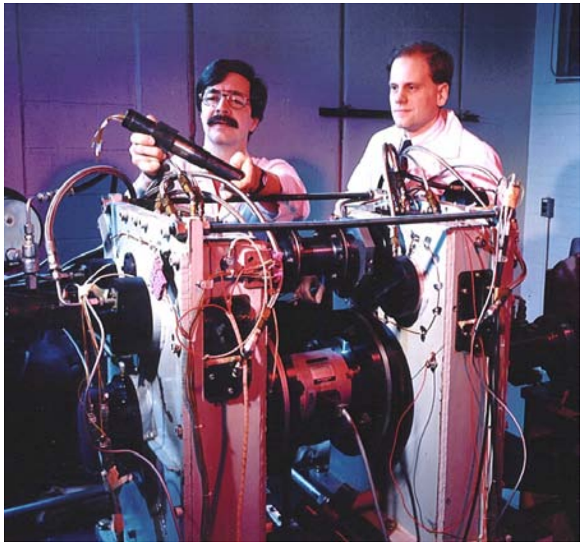
Spur Gear Fatigue Test Rigs



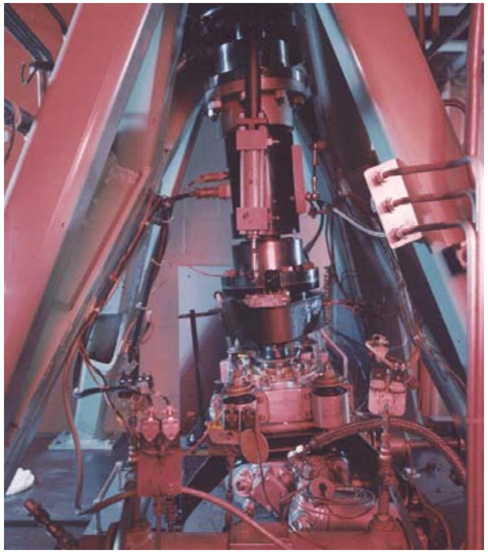
Spiral Bevel / Face Gear Test Facilities



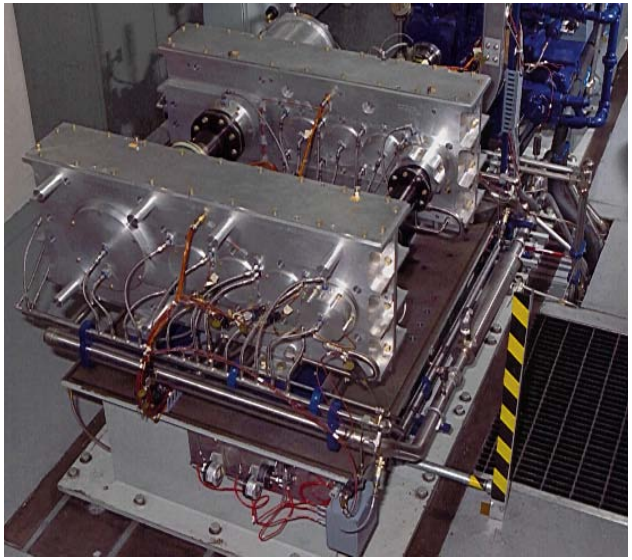
Gear Noise / Dynamics Test Facility



Split Torque Test Facility



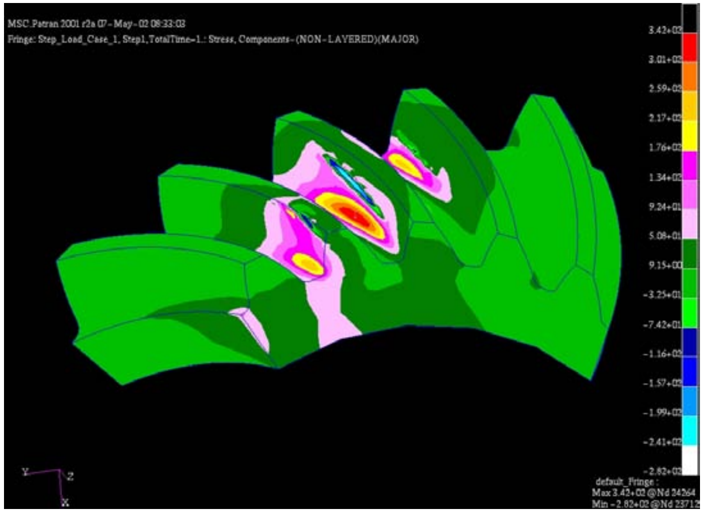
OH-58 Transmission Test Facility

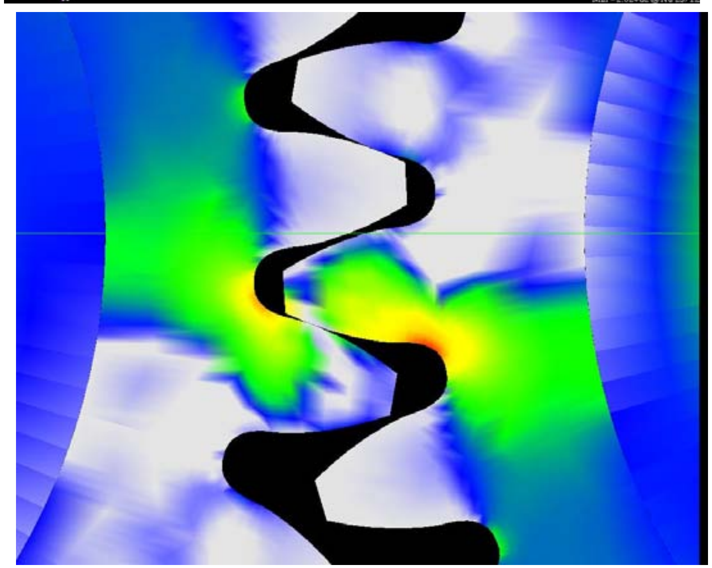


High Speed Helical Gear Train Facility

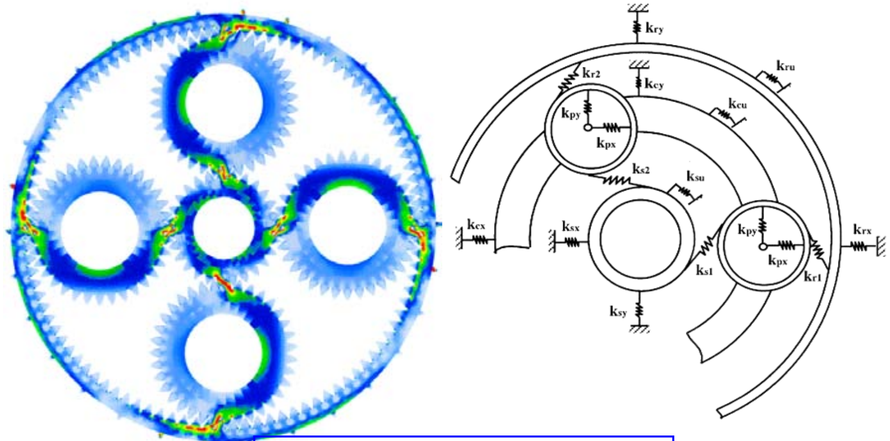
Drive System Analytical Capabilities

Finite Element Based Structural - Thermal

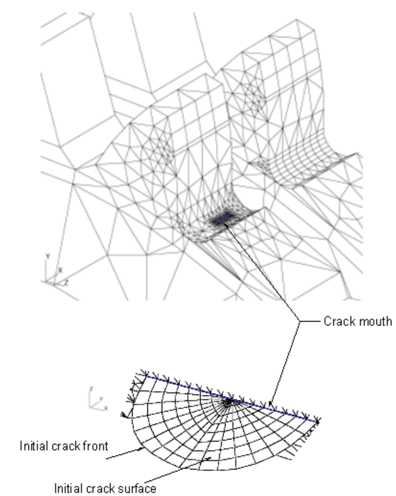




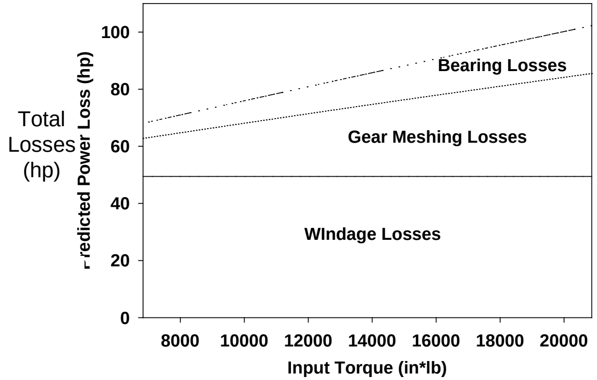
Planetary Gear Dynamics

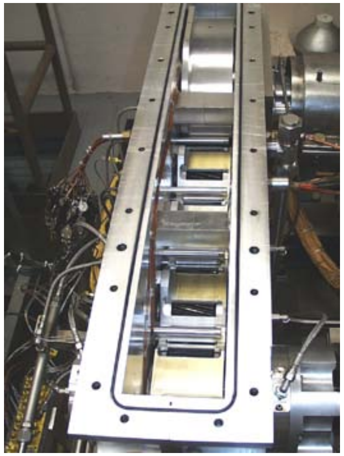


Fracture Mechanics - BEM

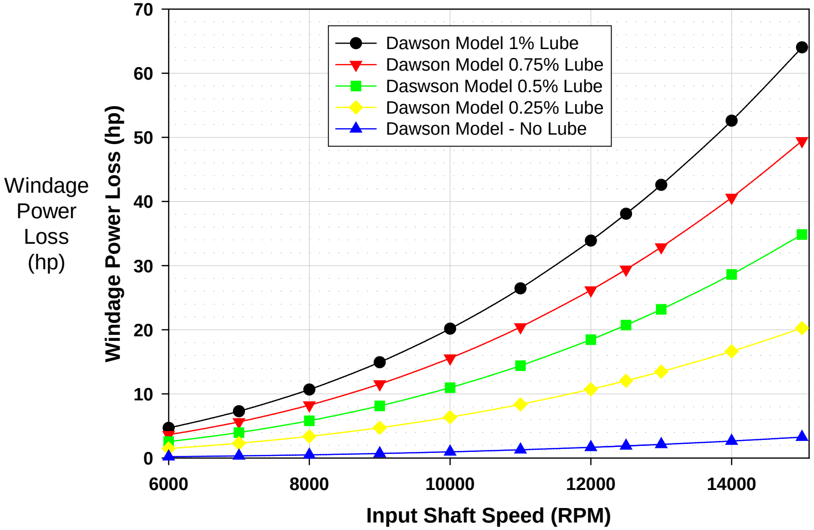


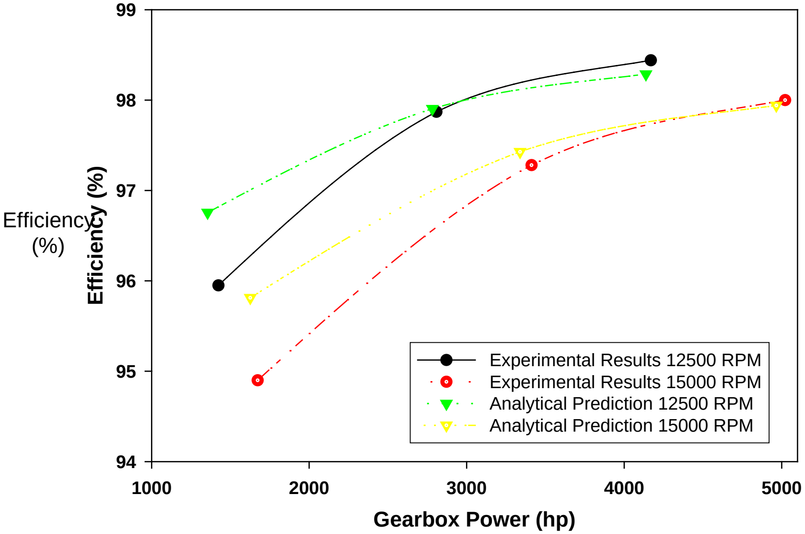
High Speed Gearing - Windage





$$P_{Windage} = C_3 C' \rho N^{2.85} D^{4.7} \nu^{0.15} \lambda$$

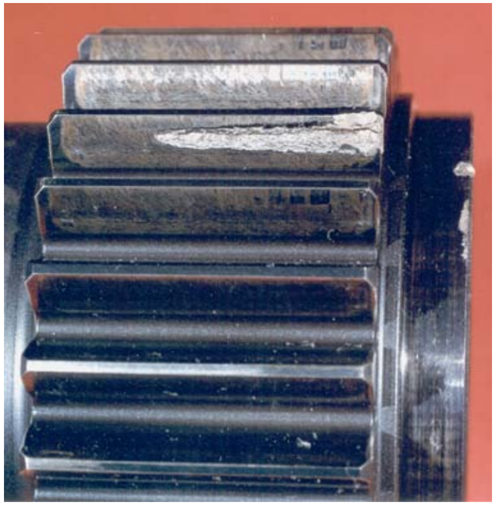


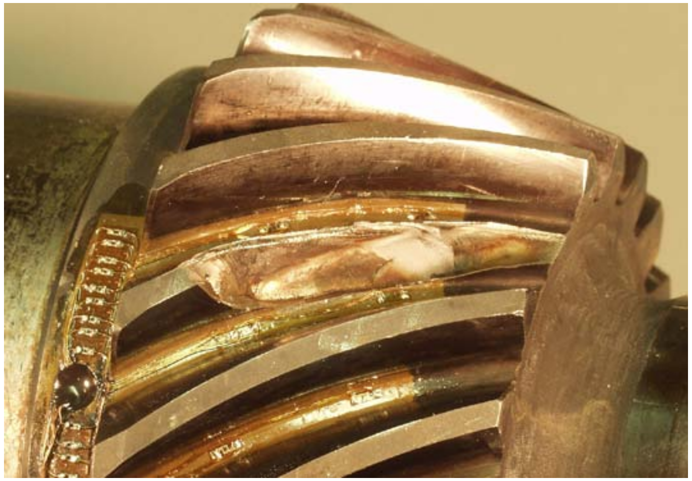


Condition Based Maintenance

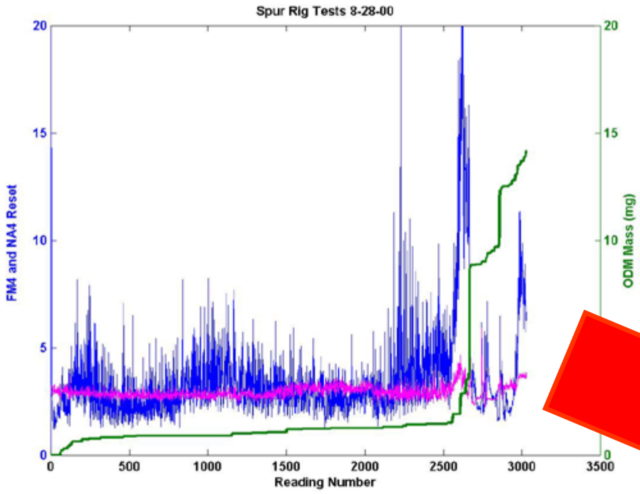
Objectives: Increase reliability and decrease false alarms for mechanical component diagnostics. Demonstrate integration of oil debris and vibration based damage detection techniques results in improved capability.

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

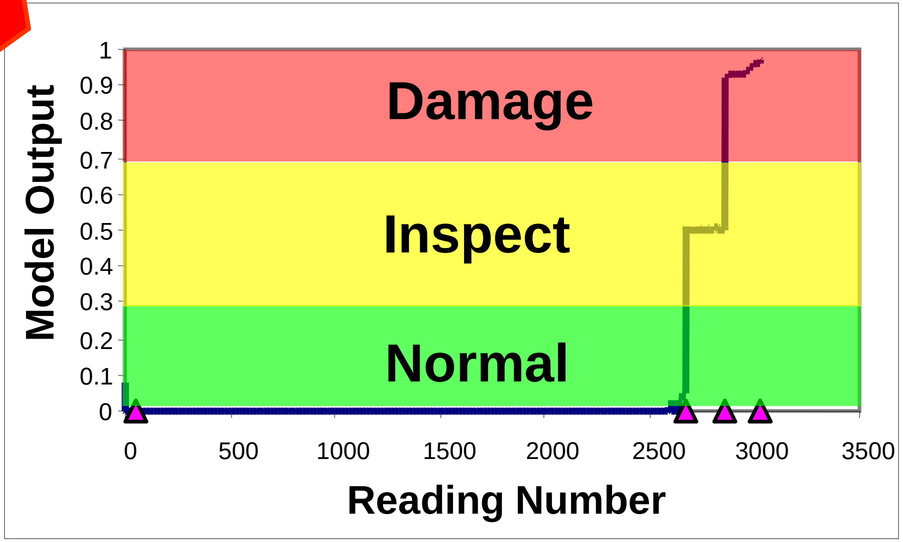




Condition Based Maintenance



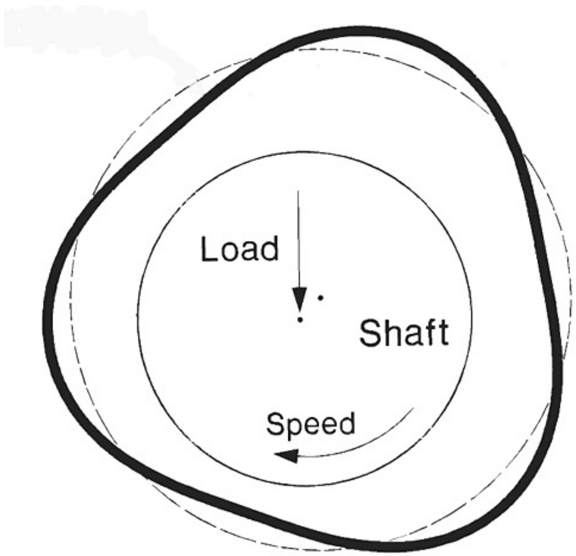
Vibration Techniques (FM4,NA4) and Oil Debris



Output of Fuzzy Logic Model

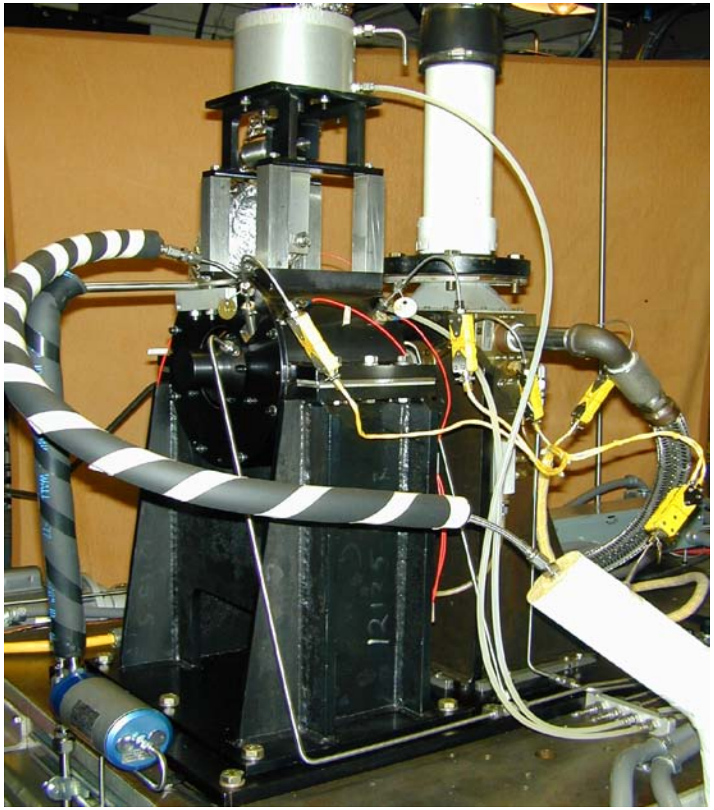
Wave Bearing Technology

Bearing Concept



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

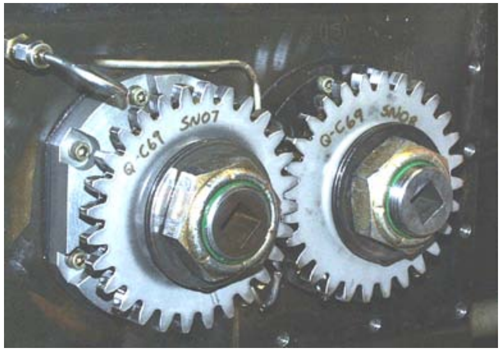
Test Facility

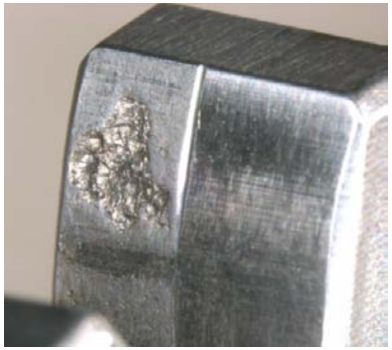


Advanced Gear Material

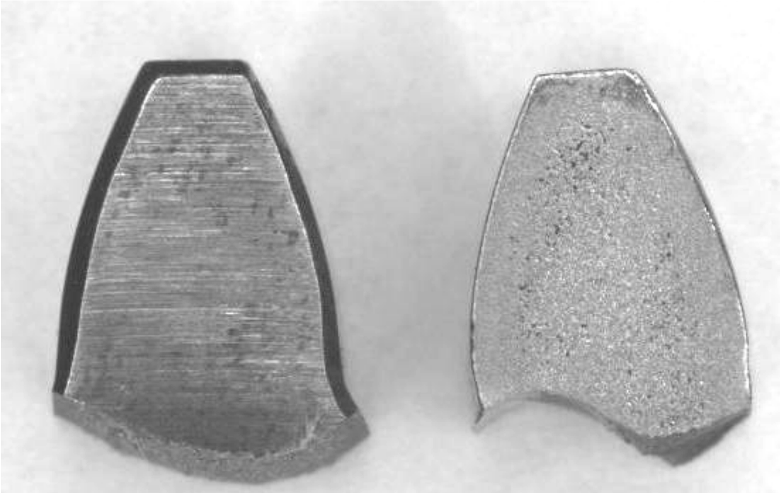
Surface Fatigue Results

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





Fracture Toughness

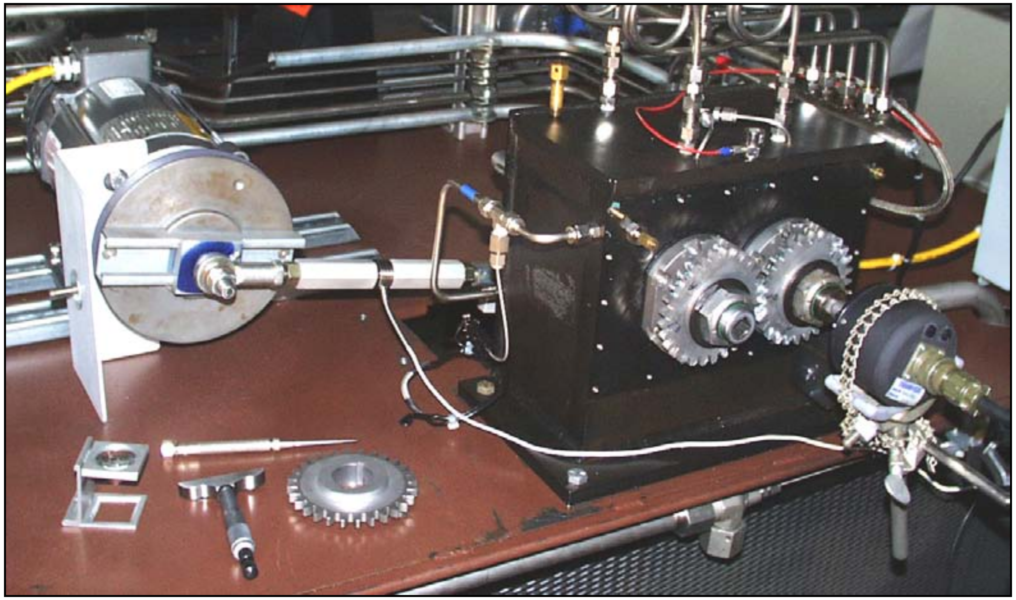


Ferrium® C69   AISI 9310

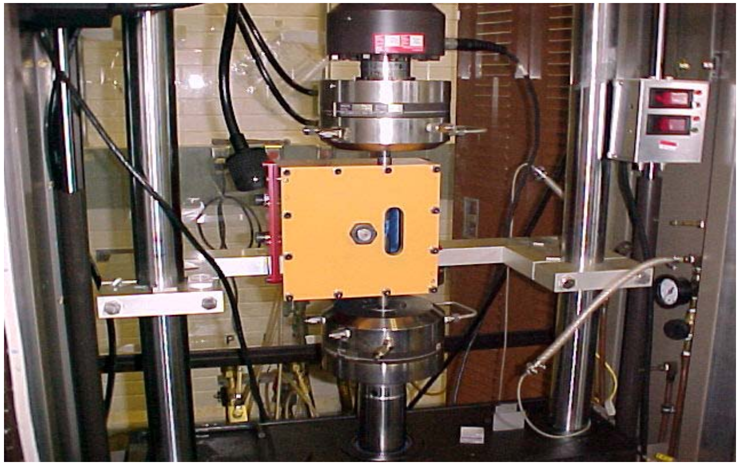
- Excellent Contact Fatigue
- Poor Fracture Toughness

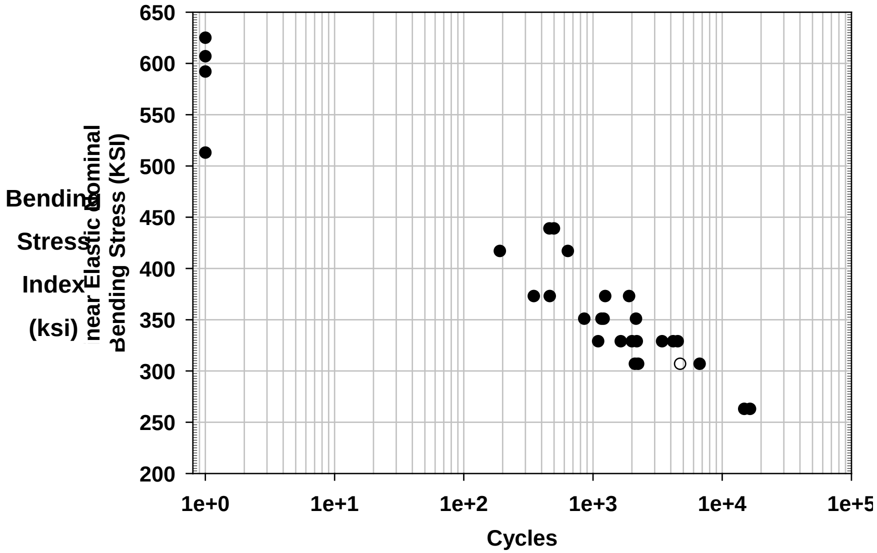
Space Mechanism Wear

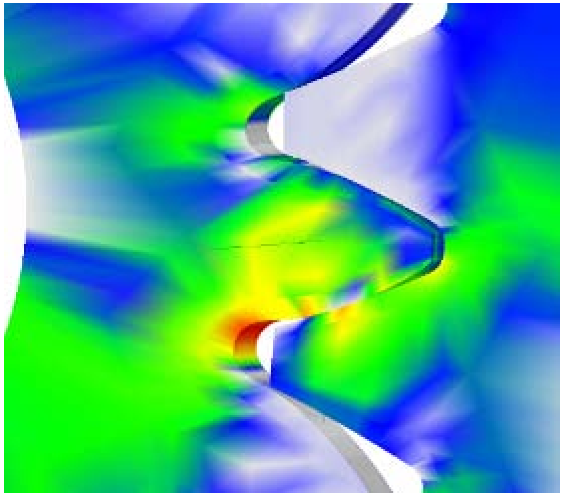
Dither Damage Assessment

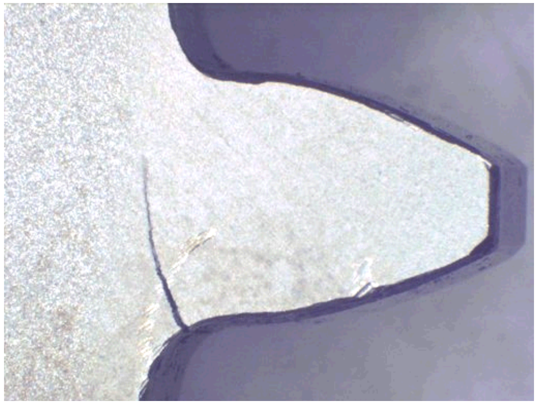


Low Cycle Bending Fatigue





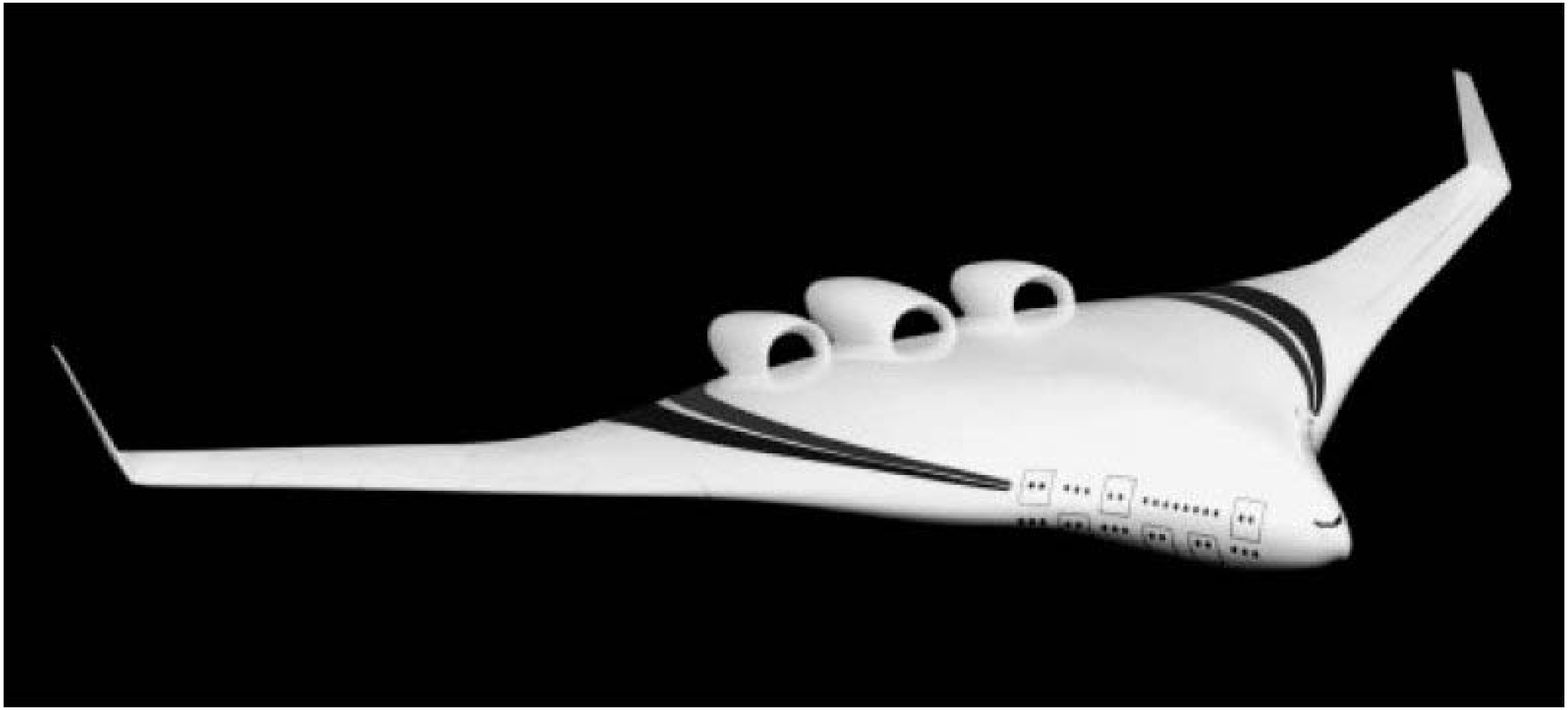




Where are we headed in aviation?

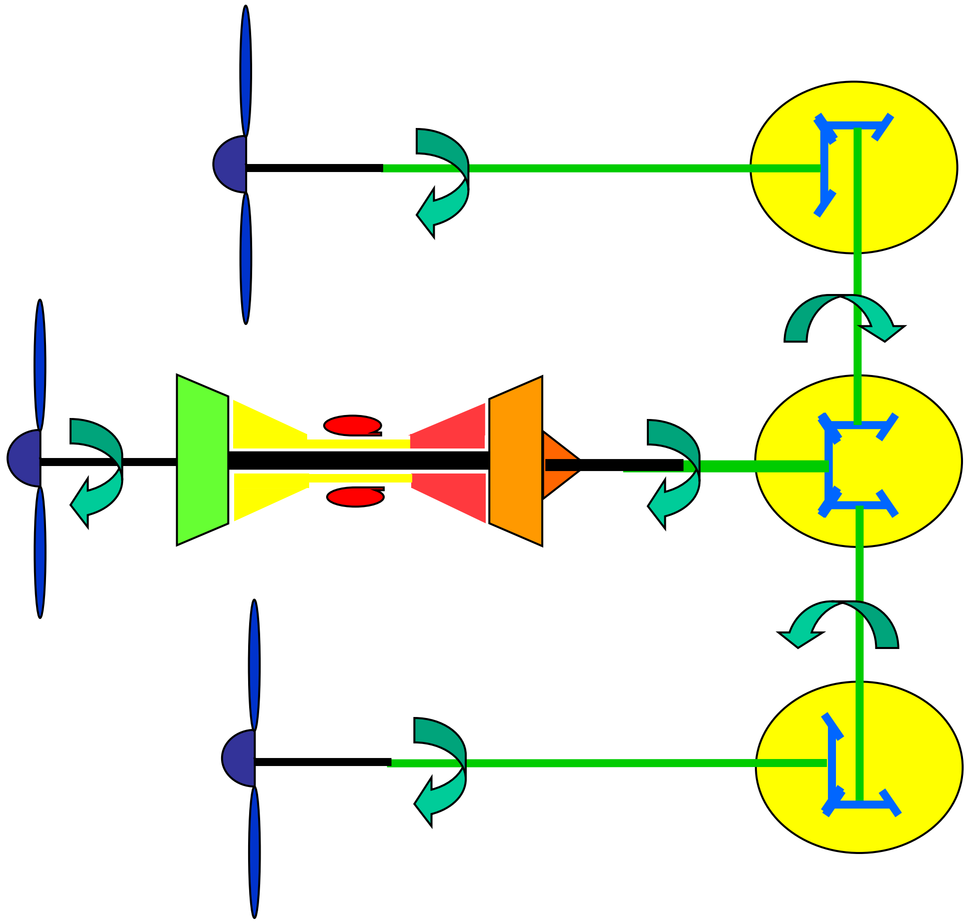
(Still need drive system technology to make configurations possible)

Future Aircraft

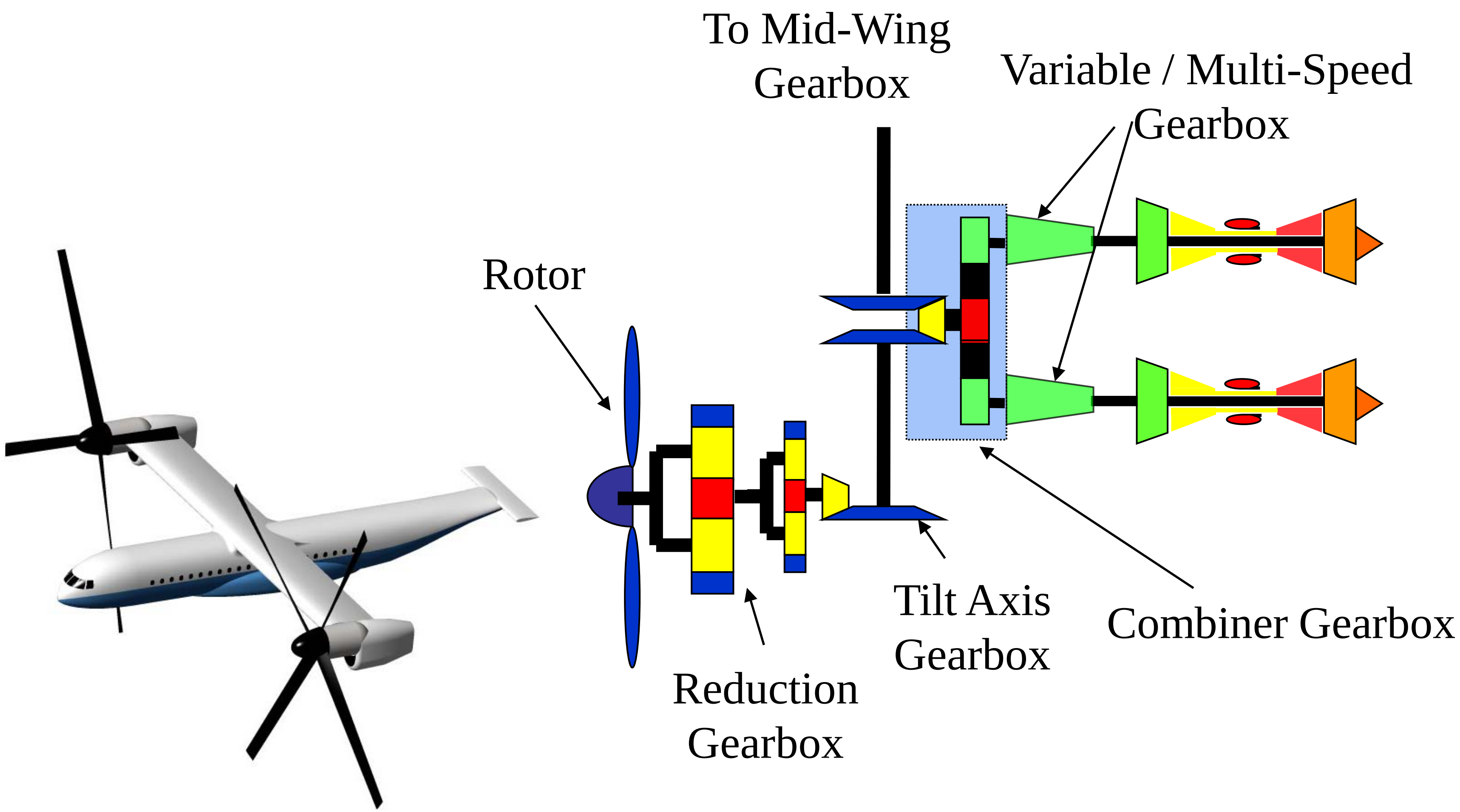


Blended Wing Propulsion Schematic

Tri-Fan Configuration

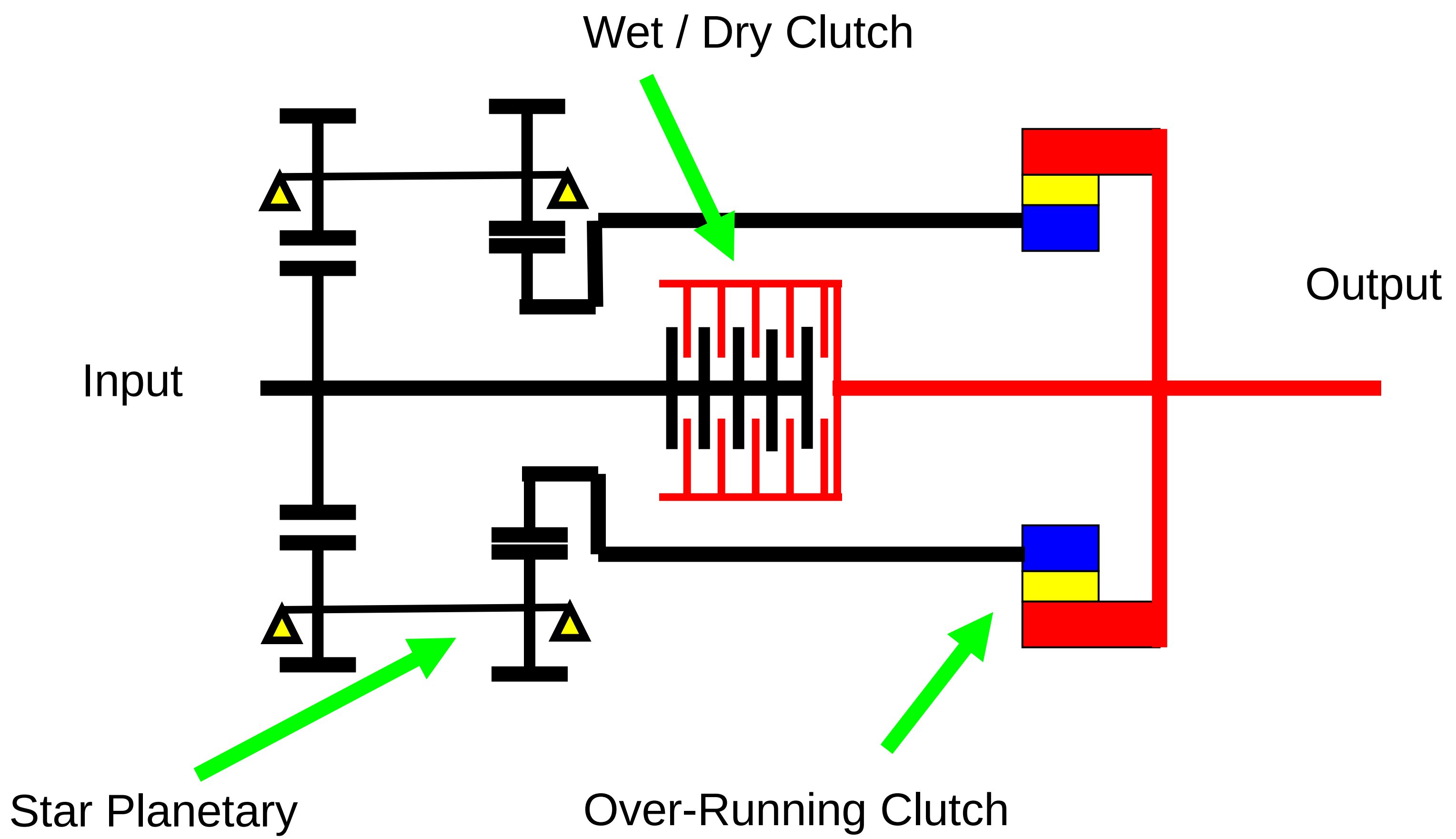


Civil Tiltrotor Drive System Configuration



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!