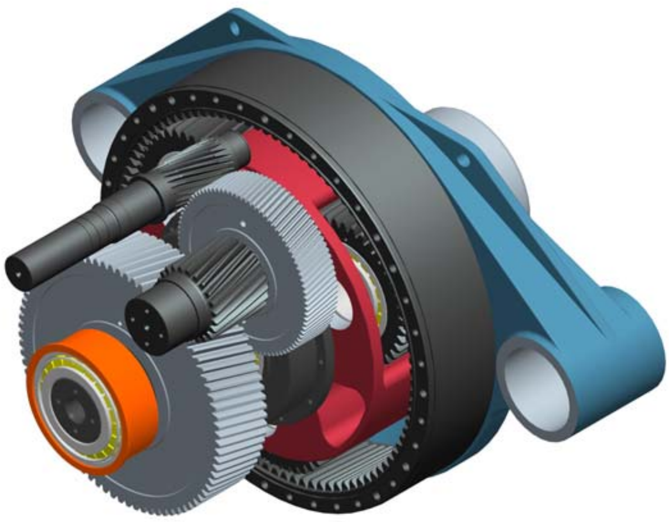
INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems
Task 11

57th IEA Topical Expert Meeting

Wind turbine drivetrain dynamics and reliability

Jyväskylä, Finalnd, September 2008
Organised by: VTT/Moventas



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For more information about IEA Wind see www.ieawind.org

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IEA RD&D Wind Task 11

Topical Expert Meeting #57

WIND TURBINE DRIVETRAIN DYNAMICS AND RELIABILITY

WIND TURBINE DRIVETRAIN DYNAMICS AND RELIABILITY

IEA RD&D Wind, TEM #57, Sep 4-5 2008, Jyväskylä, Finland

Sandy Butterfield, Esa Peltola, Claus Kurt Christensen, Sven-Erik Thor

Business from technology

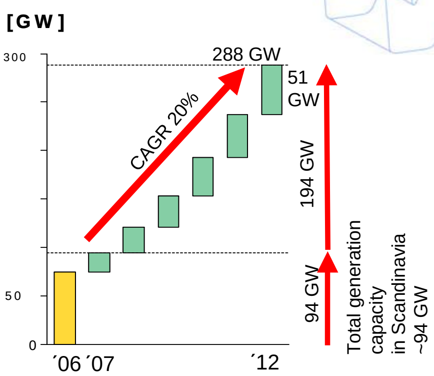
Agenda

1. **Introduction**
2. **Introduction by Operating Agent, recognition of Participants**
3. **Collecting proposals for presentations and for relevant discussion matters**
4. **Presentation of Introductory Note**
5. **Individual presentations**
6. **Discussion**
7. **Summary of meeting**

Introductory note

Background
Aims and objectives
Expected outcome

Rapid deployment of wind turbines



Sources: BTM Consulting 3/2008,
Nordel, ETSO
Original figure: Technology Industries Finland

- High growth rates continue
- Increasing growth rates

- Increased material costs
- Supply chain challenges
- Increasing capital costs

Growth of turbine size

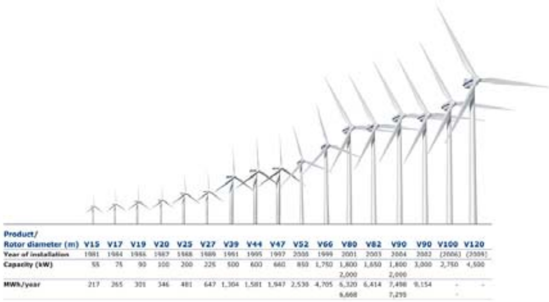


Figure: Vestas

- Rated power 10-fold in 10 years, 100-fold in 20 years
- Rated rpm ~1/3 in 10 years, ~1/10 in 20 years
  - Specification, design and manufacturing challenges
  - Design/supply challenges
  - Lower than expected reliability
  - Higher than expected lifetime operation costs

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Different operational conditions


Figure: VTT

- Offshore
  - Growth of turbines
  - Loads specifications
- Cold and icing climate
  - Loads specifications (asymmetry)
  - Temperature
- Turbine/access for o&m, repair
- Lower than expected reliability
- Higher than expected lifetime operation costs

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Outcome

Gather existing knowledge

Recommendations on how to proceed

Recommendations to research activities with IEA RD&D Wind agreement

Subject areas

Drive trains of future wind turbines

- status: failures modes, causes and statistics
- future: growth of wind turbines
- generator topologies and topology trade offs

Subject areas

Design requirements for drive trains

- design loads
  - load control tradeoffs
  - external conditions
- electrical system requirements
  - low voltage ride through
- options to allow for variable speed operation
- standards development

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Subject areas

Design and development process

- Drive train dynamic analysis and modeling
  - including drive train DOF's into aeroelastic models
  - drive train eigenfrequencies estimation and risks
- Component life rating
- Reliability analysis, failure risk estimation
- Virtual prototyping
- quality and material issues
  - New materials, needs and possibilities
  - Steel cleanliness
  - Material strength data

Subject areas

Quality assurance

- Dynamometer testing
  - Prototype testing for design validation
  - Endurance test acceptability
  - Acceptance testing

Subject areas

Operations and maintenance

- Failures modes, causes and statistics
- The role of condition monitoring
  - On-line load monitoring
  - Predictive methods

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Subject areas

Research consortiums in

- Design tools
- Life-time reliability

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Other related topics of interest?

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Outcome

Gather existing knowledge

Recommendations on how to proceed

Recommendations to research activities with IEA RD&D Wind agreement

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

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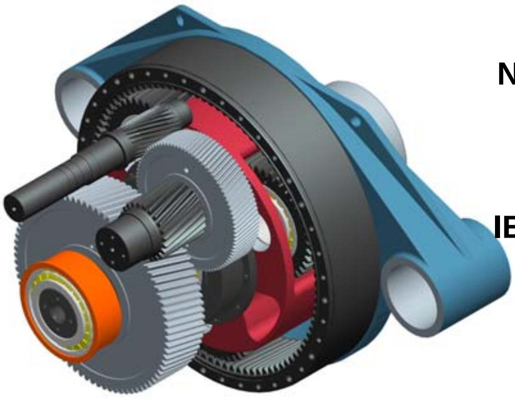
Innovation for Our Energy Future

Gearbox Reliability Collaborative Overview



Sandy Butterfield
Chief Engineer
National Wind Technology Center

NREL

IEA Drive Train Reliability Meeting
Hosted by Moventas
September 4 – 5, 2008

NREL is operated by Midwest Research Institute • Battelle

Observations on the Basic Problems

- Actual bearing life is below expected design life.
- Problems are generic in nature.
- Poor quality is not the primary cause.
- Most failures initiate in the bearings, not gears.
- Problems may be dependent on:
  - configuration (different bearings, suppliers & topologies)?
  - size (problems getting worse with size)?
  - Material quality?
  - Lubrication (additives, cleanliness, delivery, temperature)?
  - operating conditions (turbulence, control induced loads, loss of line stops)?

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Bearing Failure Observations

- General adherence to design standards
- AGMA 6006, IEC 61400-4, ISO 281:2007
- Proprietary codes prevent design transparency.
- Bearing manufacturers are not equipped to solve the problem.
- No single, simple solution is expected.
- Collaborative approach is needed.
- GRC approach will be required
- Weaknesses in the design process are **strongly** suspected.

Possible Design Process Weaknesses

- Missing Load Cases (or site specific load cases)
- Irregular or unanticipated bearing responses
- Excessive flexibility of gearbox mount.
- Non-uniform safety applied to gearbox subcomponents.
- Inappropriate lubrication delivery

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GRC Motivation

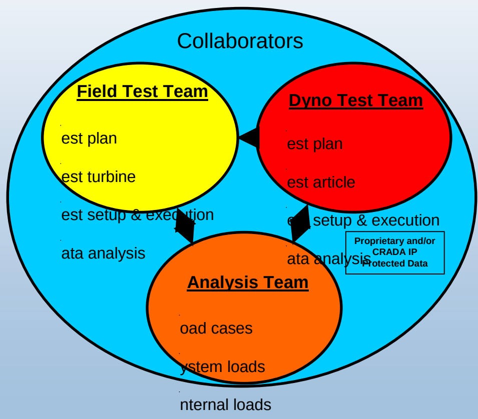
- Preliminary studies on failure statistics not conclusive
  - No gearbox/bearing data bases
  - European projects
    - Reliawind (use existing commercial statistics plus analysis)
    - ProTest (isolating gearbox measurements in field tests)
    - Commercial test programs
- Need unambiguous, transparent technical information.
  - US gearbox failure data base
- Must have both test and analytical data to reveal gaps in design process
- Credible experts and industry insights critical

NREL Gearbox Reliability Collaborative

Objectives

- Understand and isolate sources of gearbox failures.
- Suggest solutions leading to greater reliability
- Develop dynamometer testing capability to assess gearbox/ drivetrain problems and solutions
- Understand how gearbox loads translate to bearing response (stress, skidding, load distributions, deflections).
- Develop a more comprehensive gearbox design load case matrix.
- **Evaluate and validate current drive train design process and analytical tools.**

Project Strategy



GRC Core Team

- Assembled credible experts
  - Errichello (failure diagnoses, bearing benchmark, failure database design, scientific guidance)
  - Hahlbeck (redesign, design practice, test hardware)
  - Harris (bearing design, research guidance, application, link to bearing design community)
  - McNiff (gear industry link, test design)
  - Walford (bearing instrumentation & failure data base implementation,)
- The Gear Works (rebuild test articles, re-machine, new parts, assembly, document, instrumentation assembly, calibration)
- Xcel (field test turbine, dyno balance of equipment)

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Collaborators / Advisory Team

- Xcel Energy
- Vattenfall
- DONG Energy
- FPLE
- enXco
- Terra-Gen
- SKF
- Timken
- Romax
- Ricardo
- GE Transportation
- Winergy US
- ReliaWind (European Reliability project)

- Support contracts (controller, ancillary machinery refurbishment, instrumentation)

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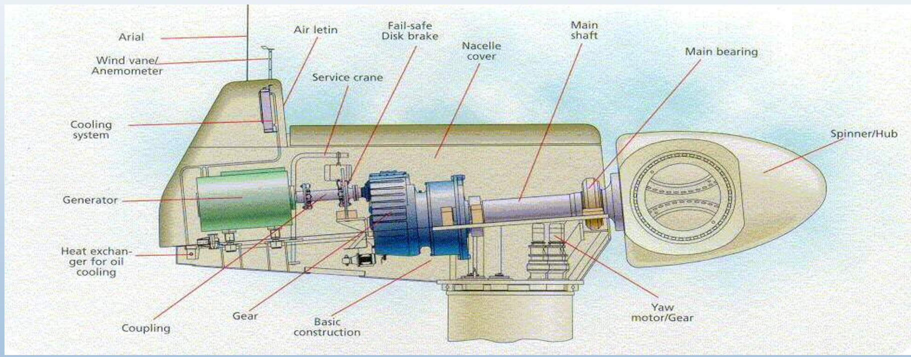
Typical Wind Turbine Architecture (GRC Turbine)



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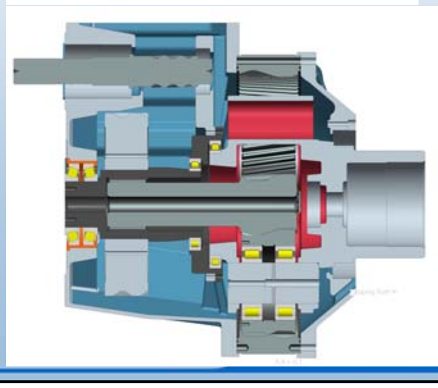
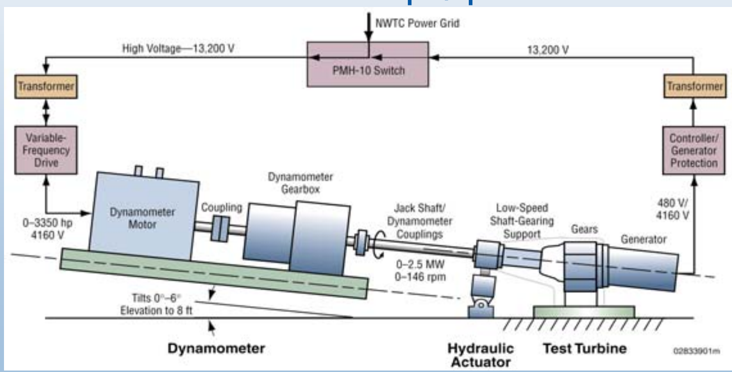
Test Articles

- Test platform 750kW.
- 2 gearboxes with identical instrumentation.
- Upgrade both units to state-of-the art.
  - Cooling, gear finish, lubrication delivery, filtration, and bearing types.
- Measure External and internal loads and displacements.
- Thermal measurements
- Condition monitoring
- Expert failure analysis and forensics



NREL Dynamometer Specifications

- 2.5 MW power delivery
- Full power regeneration at 480/575/690 or 4160 volts
- Torque input range 0 - 1.62 million N-m.
- Speed range from 0 - 2250 RPM
- ~500 kN non-torque shaft loads capacity.
- SCADA and automated torque/speed controls

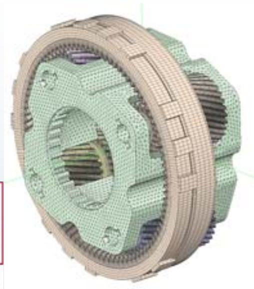


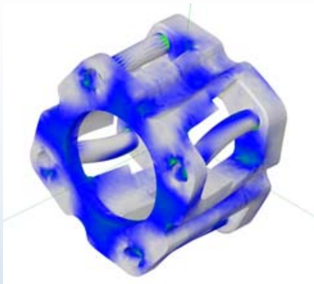
Field Testing

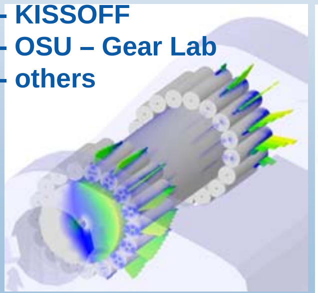
- Ponnequin Xcel Windfarm in Northern Colorado USA
- Extensive measurements on a single turbine.
- Characterize load events
- Correlate loads with component internal gearbox responses.
- Site-wide failures and statistics.

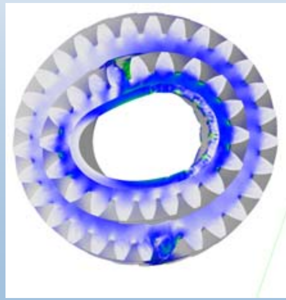
Multiple analytical approaches will be vetted

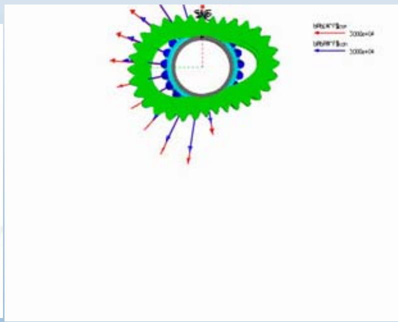
- SKF
- CENER
- NREL
- Romax
- Ricardo
- GE Transportation
- KISSOFF
- OSU – Gear Lab
- others











SKF

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Gearbox Failure Database

- Need a unambiguous failure data base to focus research accurately.
- Inspection training is crucial
- Data input software to aid inspection, data consolidation and consistency
- Aid in bearing failure interpretation
- Participation welcome

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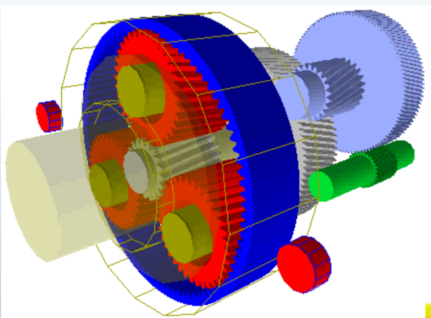
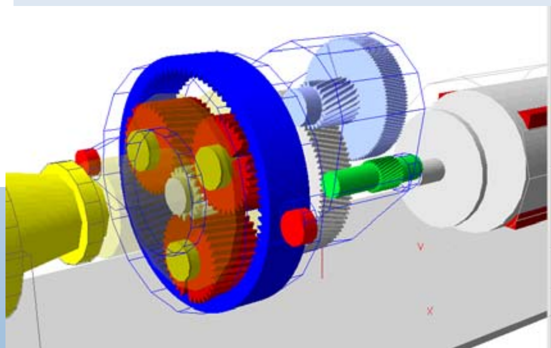
IEA Gearbox Reliability Annex?

- GRC could supply information to broader scope
- IEA provides convenient agreement mechanism to control dissemination of information and data
- Must honor existing GRC agreements
- Ultimately GRC reference data set published

Research Towards Greater Reliability NREL - Gearbox Reliability Collaborative



Simpack - Intec



Gearbox Reliability Collaborative
- Test Engineer's Views -

Brian McNiff, McNiff Light Industry
And, oh, yeah, ...Sandy Butterfield, NREL

NREL

McNiff Light Industry
Wind Turbine Testing and Analysis

GRC Test Approach

- looking for bearing behavior that is unexpected, non-linear, or suspect under all conditions
- not necessary to reproduce every type of bearing or gear failure
- IF subsequent analysis demonstrates that behavior can result in reduced bearing life.
- IF behavior can be accurately documented, modeled and understood

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Wind Turbine Testing and Analysis

Critical Measurements

1. motion, forces,moments on shaft & mounts;
2. shaft axial and radial motions;
3. load sharing between planet gears;
4. radial load distribution along each bearing;
5. bearing inner ring to outer ring relative motions;
6. bearing slip or skidding;
7. temperature of bearing inner & outer rings;
8. relative motion of carrier to housing;
9. sun pinion motion and displacement;

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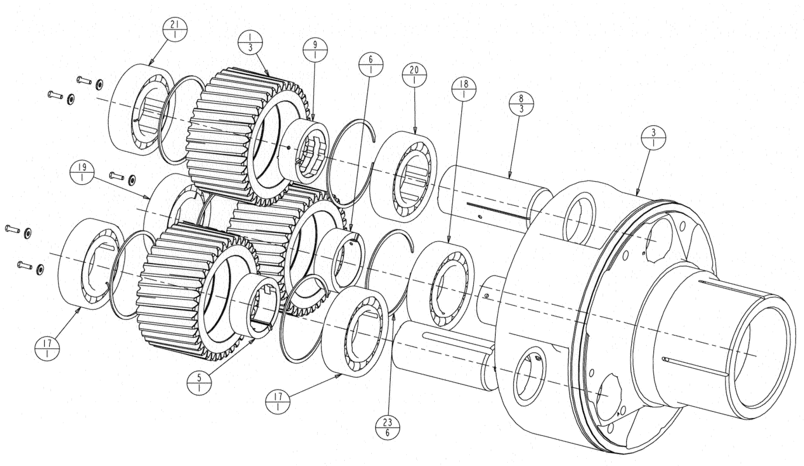
Wind Turbine Testing and Analysis

Expanded Planetary Assembly



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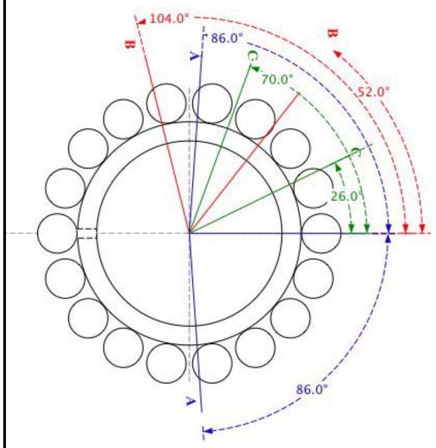
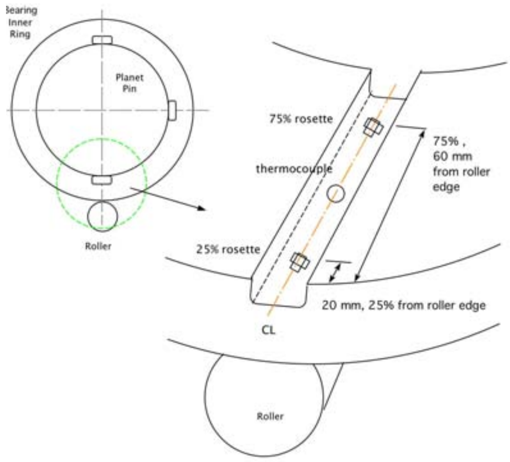
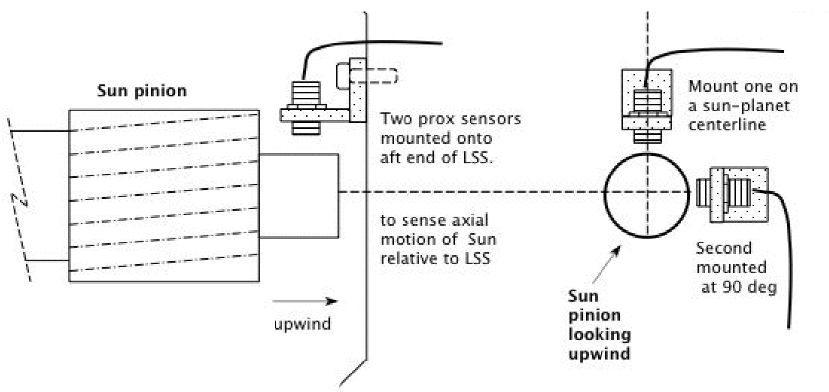
Bearing radial load distribution

- shifting arch location to get distribution
- measures arch bending as each roller passes





Sun Pinion Radial Motion



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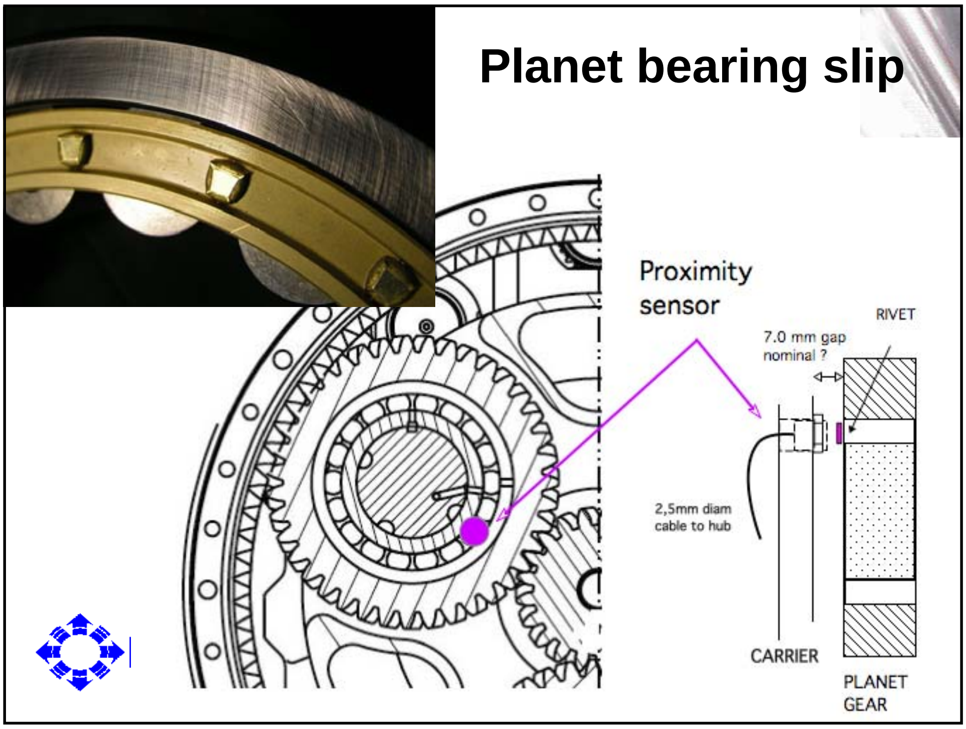
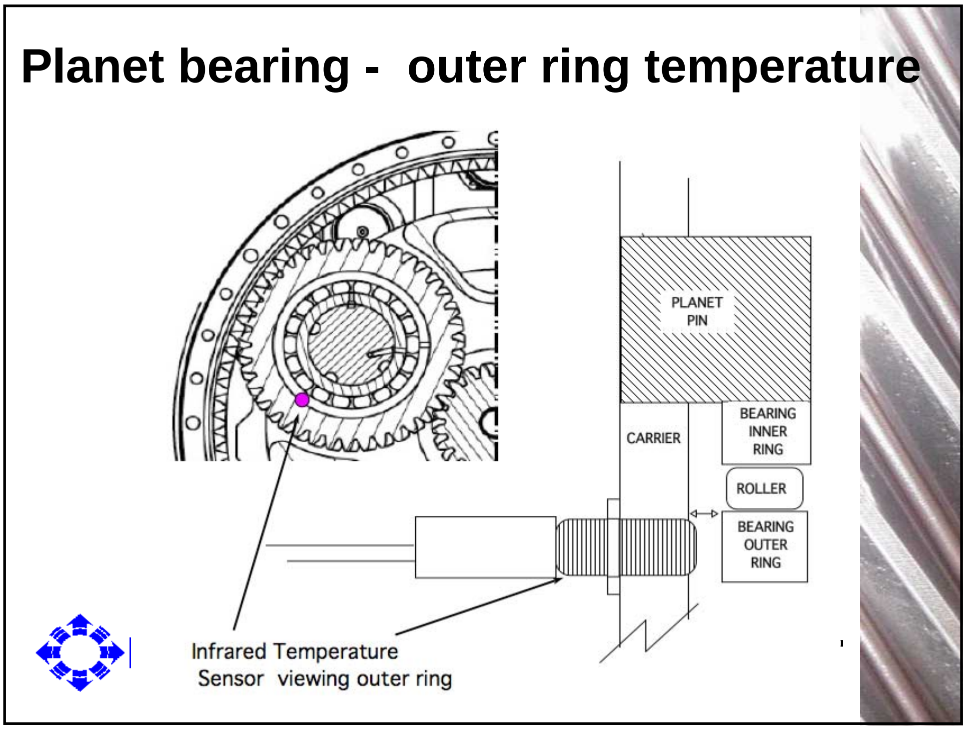
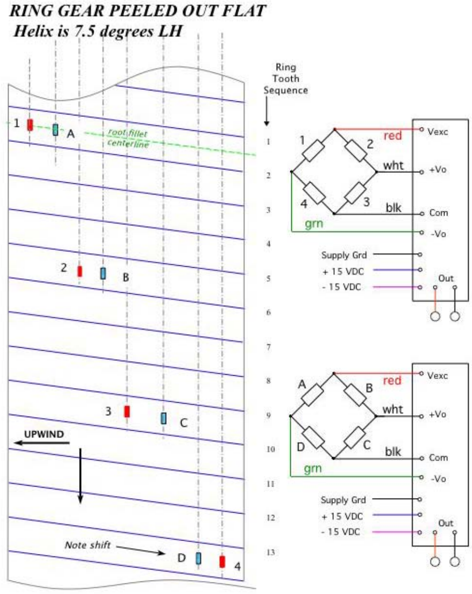
Wind Turbine Testing and Analysis

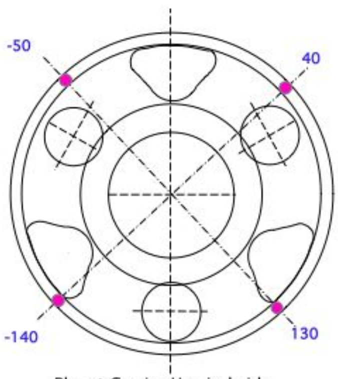

Planet bearing slip
Proximity sensor
RIVET
7.0 mm gap nominal ?
2,5mm diam cable to hub
CARRIER
PLANET GEAR


Planet bearing - outer ring temperature
PLANET PIN
CARRIER
BEARING INNER RING
ROLLER
BEARING OUTER RING
Infrared Temperature Sensor viewing outer ring

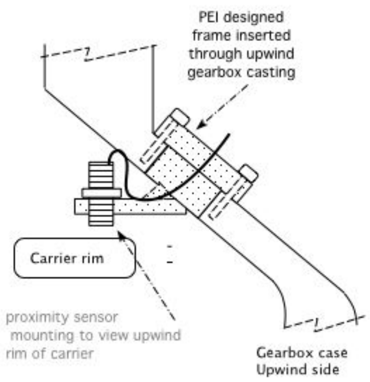
Ring Gear - Load Distribution



Carrier Rim Deflection - Radial



Planet Carrier Upwind side



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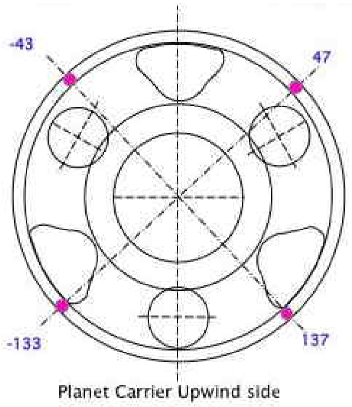
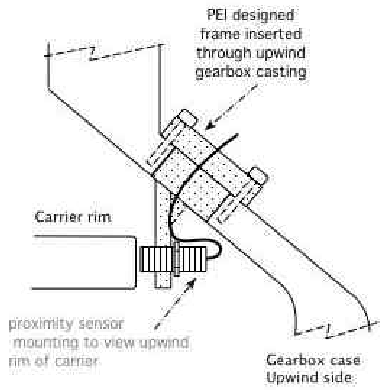
Carrier Rim Deflection - Axial





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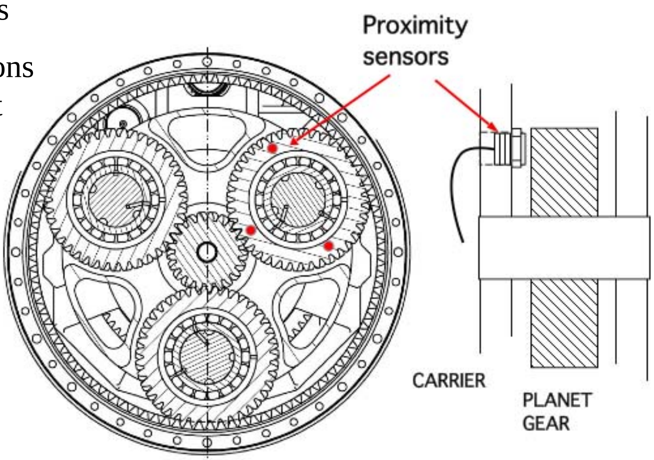
Planet Rim Deflection

- 2 planets
- 3 locations per planet



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Other signals (120+)

- Low speed shaft torque, bending,thrust & motion
- High speed shaft torque and motions
- Encoders to give accurate speed and shaft positions
- Motion and deflections at trunion mounts
- Triaxial gearcase stress to match Dyno non-torque loading with in-field response
- Electrical response and control actions/ states

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Drivetrain Design and Validation Needs

- Improved design analysis tools
  - increase drivetrain DOFs in WTG aeroelastic models
  - Integrated FEA/ multibody/ mesh models needed?
  - Transparency in bearing rating methodology
- How to use Dynamometer testing to validate as-built
  - What situations / DLC to simulate
  - Should verify design assumptions, to reduce uncertainty and increase confidence
  - Use to shake out prototype issues before field test

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Wind Turbine Testing and Analysis

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A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Gearbox Reliability Collaborative (GRC) Analysis Round Robin IEA Meeting

Presented by
Francisco Oyague
September 3-4/2008

NREL is operated by Midwest Research Institute • Battelle

Introduction
GRC Analysis Team Goals

- Evaluate common design practices?
- What are the existing tools?
- What tools are used by the industry?
- What level of model fidelity is required?
- Assumptions?

The GRC Analysis Round Robin

- The GRC gearbox
  - Detailed technical specifications (confidential to GRC participants for a limited period)
  - Drawings and solid models
  - Material
- Many standard analytical approaches
- Results from many commercial and in-house codes

Analysis Round Robin List of Participants

- ALSTOM-ECOTÈCNIA
- CENER
- DONG Energy
- GE Transportation
- Intec
- KISSsoft
- NREL
- Harris Consulting
- OSU Gear Lab
- Ricardo Inc.
- Romax
- SKF
- Timken
- Vattenfall
- Vestas
- Ansol

Loading Conditions

Calibration load cases

Load Matrix Simulated Load Cases					
Phase	Classification	Load Case	HSS RPM	INP Torque	Units
Phase 1	Static	CLC 1.1	N/A	120.77	kN.m
Phase 1		CLC 1.2	N/A	322.61	kN.m
Phase 1	Dynamic	CLC 2.1	1208	120.77	kN.m
Phase 1		CLC 2.2	1208	128.83	kN.m
Phase 1		CLC 2.3	1809	322.61	kN.m

Simulated Time Series

- Aeroelastic Simulations (FAST)
- Load spectrum follows IEC
  - Time at level load spectrum
  - Time series

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Modeling Overview

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Planet Carrier Deflections

- Rigid planet carrier
- Flexible planet carriers
  - – Gear mesh misalignment
  - – Planet load share
  - – Bearing loading

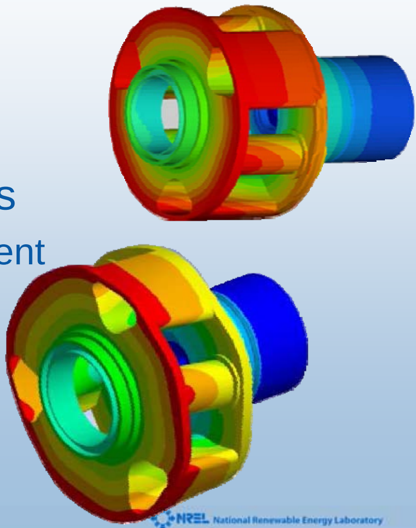


Figure 1: Ricardo Inc.
Figure 2: Ge transportation

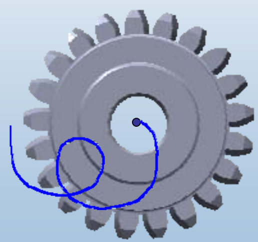
Floating Sun Configuration

Floating Sun Configuration

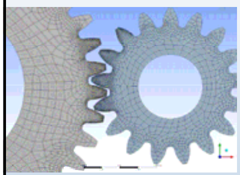
- Planet load share
  - Dynamic transient events
- Sun motion with respect to the planet carrier

Floating Sun Configuration

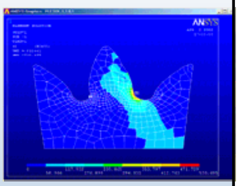
- Planet load share
  - Dynamic transient events
- Sun motion with respect to the planet carrier

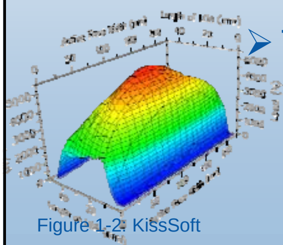


Gear Mesh Stiffness and Tooth Loading



- Gear mesh stiffness
  - FEA based
  - Beam approximation
  - Parabolic function





- Tooth load distribution
  - Max loading
  - Tooth discretization

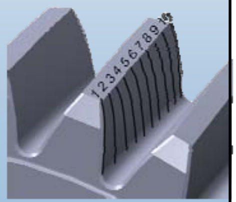
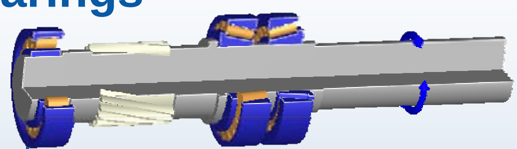
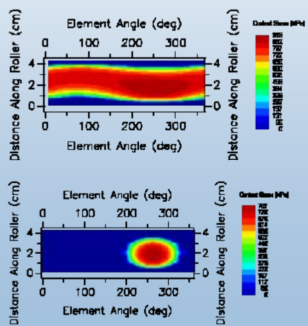


Figure 1-2: KissSoft
Figure 3: Ge transportation   Figure 4: NREL

Bearings

- Bearing linear stiffness
- Bearing non-linear diagonal terms
- 5x5 stiffness implementation
- Bearing life
- Contact stress





Figures: Romax technologies

Shaft Bending and Torsional Contribution

- Shaft bending at discretized locations
- Shaft bending at specified locations
- Shaft torsional contributions

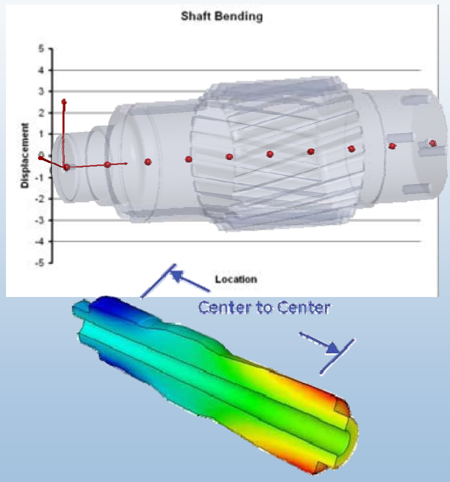


Figure 1: NREL
Figure 2: Ge transportation

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Assumptions

- Revision and comparison of assumptions among the different analysis
- Revision of assumptions with experimental data

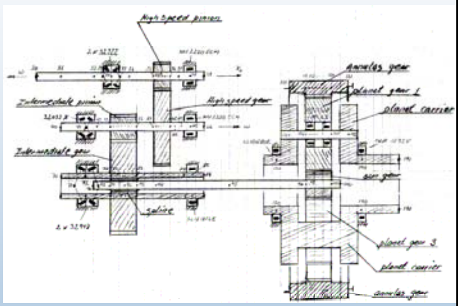

Figure 1: DONG Energy

NREL National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Gearbox Reliability Collaborative (GRC)
Analysis Round Robin
IEA Meeting

Presented by
Francisco Oyague
September 3-4/2008

NREL is operated by Midwest Research Institute • Battelle

Introduction
GRC Analysis Team Goals

- Evaluate common design practices?
- What are the existing tools?
- What tools are used by the industry?
- What level of model fidelity is required?
- Assumptions?

NREL National Renewable Energy Laboratory

The GRC Analysis Round Robin

- The GRC gearbox
  - Detailed technical specifications (confidential to GRC participants for a limited period)
  - Drawings and solid models
  - Material
- Many standard analytical approaches
- Results from many commercial and in-house codes

Analysis Round Robin List of Participants

ALSTOM-ECOTÈCNIA	OSU Gear Lab
CENER	Ricardo Inc.
DONG Energy	Romax
GE Transportation	SKF
Intec	Timken
KISSsoft	Vattenfall
NREL	Vestas
Harris Consulting	Ansol

Loading Conditions

Calibration load cases

Load Matrix Simulated Load Cases					
Phase	Classification	Load Case	HSS RPM	INP Torque	Units
Phase 1	Static	CLC 1.1	N/A	120.77	kN.m
Phase 1		CLC 1.2	N/A	322.61	kN.m
Phase 1	Dynamic	CLC 2.1	1208	120.77	kN.m
Phase 1		CLC 2.2	1208	128.83	kN.m
Phase 1		CLC 2.3	1809	322.61	kN.m

Simulated Time Series

- Aeroelastic Simulations (FAST)
- Load spectrum follows IEC
  - Time at level load spectrum
  - Time series

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Modeling Overview

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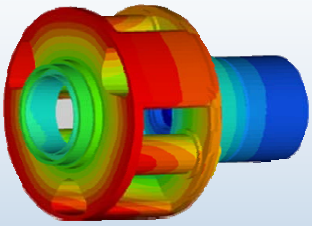
Planet Carrier Deflections

- Rigid planet carrier
- Flexible planet carriers
  - – Gear mesh misalignment
  - – Planet load share
  - – Bearing loading



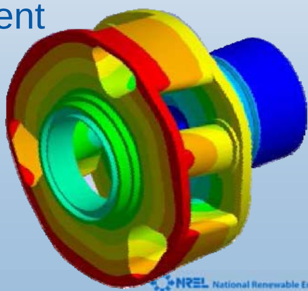


Figure 1: Ricardo Inc.
Figure 2: Ge transportation

NREL National Renewable Energy Laboratory

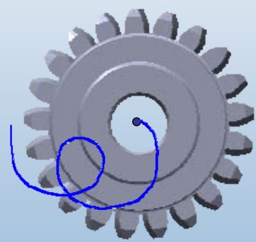
Floating Sun Configuration

NREL National Renewable Energy Laboratory

Floating Sun Configuration

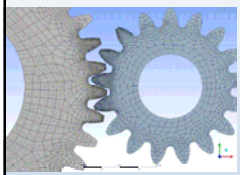
- Planet load share
  - Dynamic transient events
- Sun motion with respect to the planet carrier

Floating Sun Configuration

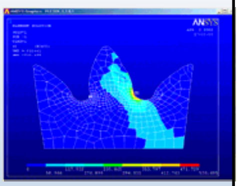


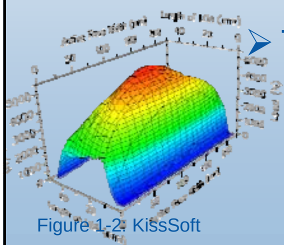
- Planet load share
  - Dynamic transient events
- Sun motion with respect to the planet carrier

Gear Mesh Stiffness and Tooth Loading



- Gear mesh stiffness
  - FEA based
  - Beam approximation
  - Parabolic function





- Tooth load distribution
  - Max loading
  - Tooth discretization

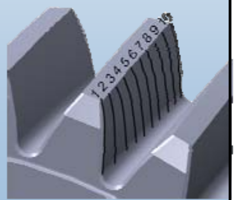


Figure 1-2: KissSoft
Figure 3: Ge transportation Figure 4: NREL

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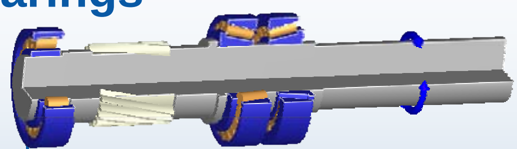
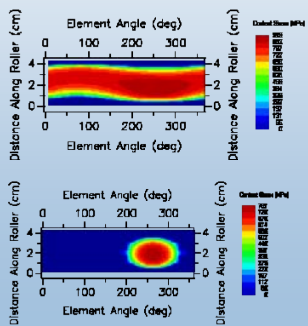
Bearings



- Bearing linear stiffness
- Bearing non-linear diagonal terms
- 5x5 stiffness implementation
- Bearing life
- Contact stress



Figures: Romax technologies

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Shaft Bending and Torsional Contribution

- Shaft bending at discretized locations
- Shaft bending at specified locations
- Shaft torsional contributions

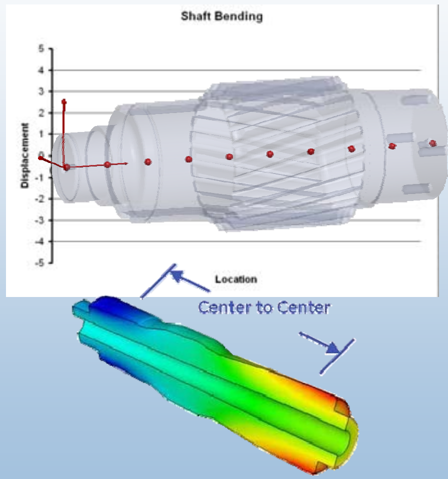


Figure 1: NREL
Figure 2: Ge transportation

NREL National Renewable Energy Laboratory

Assumptions

- Revision and comparison of assumptions among the different analysis
- Revision of assumptions with experimental data

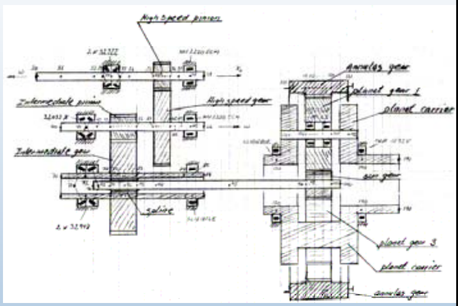


Figure 1: DONG Energy

NREL National Renewable Energy Laboratory

ECN

Energy research Centre of the Netherlands

The EC funded project PROTEST
(PROcedures for TESTing and measuring wind energy systems)
Henk Braam, Luc Rademakers

www.ecn.nl

ECN

Contents

Outline of project PROTEST

- Background and objective
- Approach
- General information

PROTEST measurements at ECN

- EWTW (ECN Wind Turbine test site Wieringermeer)
- ECN measurement system
- Measurement campaign

Energy research Centre of the Netherlands www.ecn.nl

ECN

PROTEST: Background

Main components are designed for lifetime of turbine

But: Some fail too early!

- offshore: 2 - 5 failures per year requiring a visit not abnormal
- electrical components and control system fail more often than mechanical components (gearbox etc.)
- maintenance costs for mechnical components are dominant

What about loads in field??

Energy research Centre of the Netherlands www.ecn.nl

ECN

PROTEST: Background

Experts opinion

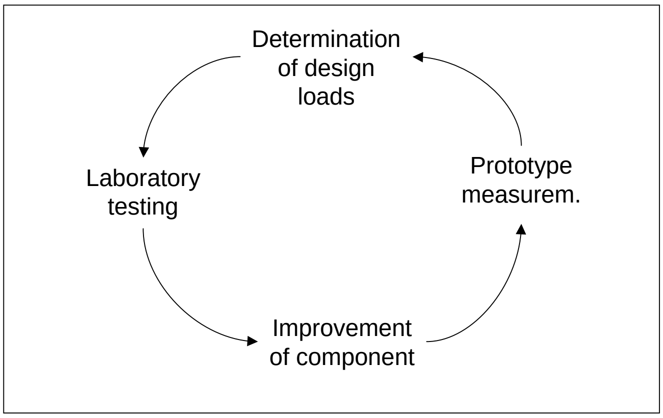
- major cause of failures of mechanical systems is insufficient knowledge of the actual loads acting on these components
    - shortcoming in load simulation models
    - shortcomings in load measurement procedures (validation of models etc.)
- WT codes and guidelines (IEC-61400, GL guidelines) do not cover the mechnical components properly
    - aim at rotor and tower for safety reasons
    - design loads in IEC 61400-1 and GL guidelines: only external loadings mainly due to wind and electrical conditions
    - IEC 61400-4 (gearbox)
        - in addition to IEC 61400-1 specific DLC's shall be considered
        - however, these DLC's are not specified

Energy research Centre of the Netherlands www.ecn.nl

ECN

PROTEST: Background

Design proces for blades (and Tower)



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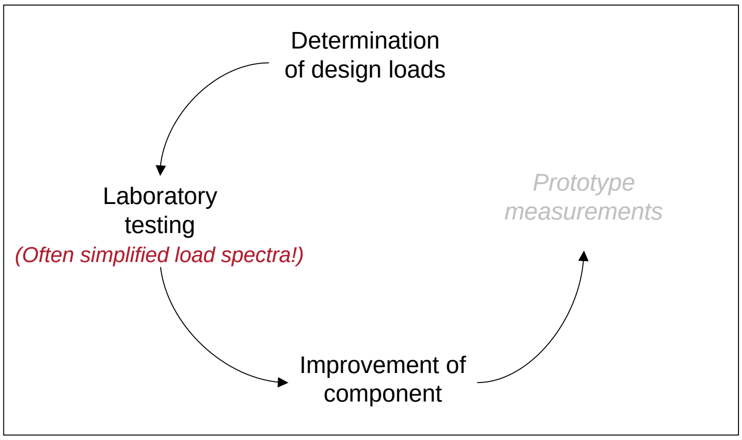
ECN

PROTEST: Background

Design proces for not safety related components



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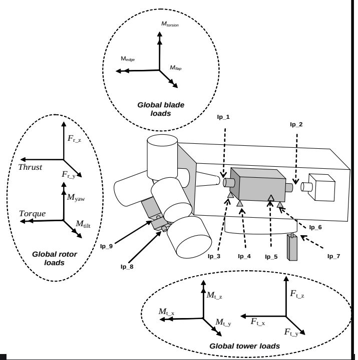
ECN

PROTEST: overall objective

- Set up a methodology that enables standardised specification of the design loads for mechanical components in wind turbines such as the main bearing, drive train, yaw bearing and pitch system
- The design loads will be specified at the interconnection points where the component can be "isolated" from the entire wind turbine structure.
- focus on measurements of “loads” at interfaces during proto type measurements mainly for validation of codes



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PROTEST: questions w.r.t objectives

- How should the loads at the interconnection points be derived from the global turbine loads?
- Which design load cases should be considered in addition to IEC 61400-1 or GL guidelines?
- Which signals should be measured during prototype testing (including sample frequency, accuracy) to enable tuning of models and validation of codes?
- How should the loads at the interconnection points be reported and communicated between turbine manufacturer and component supplier?

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ECN

PROTEST: approach

1. Description of current practice for designing and developing mechanical components (drive train, pitch system and yaw system)
2. Draft for improved procedures for specifying design loads and for measuring loads at interconnection points
   - Further specification of IEC 61400-4
   - Additional DLC's for IEC 61400-1 and GL guidelines
   - Extension of IEC 61400-13

   Questionnaires (1) inside consortium (2) manufacturers and other experts
3. Application of procedures in three case studies

   Measurements and model calculations
   - Gearbox: Suzlon S82 in India - Suzlon, Hansen, DEWI, Univ. of Stuttgart
   - Pitch system: N80 at EWTW - ECN
   - Yaw system: NM750 in Greece - CRES (complex terrain)

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ECN

PROTEST: general information

- Pre-normative research funded by EC
  - Total budget : 2,675,619 Euro (EC: 74%)
  - Manpower : 160.6 person months
  - Duration: March 2008 – Dec. 2010
- Dissimination of results
  - Standardisation committees (IEC, Measnet)
  - Public report on website: www.protest-fp7.eu
  - Via GRC of NREL
  - Within project consortium
- Consortium
  - ECN, DEWI, CRES, Hansen, Suzlon, GL, Univ. of Stuttgart

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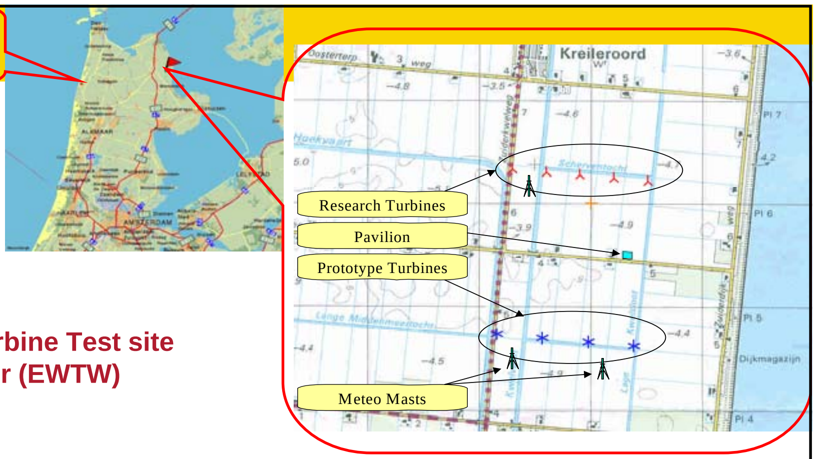

ECN Wind Turbine Test site Wieringermeer (EWTW)

- Five research turbines N80 with one 108m high meteorological mast
- Four prototype turbines with 108m and 100m meteorological masts
- Measurement Infrastructure
- Measurement Pavilion
- Scaled wind farm (10 turbines, D = 7 m, 13 met masts)

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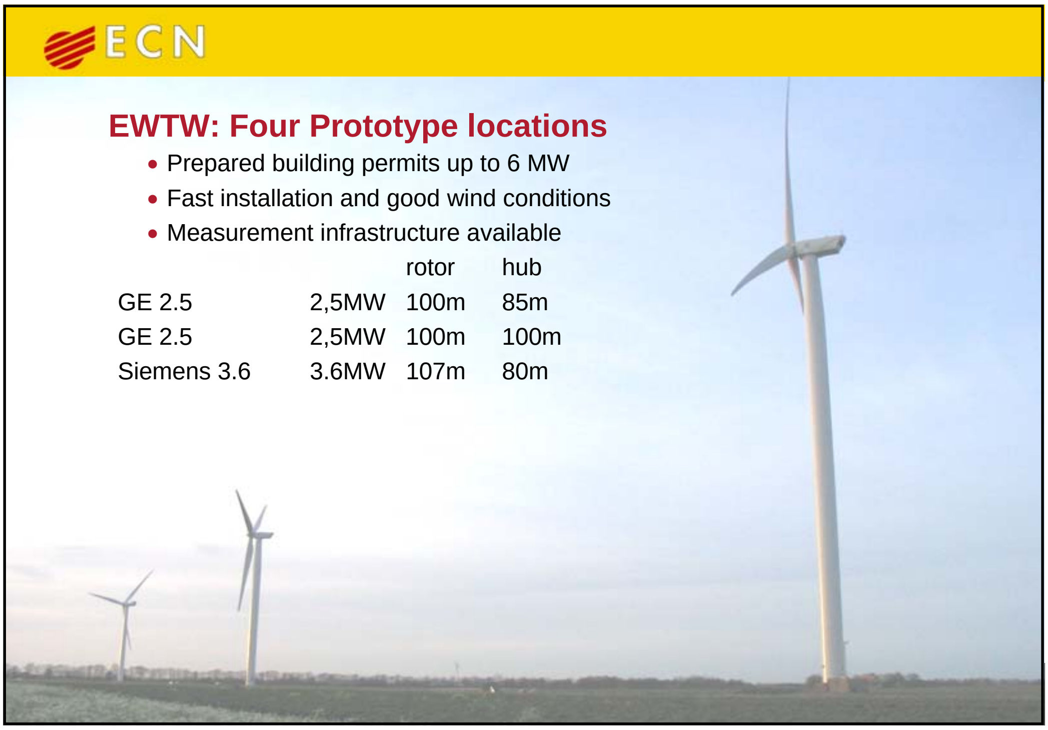
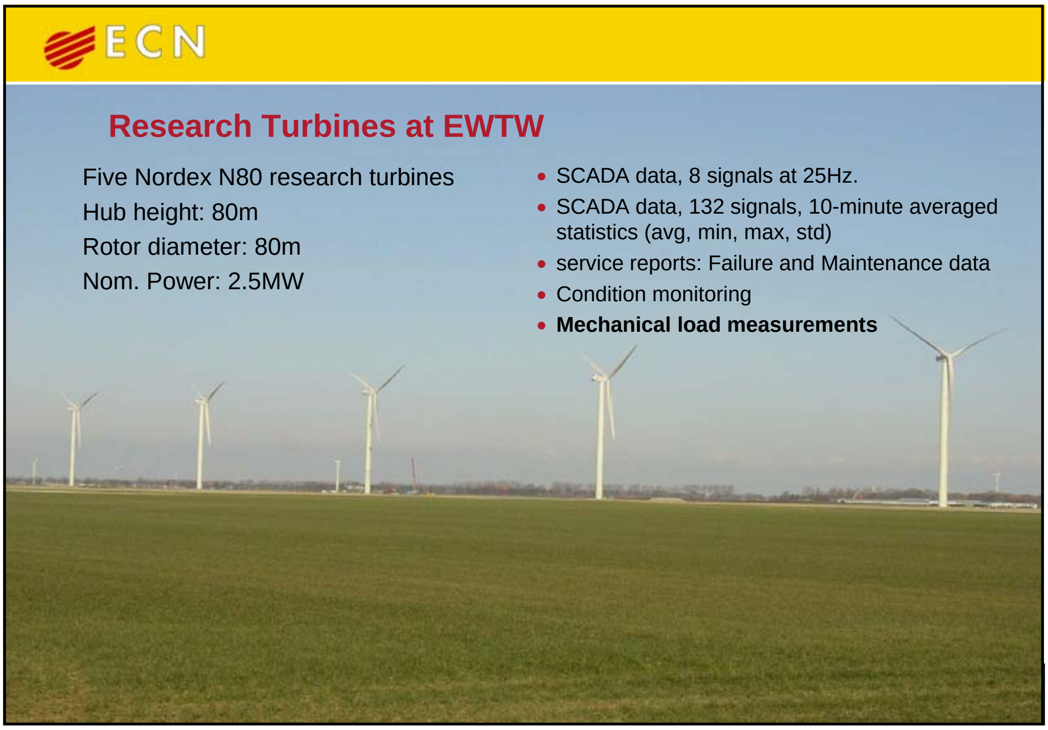

ECN
EWTW: Four Prototype locations
• Prepared building permits up to 6 MW
• Fast installation and good wind conditions
• Measurement infrastructure available
rotor hub
GE 2.5 2,5MW 100m 85m
GE 2.5 2,5MW 100m 100m
Siemens 3.6 3.6MW 107m 80m


ECN
Research Turbines at EWTW
Five Nordex N80 research turbines
Hub height: 80m
Rotor diameter: 80m
Nom. Power: 2.5MW
• SCADA data, 8 signals at 25Hz.
• SCADA data, 132 signals, 10-minute averaged statistics (avg, min, max, std)
• service reports: Failure and Maintenance data
• Condition monitoring
• Mechanical load measurements

ECN

PROTEST signallist measurement campaign EWTW

ProTest measurement campaign EWTW

Measurements	N5	N6	N7	N8	N9
Nacelle anemometry					
Wind speed (cup + sonic) and wind direction	green	green	green	green	green
Operational signals					
Electrical power	green	green	green	green	green
Generator speed	green	green	green	green	green
Operational mode	green	green	green	green	green
Yaw angle	green	green	green	green	green
Demanded torque		green		green	
Pitch system					
Pitch angle blade n=1,2,3	green	green	green	green	green
Pitch current blade n=1,2,3		green		green	
Torque pitch shaft blade n=1,2,3		red		red	
Rotational speed pitch shaft blade n=1,2,3		red		red	
Torque friction		red		red	
Deformation of pitch bearing		red		red	
Temperatures		red		red	
Blades/Rotor					
Blade root bending moments		green		green	
Rotor azimuth		green		green	
Blade torsion blade n=1,2,3		red		red	
Temperatures		red		red	
Blade deformation		blue		blue	
Blade root bending moments by means op fiber optic sensors		blue		blue	

Measurements	N5	N6	N7	N8	N9
Main Shaft					
Bending at 2 pos. (mid, shrink disk)		green		green	
Torsion at 2 pos. (mid, shrink disk)		green		green	
Deformation of bearing		red		red	
Gearbox					
displacement w.r.t. nacelle		red		red	
displacement planetary shaft w.r.t frame/housing		red		red	
eigen frequencies		red		red	
High speed shaft					
Torque		green		green	
Tower					
Tower bottom bending NS-EW		green		green	
Tower bottom bending NS+45-EW+45		green			
Tower torsion; bottom + top		green		green	
Special MLC's					
measurements with generator speeds in the range of 200 -2000 rpm, while the turbine is not coupled to the grid (Campbell diagram)					
LVDT					
stiffness of drive train w.r.t. torque of drive train					
Instrumentation already present (green)					
additional ProTest measurements (red)					
new measurements for other projects (blue)					

ECN

PROTEST measurement campaign EWTW

Suggestions for measurements gearbox in N80 WT at EWTW?

Measurement of drive system dynamics

IEA RD/D, Task 11

Vattenfall
PYST/ Technology
Claus Kurt Christensen

VATTENFALL

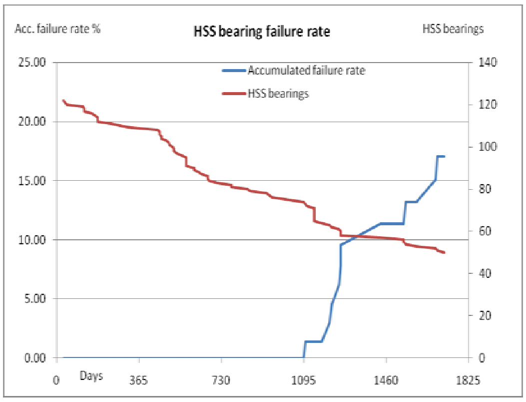
Background

- Vattenfall operates 80 Pcs 2MW offshore machines (Ownership 60/40 share Vattenfall / DONG Energy)
- Turbines are DFIG types
- After 5 years, gearbox failure rate ~ 60% (replacements)
  - All gearboxes are identical of make and manufacture
  - There are no explanations for the nature of bearing failures
  - Only HSS bearing failures show consistent failure pattern

DMT VATTENFALL

Dynamic measurements in a 2MW wind turbine

- HSS bearing failures: Seems to be a wear out phenomenon



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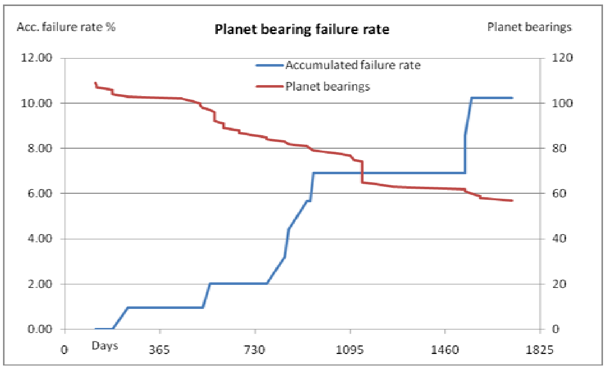
DMT VATTENFALL

Dynamic measurements in a 2MW wind turbine

- Planet bearings: Stochastic failure rate (from day 1)



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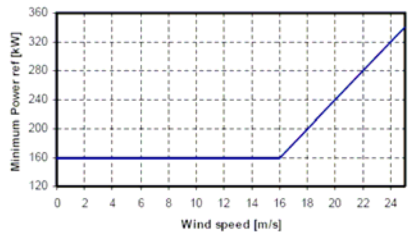
DMT VATTENFALL

Dynamic measurements in a 2MW wind turbine

- The wind farm power can be derated until 160kW/turbine for wind speeds [0 < V =< 16m/s]
- Minimum bearing load calculation will require a minimum load of >= 400kW (provided constant speed)



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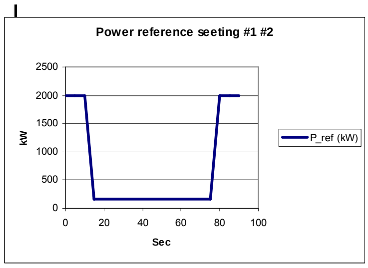

Measurement sequence

DMT VATTENFALL

Definition of the project

- High speed measurement of mechanical and electric parameters with attention to Torque, speed variations (dw/dt) and movement
  - Integration of operating data
  - Analysis of transient loads
  - Analysis of high load/low load conditions
  - Analysis of extreme single events and turbine errors
  - Long term measurement program
  - Auto Storage with triggered pre-defined conditions

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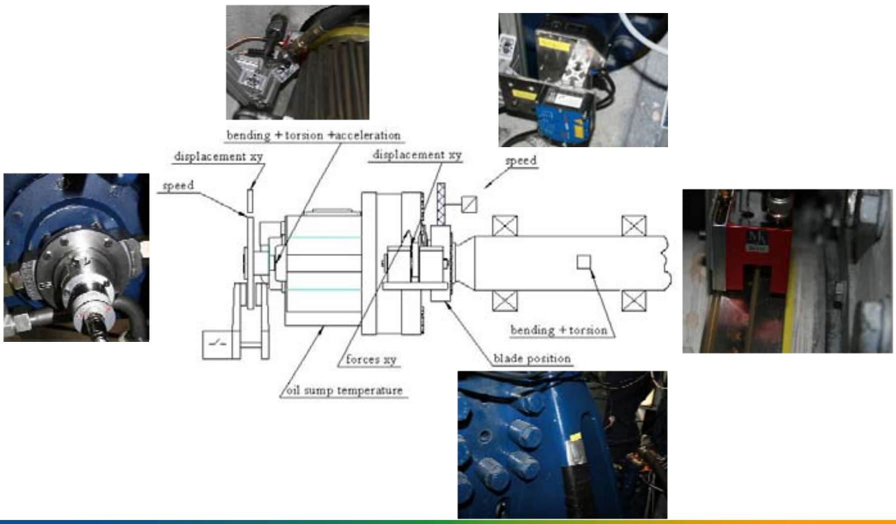
Measurement set-up



Specifications for data aquisition equipment

data evaluation		
measurement pc	Offshore compatible	
measurement card	NI 6143	250 kHz

HSS shaft		Sampling rate
speed	speed HSS oil pump	71,7 kHz
torsion	strain gauge	50,0 kHz
bending	strain gauge	50,0 kHz
acceleration	accl. sensor	50,0 kHz
bearing temperature		30 Hz
oil pressure		200 Hz

Specifications for data aquisition equipment

LSS shaft			Sampling rate
speed	speed at shrink disc		19 kHz
torsion	strain gauge		50,0 kHZ
bending	strain gauge		50,0 kHZ
displacement		resolution	
displacement	nearby HSS x,y direction	6µm	2,5 kHZ
displacement	nearby torque arms x,y direction	6µm	2,5 kHZ
Forces/strain	torque arms, left and right side		1,0 kHZ

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Specifications for data aquisition equipment

operating data / analogue signals from turbine controller	
oil sump temperature	125 HZ
wind speed	125 HZ
power	125 HZ
pitch angle	125 HZ
bearing temperature	125 HZ
brake contact	125 HZ
oil pressure	125 HZ
Power frequency	125 HZ
online condition monitoring	

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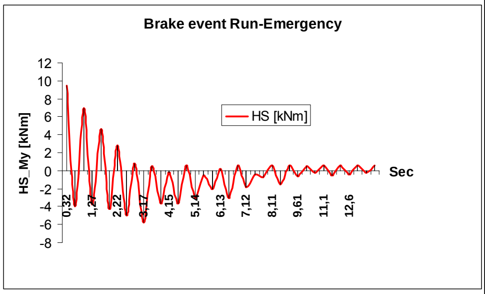
Electrical measurements

- Generator:
  - 44kHz measurements, used for deriving mechanical torque
    - Stator: Volts and Amps
    - Rotor: Volts and Amps
    - Generator shaft: RPM
- Each sampling 1,7GB @ 90 sec.

Current activities

- FFT analysis of stationary operating states
- Evaluation of torsional oscillations
- Interpretation of acceleration Δ(dw/dt) levels at various operating conditions, [LSS – HSS – Generator]
- Dynamic displacement of the gearbox (rotating bending, trust forces, gear suspension stiffness)
- Potential influences of the HSS coupling/disc brake engagement



Ongoing & Planned activities

- Analyze data and pick those with most dynamics
- Build rough model of drive train in Simulink and calibrate the model
- Load time series into dynamic and fast reacting test bench and accelerate failures
- Change parameters and derive optimum operating conditions
  - Repeat measurements at other applications.
  - Time frame:……? We are looking for one or multiple needles in a large hay-stack – that may take a while!

»Thank you.

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Wind Turbine Drivetrain Modelling at DONG Energy

IEA Meeting #57 on Wind Turbine Drive Train Dynamics and Reliability

4-5 September 2008

Stephane A. Eisen

DONG energy

Overview

- DONG Energy's Motivation
- DYSIVI – DONG Energy's Gearbox Modelling Tool
- DYSIVI Validation Projects
- Conclusion / Moving Forward with DYSIVI

DONG energy

DONG Energy's Motivation

- DONG Energy has a substantial portfolio of wind turbines and upcoming projects employing the latest turbine designs:
  - Offshore: ~335 (505) MW in operation & ~2117 MW of upcoming projects
  - Onshore: ~220 MW in operation & ~440 MW of upcoming projects
- Primary motivations of our wind turbine gearbox modelling activity:
  - Increase overall and detailed knowledge of issues surrounding wind turbine gearboxes
  - Mitigate risk with current and future projects
  - Develop constructive dialog with suppliers
- *What our motivation is not:*
  - *To design gearboxes*

DYSIVI Overview

- DYSIVI = DYnamisk SImulering af VIndmøllegear
- Non-linear FE program developed by Dr. Hans H. Sørensen over the past 6 years at DONG Energy
- Salient features of the current version of DYSIVI:
  - 2-Node Bernoulli Beam Elements
  - Linear bearing stiffness, gear mesh stiffness, and gear kinematics
  - Turbine Structural Capability, i.e. FE models of Blades / Rotor / Tower / Bed Plate
  - Simplified Aerodynamics / Generator / Control models
- Modular code design intended for continued development of new features such as:
  - Non-Linear bearing and gear mesh stiffness models
  - Timoshenko Beam and 3D Super Elements
  - State-of-the-art Aerodynamics / Generator / Control models

Validation of DYSIVI

- Enge Møllepark 750kW Measurement Program in 2005:
  - 100kHz rotational measurements and 20kHz translational measurements.
  - DYSIVI simulation results generally agreed with measurements during normal operation
  - Turbine events that resulted in gearbox backlash did not show good agreement. (No Backlash Model in current version of DYSIVI)
  - New comparison intended with an updated DYSIVI model including non-linear bearing and gear mesh stiffness
- NREL GRC Project
  - Extensive test campaign
  - These measurements will from the basis of an extensive validation project of DYSIVI

DONG energy

Conclusion

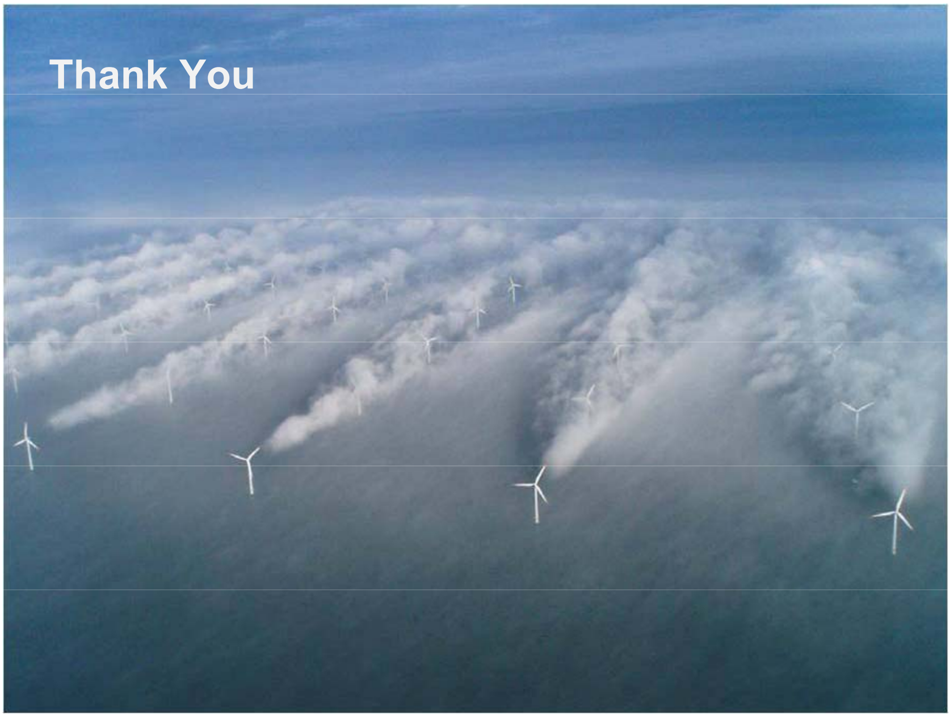
- Short Term
  - Implement non-linear bearing and gear mesh stiffness
  - Continue with NREL GRC Project with intent of extended validation of DYSIVI
- Longer Term
  - Evaluate different strategies to move forward with development and use of DYSIVI
    - Partner with Wind Turbine / Gearbox Manufacturers / Others
    - Provide DYSIVI as an open source code to interested wind turbine industry participants to capitalize on a broad range of knowledge similar to other open source engineering codes such as:
      - Code_Aster: a general purpose non-linear FE program developed by EDF
      - MBDyn: a multi-body dynamics program developed by University of Milano Aerospace Department'
      - FAST/ AeroDYN: a medium complexity aeroelastic wind turbines program developed by NREL

DONG energy

Public References on DYSIVI (*all in Danish*)

- PSO-Projekt nr. 2001, ”Evaluering af vindmøllegear”, Teoretiske beskrivelse af DYSIVI. http://www.risoe.dk/rispubl/NEI/nei-dk-4845.pdf
- PSO-Projekt nr. 2001, ”Evaluering af vindmøllegear”, Hovedrapport.
- PSO-Projekt nr. 2001, ”Evaluering af vindmøllegear”, Brugermanual. http://www.risoe.dk/rispubl/NEI/nei-dk-4844.pdf
- PSO-Projekt nr. 2001, ”Evaluering af vindmøllegear”, Eksempelsamling. http://www.risoe.dk/rispubl/NEI/nei-dk-4843.pdf
- PSO-Projekt nr. 5300, "Levetids og Lastberegninger af Gear", Slutrapport

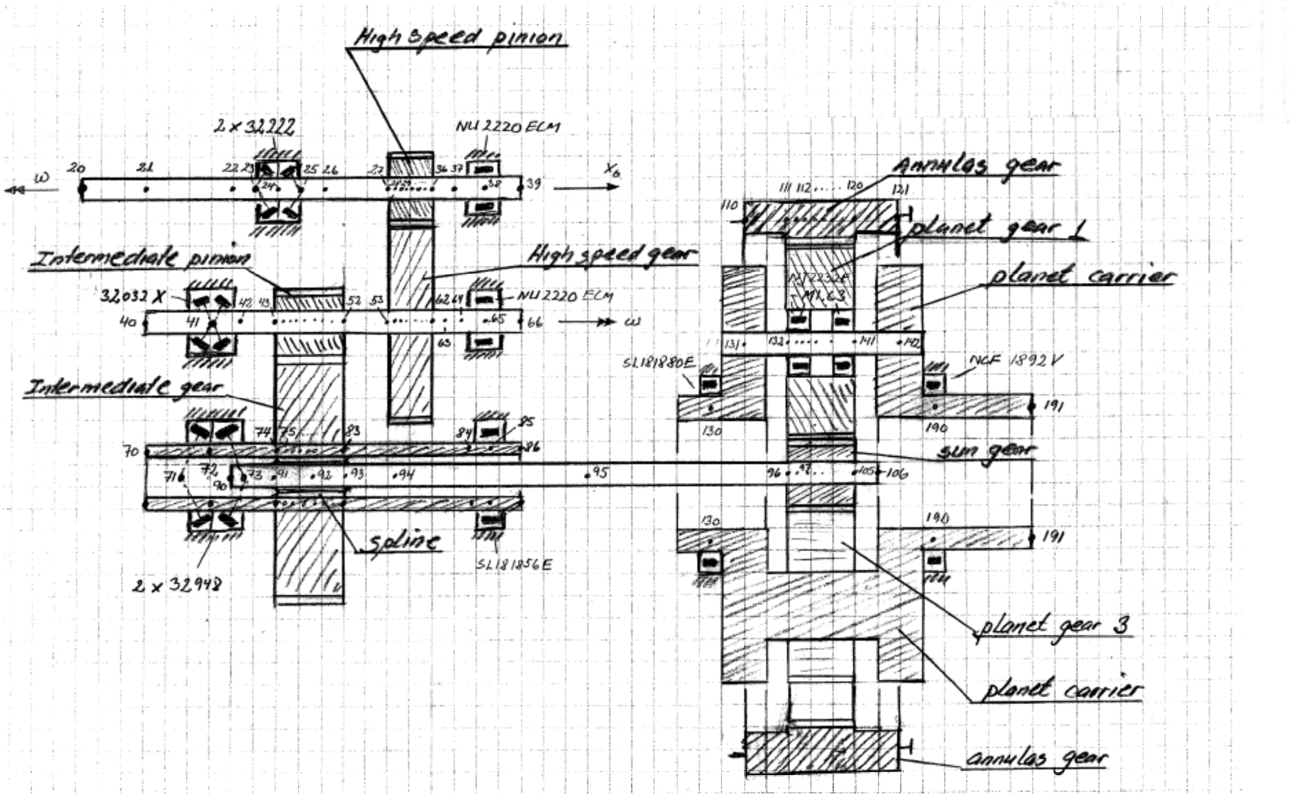
DONG energy



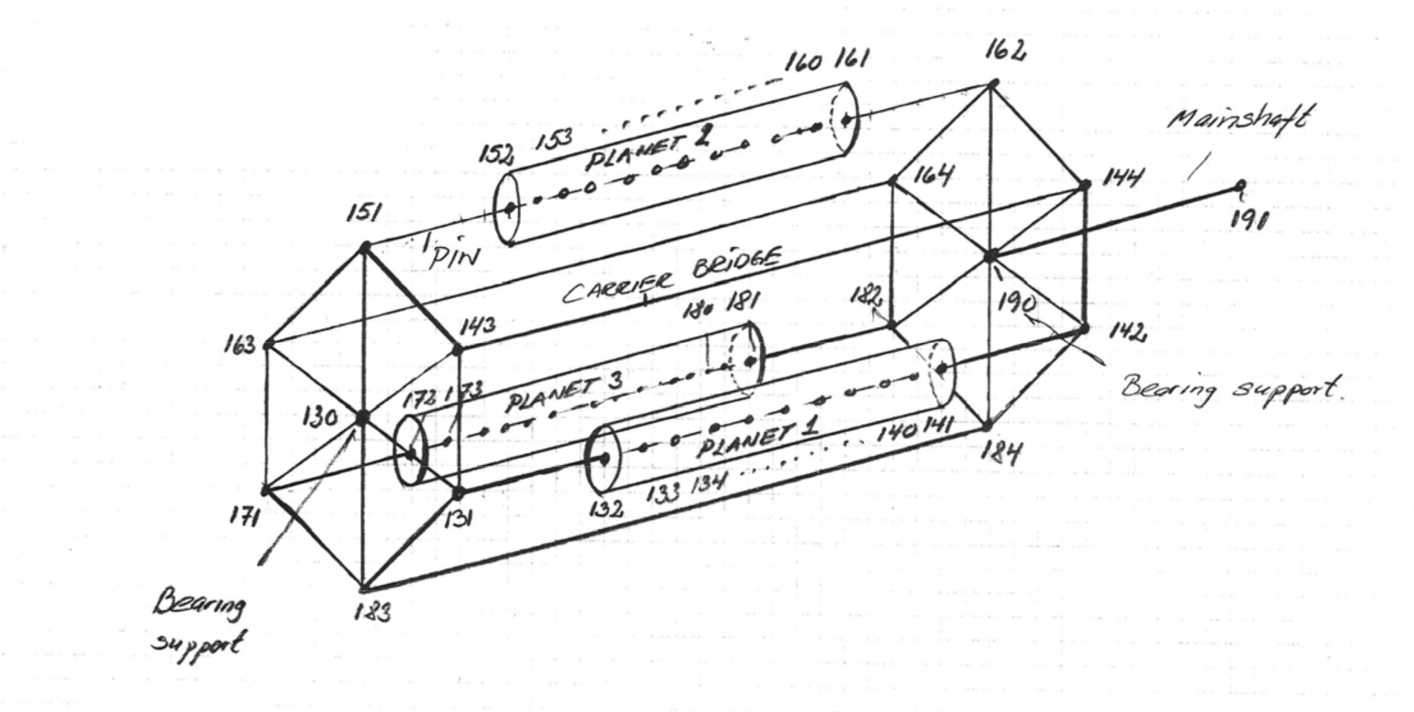
DONG energy

Supplemental Slides

DYSIVI Overview: Gearbox Model Example Highlighting Nodes



DYSIVI Overview: Gearbox Model Example Highlighting Nodes



11

Climate & Renewables

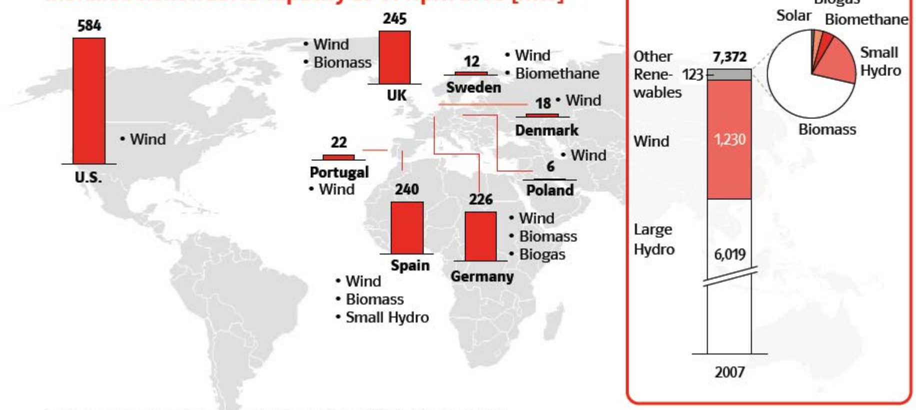
2008, IEA Wind, Drivetrain Event
ECR Introduction

September 2008
T R Morgan, Integrity Engineer, Engineering Team
Presented by Neil Brinkworth, Eon Engineering

Climate & Renewables

Current Renewables footprint: 7.4 GW

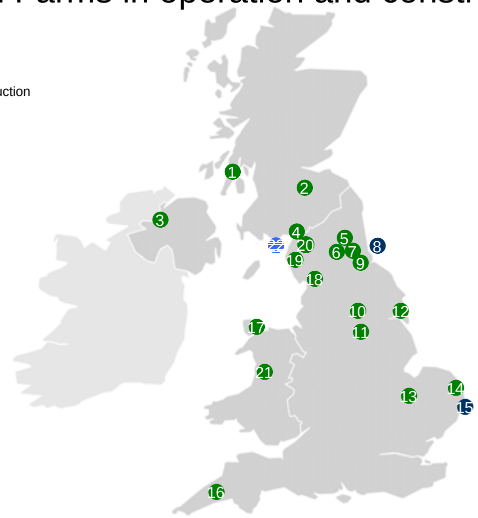
Installed Renewables capacity as of April 2008 [MW][1)]



1) Excluding Large Hydro (Central Europe 3,153 MW; Nordic 2,742 MW; U.S. 74 MW; UK 50 MW)

UK Wind Farms in operation and construction

- Onshore
- Offshore
- Offshore in construction



1. Deucheran Hill
2. Bowbeat
3. Bessy Bell
4. Siddick
5. Holmside
6. Harehill
7. High Volts
8. Blyth
9. Great Eppleton
10. Ovenden Moor (50%)
11. Royd Moor (50%)
12. Out Newton
13. Stag's Holt
14. Blood Hill
15. Scroby Sands
16. St. Breock
17. Rhyd-y-Groes
18. Askam (50%)
19. Lowca
20. Oldside
21. Rheidol
22. Robin Rigg

UK Wind Portfolio

<u>Turbine technologies</u>

- Vestas: V27, WD34, V39, V42, V47, V80, NM80 (V90 in construction)
- Siemens: S300, S450, S500, S1.3
- Nordex: N60

<u>Gearbox suppliers</u>

- (Vestas) Hansen, Winergy, Lohmann & Stolterfoht, Valmet
- (Siemens) Winergy, Valmet
- (Nordex) Winergy, Eikhoff

e·on | Climate & Renewables

Gearbox reliability

- Gearbox reliability is the biggest technical issue affecting onshore & offshore wind farms in our UK wind farm portfolio
- The issues affect turbines and gearboxes from all suppliers
- The frequency of failures is higher on larger turbines and the consequences of the issues are compounded offshore
- There are many potential factors causing the failures (see next slide)

Mean time between failures on ECR UK wind farms

Failure Type	All turbines	MW+ Offshore	MW+ Onshore	Sub-MW Onshore
	Mean Turbine-Years Between Failures			
Total	**6.2**	0.8	7.2	15.0
Full replacement / refurbishment	**14.7**	3.0	10.2	26.7
In-situ repair	**10.7**	1.1	24.5	34.2
Sample size (years since 2000)	1437	98	245	1094

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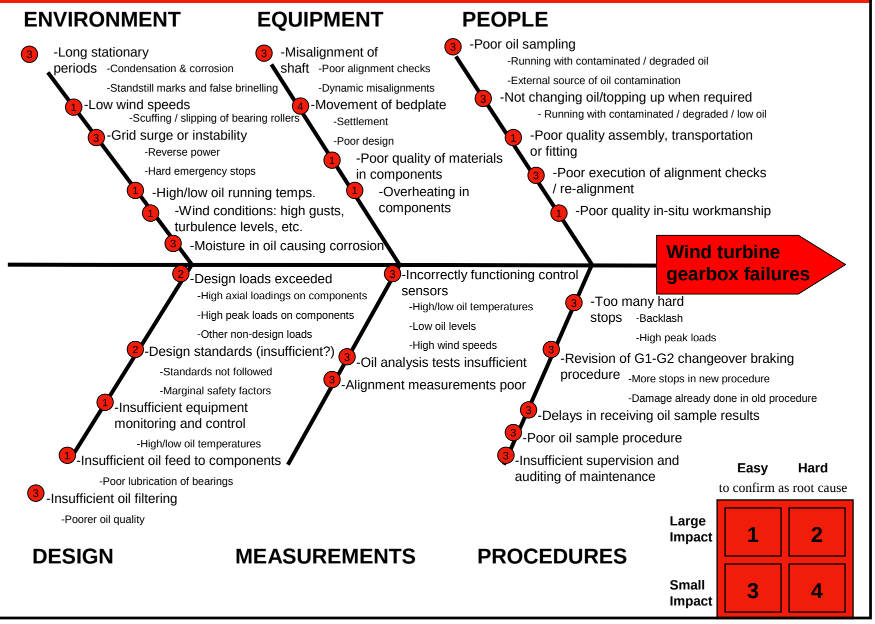

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Introducing GE Transportation

IEA, Jyväskylä, Finland
4 September 2008

General Electric Company

GE Transportation

Propulsion and Specialty Services

GET 1.5MW Gearbox

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Prepared for IEA Conference – 9-4-2008

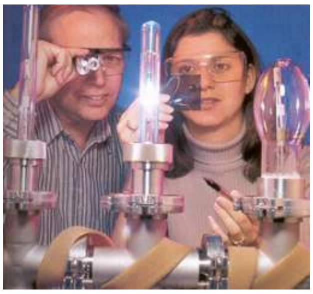
GE … a tradition of innovation

Founded in 1878 as the Edison Electric Co.

130 years of successful operation

320,000 employees worldwide

Strong technology focus … Research centers in Germany, India, China and the U.S.



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Prepared for IEA Conference – 9-4-2008

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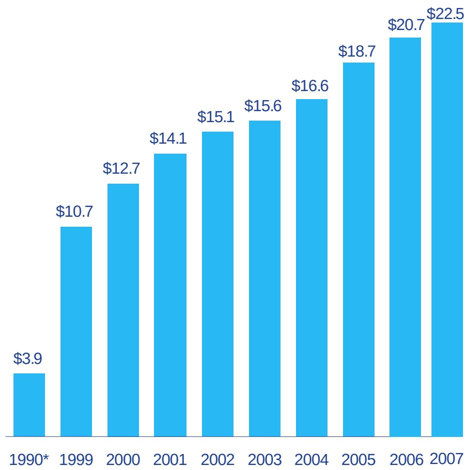
A company with a strong track record of performance for all stakeholders

The only company listed in the Dow Jones Industrial Index today that was also included in the 1896 original index

Earnings have multiplied more than 5x since 1990

$173 billion in revenue in '07



Earnings ($ in billions)

** Excluding Restructuring, Lockheed Martin & Kidder Peabody*

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Prepared for IEA Conference – 9-4-2008

GE … four market verticals … aligned for growth

GE Capital

Technology Infrastructure

NBC Universal

Energy Infrastructure

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GE Technology Infrastructure

One of the world's leading providers of fundamental technologies including aviation, transportation, healthcare, enterprise solutions.

- Aviation
- **Transportation**
- Healthcare
- Enterprise solutions

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Prepared for IEA Conference – 9-4-2008

Transportation headquarters

Erie, Pennsylvania

High value exports and high value jobs

Nearly 5,000 employees

Home to Transportation since 1907

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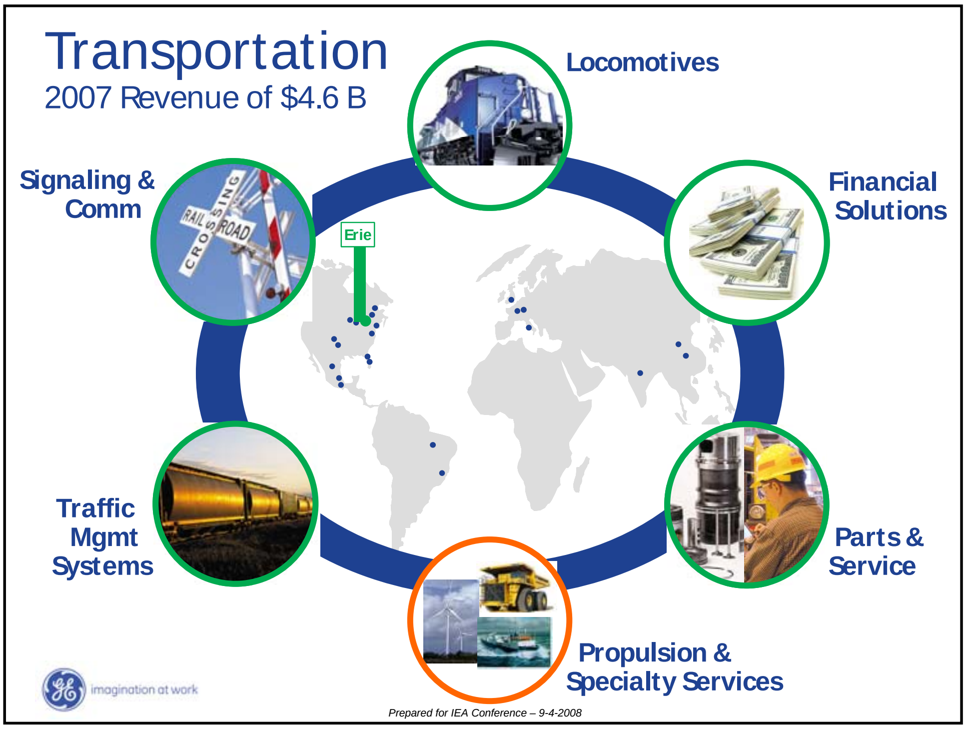
Transportation
2007 Revenue of $4.6 B
Locomotives
Signaling &
Comm
Financial
Solutions
Erie
Traffic
Mgmt
Systems
Parts &
Service
Propulsion &
Specialty Services
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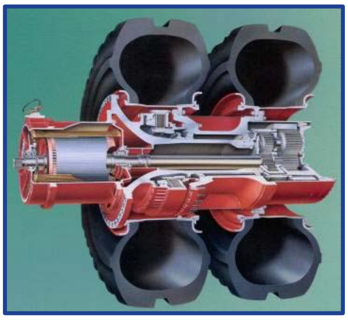
P&SS …a derivatives business
15,000 Engines Operational in 20 countries
Mining / OHV
Drive Systems
for Mining Trucks
18000 drives shipped
Transit
Propulsion for
Transit Cars
Drill
DC/AC Motors
for Drill Rigs
Marine & Stationary
Engines for Boats
& Power Generators
Drivetrain
Technologies
Wind Turbine
Gearboxes
imagination at work
Prepared for IEA Conference – 9-4-2008

Why wind turbine gearing … leverage OHV drivetrain experience

18,000+ Wheels Shipped



AC – Two Stage Planetary
1,700 Hp (1.3 MW) motoring
2,700 Hp (2.0 MW) retarding

AC/DC – Compound Planetary
1,200 Hp (900 KW) motoring
2,000 Hp (1.5MW) retarding

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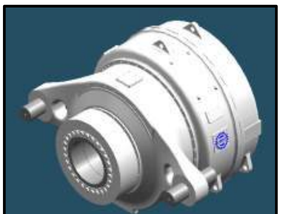
GET Wind Program History



October 2002 GETS acquires rights to Cincinnati Gear 1.5MW design

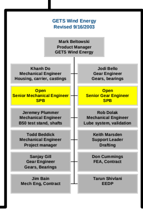
December 2003 Startup of HALT stand with Cincinnati Gear prototypes

January 2005 Three prototypes installed at Trent Mesa

2002 | 2003 | 2004 | 2005

The Cincinnati Gear Company

June 2002 Cincinnati Gear exits business



July 2003 GETS Wind Team created

May 2004 First prototype installed

October 2005 First production gear boxes roll off the line

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9-4-2008

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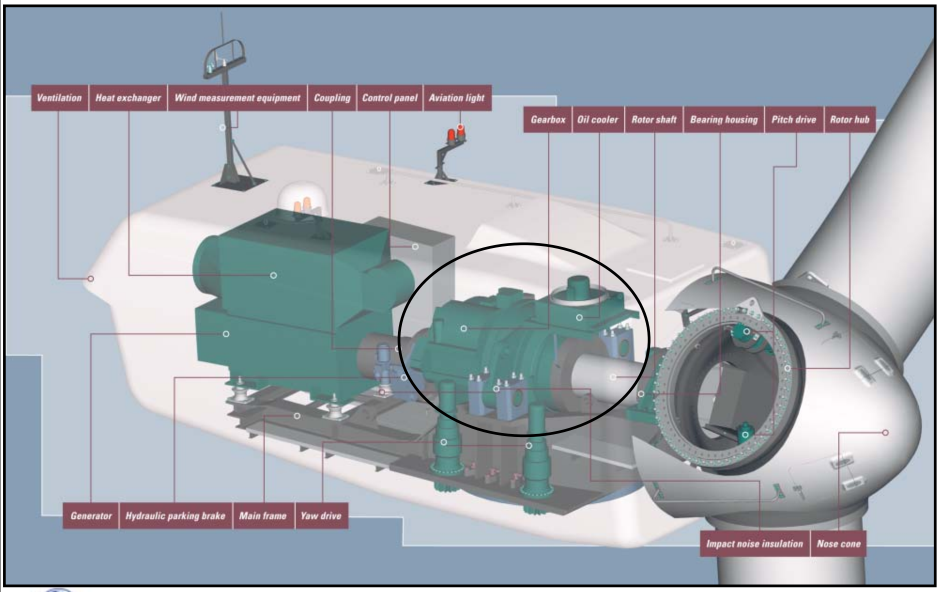
7GA87 Gearbox



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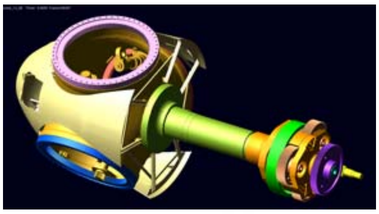
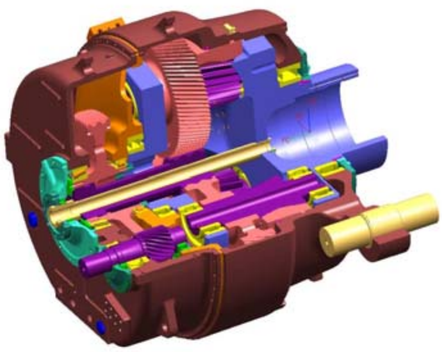
7GA87E – 1.5MW 1:78 ratio Compound Planetary





- 3 stage CP design with helical gearing
- Straddle mounted planet bearings
- Flexible, splined ring gear
- No reversed bending loads on planet teeth
- One high speed stage
- Over 850 produced
- Oldest fleet at 28 months

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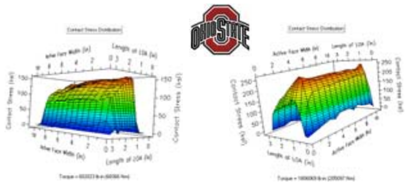
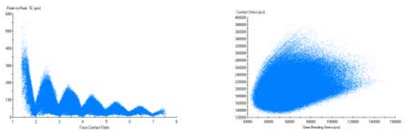
Advanced analysis tools

Load Distribution Program (LDP)
- 3rd mesh analysis
- Root/contact stress
- Transmission error



Run Many Cases (RMC)
- Optimization
- DOE



Romax
- Analysis of housing influence on gear mesh
- Concept study
- Centralized analysis
  - › Shaft deflection
  - › Bearing reaction
  - › Gear forces

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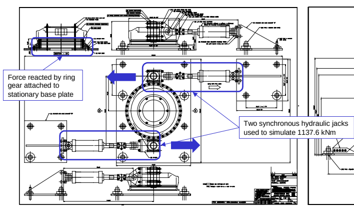
Prepared for IEA Conference – 9-4-2008

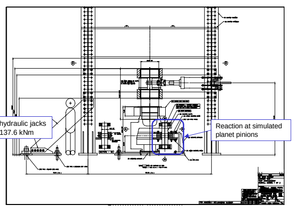
Component testing … demonstrated 99% reliability at 95% confidence

Input Housing

Carrier

High Speed Gear Bearing





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Systems level testing

Cold Chamber

Lube System Flow Rate

Strain Gauge Testing

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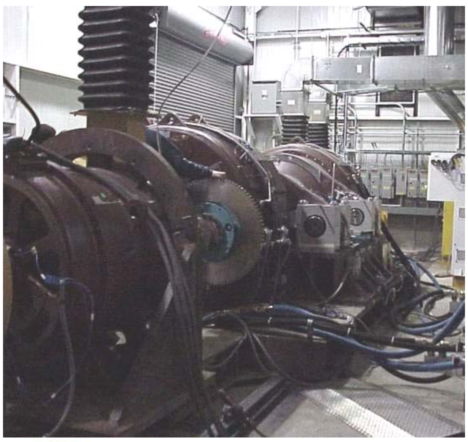
HALT "graduation" test



Simulates 20 yr life on gearing
- Loads increased to decrease total test time
- 3x and 2x overloads
- Run on dedicated engineering test stand

Monitoring
- Bearing and oil temperatures
- Oil pressures
- Stresses in critical components
- Power, torque, and speed
- Gear wear patterns
- Particle count

Capability
- 2.5 MW @1440 rpm continuous

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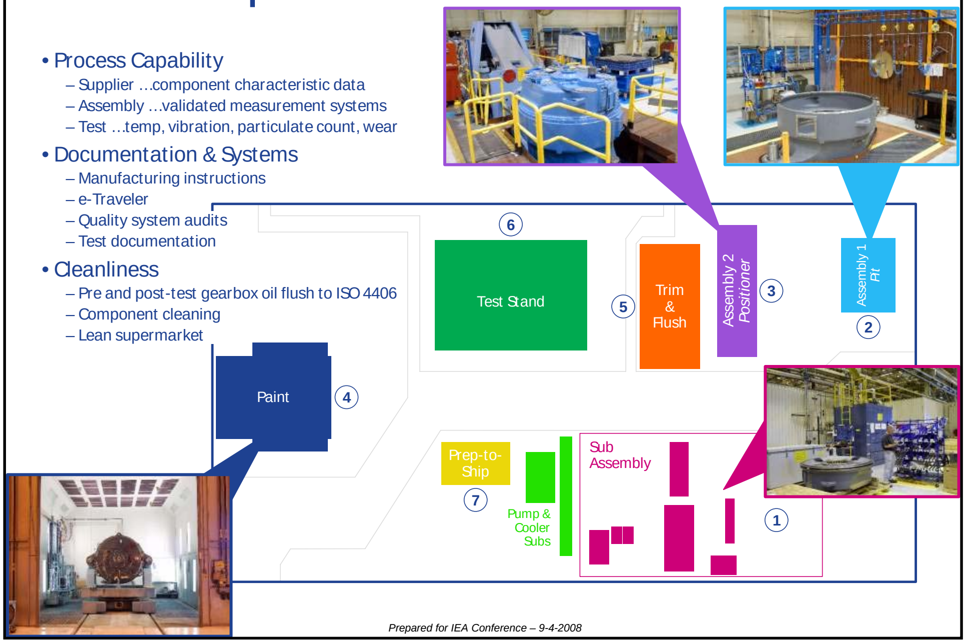
Gearbox production

- Process Capability
  - Supplier …component characteristic data
  - Assembly …validated measurement systems
  - Test …temp, vibration, particulate count, wear
- Documentation & Systems
  - Manufacturing instructions
  - e-Traveler
  - Quality system audits
  - Test documentation
- Cleanliness
  - Pre and post-test gearbox oil flush to ISO 4406
  - Component cleaning
  - Lean supermarket



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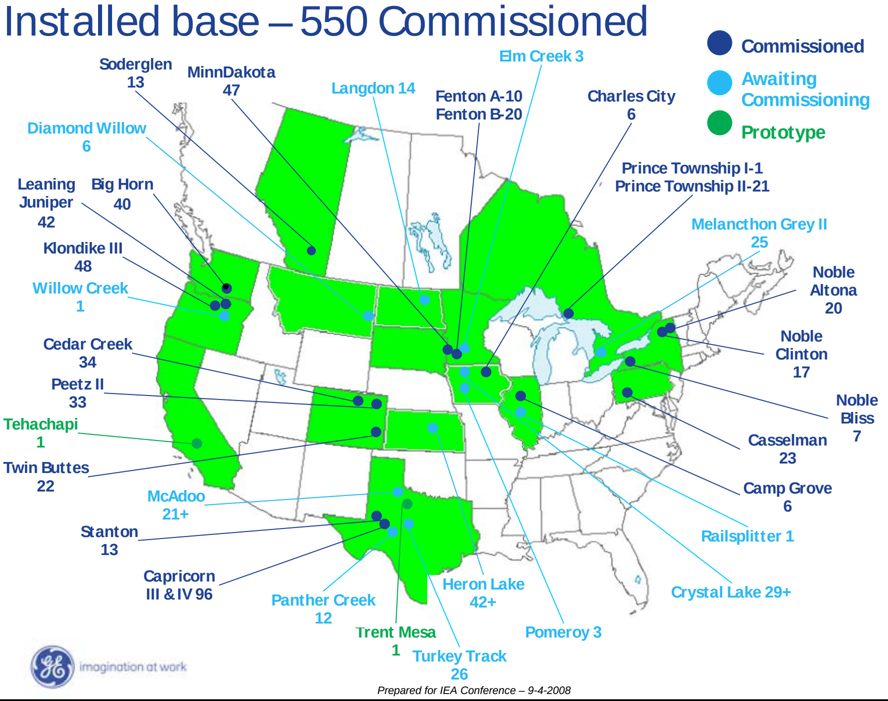
Installed base – 550 Commissioned



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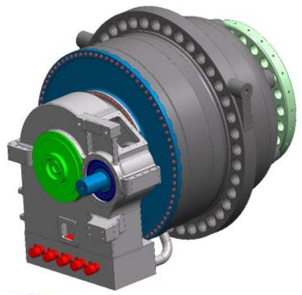
New Gearbox Designs

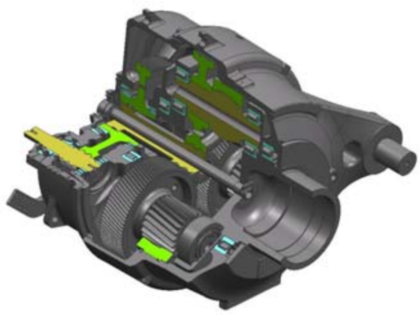
Higher Torque/ratio CP Gearboxes

2+MW Simple Planetary

2+MW Differential Planetary

IntegrDrive Gearbox/Generator





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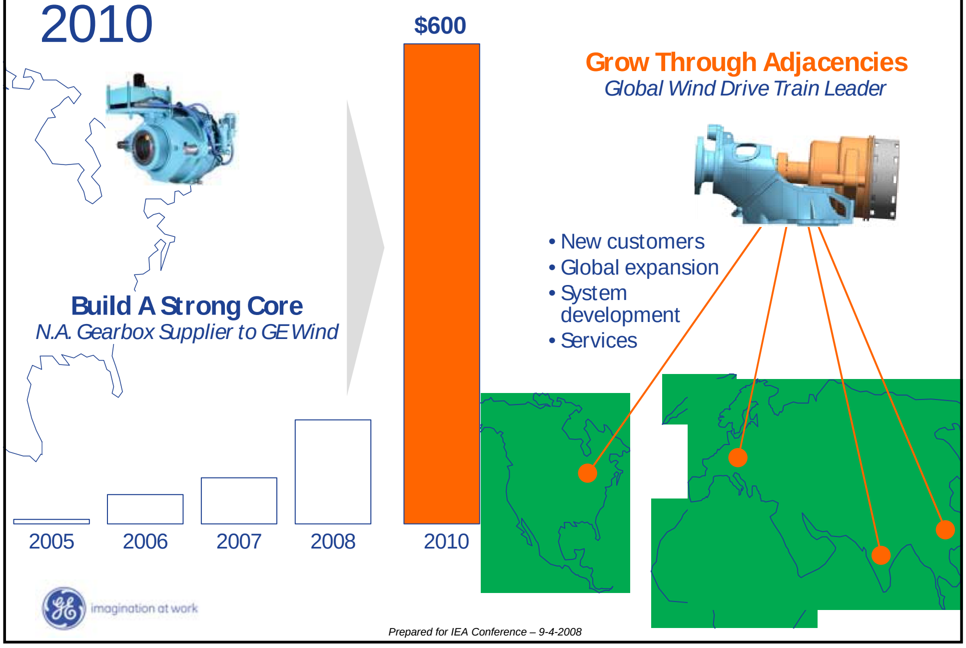
Drivetrain Technologies …$600 MM by 2010



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Thank You!

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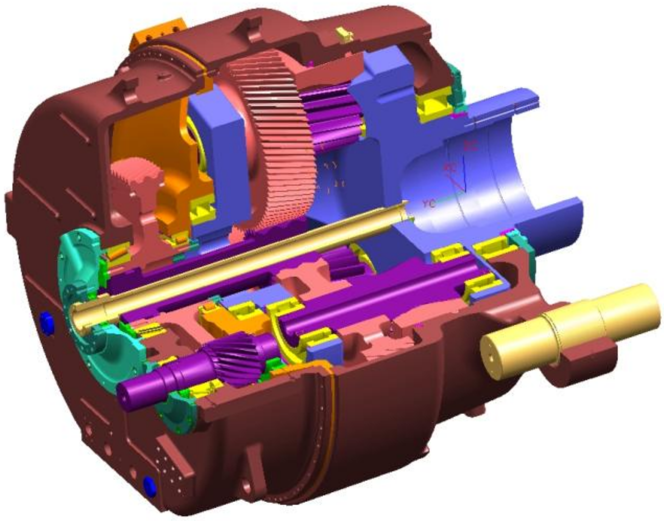
Wind Drive Train Dynamics and Reliability Sept4/5 2008



AW Giammarise GE Transportation, Erie, Pa. USA

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1 /
GE /
September 8, 2008

Cold Weather Cast Ductile Iron requirements and possible long term bearing fit issues on Wind Gear Box Structures

General statement:

Insuring bodies have been consistent in requiring the use of certain grades of ductile iron for maximizing cold weather toughness. One such DIN EN 1563 Grade GJS-400-18 LT is frequently required

Properties of DIN EN 1563 / ISO 1083 Gr 400/18/LT or /U

Tensile 400 N/mm2

Yield Str. 240 N/mm2

Elongation 18%

Typical Hardness less than 160 HBW

Typical fracture Toughness 30 Mpa/mm3/2

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GE /
September 8, 2008

The impact requirements for JS/400/18 only extent to –20C because wide scatter at –40C makes acceptance/rejection diffcult

Table 2 — Minimum impact resistance values measured on V-notched test pieces machined from separately cast samples

Material designation	Minimum impact resistance values J					
	room temperature (23 ± 5) °C		low temperature (– 20 ± 2) °C		low temperature (– 40 ± 2) °C	
	Mean value from 3 tests	Individual value	Mean value from 3 tests	Individual value	Mean value from 3 tests	Individual value
ISO1083/JS/350-22-LT/S[a]	—	—	—	—	12	9
ISO1083/JS/350-22-RT/S[b]	17	14	—	—	—	—
ISO1083/JS/400-18-LT/S[a]	—	—	12	9	—	—
ISO1083/JS/400-18-RT/S[b]	14	11	—	—	—	—

NOTE 1 The impact resistance values for these materials apply to castings cast in sand moulds of comparable thermal behaviour. Subject to amendments to be agreed upon in the order, they can apply to castings obtained by alternative methods.

NOTE 2 Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces machined from samples separately cast in a sand mould or a mould of comparable thermal behaviour.

NOTE 3 These material grades may be suitable for some pressure vessel applications. (For fracture toughness, see Annex C.)

[a] LT for low temperature.

[b] RT for room temperature.

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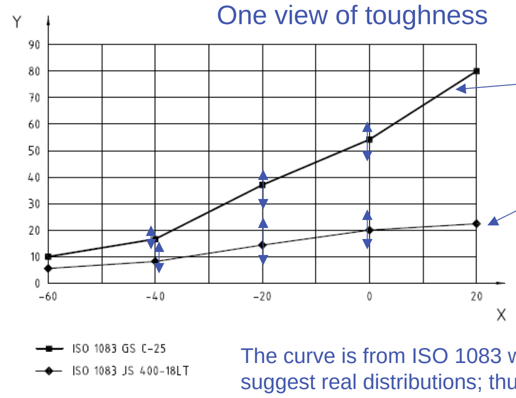
Impact properties (CVN) as a function of temperature

One view of toughness



Cast carbon steel

JGS/400/18/LT

The curve is from ISO 1083 with added arrows to suggest real distributions; thus the scatter is about small values at temperatures less than –40C

Key
X Temperature, °C
Y Impact resistance value, J (ISO-V)

Figure C.1 — Impact strength of ferritic spheroidal graphite cast iron and cast steel

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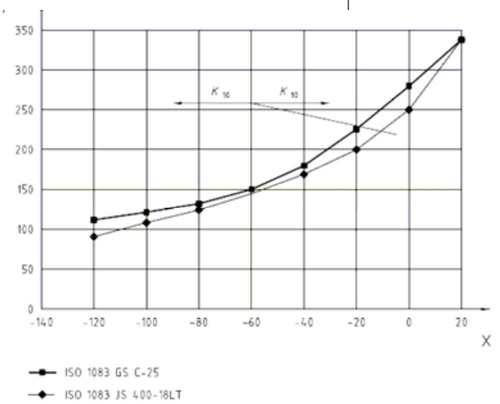
ISO 1083 addendum

In view of the above comments it is understandable that evaluating only the notch impact energy of a ferritic spheroidal graphite cast iron does not represent a suitable measure for comparing its toughness or ductility with that of steel, because it is not possible to make any statement regarding the plastic deformability and cracking behaviour of the material.

Ferritic spheroidal graphite cast irons which in the ductile range have a notched impact energy of 12 J to 20 J, have a crack initiation behaviour comparable to unalloyed and low alloyed steels (with a notch impact energy of around 50 J in the higher range). The fracture toughness values of ferritic spheroidal cast iron result in elasto-plastic fracture behaviour even down to – 60 °C, i.e. a tough fracture characteristic, so that the K_{IC} values are on the same level as that of unalloyed and low alloyed steels (see Figures C.1 and C.2).

An alternate view using Fracture toughness again cast steel and ferritic Ductile iron are plotted. Much closer agreement



Key
X Temperature, °C
Y Fracture toughness, MN/m$^{-3/2}$

Figure C.2 — Lower borderline of the fracture toughness of ferritic spheroidal cast iron and cast steel

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In Addition Ferritic Ductile Irons are:

•Relatively soft microstructures, less than 160 HBW

•Lower yield strength,easily deformed

GE Transportation experience in using fully ferritic Ductile irons for locomotive applications such as traction motors, locomotive bogie structures/components suggests the following:

•Bearing bores tend to grow as service life lengthens

•This is a combination of fretting type wear, impulse loading, and bearing race creep because of the low strength/low fit

•This can result in loss of proper raceway fit, proper support of the rolling element bearings

GE Transportation experience now utilizes higher strength grades of Ductile Iron such as:

JGS/500/7, or JGS/600/3 increased strength, mixed microstructure, lower impact properties but only slightly lower fracture toughness . Hardness up to 220 HBW can improve raceway fits over extended life.

6 /
GE /
September 8, 2008

Conclusions:

•Crack initiation behavior of ferritic ductile iron may be equal to cast low carbon/ low alloy steels

•Measuring toughness in fully ferritic ductile irons using CVN may not tell the whole story. Material selection needs to consider other design / life needs.

•Alternate microstructures with increased hardness/ wear resistance can improve life by maintaining dimensional features

•Attention to designed in or machined in notches is needed when using any grade of ductile iron

•Improvements to bearing bore service life, ability to increase bearing fits, overall weight reductions are possible, with out major risks for cold weather service

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7 /
GE /
September 8, 2008

Wind Turbine Drivetrain Dynamic & Reliabilty – SKF Capabilities

Presented to: IEA Topical Expert Meeting 57

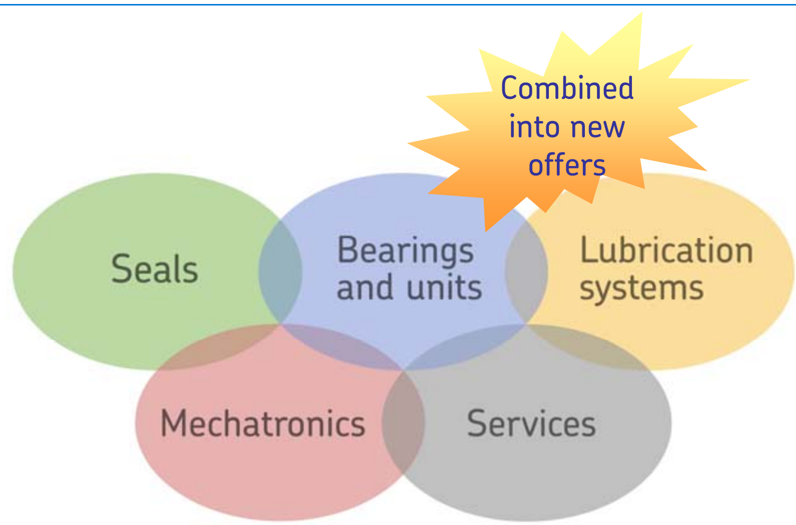
Presented by: Pär Malmberg

2008-09-04--05

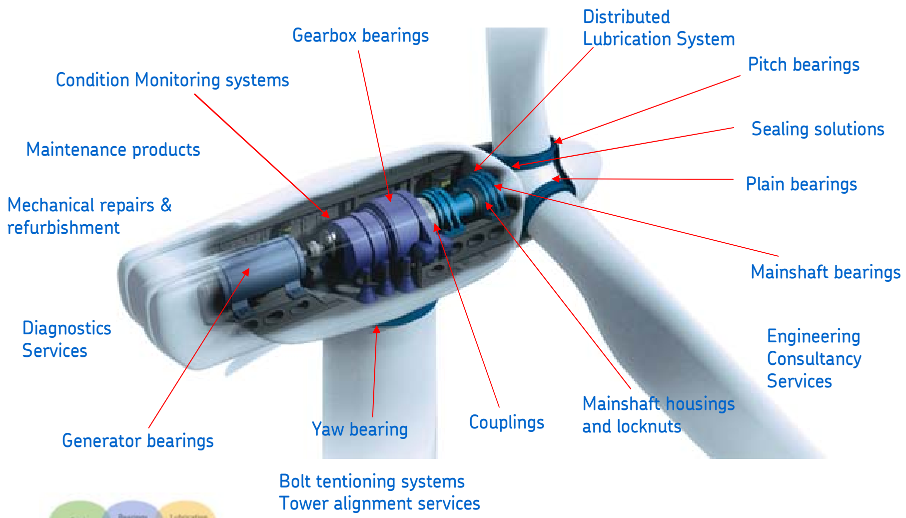
1

SKF contribution to wind turbine technology

SKF Platforms



SKF contribution to wind turbine technology



SKF

2

Selection of bearing type

2008-09-08 ©SKF Slide 5 [Code]
SKF [Organisation]

SKF

Turbine development and launch

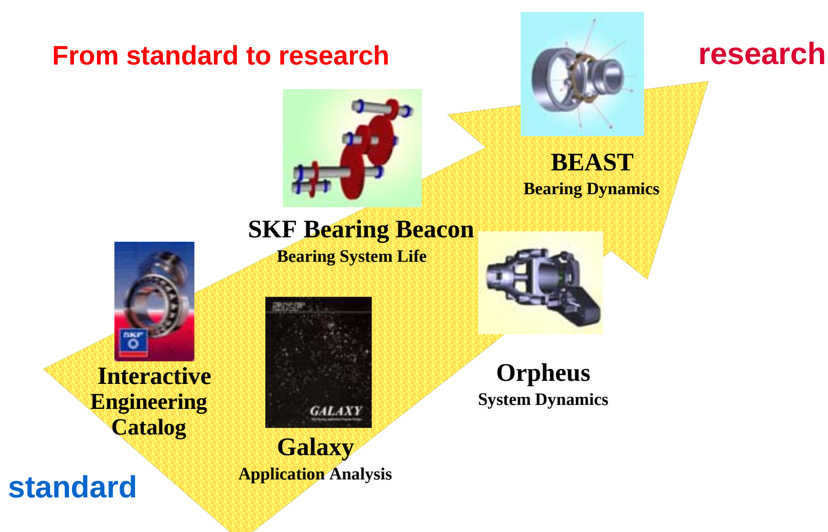
New concept design

Fewer tests in the field means shorter time to market and cost-effectiveness

October 30, 2007 © SKF Group Slide 6

SKF

SKF Modeling & Simulation tools



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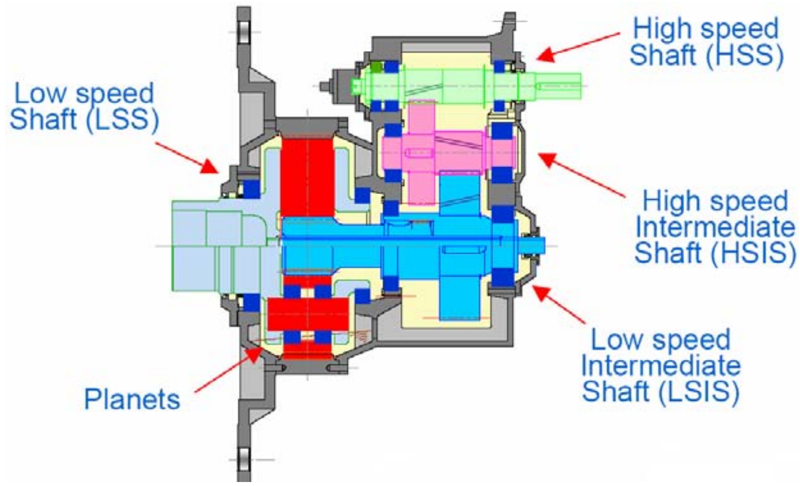
SKF

A typical windturbine gearbox



Bearing selection flowchart

- Gearbox concept
  - Shaft position 1
    - Rotor side
      - requirements
    - Generator side
      - requirements
  - Shaft position 2
    - Rotor side
      - requirements
    - Generator side
      - requirements
  - Shaft position 3
    - Rotor side
      - requirements
    - Generator side
      - requirements

Reliable bearing selection in WTGU

Example

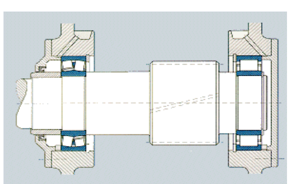
1) Selection bearing type and design:

- Design wind turbine drive train
  e.g. three-point suspension of rotor, special coupling, ...
- Specific requirements for the different shaft positions
  e.g. smearing risk on HSS, ring creep IR and OR, loads at reverse torque, backlashing, bearing stiffness, ...
- Cage design
- Mounting requirements
- Customer preference

2) Selection bearing series and size:

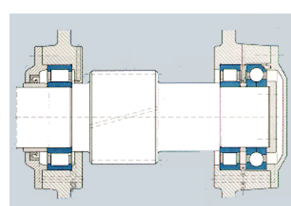
- Limitations due to housing and shaft dimensions
- Low and high load conditions
- Load sharing
- Calculated advanced life ratings (AFC)
- Calculated contact stresses, misalignments
- Customer requirements, including e.g. AGMA and ISO-standards

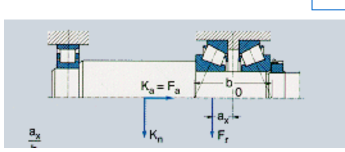
Commonly used bearing arrangements – HSS



Requirements:

- High speed
- High operating temperatures
- Cooling
- Large ΔT_{IR-OR}
- Vibrations
- Idling under light low

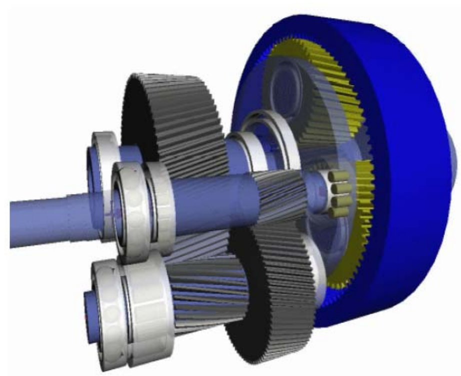




SKF Bearing Beacon

SKF Bearing Beacon is a state-of-the-art simulation program for quasi-static and modal analysis of roller bearings and roller bearing applications.

Bearing beacon can for example calculate the internal stress distribution within the bearings, and by this you can avoid building in local stress raisers like edge stress due to misalignment or shaft deflection.



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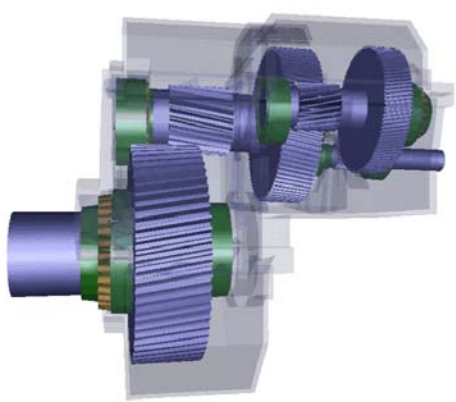
SKF

Bearing Beacon – Analyzing gearbox design

- System load sharing due to
  - Carrier stiffness
  - Ring gear stiffness
  - Gear ovalization
  - Housing stiffness
  - Bearing clearances
  - Mounting tolerances
- Gear performance
  - Teeth loading
  - Gear contact loads/stresses
- Efficiency / Power density



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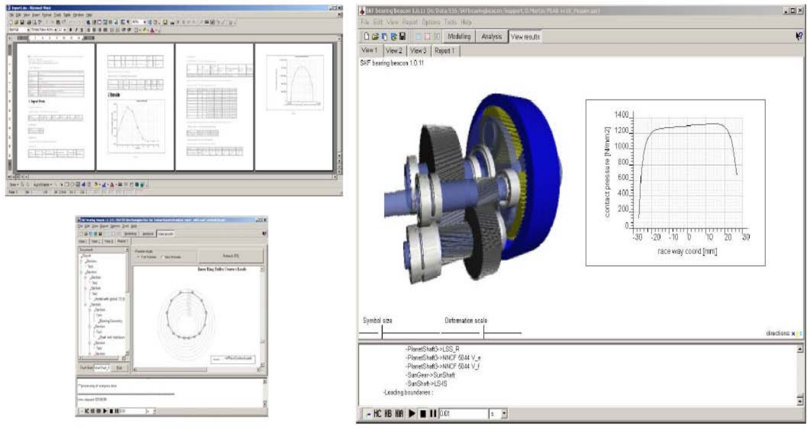
SKF Bearing Beacon, output

Express Report Animation Charts



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3

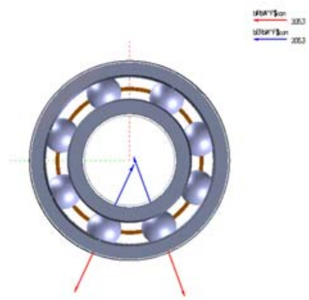
BEAST – SKF most advanced bearing simulation tool

SKF

BEAST - a virtual test rig

BEAST is Multi-body simulation software specialized in contact problems and based on:

- ✓ Detailed geometry and surface description
- ✓ Accurate tribological models
- ✓ Accurate modeling of application operating conditions (temp, vibrations, loads, etc.)



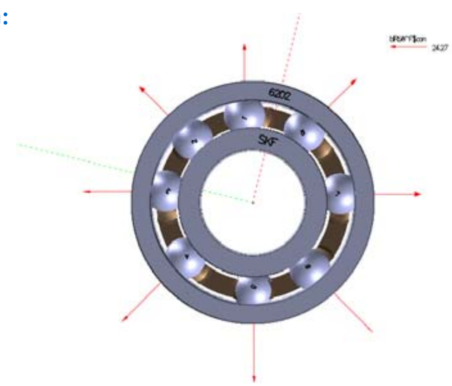
BEAST is capable of carrying out different types of transient analysis:

- ✓ Thermal
- ✓ Modal
- ✓ Flexible

BEAST - a virtual test rig

Simulation results and evaluation:

- ✓ Movements of components
- ✓ Contact forces
- ✓ Vibrations
- ✓ Cage instability
- ✓ Friction torque
- ✓ Lubrication
- ✓ Risk of excessive wear
- ✓ Risk of smearing damages

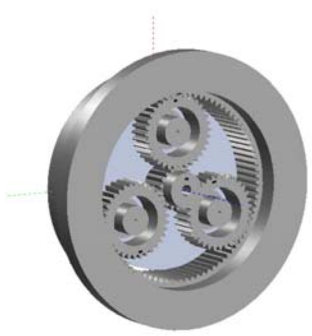


4

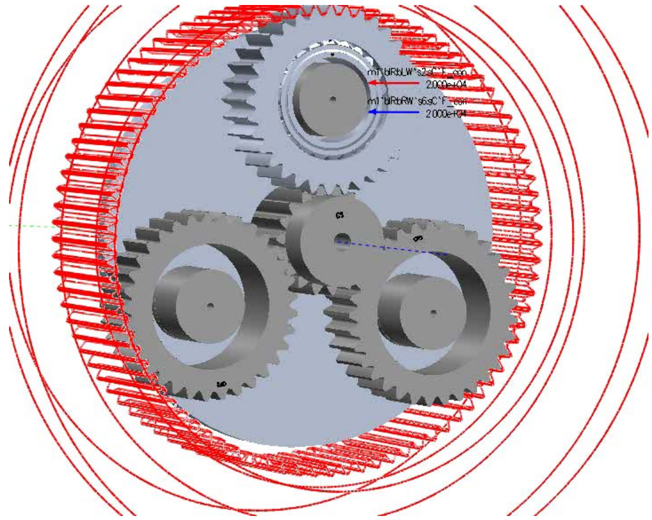
Simulation of planetary gear

Purposes of the different models

- Simplified model to create overview on the application
- Detailed models to create deeper insight of the bearing performance
  - One of the bearing modeled as a “full” bearing
  - The full bearing has an flexible outer ring
  - Remaining bearings modeled as simplified bearings with corresponding stiffness



Bearing forces



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5

Example: Bearing response to blade passing force variations

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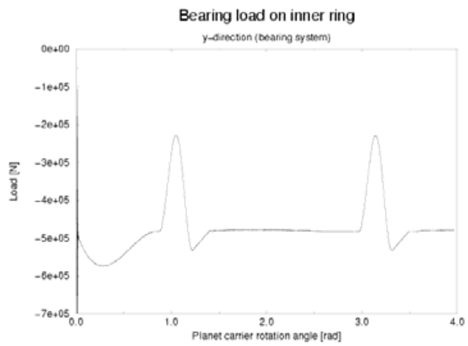
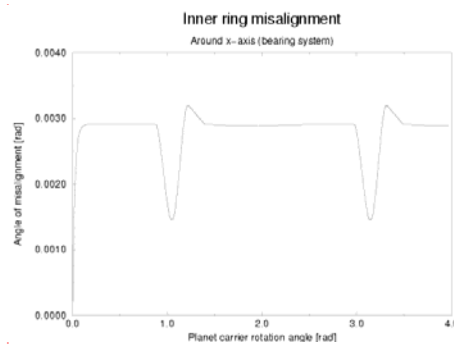
Blade passing variations

Assumed variation of load and misalignment when the blades pass the tower ("Wind turbines – Fundamentals, technology, application, economics", by Erich Hau)

Bearing:	SRB 24136CC
Radial load:	500 kN (536 kNm)
Operating conditions:	Planetary motion
Lubricant:	Mineral oil (ISO VG 220) at approx. 80 deg C

Assumed inner ring misalignment and flexible outer ring





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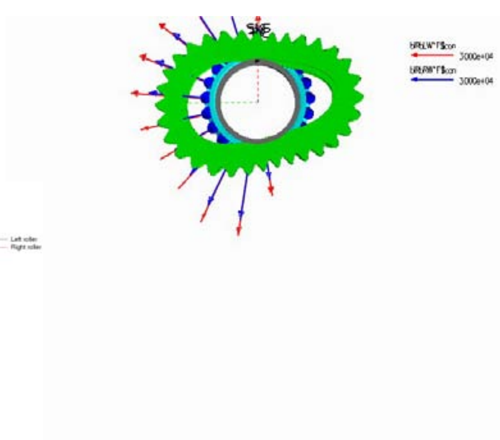
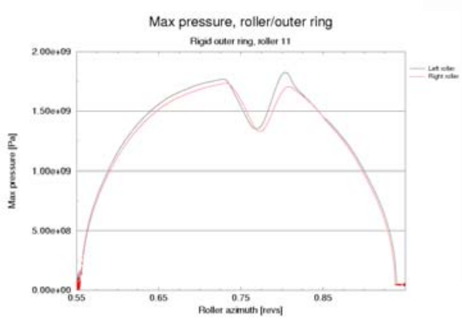
Roller load variations

- ✓ No outer ring support will give large deformation of the outer ring
- ✓ The deformation has a large effect on the contact conditions in the bearing
- ✓ The contact situations are well accommodated by the bearing





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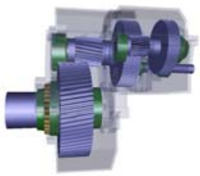
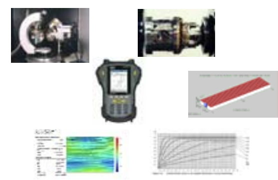
What knowledge does SKF bring to the table?





Advanced system modeling:

- Housing (Fully Flexible)
- Shafts and Gears
- Bearings
- All Bearing Components (Cage, Rollers, Rings)
- Lubrication

Results:

- Loads
- Life
- Stresses
- Friction
- N&V
- System Optimization

Competences/tools:

- Test design, rig design, testing, results analysis and evaluation
- Surface mapping/analysis
- Lubrication/tribology
- Advanced materials expertise
- Application experience
- Project leadership skills

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2

OVAKO driveline - RFA (Root Cause Analysis)

RCA method

RCA is used to determine what really happened. And to see if it can be avoided by “redesign – training – maintenance” and/or predicted

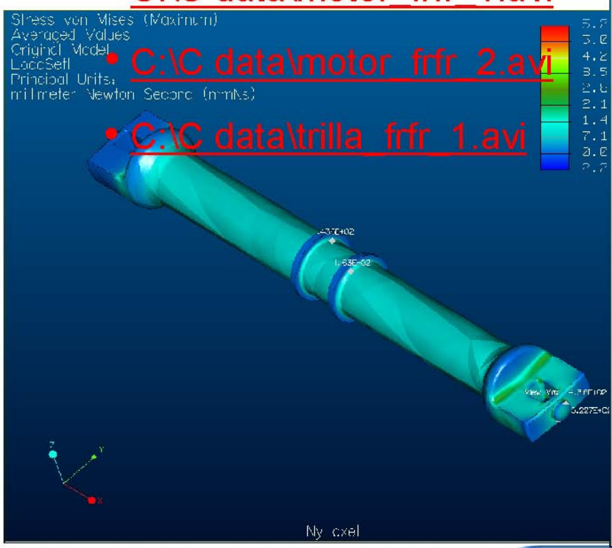
1. What have happened? How did it start? Failure mode!
2. Have it happened before? (History).
3. Common things
4. Hypothesis – Root cause analysis.
5. Verification
6. Action plan

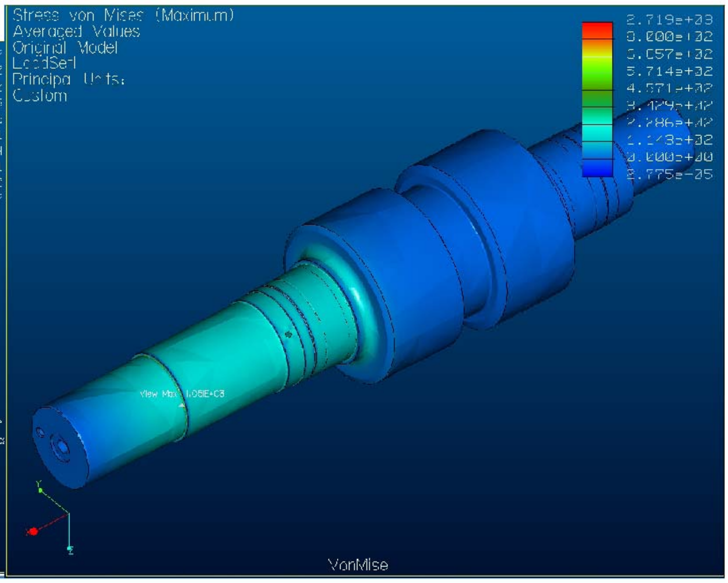
Identified problems at OVAKO

- High vibration level (accelerations)
  - Cable failures.
  - Bearing cage failures
  - Lock nuts getting loose
- Short service life of gears in pinion drive
- High wear rate on drive spindle blades
- Failure risk, fatigue, on drive spindles

Analysis of drivelines. FEM-calculation, verification and evaluation.

- C:\C data\motor_frfr_1.avi
- C:\C data\motor_frfr_2.avi
- C:\C data\trilla_frfr_1.avi





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Verification

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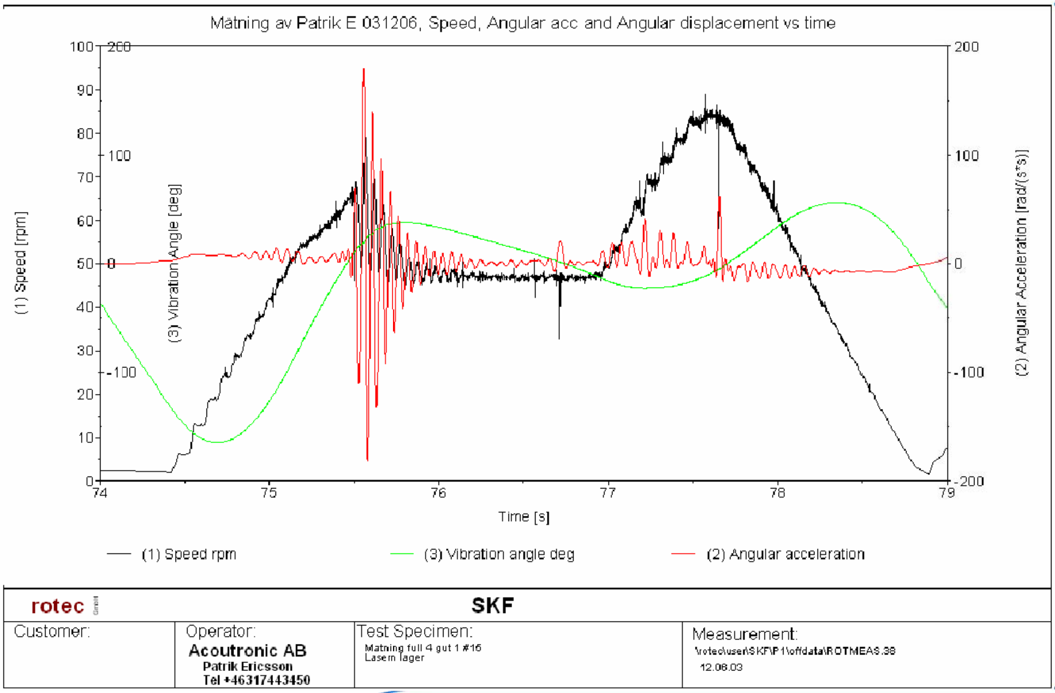
Verification 2003-06-12. Laser measurement



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Results

Driveline changes

Two major changes introduced

-New improved drivespindels with new balancing system

-Improved gearset. Modified from 1980 technology to 2004 technology

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Gear-set improvement

- New material and hardening method
- New finish quality
- New geardesign
- Old overall dimensions

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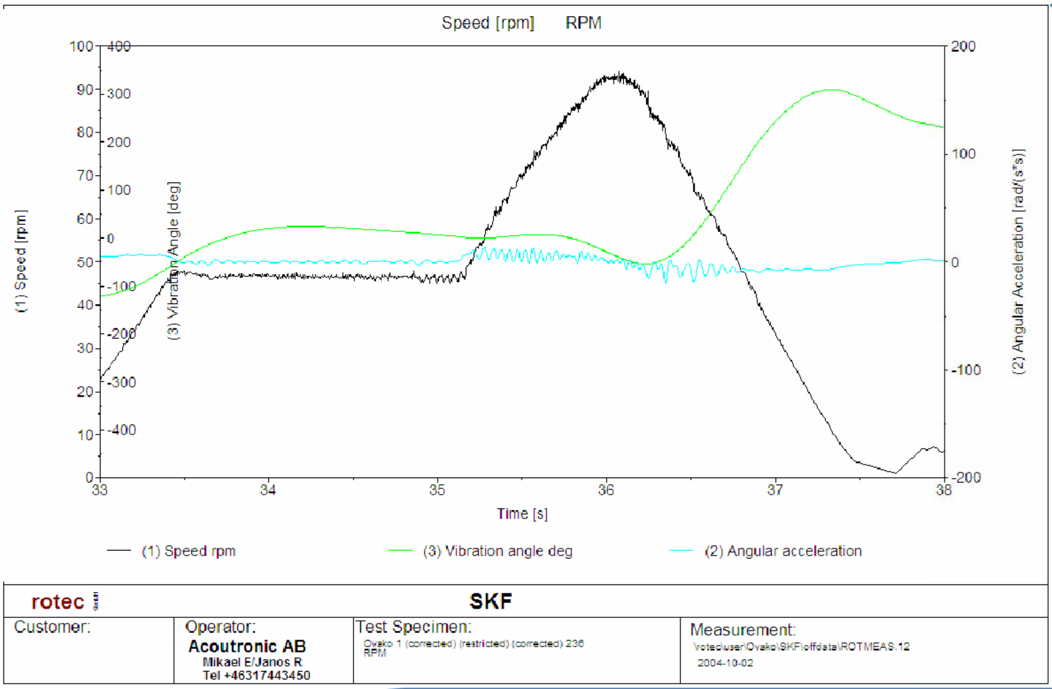
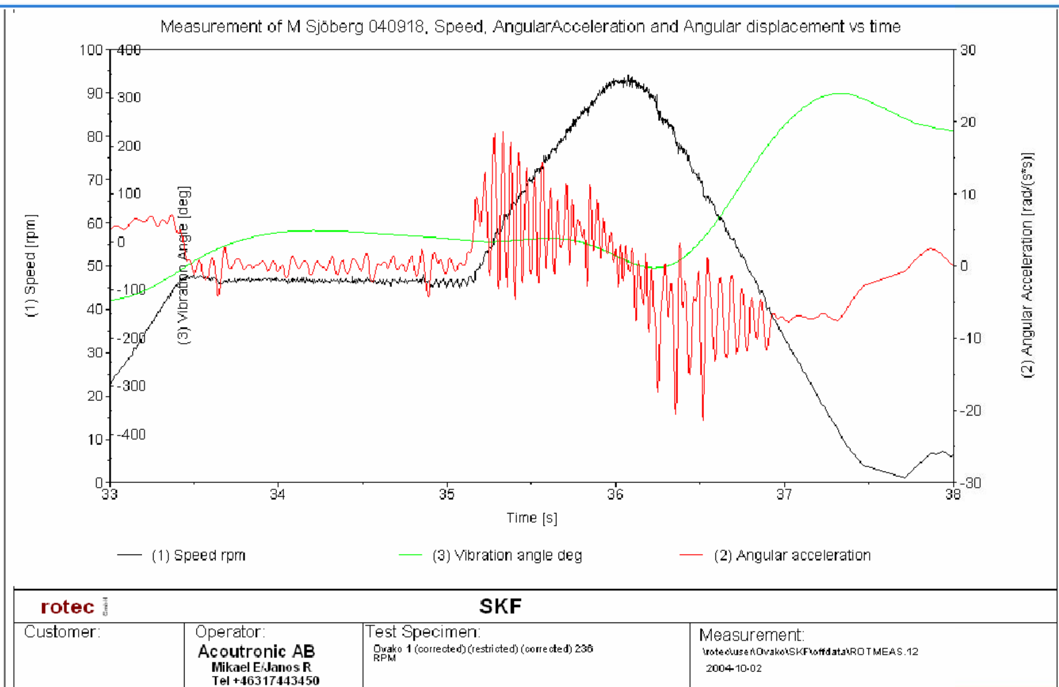
Results after improvement. Look at light blue line.



Rescale 7x. Red line



Sum up

- No ”torsions twist” remain
- Small accelerations when unloading
- Torsions accelerations decreased to 30 rad/s^2 down from 190 rad/s^2

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IEA Event – September 2008

Presented by: Matthew Hunt - Macom / Neil Brinkworth - E.ON UK

MACOM Technologies Ltd.

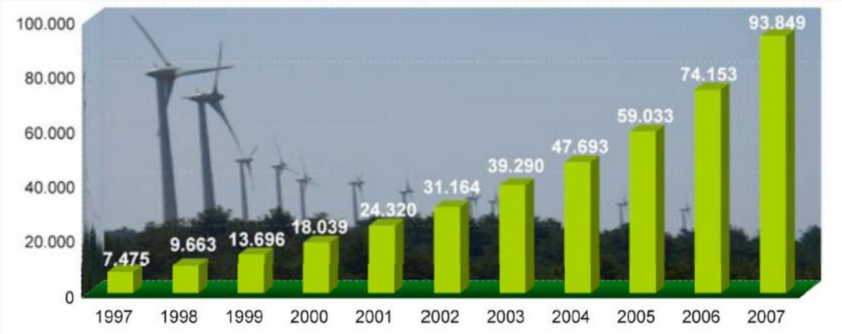
"Macom Technologies is dedicated to providing industry with a real time, on-line solution for the detection of wear debris within the lubrication system of rotating machinery. Giving a means to significantly improve machine uptime and productivity, while simultaneously minimising human and capital resources."

- **Scottish Limited Company - established in September 1999**
- **OEM fit on a US based Wind Turbine manufacturer**
- **Recommended wear debris sensor of choice by a leading oil additive company to major wind turbine manufacturer**
- **Preferred supplier status growth over competitors in the face of direct competition**

For further information please contact Macom on:

Tel: +44 141 882 0077
E-Mail: info@macom.co.uk

Wind Market as of 2007



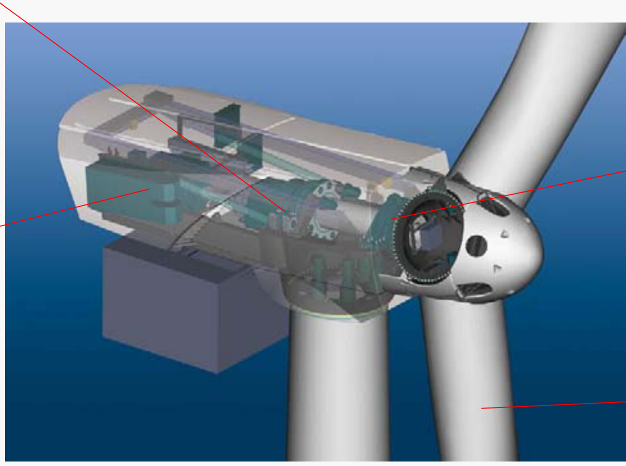
Source: World Wind Energy Association

Installed capacity > 94,000 MW

100,000 Wind Turbines Worldwide

Breakdown of Wind Turbine faults

Gearbox 32%

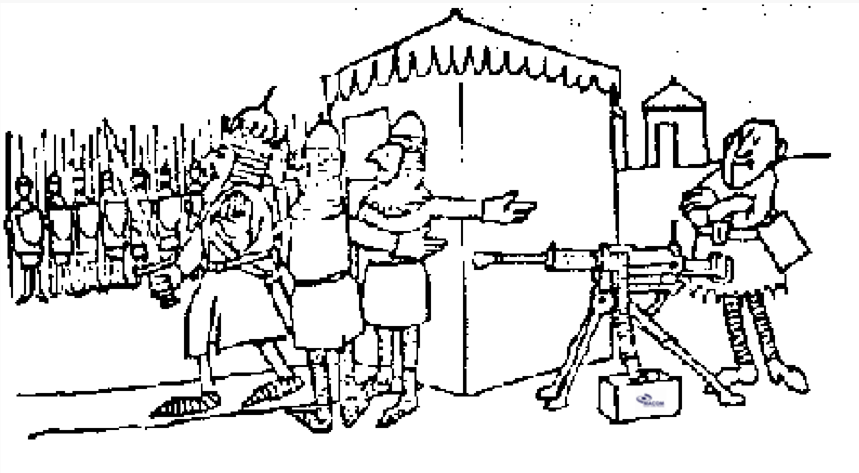


Generator 23%

Main Bearing 11%

Blades <10%

Information by **Germanischer Lloyd**



I don’t have time to see salesmen
I’ve got a battle to fight !

Need for Condition Monitoring !

- **Manage the asset**
  - **Maintain the performance of a valuable asset –** Millions have been spent installing wind turbines don’t leave them to degrade due to bad maintenance.
  - **Increase the ROI of wind turbines –** A wind turbine is only generating electricity when it is turning, equally it is only generating money when it is turning. The only way to get a return on investment is to keep the turbine running.
  - **Proactive maintenance planning –** arrange your maintenance schedule when it suits you rather than responding to problems after they happen.

What can Macom offer ?

"Macom TechAlert benchmark trial has proved that real time online wear debris monitoring is a baseline requirement for all new turbine developments."

Mr Graham Berry, European Operations Manager, Airtricity

" Detection and monitoring particles down to 50micron could extend the advanced failure warning by as much as four months"

Senior R&D wind turbine gearbox designer for a top 5 global wind turbine manufacturer

TechAlert™ 10 Ferrous and Non-Ferrous Wear Debris Sensor

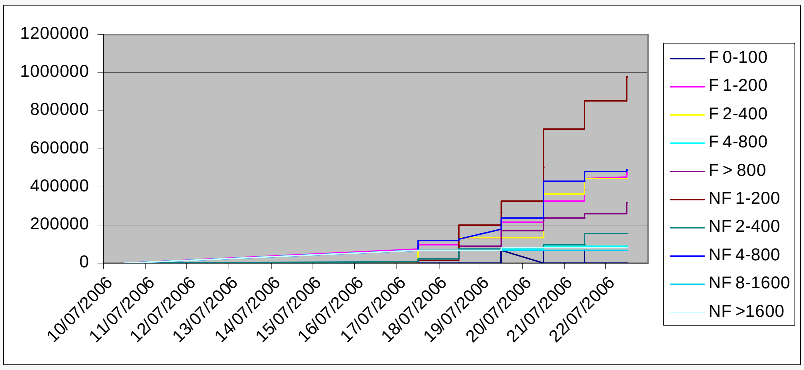
- ***Proven ROI of sensors***
  - ***Reduce lost revenue***
  - ***Reduce logistics costs***
  - ***Reduce spares costs***
- ***Increased up-time***
  - ***Improved detection due to high sensitivity of sensor***
  - ***Improved planning due to early detection of wear***
  - ***Improved generation revenue due to better planning of maintenance***

Wind Turbine Case Study

Installation on an Airtricity wind farm with turbines still under manufacturers warranty

Increased levels of wear debris particles were detected leading Airtricity to investigate further

Full magnetic sweep of the gearbox sump confirms debris at the bottom of the sump



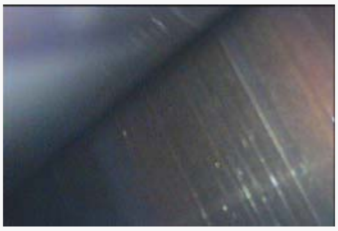
An endoscope inspection (see pictures) reveals intermediate bearing rollers to be wearing

Other bearings are in good condition

Early detection of intermediate bearing wear before causing further damage to remaining bearings leads gearbox engineer to comment that normally a problem would not be detected this early.

Turbine was left running for additional 6 months whilst scheduling and planning for the downtime and replacement of bearings.

Gearbox supplier upgrades bearings on similar gearbox's on this particular wind farm.



Potential Cost Savings for Airtricity/Turbine Supplier

Example: Failed Gearbox

Typical gearbox cost	£250,000
• Crane Hire	£ 75,000
• Lost Revenue	£ 45,000
(based on 6 month lead time for gearbox)	
• Total cost to repair	£ 370,000

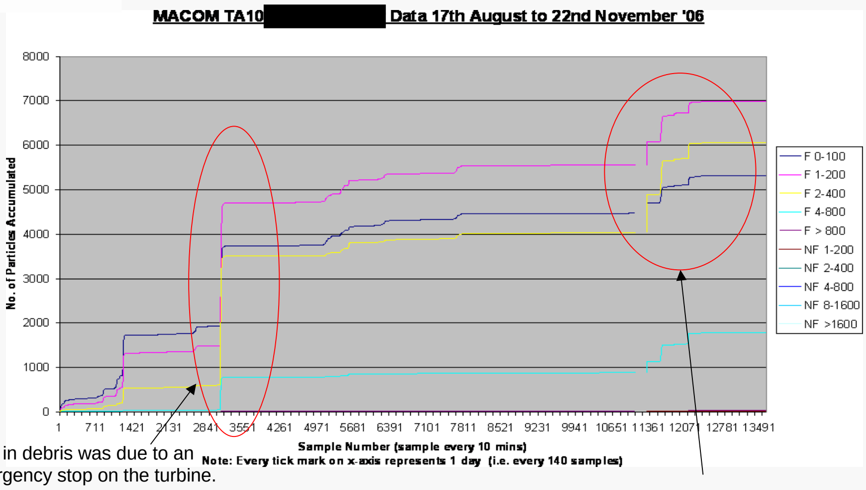
Example: Preventative Maintenance (initiated by Macom debris sensor)

• TA10 Sensor	£ 4,000
(installed and configured as stand alone unit)	
• Re-align rotor and replace bearing	£ 30,000
• Lost Revenue	£ negligible
(maintenance scheduled for low production period)	
• Total cost to repair	£ 34,000
• **Saving:**	**£ 336,000**

ROI = Gain-investment/investment * 100 = 988%

Figures are approximate and based on several assumptions

The following data is courtesy of *E.ON* Engineering Condition Monitoring Group



Rise in debris was due to an emergency stop on the turbine. Most likely cause of high counts is due to excessive load on high speed bearing as result of mechanical brakes

This rise was put down to service work being carried out on the turbine

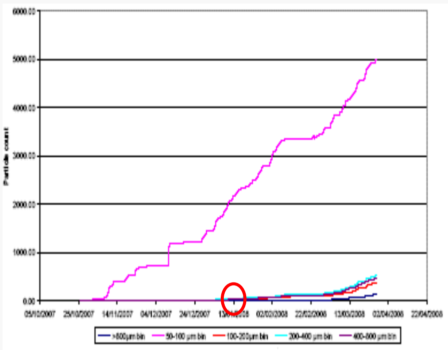
The following data is courtesy of *E.ON* Engineering Condition Monitoring Group – Neil Brinkworth

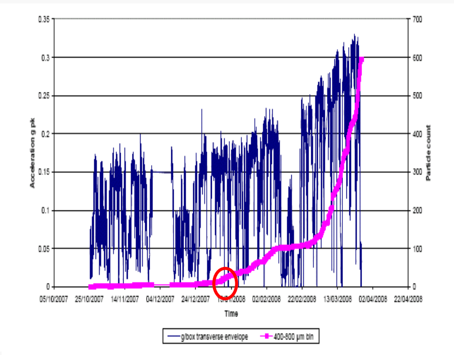
Abstract – Multi-Turbine Wind Farm Installation

Following on from the installation Macom TechAlert10™, on-line condition monitoring sensors on a UK wind farm, two turbines were found to have wear related faults leading to the shut down of both turbines. Detailed investigation showed damage to both the High speed generator end inboard bearing and the Planetary gear. The damage and therefore the failure have been caught early enough so as not to cause further damage to the remaining bearings and gearbox with the hope that reconditioning of the gearbox will suffice rather than a complete replacement.

The following data is courtesy of *E.ON* Engineering Condition Monitoring Group – Neil Brinkworth

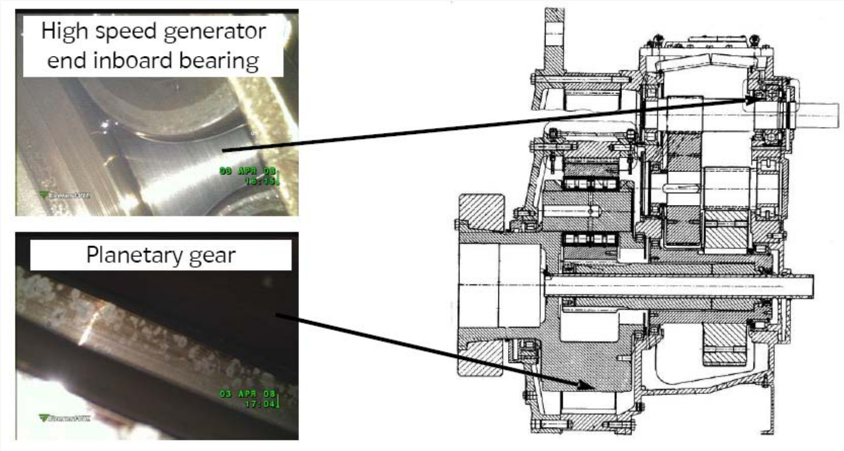
Turbine 1: From install the wear debris data showed a continual rise in the 50µ-100µ size range indicating the start of a wear related problem. As the damage increased this led to a rise in the level of debris in the other ranges which along with the vibration data led the client to investigate the cause which was shown to be damage to both the high speed generator end inboard bearing and the planetary gear.





Indicates same time period

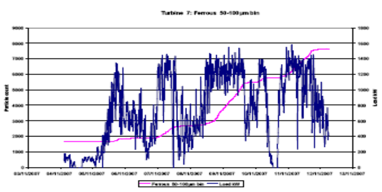
The following data is courtesy of E.ON Engineering
Condition Monitoring Group – Neil Brinkworth

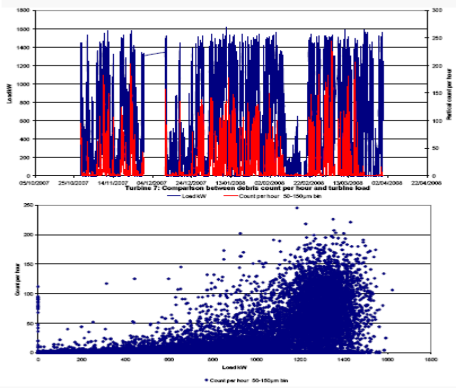


The following data is courtesy of E.ON Engineering
Condition Monitoring Group – Neil Brinkworth

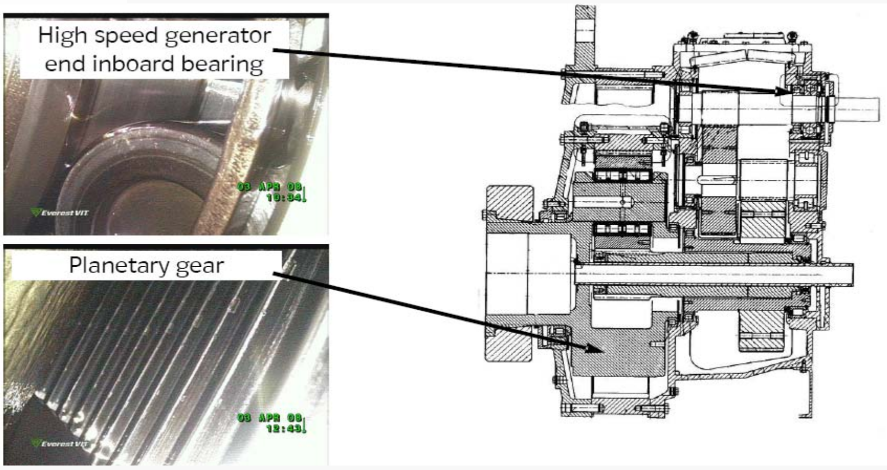
Turbine 7: On this turbine it was found that there was a direct correlation between the load increase on the turbine and the rate at which debris were generated. After 800KW the debris count increased significantly. After investigation it was discovered that there was wear to both the high speed generator end inboard bearing and the planetary gear.

NB. Vibration monitoring did not show any signs of problems on this turbine





The following data is courtesy of *E.ON* Engineering Condition Monitoring Group – Neil Brinkworth



Summary – Why Condition Monitoring ?

- **Protect your investment**
- **Increase turbine life**
- **Reduce repair costs**
- **Maintain revenue stream**

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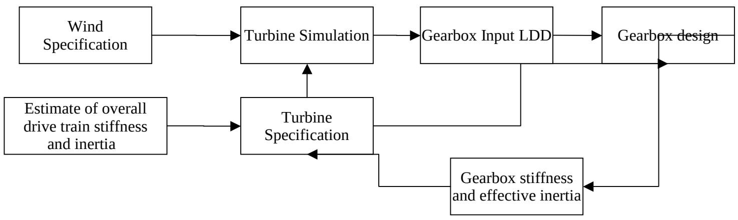
The Effect of Gearbox Flexibility on Wind Turbine Dynamics

Paper presented for IEA 4-5 Sept 2008

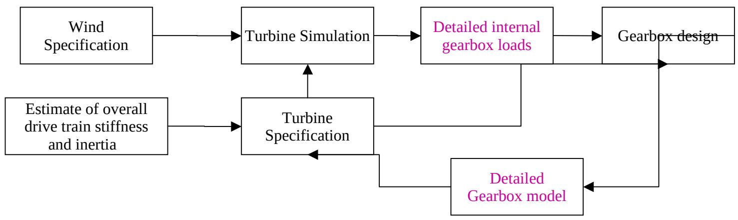
Ervin Bossanyi[†], Richard Dorling[‡], Roger Haines[†], Nawazish Ali Zaidi[‡], Andy Poon[‡]
[†]Garrad Hassan, Bristol, England
[‡]Romax Technology Limited, Nottingham, England.

Specification and design of Wind Turbine Gearboxes



- In the current specification and design process, only the overall stiffness and effective inertia of the drive train are taken into consideration. Higher order effects due to modes of vibration of the gearbox are generally ignored.
- Note: the gearbox is generally designed using quasi-static methods and so only an input LDD is required to specify its loading characteristics, which is consistent with the above approach

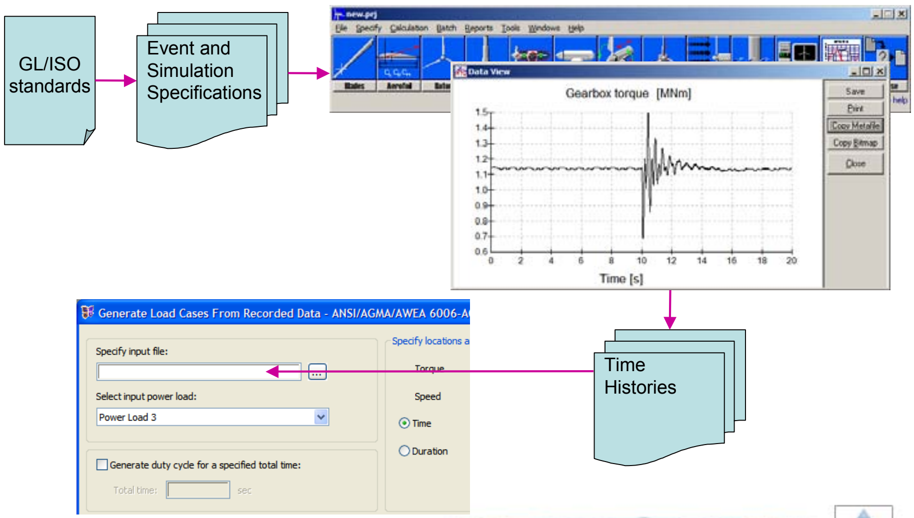
A detailed gearbox model can now be used



- It is now possible to take the full dynamics of a gearbox into account. This means that all modes of the gearbox effect the LDD which drives the specification of the gearbox.
- Gives separate LDDs for different gearbox components
- Some changes to the other turbine loads may also occur.

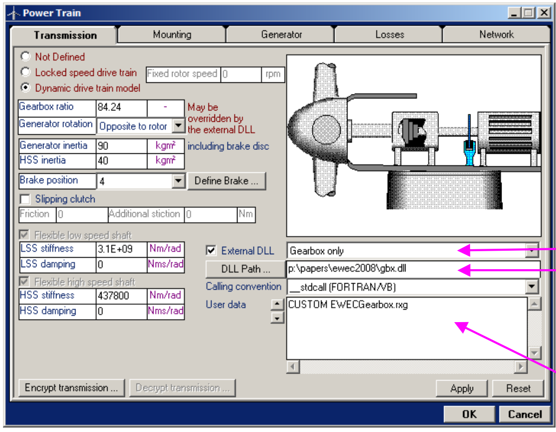
EWEC2008 GH/Romax slide 3

GH Bladed and RomaxDesigner



EWEC2008 GH/Romax slide 4

RomaxDesigner and *GH Bladed*



Select:
- Gearbox only, or
- Gearbox, HSS and generator inertia

Select the gearbox DLL file, e.g. exported from RxD

Any custom data

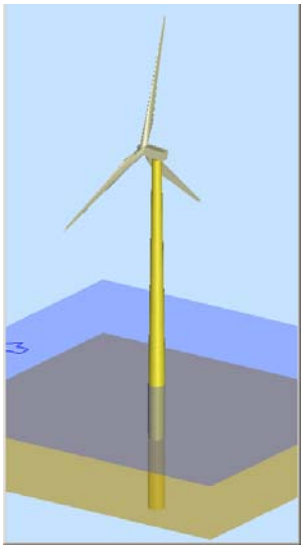
Use RomaxDesigner to design the gearbox

Option to also include Brake, HSS and generator inertia inside the DLL

Export the gearbox DLL from Romax Designer

Example Wind Turbine

- 2 MW generic offshore wind turbine
- Variable speed, pitch regulated
- 75m diameter
- Gearbox ratio 84.24
- Overall drive train stiffness 2.4×10^8 Nm/rad

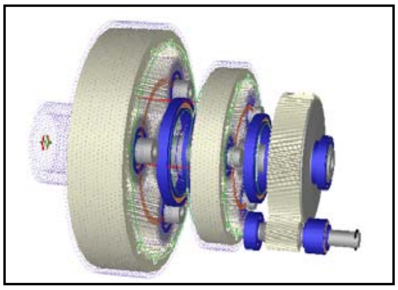


Example Gearbox

Specification:

- Capacity: 2 MW
- Ratio: 84.24
- Layout:
  Planetary – Planetary – Parallel
- Life: 20 years

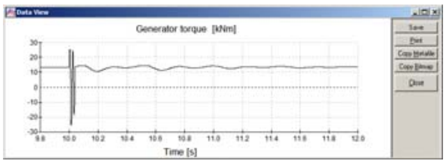
Initial design based on GH Bladed output with overall drive train stiffness of 2.4×10^8 Nm/rad



Dynamic Analysis

The events chosen to study the impact of using a full dynamic gearbox model over a rigid gearbox model were:

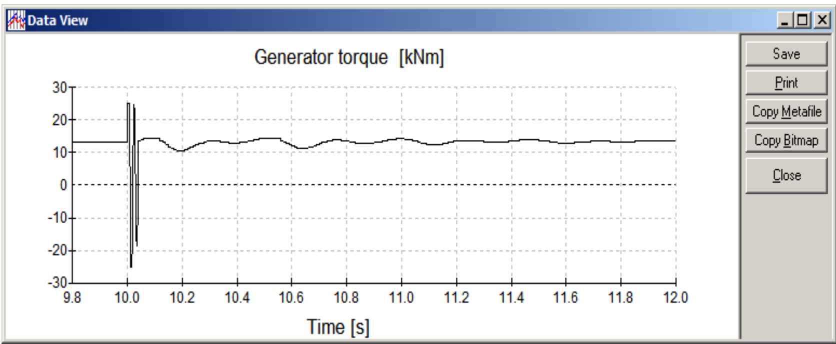
- A three phase short circuit event



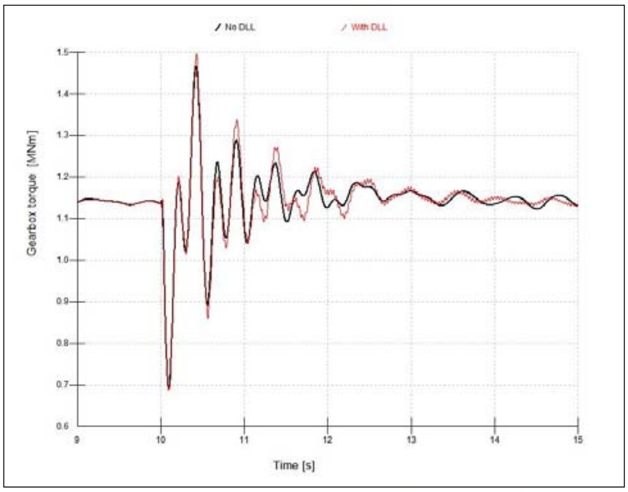
- Normal running in turbulent wind, to generate LDD
  - 10-minute simulations with IEC turbulence
  - Idling at low and high wind speeds
  - Power production at 2m/s intervals from cut-in to cut-out

Note: All comparison runs have LSS & HSS shaft stiffnesses adjusted to maintain the same overall stiffness

Dynamic Analysis - short circuit event

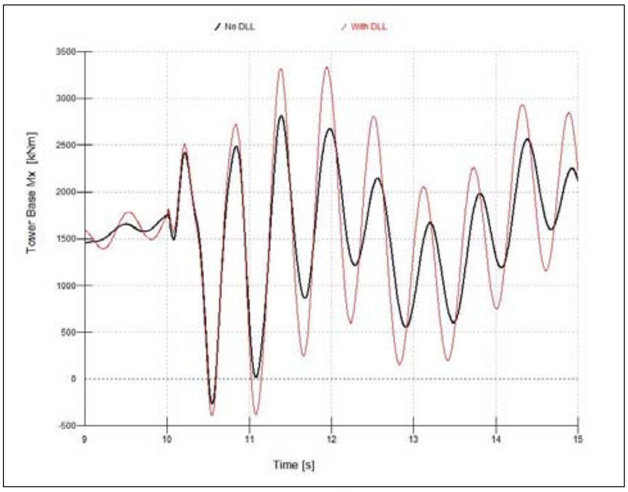


Transient Dynamics – Three phase short circuit



Romax TECHNOLOGY | GARRAD HASSAN

Transient Dynamics – Three phase short circuit



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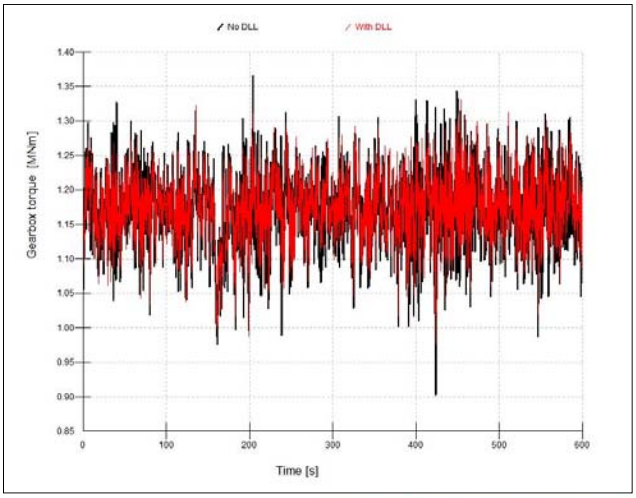
Turbulent simulation: example at 19 m/s



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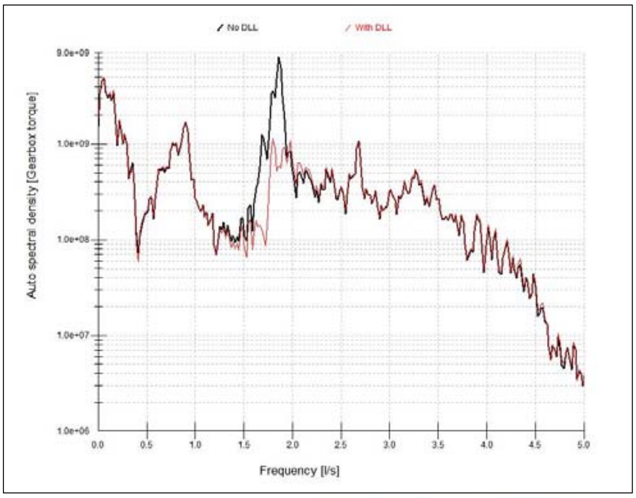
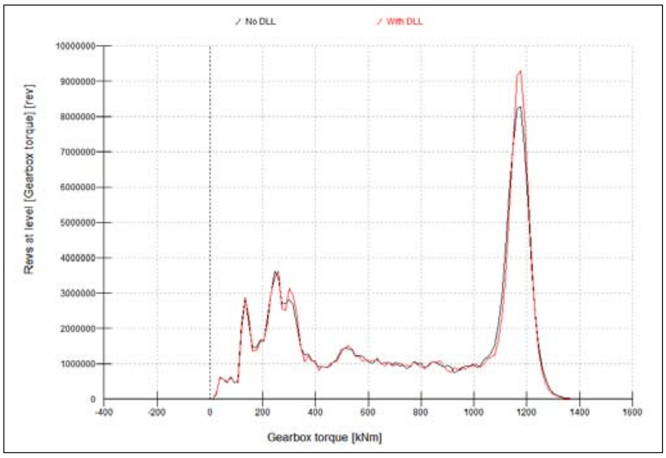
Turbulent simulation – 19 m/s



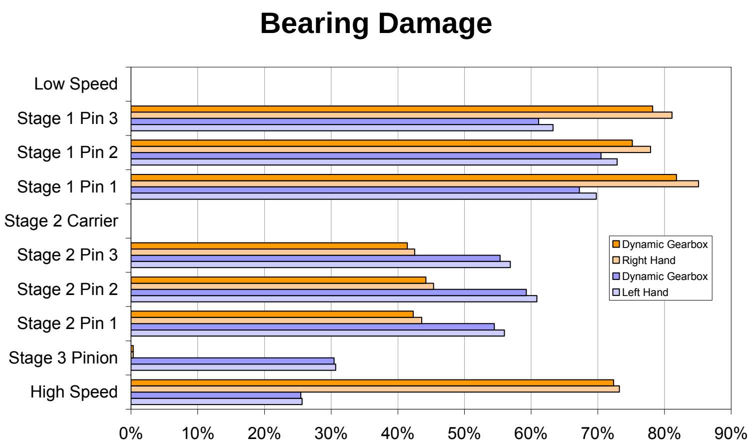
EWEC2008 GH/Romax slide 14

Changes to Load duration distribution



EWEC2008 GH/Romax slide 15

Changes to gearbox life estimates



EWEC2008 GH/Romax slide 16

Future work programme

- Slip-clutch, brake, flex coupling and torque arm.
- Torque load-dependant non-linearities, clearances of bearings and gears
- Apply Bladed dynamic loads for more detailed component simulations.
- Start/stop events; grid ride-through events; exciting events

Axial motions and reverse torque

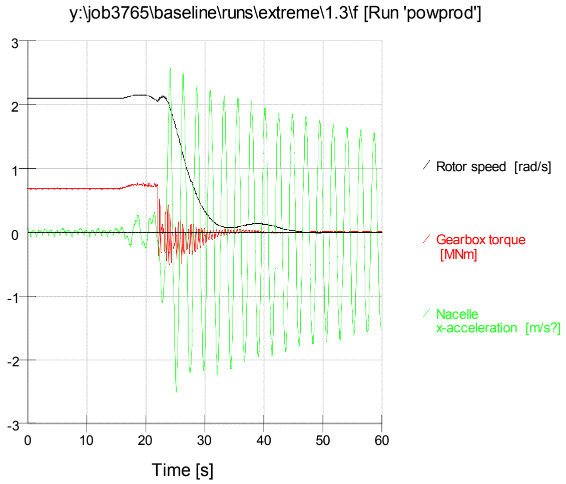
Stopping cases – off wind

2.5 m/s accelerations

Fwd rotation

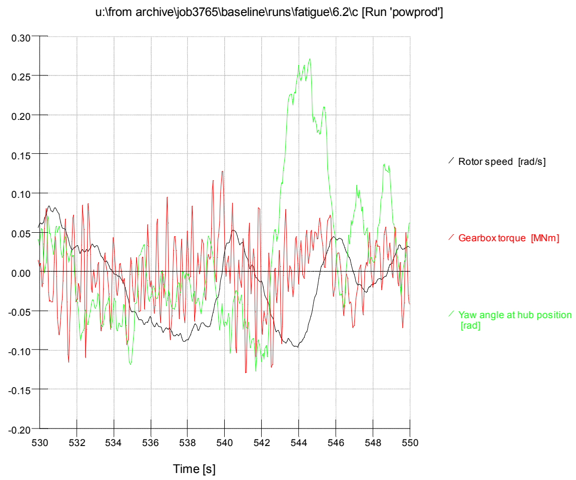
50% reverse Q

Result – shaft thrust reversed, bearings skidding

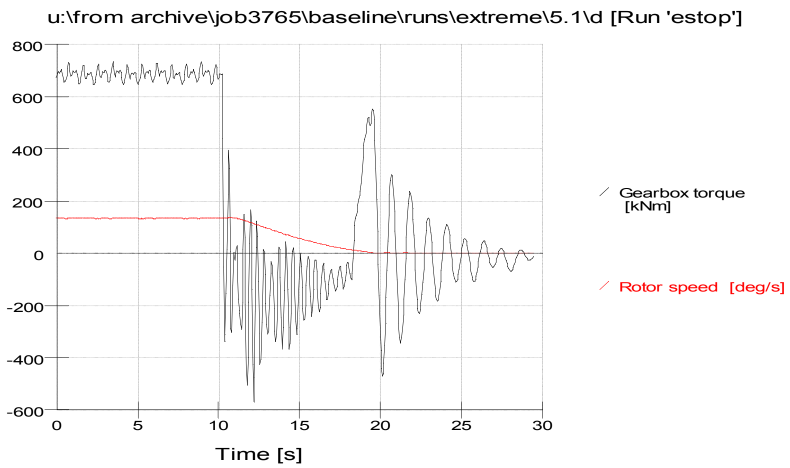


			x-acceleration	y-acceleration	Low speed shaft torque	Rotor speed
		Load case	m/s?	m/s?	kNm	rad/s
x-acceleration	Min	1.3f	-3.4	0.25	-364.4	2.2

Standby; high wind



Torque reversals in a shutdown



Thanks for listening … again

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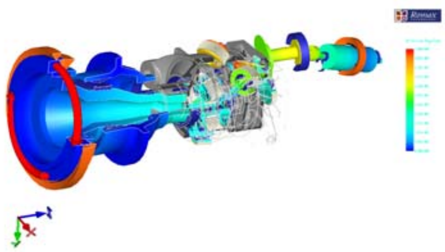
Influence of Housing and Carrier Flexibility on Gear and Bearing Loaded Contact

Presented at the IEA Wind Gearbox and Drivetrain Dynamics Meeting

Dr. Ashley Crowther (R&D Manager – Wind)
Dr. John Coultate (Simulation Engineer)
Romax Technology Ltd.
September 2008

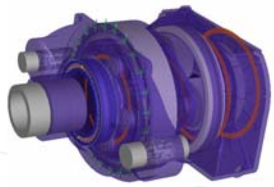
Outline

- Introduction to RomaxDesigner
- NREL gearbox model
- Illustration of a load distribution graphs
- Influence of non-linear bearing, flexible housing and carrier on gear mesh misalignment
- A brief example of gear micro geometry modifications on NREL gearbox
- Additional Romax capabilities

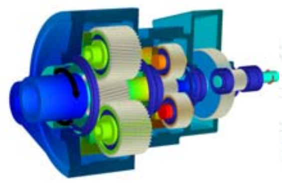


Introduction to RomaxDesigner

- **RomaxDesigner**
  - "A virtual product development tool for transmissions"

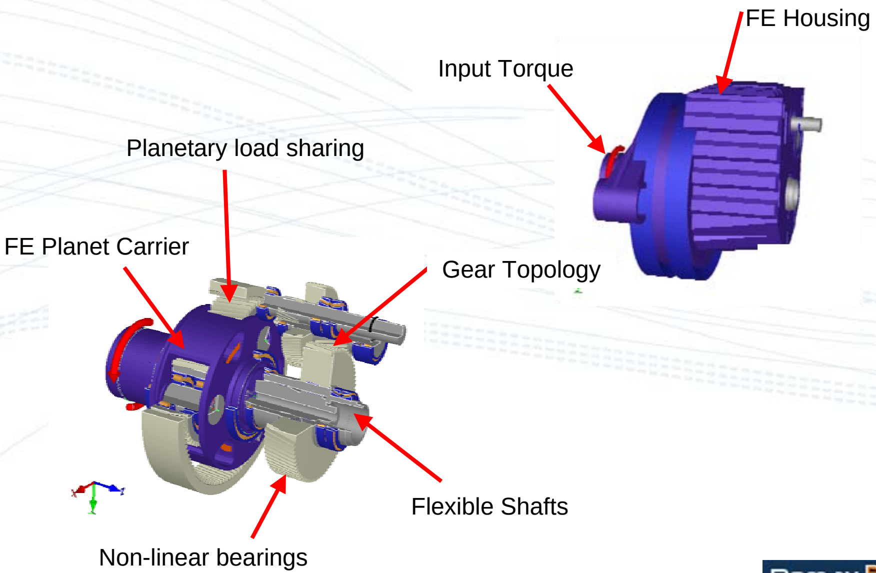


- **Modelling** Creating a model of the whole assembly



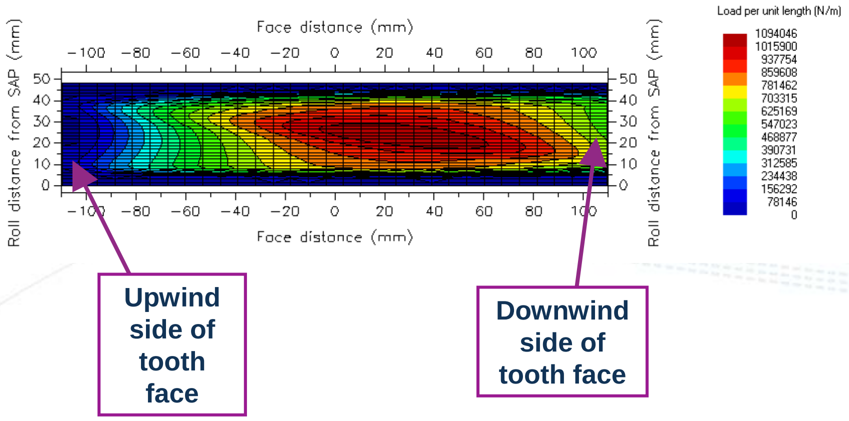
- **Analysis** Predicting how the assembly and its components will work
  - o System deflections
  - o Component life
  - o Advanced analysis

NREL GRC Gearbox Model



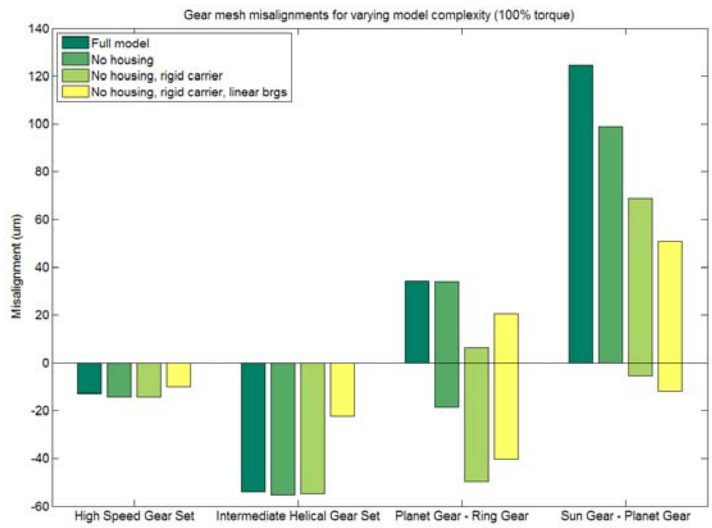
Load distribution graphs

- The load distribution graphs show load per unit length (along the line of contact):



Romax TECHNOLOGY

Influence of Non-Linear Bearing & Flexible Carrier/Housing



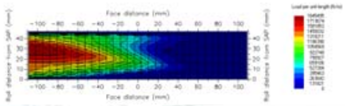
Case: 100% Torque

Romax TECHNOLOGY

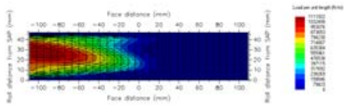
Influence of Micro-Geometry Modifications

- Results using original design for micro-geometry corrections

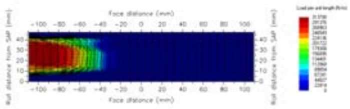
100% torque



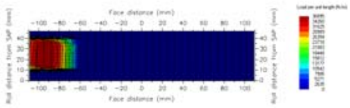
50% torque



10% torque



1% torque

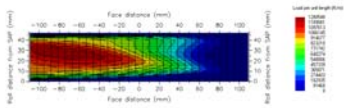


Sun-planet gear loaded contact distribution

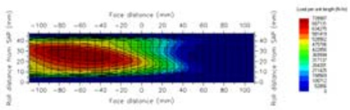
Influence of Micro-Geometry Modifications

- Results using the revision I for micro-geometry corrections

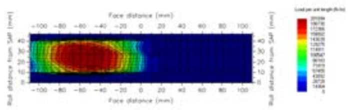
100% torque



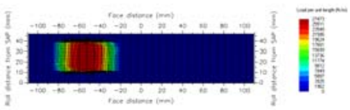
50% torque



10% torque



1% torque



Sun-planet gear loaded contact distribution

Romax analysis capabilities

- Full system deflection including FE components
- Component deflection includes coupled effects from other components
- Dynamic analysis with excitation at the gear meshes
- Natural frequencies and mode shapes
- Transient dynamic analysis

Gear

- Gear misalignment
- KhB value for gear loading
- Tooth load distribution
- Gear Microgeometry effects and restoring moments on the gears
- A DoE study on Microgeometry parameters, macrogeometry, tooth clearance etc.
- Planet load share in planetary gear system

Bearings

- Bearing misalignment
- Element load distribution and contact stresses
- Roller profiles are taken into account.
- Bearing life and failure limit.
- Sensitivity study on the bearing clearance, preload, outer/inner ring mounting errors etc.

Romax TECHNOLOGY

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Modelling of loads and dynamics of wind turbines

Esa Peltola, Petteri Antikainen, Tomas Wallenius

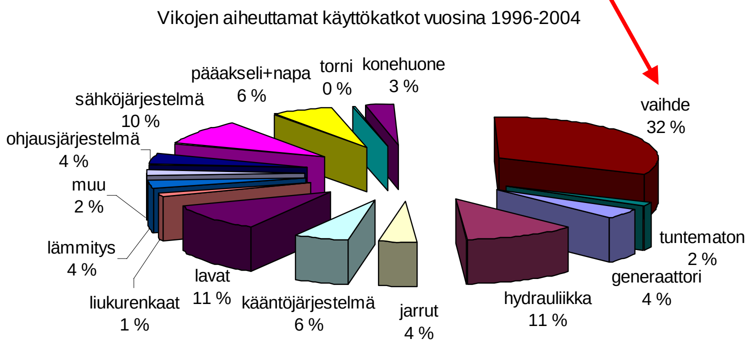
Business from technology

Contents

- Statistics
- Modeling of loads and dynamics
- Measurements
- Technology development

2

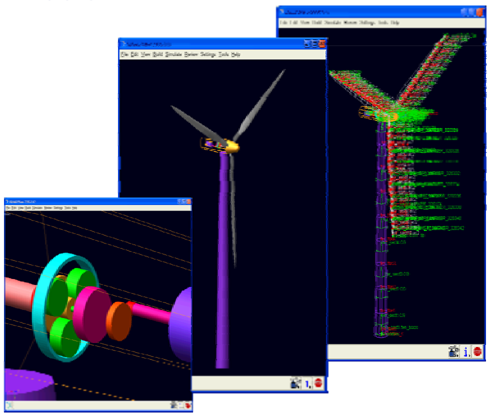
Wind turbine production and failure statistics in Finland - 32 % of total downtime due to gear box failures in 1996-2004

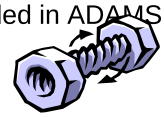


Simulation tools

ADAMS

- Commercial versatile dynamic simulation tool
- ADAMS/WT and Aerodyn developed by NREL
- Detailed wind field, aerodynamic and mechanical modeling
- Modifications to Aerodyn to enable individual blade aerodynamic properties by VTT
- electrical phenomena not modeled in ADAMS





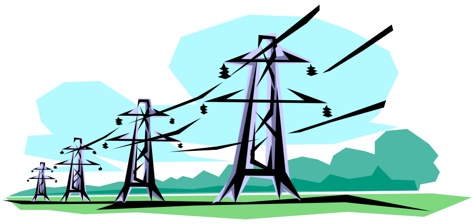
Simulation tools

PSCAD/EMTDC

- Detailed electrical component and network modeling
- Efficient dynamic simulation tool
- Aerodynamic and mechanical side is not modeled in sufficient detail

Simulink

- Very convenient for control system modeling
- Used for combining simulations

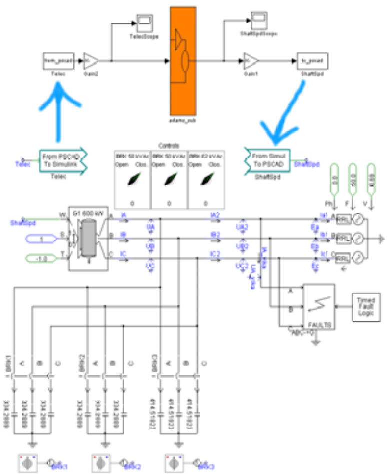


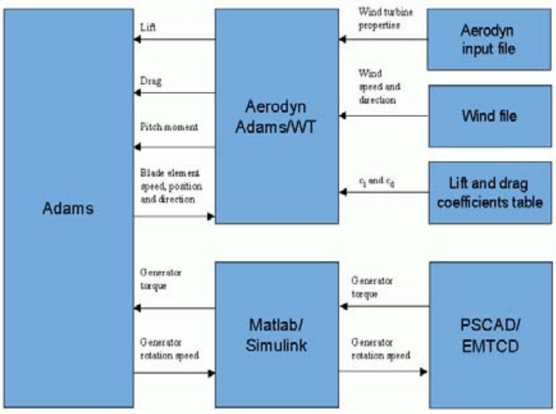
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Combining simulations

- Code developed by VTT
  - New block libraries for Simulink and PSCAD
- Adjoint simulation developed to enable to study:
  - which mechanical phenomena are transferred to the electrical side
  - the influence of network disturbances to the mechanics of the turbine
  - Fault-ride-through simulations
  - the impact of control actions and development of new control strategies
  - indicators that can be used for condition monitoring purposes
  - new technical solutions and materials in order to reduce harmful forces and events on e.g. drive train

Data exchange between simulation programs



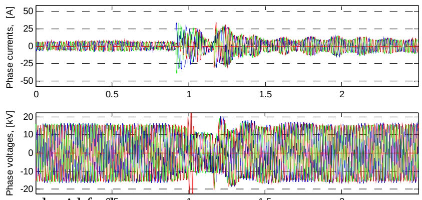


Transient measurements and simulations - example

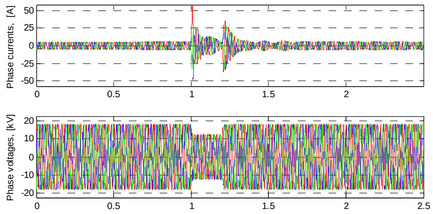
- Power measurement in Olos wind farm
  - Power has been measured from 4 turbines
- Disturbance recorder
  - records electrical data, i.e. currents and voltages, triggered by significant change in zero voltage, which usually indicates a fault in the network
  - The recorder stores measurement data in two frequencies; in 500 Hz a period of 2.5 s, and in 3 700 Hz a period of 0.338 s

Simulation example: Grid fault

- Bonus 600 kW Mark IV turbine
- Fault type is changing in measured case
- In simulated case only 3 phase fault
- network and fault were not very accurately modelled

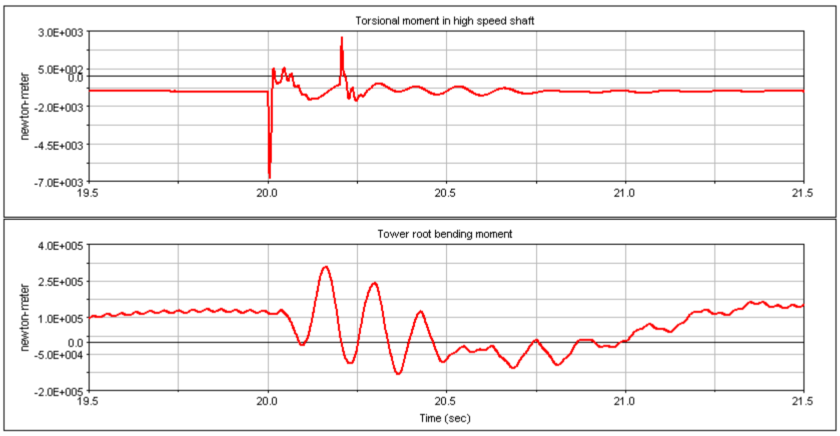


Measured grid fault



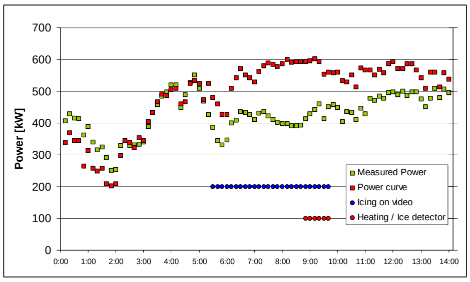
Simulated grid fault

Simulation example: Grid fault

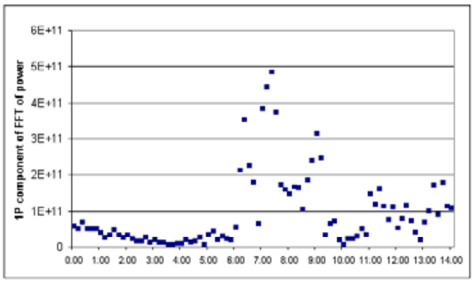


Rotor imbalace

- Irregularly iced blades cause aerodynamic and mass imbalance
- 1p component to loads and power
- Fits with simulations using ADAMS



Icing event 22.2.2002 at northern Finland



1p-component of power

Ricardo Wind Turbine Drivetrain Overview

Presentation to IEA Expert Group Meeting
4th September 2008

Giles Hundleby

Project Director - Clean Energy, Ricardo UK Ltd

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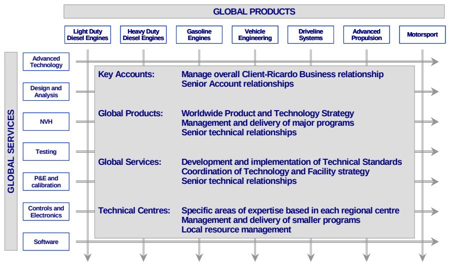
Ricardo is a 100 year old, independent global product development firm with the capability to respond complex programs with a focus on Transport & Clean Energy

Critical Mass and Global Flexibility

- Critical mass with over 1800 staff
- Global engineering centers
- Technology and product teams managed globally for consistency of program delivery
- Engineering disciplines and resources managed globally for maximum utilization and flexibility



International Presence

 2

Ricardo has a track record of delivering high profile, industry benchmark products on time, on cost, helping customers maintain leadership positions

Strategic programmes

Turnkey

Fast track

On time

On cost

Targets met

Great products

Great reviews

- **System design, analysis, validation and integration**
  - front and rear axles
  - transfer case and driveline
  - traction control system
  - Suspension & chassis
  - induction, exhaust and fuel system

- **Design, analysis, development and validation of the world's first all – Aluminium 5 cyl diesel**
- **Technology transfer to Volvo**
- **Close co-operation with suppliers**
- **Common production intent with gasoline**

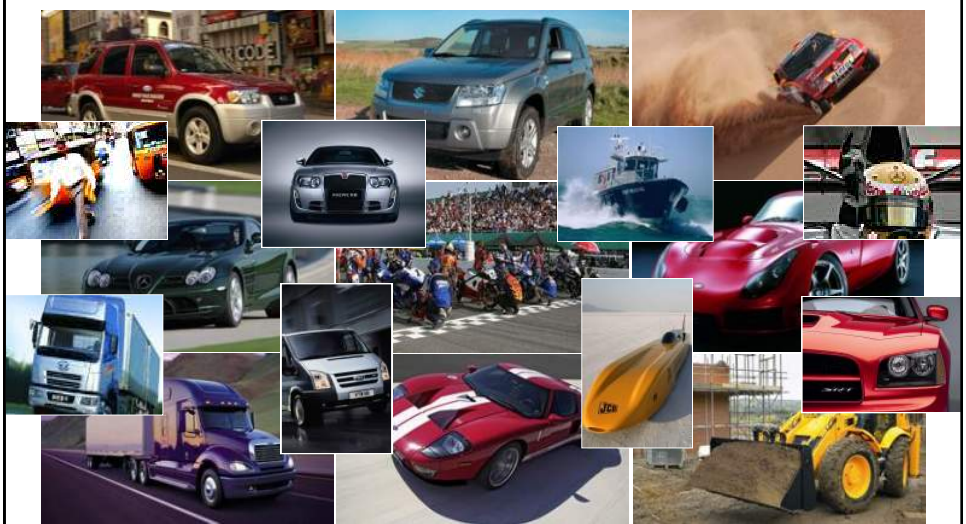
- **Concept to production, high value global V6 engine family**
- **Total engineering programme**
  - multi-platform
  - multi-customer
  - multi derivatives
- **Base engine design, development and validation, delivered 12 months faster than customer process**

- **Powertrain integration**
  - multi-engines, transmissions and derivatives
- **Cost down**
  - application, systems
  - multiple roll-out
- **Current engineering**
  - base engines
  - application support

- **Concept design and development of DCT and driveline system**
- **Manufacture of prototype and pre-production units**
- **Full transmission and driveline control software system, including active rear axle**
- **Design and engineering of advanced TCU**

- **Concept to production power upgrade and reduced emissions of iconic V8 engine**
- **Co-location, technology leverage and transfer**
- **Concept, combustion, CAE, NVH, valve train dynamics, thermal and ancillary systems design**
- **Launch support**

Additional projects



Ricardo client base covers global energy and financial companies and government agencies

Partial List

Global Client Base

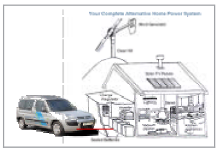
Clean Energy	Financial Firms	Oil Companies and Utilities	Governmental Agencies
NTDA, Planet, Mechanology, QinetiQ, Infinia, AFS Trinity Power Corporation	Greenbriar, Clayton Dubilier & Rice, Berkshire Partners, Baring Private Equity Partners, Barclays Private Equity, 3i, Rothschild, GE, Charterhouse, Nordic Capital, UBS	bp, Shell, npower, ExxonMobil, Duke Energy, Gaz de France, British Gas, Hawaiian Electric Company, Inc.	ECN, United States Environmental Protection Agency, ie, DTI New & Renewable Energy Programme, ifp, CARB California Air Resources Board

Automotive OEM	Heavy Duty Diesel	Production and Aftermarket
BMW, Toyota, Honda, GM, Ford, Jaguar, Fiat, Mitsubishi, Nissan, VW, DaimlerChrysler	John Deere, Cummins, Caterpillar, Paccar, Scania, Volvo, International, Freightliner	Detroit Diesel, ZF, Delphi, GKN, Eaton, Visteon, ATC Aftermarket Technology Corp., Honeywell

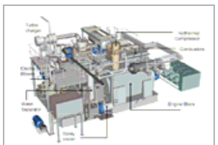
 5

Ricardo has successfully delivered many challenging, high profile clean energy product development programmes

Selected Examples



Vehicle to Grid (V2G)
Integration & Controls Strategy



Novel 3MW power plant
Engineering Demonstrator

Stirling Micro CHP
Commercialization Support

Tidal Turbine
Failure Mode Analysis

Novel Wind Turbine
Compressed Air Storage

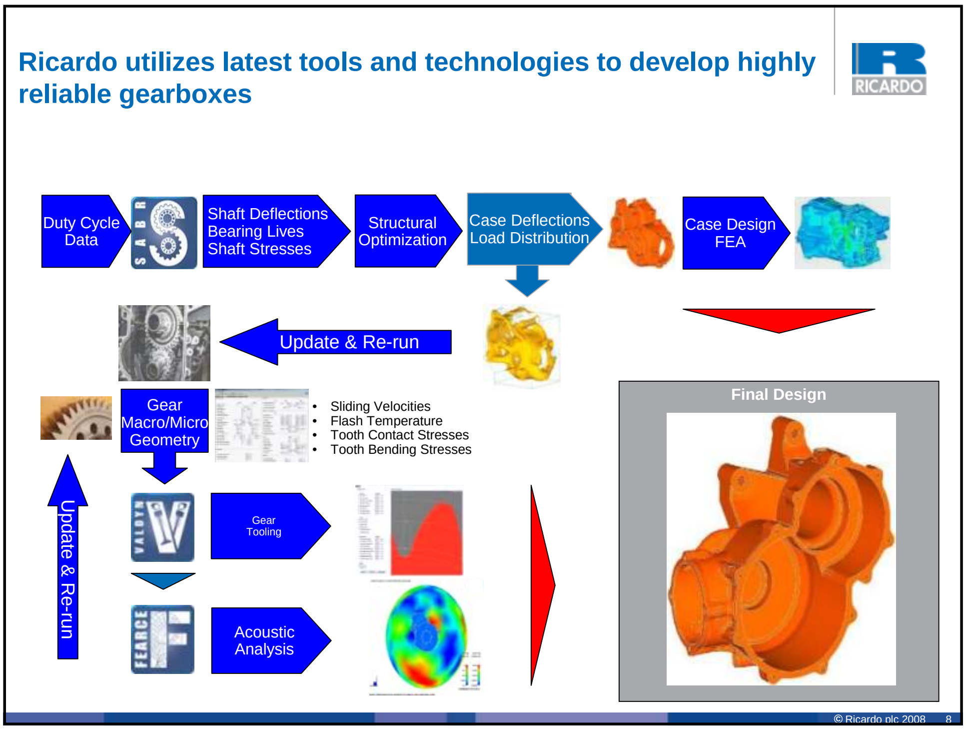
PHEV
Technology Demonstrator

STEG – Stirling Engine
Design for Manufacture

DG SOFC
Balance of Plant Cost Analysis

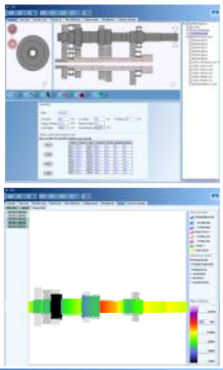
 6


Ricardo has taken a strategic decision to develop its capabilities to support the wind industry
RICARDO
EWEC 2008
Launch at conf reception
NREL Round Robin
WT Gearbox Analysis
Software Evaluation
Samcef & others
Magnetic Gearbox R&D
Concept
Superlife Bearing R&D
Patent application
EWEA
AWEA
Association Activity
Identify key R&D needs
GLOBAL WINDPOWER 2008 29-31 October Beijing, China
Conference Activity
Attendance & Papers
Ricardo Wind Turbine Drivetrain Overview
IEA
TEM support
© Ricardo plc 2008 7


Ricardo utilizes latest tools and technologies to develop highly reliable gearboxes
RICARDO
Duty Cycle Data
Shaft Deflections
Bearing Lives
Shaft Stresses
Structural Optimization
Case Deflections
Load Distribution
Case Design FEA
Update & Re-run
Final Design
Gear Macro/Micro Geometry
Sliding Velocities
Flash Temperature
Tooth Contact Stresses
Tooth Bending Stresses
Gear Tooling
Acoustic Analysis
Update & Re-run
© Ricardo plc 2008 8

Combined modelling techniques use Ricardo's shaft and bearing software (SABR), finite element models and Ohio State gear program (LDP).

- Torsional deflection results, gear tooth loading and gear mesh stiffness have been calculated as well as housing deflections.
- SABR Tool developed by Ricardo for enhancing durability and refinement of transmission design in short design cycles – user-friendly operating environment means whole transmissions can be modelled rapidly and results evaluated early in the design process
- Analysis results assessed against user-defined targets
- Stress results presented graphically with bending moment and shear force diagrams to aid robust shaft design.



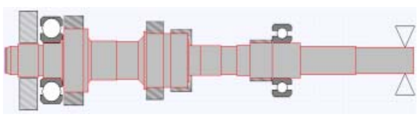
 9

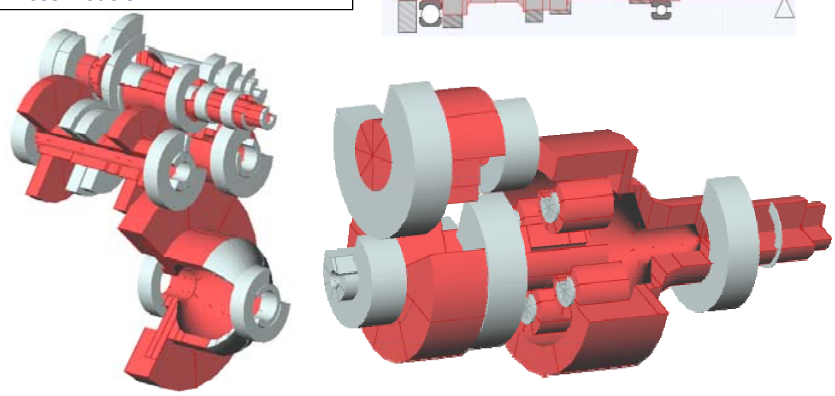
Analysis solutions for internal components SABR (shafts and bearings)

Gearbox models built up with shafts bearings and gears

Shaft sections build up complex geometries

Ricardo designed 5 degree of freedom non-linear bearing models are solved together with the shaft stiffness models

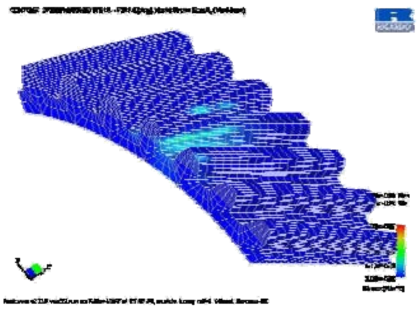


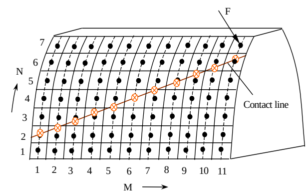


 10

Analysis solutions for internal components VALDYN (Dynamics)

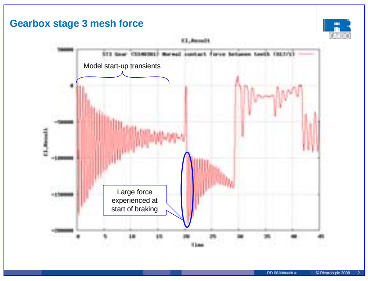
- Complete driveline dynamic assessment for vibrations, noise and transmission error.
- Detailed compliance modelling across tooth profile.
- Gear Micro Geometry can be specified for investigations of:
  - Corrections to tooth profile (Tip relief, crowning, lead correction).
  - Manufacturing errors
  - Improve meshing performance
- Prediction of the coupled elastic and rigid-body motion of transmission components in the time domain.

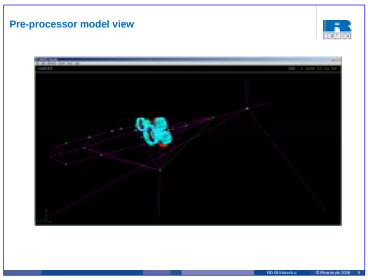




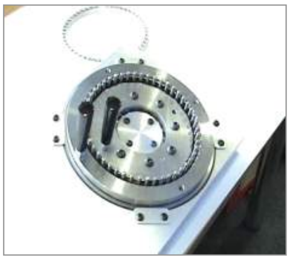
Holistic WT software evaluation

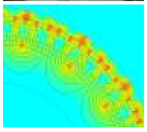
- Samcef for WT being evaluated
- Initial focus on dynamic loads
- Next phases
  - Load generation for detailed gearbox modelling
  - Control strategies to reduce loading
  - Modelling of magnetic gearbox





Ricardo Magnetic Gear





Situation and Objective

- Conventional geared systems suffer reliability issues in wind turbine applications
- Objective to assess a technology to provide:
  - Reliability – less sporadic failures
  - Eliminate wear
  - Overcome requirement for "average loads" in gear design
  - Reduced oil contamination – potential for sealed circuits for bearing lubrication – reduced oxidation
  - Overload protection (a resettable torque fuse)

Approach

- Principle: interaction of inner and outer rotor magnets with fixed pole pieces generates a ratio by superposition of flux harmonics
- Work : theory/lit. search, Analysis using magnetic FE, Design, Manufacture
- Design utilized stock components to achieve very tight deadline for client demonstration – higher torque capacity predicted for optimized
- IPR search to understand ownership and "road-block" patents, if any.

Results and Benefits

- A working prototype was analyzed, built and demonstrated – thus validating this as a realistic solution route.
- Client interest in assessing a competing technology that displace their product.
- Support to develop a migration plan
- Next steps will involve analysis to optimize the design and develop angled drives
- Will derive detailed cost/benefit for magnetic gears versus alternatives (inc bearings, material costs etc)

WTG Transmissions – next generation – which solution(s) ?

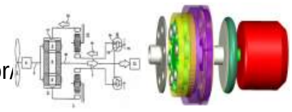
- Anticipate analogue of automotive industry: *diversity & periodic convergence*
- Fixed Ratio
  - Conventional Gears
  - Combination (Epicycle + magnetic)
  - Full Magnetic with/without integrated generator
  - Traction Epicyclics
- Variable ratio
  - Split path
    - Fluid Variator
    - E-variator
- Direct Drive

Source : Ricardo

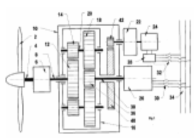
Source : Milner

Source : Ray Hicks MBE

Optimised Gearbox design for modern wind turbines



Source : Voith Patent US 2007007769



Source : Frank Meuller Pat 2429342

Serious Cost/ benefit analysis required to ensure product plans are robust 5,10 years

WTG Bearings – locations and challenges

- Hub
  - Mass of Hub and Blades, Wind Thrust, Gyroscopic (pitch arising from wind/wave flexure of tower)
  - Most difficult to replace ?
  - Typically, bearing has one element fixed(outer race)
  - Concentrated wear at 12 and 6 o'clock due to gravity/ wind buffet during storm parking
- Planet
  - Typically lubrication flow is via several rotating shafts/seals
  - Does the lube flow meet instantaneous requirements and avoid extremes of metal/metal contact or hydro-planning ?
- Fast shaft into generator
  - High acceleration/TVs leading to in indeterminate rolling rolling and lubrication regime of rolling elements
  - Field data indicates this bearing has greatest risk of failure
- Superlife bearing concept under development & patent application process

 15

Forthcoming Papers

- **Improved WTG Transmission Reliability through Novel Solutions**
  - Technical Session - 2.13 - Innovative turbines, components and systems
- **Non-linear Gear and Bearing Analysis for Improved Reliability of WTG Transmissions**
  - Poster Session

 16

Thank-You!

Ricardo Wind Turbine Drivetrain Overview

Presentation to IEA
Expert Group Meeting
4th September 2008

Appendix

Ricardo Wind Turbine Drivetrain Overview

Presentation to IEA Expert Group Meeting
4th September 2008

Case Study: Business & Technology Strategy

Ricardo co-ordinates the EU FP6 Project Roads2HyCom - to assess and monitor research in the field of Fuel Cells and Hydrogen for stationary & transport power.

Background

Ricardo's Responsibilities

- Overall Project Coordinator
- €7.8M over 42 months (EC funding: €4.5M)
- Programme leadership & management, reporting, communication & dissemination
- Mapping research, technology development activity and technology watch
- Providing support to the EC in initiating R&D

Project Objectives

- To assess and monitor **Hydrogen** and **Fuel Cell** technology for stationary and mobile energy applications by considering:
  – **Research** landscape and **technology** capability
  – Current / future **Hydrogen infrastructure** and **energy resources**
  – Needs of **communities** that may be early adopters
- ***Duration: October 2005 – April 2009***

Roads2HyCom Key Achievements:

- Wiki-media resource for the SOTA launched and mostly completed
- On-line H2&FC databases launched and completed
- Two "Communities" workshops and Handbook Vol. A delivered – Vol. B to be published in June 2008
- Thirteen key reports published, and at least 6 key presentations of R2H results in the public domain
- All Roads2HyCom reports and resources are available from www.roads2hy.com

Case Study: Product Development & Program Management

Ricardo provides product development support to wind power start-up

Background

Approach

- Ricardo applies well-proven product engineering & automotive practices
  – Design optimization & material selection
  – Performance modeling and analysis
  – Mechanical dynamic analysis
  – Reliability and robustness engineering
  – Design for manufacture & cost optimization

Situation

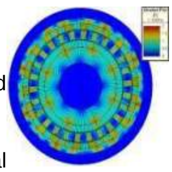
- Mechanology sought a product development partner to augment their technical skills in developing a next generation wind turbine system
- Mechanology needed specific expert support in developing the *Dragonfly*™, a compressor for wind power that will meet or exceed the rigors of round-the-clock operation with an expected life span exceeding 20 years

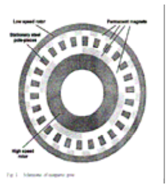
Added Value

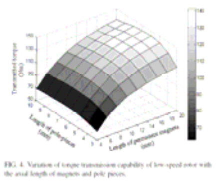
- Ricardo's unique combination of being able to simultaneously develop innovative ideas and apply highly disciplined engineering techniques convinced Mechanology that it had found the perfect fit for its *Dragonfly* Wind Compressor development program

Magnetic Gears

- Typically efficiency > 98.5% at full load
- Torque density of up to 150 kN/m^3 can be achieved
- Wide Ratio Span (upto 10:1 per stage)
- Magnetic gears machine designs include radial, axial or linear topologies
- Considerations
  - Mechanical isolation between input and output shafts (generally a benefit some issues of reduced damping)
  - Gear meshing excitation avoided – reduced acoustic noise and vibration
  - No parts to wear hence reduced maintenance and improved reliability,
  - A resettsable torque fuse - precise peak torque transmission capability and inherent overload protection
- Ricardo have experience in design of such systems. Patented small devices applied in F1 KERS for connection to in-vacu 70 krpm flywheel

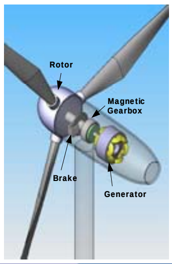


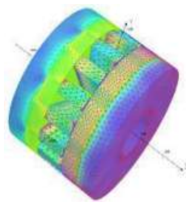




Ref Howe, Sheffield Univ.
EPSRC Reference: GR/S70685/01

Ref
Magnetomatics, UK

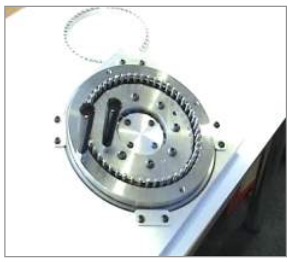




Magnetic gear

- Objectives
  - Reliability
  - Eliminate gear error
  - Avoid requirement for “average loads” in gear design
  - No wear
  - Reduced oil contamination – potential for sealed circuits for bearing lubrication – reduced oxidation
  - “balanced loads”
- Additional advantages
  - Overload protection
- Ricardo first prototype shown in pics/video

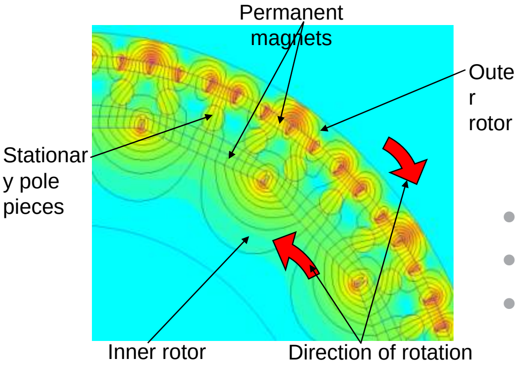
- Design
  - Inner 8-pole pairs
  - Outer 41 pole pairs
  - Pole pieces 49
  - Harmonics
    - 49-8 = 41
    - 49-41 = 8
    - Ratio = 41/8 =5.125
- Concept prototype using rectangular magnets and circular pole pieces



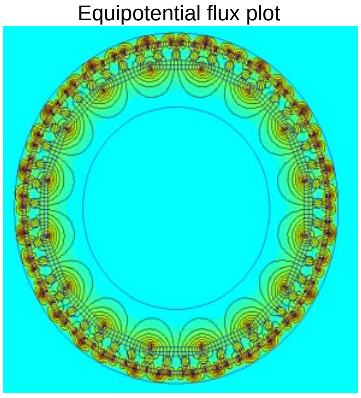
Video Clip – Ricardo version 1.0

Magnetic Gear

- High torque density
- Reduced wear
- Bearing lubrication only
- Shock loading protection



Equipotential flux plot



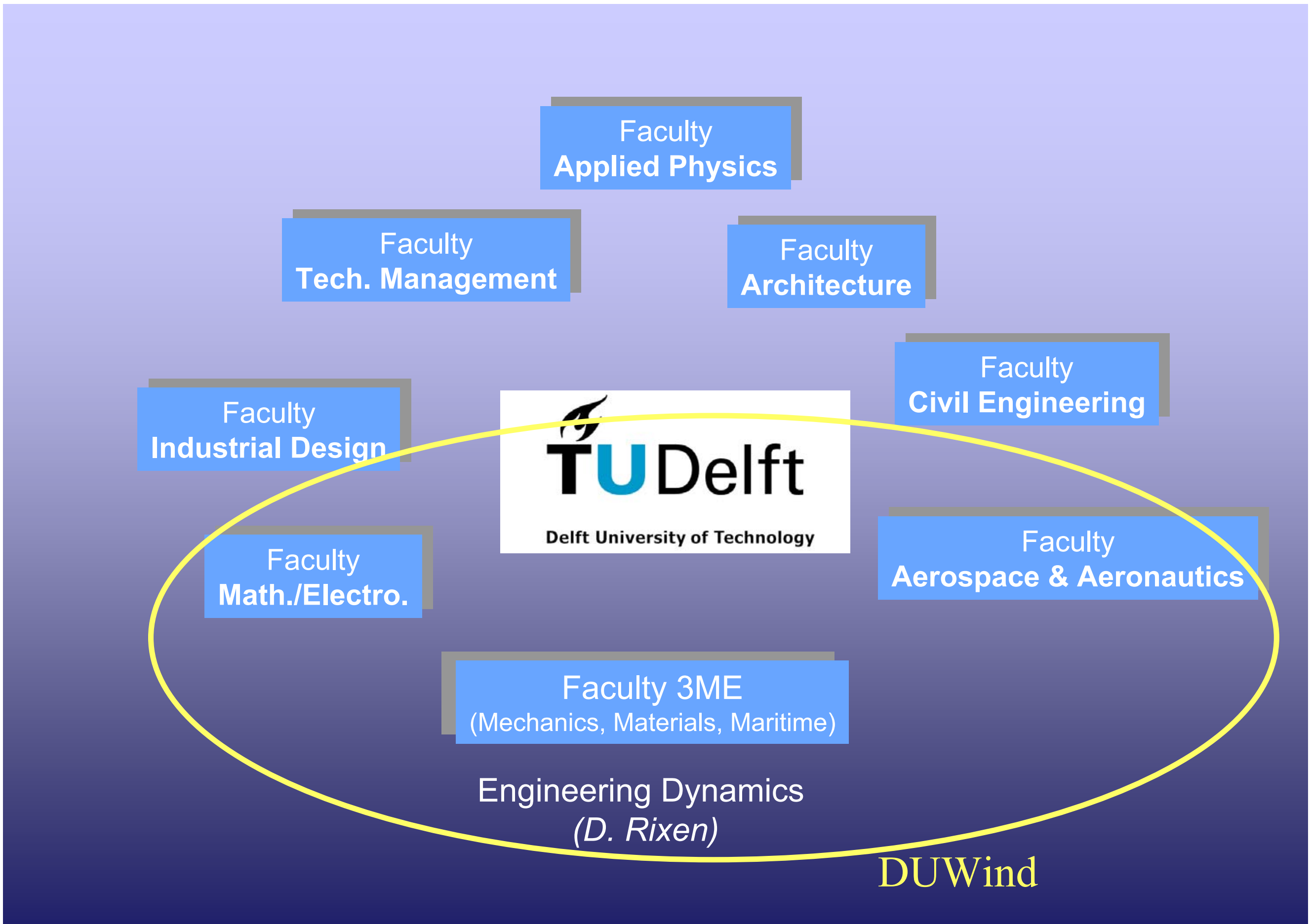
- 8 inner rotor pole pairs
- 41 outer rotor pole pairs
- 49 stationary pole pieces

Research in Dynamics & Vibration

Future directions for wind-energy

TU Delft, The Netherlands

Prof. Daniel Rixen



Research Overview

Engineering Mechanics/Dynamics
Current Research

Numerical Methods
Model reduction
Parallel computing

Multi-field
Fluid-structure iteraction
Electromechanic simulations

Staff (3)
Ph.D. students (8)
M.Sc. Students (15)

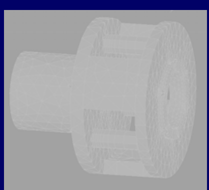
Multi-body
Flexible mechanisms
Bicycle simulation

Experimental
Operational modal analysis
Frequency Based Substructuring

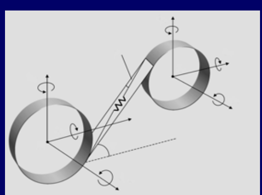
Earlier drive train investigation

Investigate if cause for gearbox failure is of dynamic origin

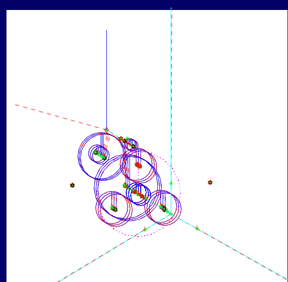
Linear(ized) FE model



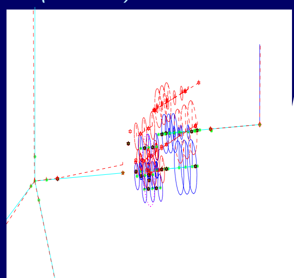
Reduced component models

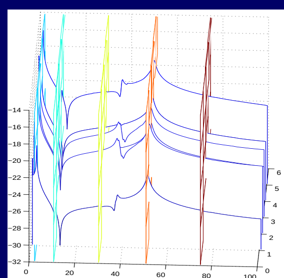


Linearized gear models



Assembling Drivetrain model (Matlab)





Vibration analysis

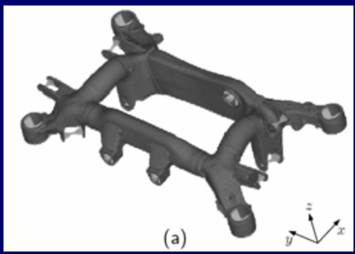
Conclusion:

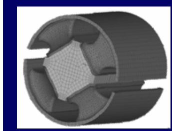
- Vibration models seem sufficient to understand global dynamics
- Difficulties to get stiffness and damping information of components
- Excitation sources ?
- Are highly complex multibody, fully non-linear models necessary ?

Current research

Experimental Dynamic Substructuring

Vibration of drive train of cars (BMW) per component then assemble





FE models
\+ = *full car model*
Experimental FRFs

Now applied and extended for wind turbines
(Research project with Siemens)

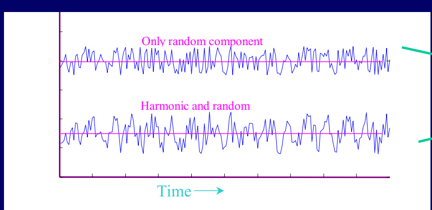
Current research

Operational modal analysis / optical measurements

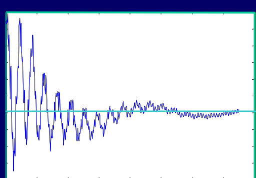
For future wind turbine monitoring (off-shore)

Photogrammetry
&
Laser Vibrometry

Measure vibration under operation and random wind



correlation of signals



frequencies

Damping

Modes

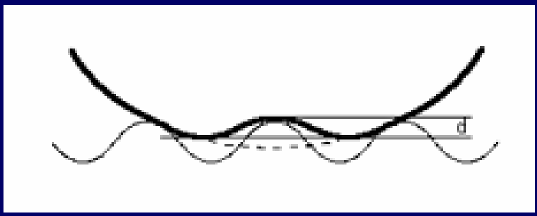
Can we see drive train vibrations?

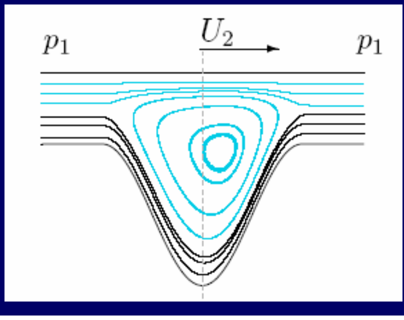
WE&Sea project with ECN (looking for future financing …)

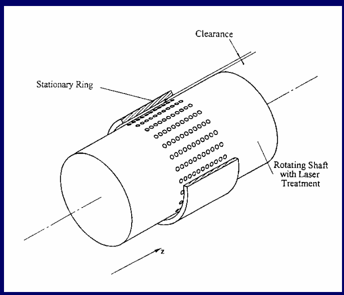
Current research

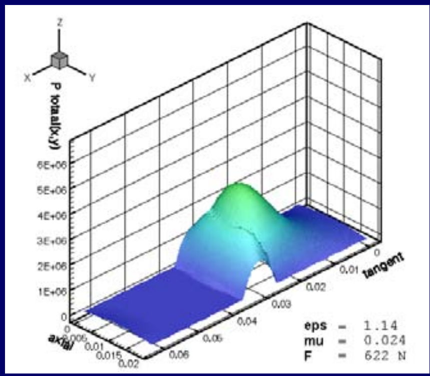
Mixed lubrication in elasto-hydrodynamic bearings

Simulation design and testing of flexible bearings, including textures









Strategy for user orientated simulation of wind turbines to calculate realistic load conditions

IEA Meeting on WIND TURBINE DRIVETRAIN DYNAMICS AND RELIABILITY

Prof. Dr.-Ing. **Berthold Schlecht** – Dipl.-Ing. **Thomas Rosenlöcher**

4 / 5 September 2008

Content

- Motivation, state of the art
- Basics of drive train simulation
- Field of application for the MBS-method
  - Wind turbines
- Summary

Content

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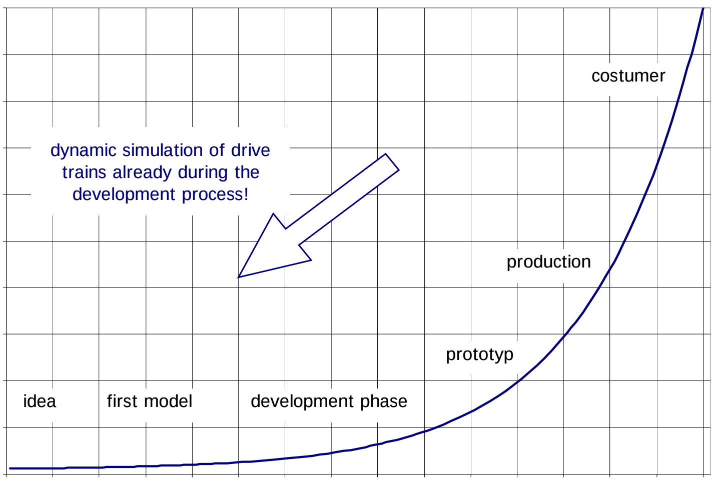
Motivation for investigations

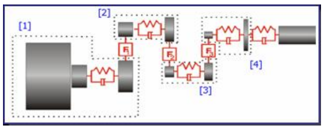
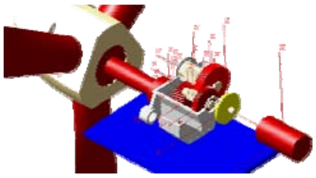
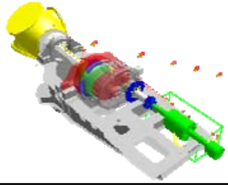
Improvement and verification of simulation techniques to identify critical components and operating conditions already during the development process

Analysis of damages by identification of critical natural frequencies and excitations as well as the recalculation of load cases by the usage of the MBS method

cost of faults in the product development process



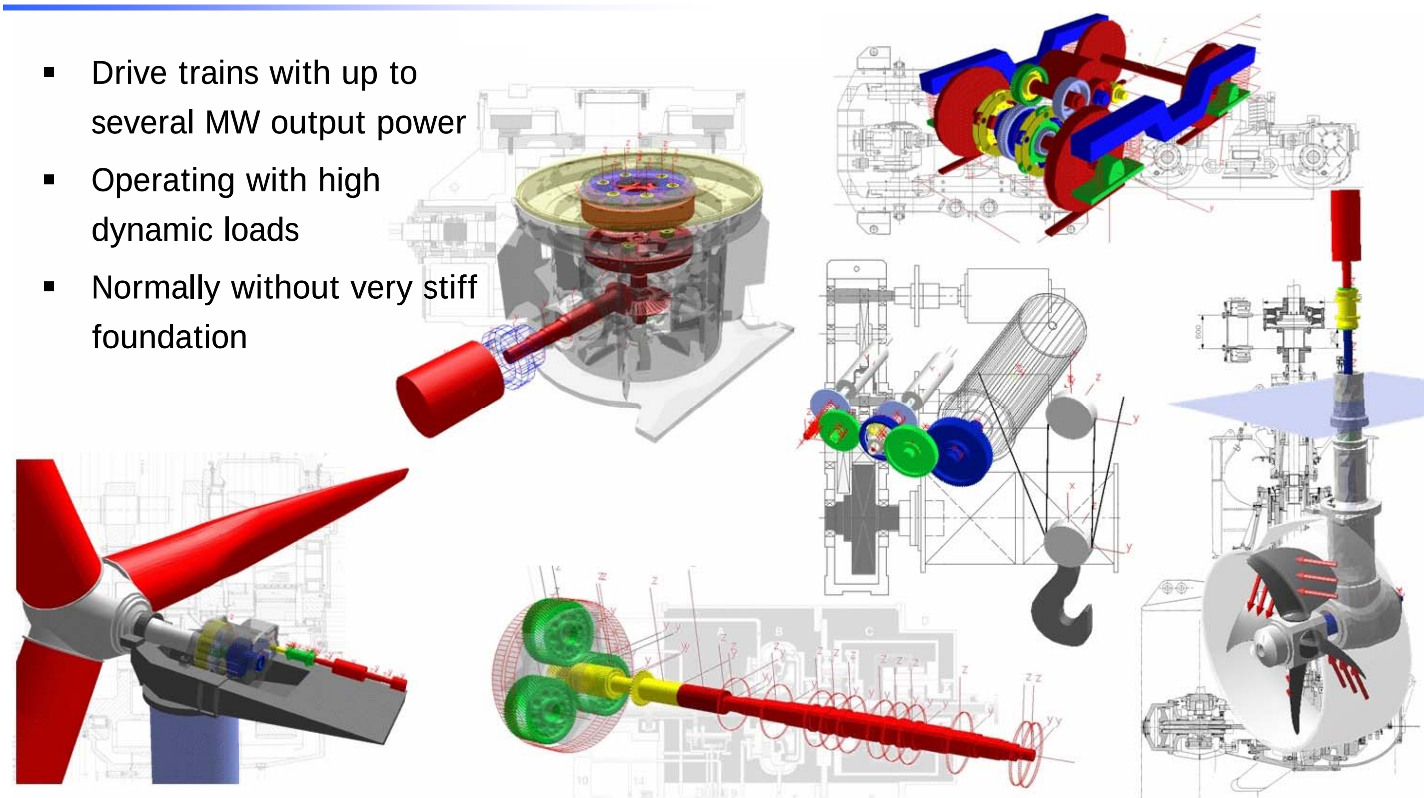
State of the art

	Torsional vibration model 	Stiff MBS model 	Flexible model 
Degree of freedom	1 DOF	6 DOF	6 DOF + FEM
States of bodies	Rot: 1, Trans: 0	Rot: 3, Trans: 3	Rot: 3, Trans: 3, Flexible states
Forces and Torques	Forces: 0, Torques: 1	Forces: 3, Torques: 3	Forces: 3, Torques: 3
Bearing forces	axial: 0, radial: 0	axial: 1, radial: 2	axial: 1, radial: 2
Gearing Forces	circum: 1, radial: 0, axial: 0	circum: 1, radial: 1, axial: 1	circum: 1, radial: 1, axial: 1

- Using of the advantages of MBS and FEM in flexible MBS models
- Increase of the model significance
- Verification of the simulation models by measurement results
- Different parts of the whole system model must be at the same level of modeling
- Reduction of the modeling effort – user orientated modeling techniques
- Searching for the maximum model to find the required minimum model

Field of research

- Drive trains with up to several MW output power
- Operating with high dynamic loads
- Normally without very stiff foundation



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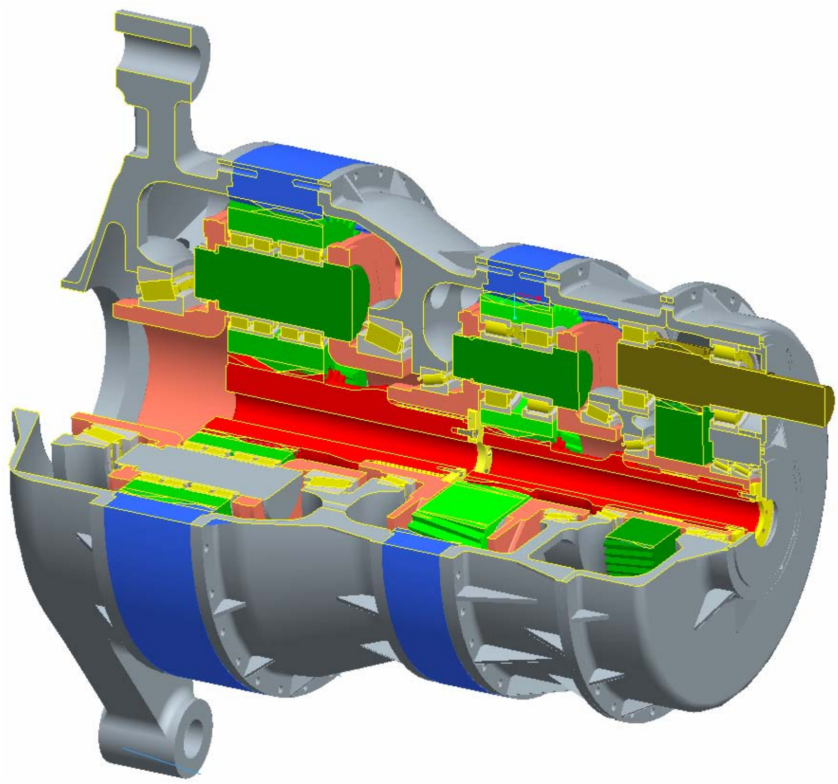
Basics of drive train simulation

- Assembly of a multibody-system simulation model for a wind turbine, 3 MW electrical power
  - 90 m rotor diameter
  - 3 point support
  - 2 planetary gear stages
  - 1 helical gear stage

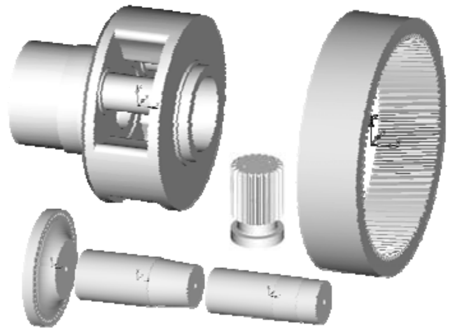
- Available information: drawings, bearing stiffness, gearing data, load cases



Basics of drive train simulation

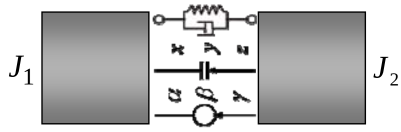
Determination of parameter

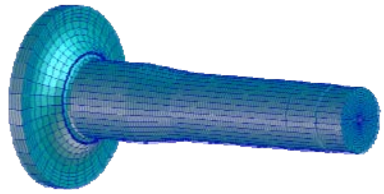
- Identification of geometry information and connection points
- 2D drawings: theoretical approaches or modelling of the components
- 3D models
- Parameter: mass of inertia, mass, centre of gravity



Modelling of the shafts

- Discretisation according to FVA 95 part B
- (Modelling of shaft segments by masses and mass of inertia, calculation of stiffness)
- Import of FEM models
- (Creation of the FEM model of a shaft, modal reduction of the model)

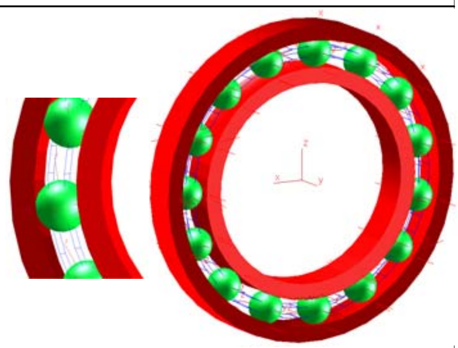




Basics of drive train simulation

Bearing model

- Modelling of the bearing by spring-damper-elements and presetting of radial and axial bearing stiffness
- Consideration of the complete bearing characteristic
- MBS model of a bearing
  (Including the stiffness, the clearance and the friction in the bearing)



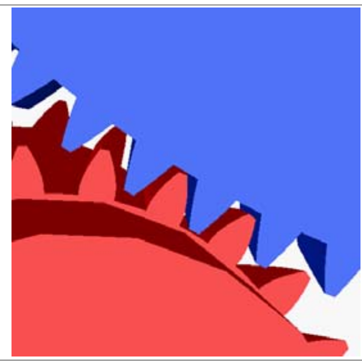
Modelling of tooth contacts

- Usage of self-programmed functions
- Consideration of torsional, axial and radial DOF, with linear or nonlinear tooth stiffness and clearance

Theoretical tooth stiffness according to DIN 3990

$$\frac{1}{c_{th}} = 0.047 + \frac{0.155}{z_{n1}} + \frac{0.258}{z_{n2}} - 0.006 \cdot x_1 - 0.116 \cdot \frac{x_1}{z_{n1}} - 0.002 \cdot x_2 - 0.242 \cdot \frac{x_2}{z_{n2}} + 0.005 \cdot x_1^2 + 0.002 \cdot x_2^2$$

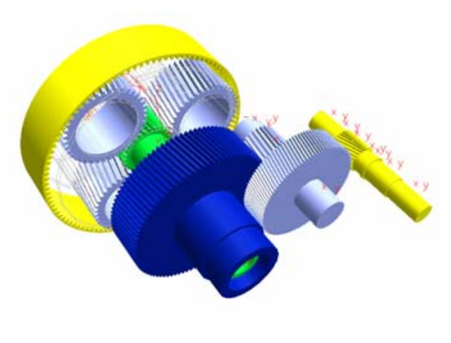
$$z_{n1/2} = \frac{z_{1/2}}{\cos^3 \beta}$$

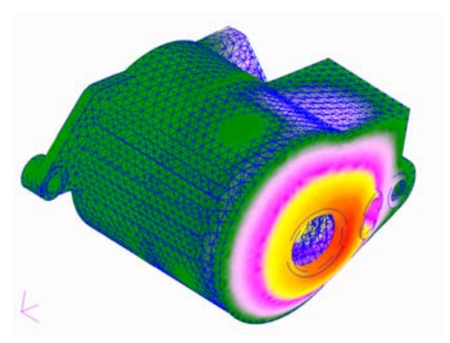


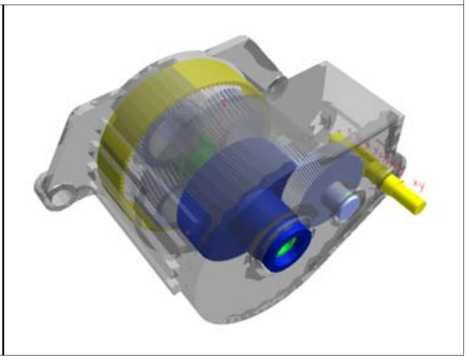
Basics of drive train simulation

Consideration of flexible structures

MBS model	+	FEM model	=	MBS with FEM structure
Definition of body properties *Body connections by springs and dampers* *Excitation by forces and torques*		*Import of the CAD model* *Creating the mesh* *Definition of material properties*		*Reduction of the FEM model by usage of techniques by Guyan and Craig Bampton* *Converting the model data into a SIMPACK format*
Calculation of rigid body states in the time and frequency domain		Calculation of elastic body states, natural frequencies, deformation…		Calculation of rigid and elastic body states in the time and frequency domain







Basics of drive train simulation

Simulation in the frequency domain

Natural frequencies

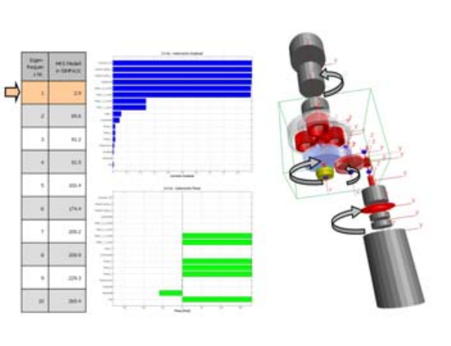
- Animation of mode shapes
- Analysis of amplitudes and phase

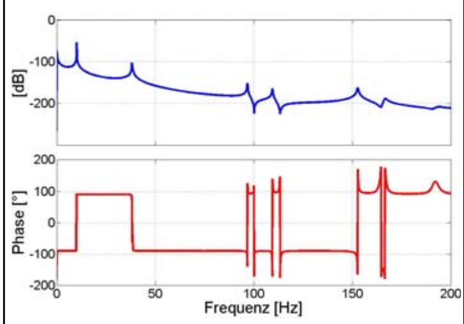
Transfer behaviour

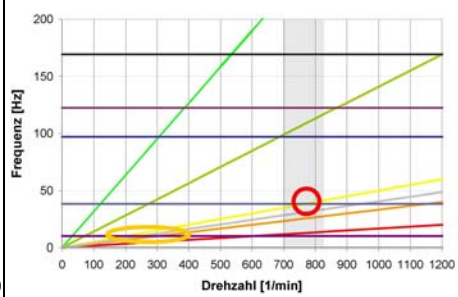
- Transfer behaviour of the drive train und consideration of an excitation
- Estimation of different transfer path

Campbell-Diagramm

- Comparison of natural frequencies und excitation
- Determination of critical operation points

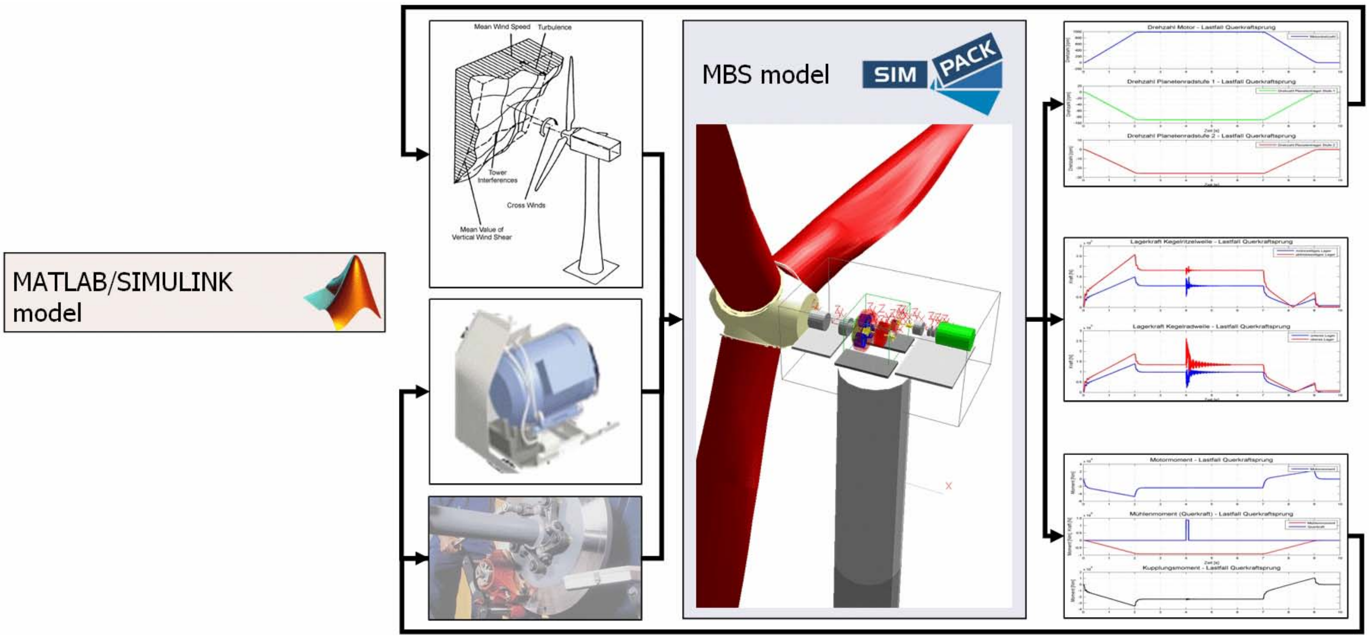






Basics of drive train simulation

Simulation in the time domain

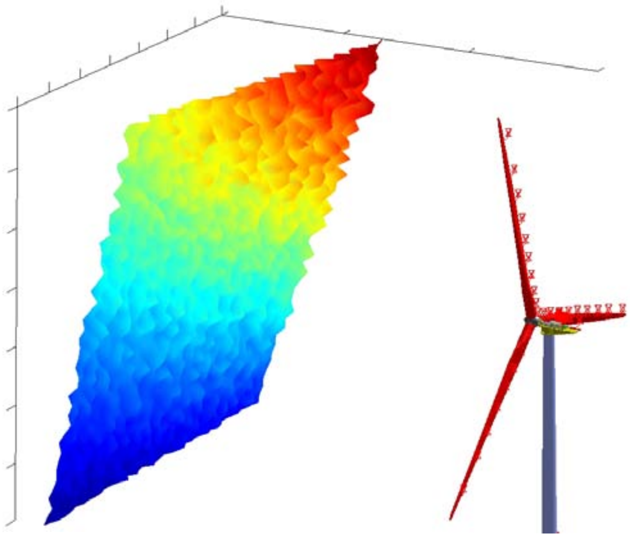


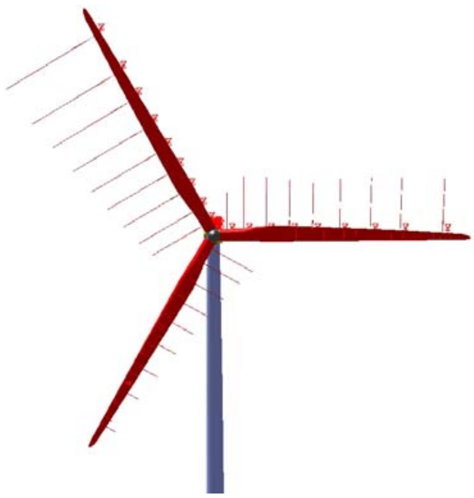
Basics of drive train simulation

Simulation in the time domain

Modelling of the wind forces

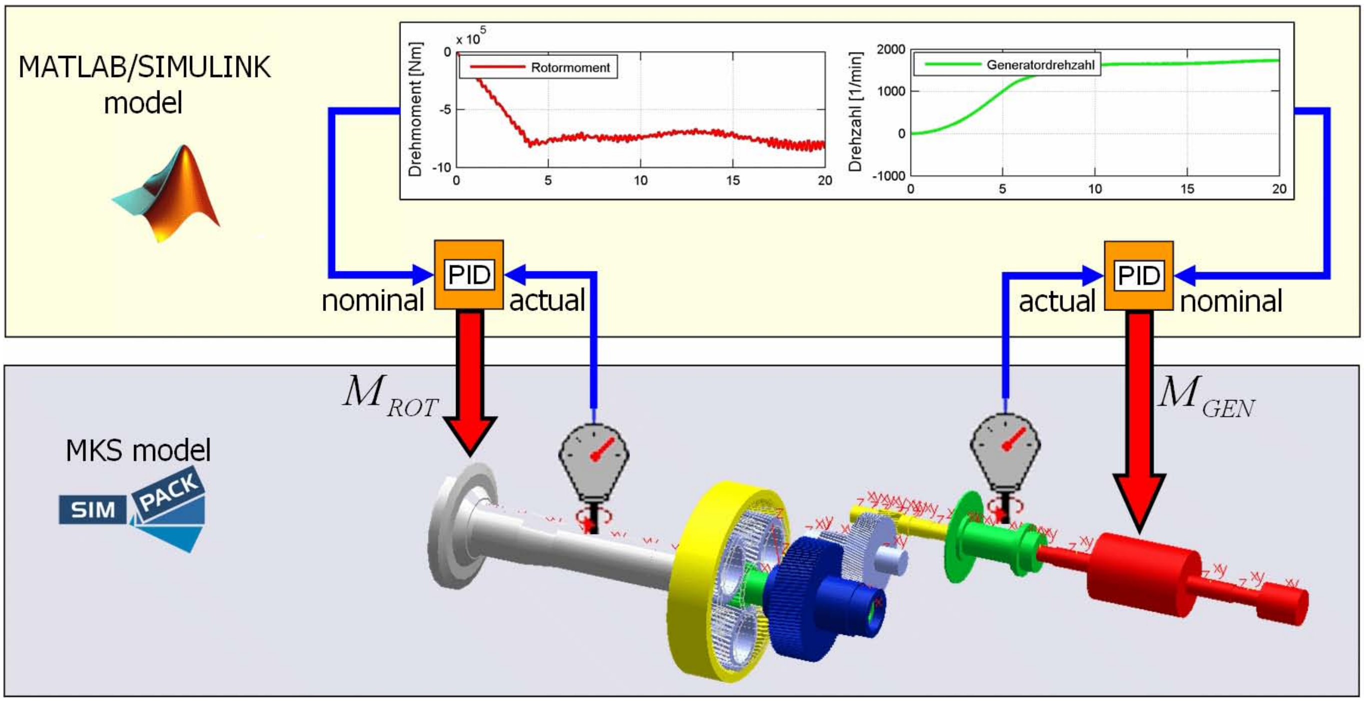
- Consideration of a wind field (wind shear, yawed flow)
- Calculation of the resulting forces for current position, each blade segment and each blade





Basics of drive train simulation

Simulation in the time domain – measurement data based simulation



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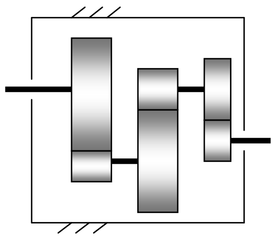
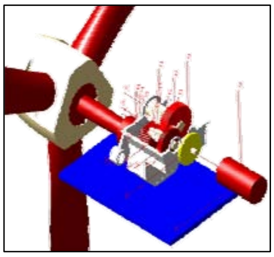
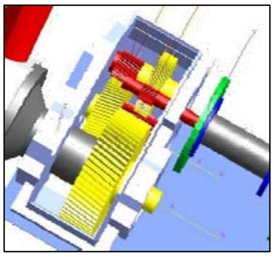
Simulation of wind turbines

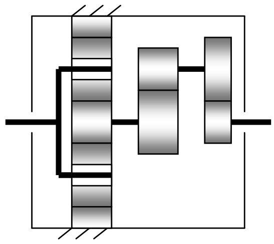
3-stage helical gear unit

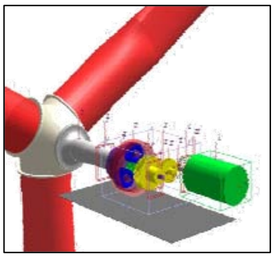


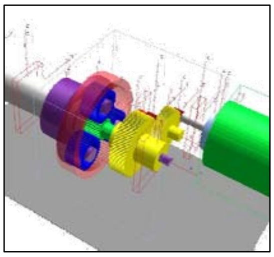




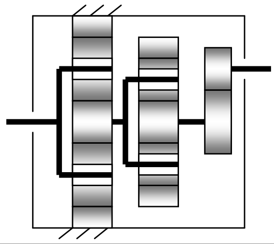
3-stage planetary- / spur gear unit

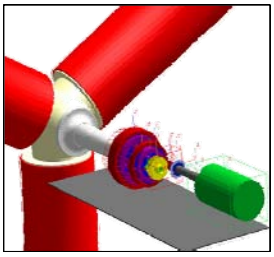


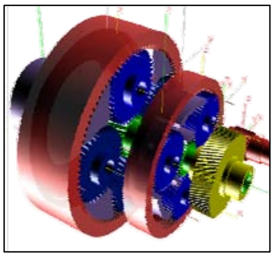




3-stage planetary- / helical gear unit

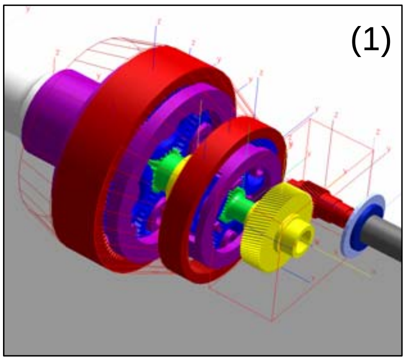


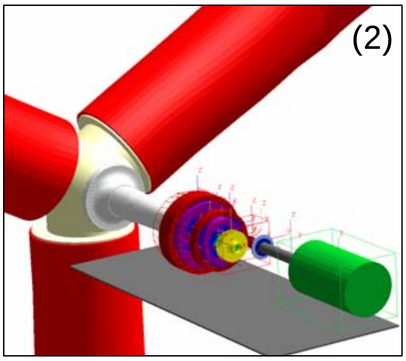


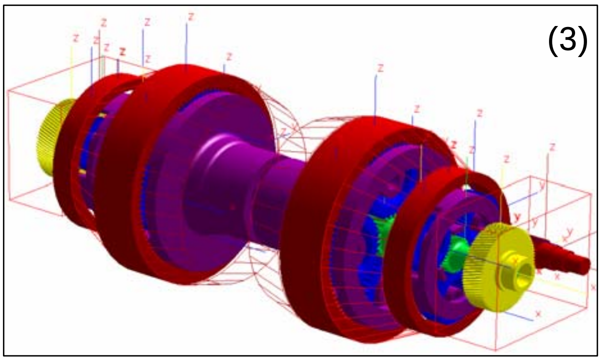


Simulation of wind turbines

- Different model scale for different question formulations:
  - Gear box simulation (1)
  - Drive train simulation (2)
  - Test bed simulation (3)

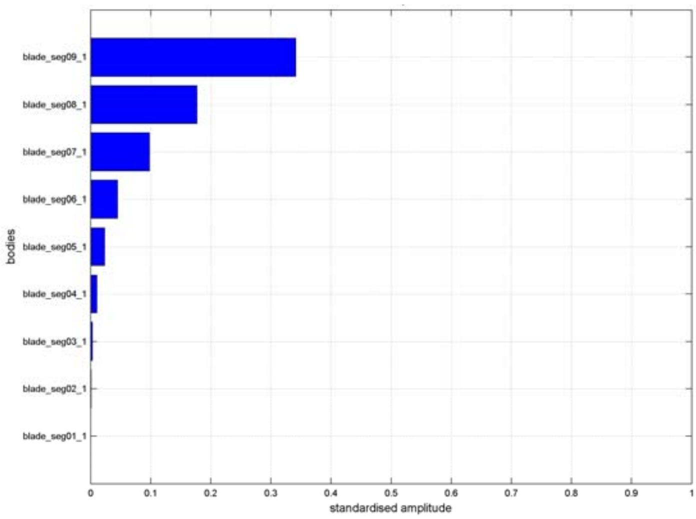


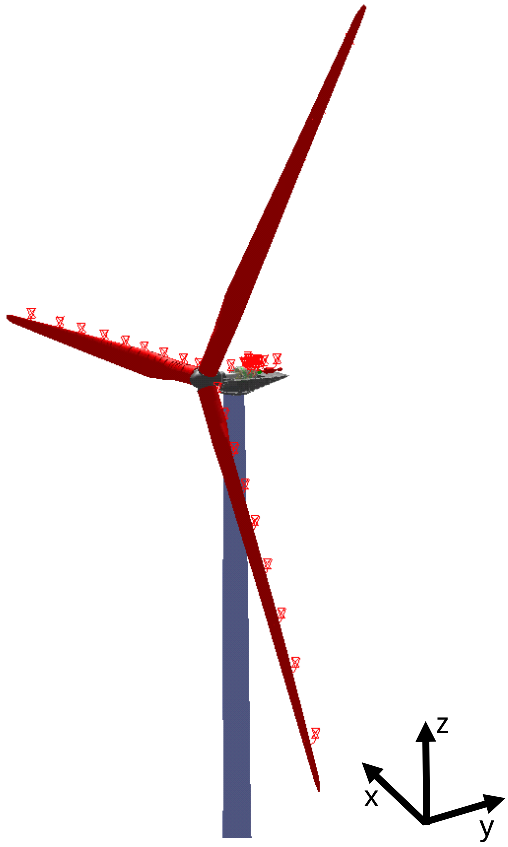




Simulation results – frequency domain

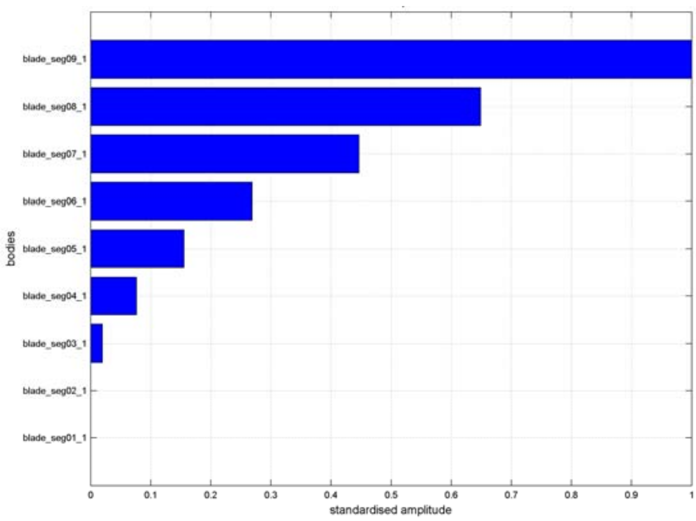
- ~ 1.0 Hz
  bending mode shape of the blades (flapwise)
- Amplitude of the blade sections, y-direction

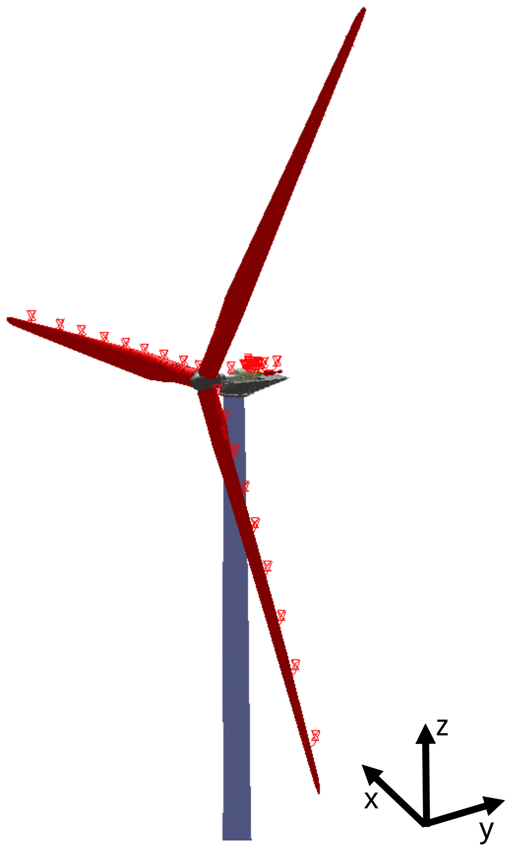




Simulation results – frequency domain

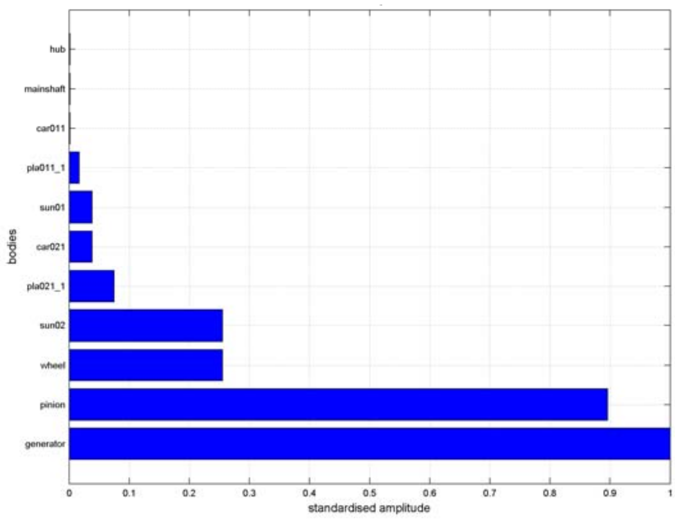
- ~ 1.5 Hz
  bending mode shape of the blades (edgewise)
- Amplitude of the blade sections, z-direction

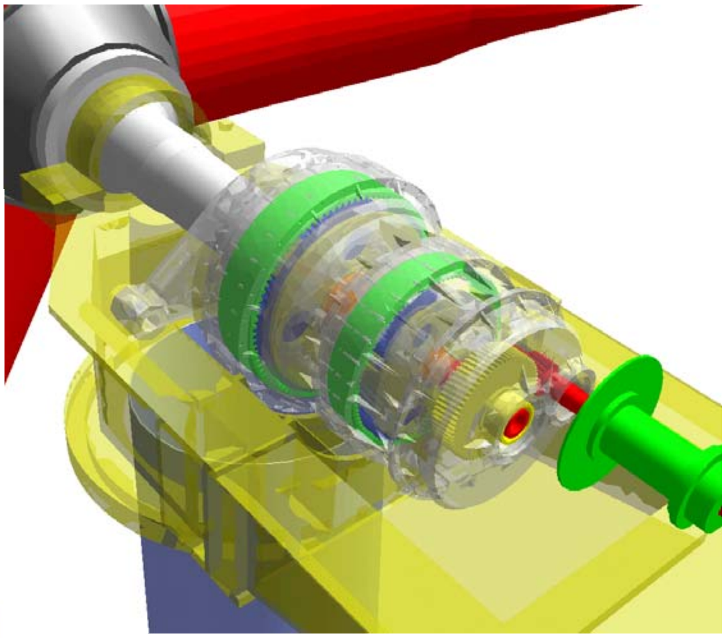




Simulation results – frequency domain

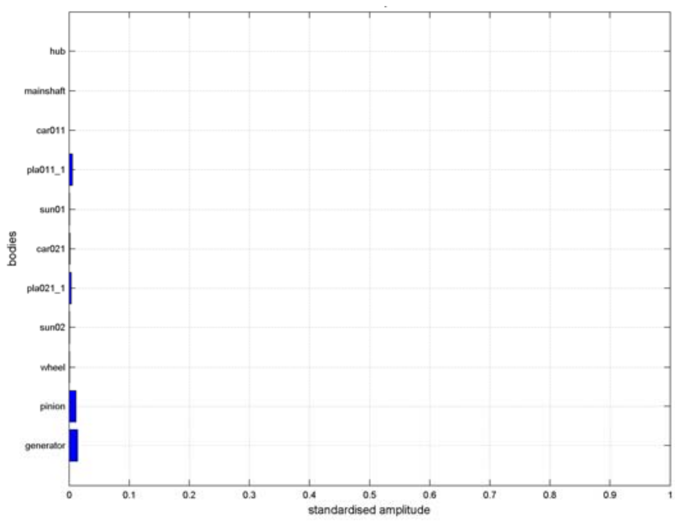
- ~ 5.5 Hz
  first torsional mode shape
  of the drive train

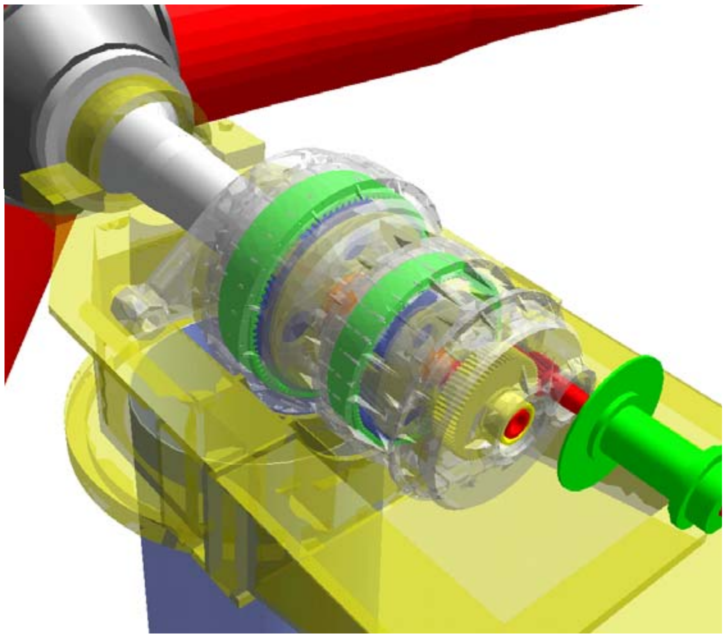




Simulation results – frequency domain

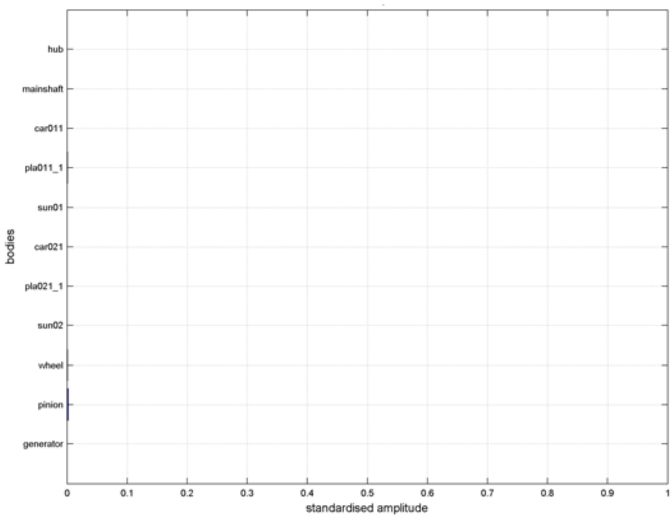
- ~ 22.7 Hz
  bending mode shape of the
  gearbox and the main frame

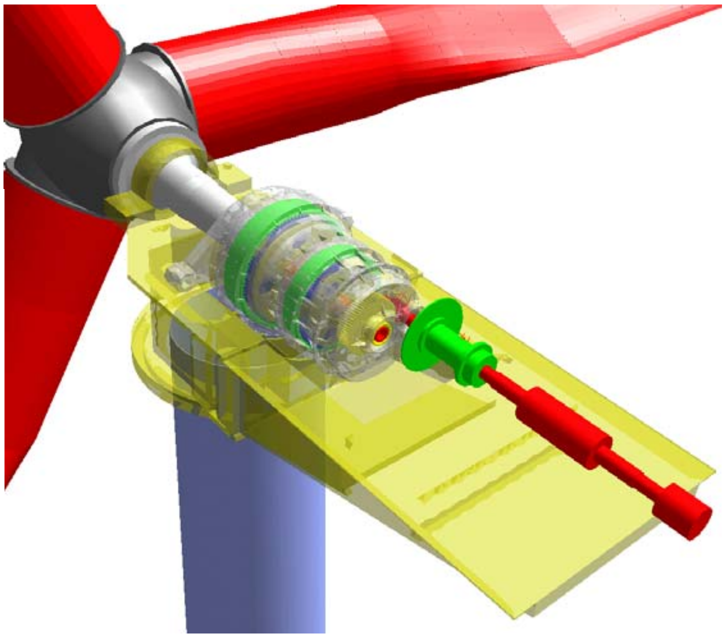




Simulation results – frequency domain

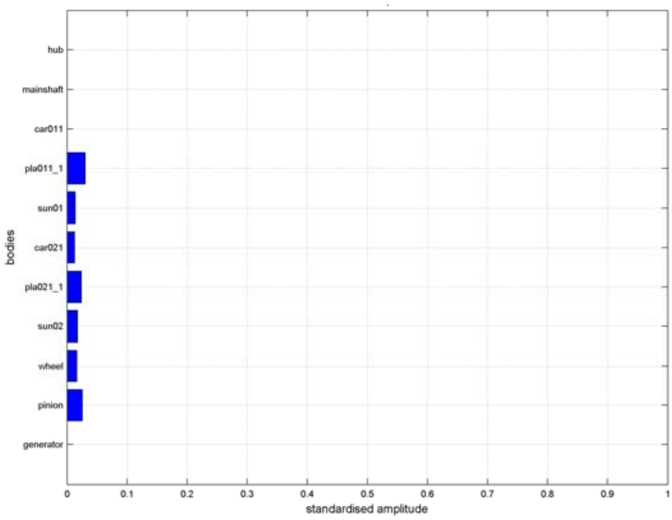
- ~ 40.6 Hz
  bending mode shape of the main frame

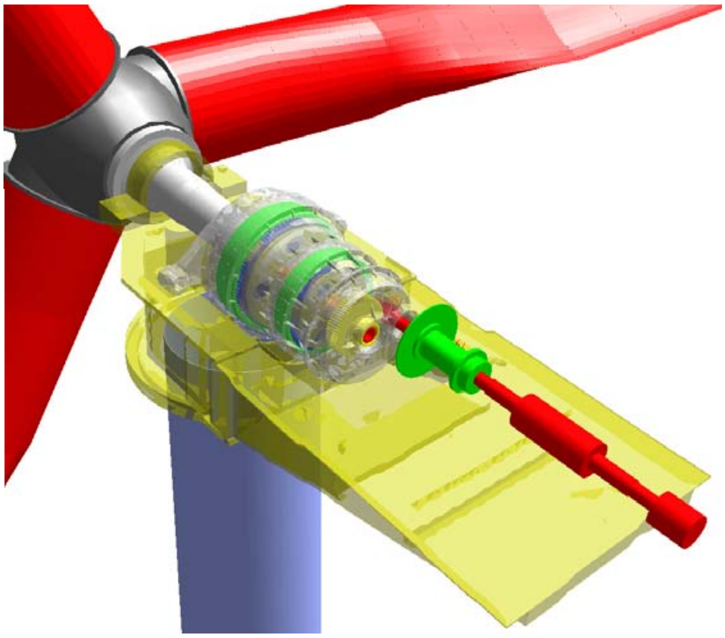




Simulation results – frequency domain

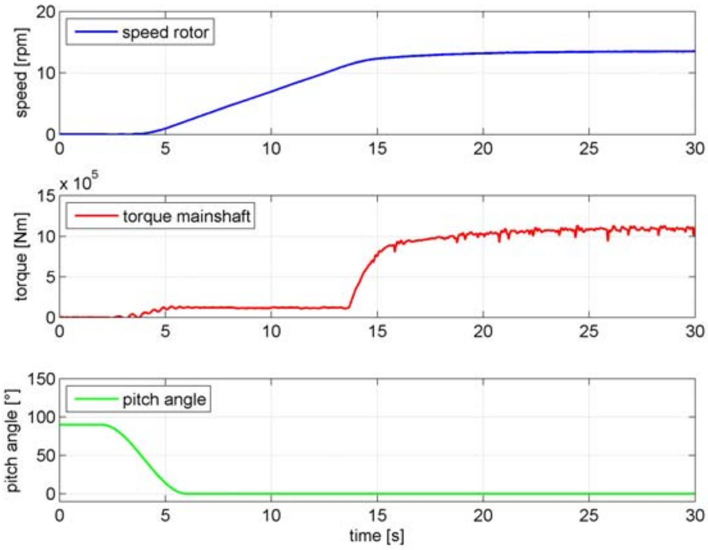
- ~ 126.7 Hz
  axial mode shape of the drive train against the gear box

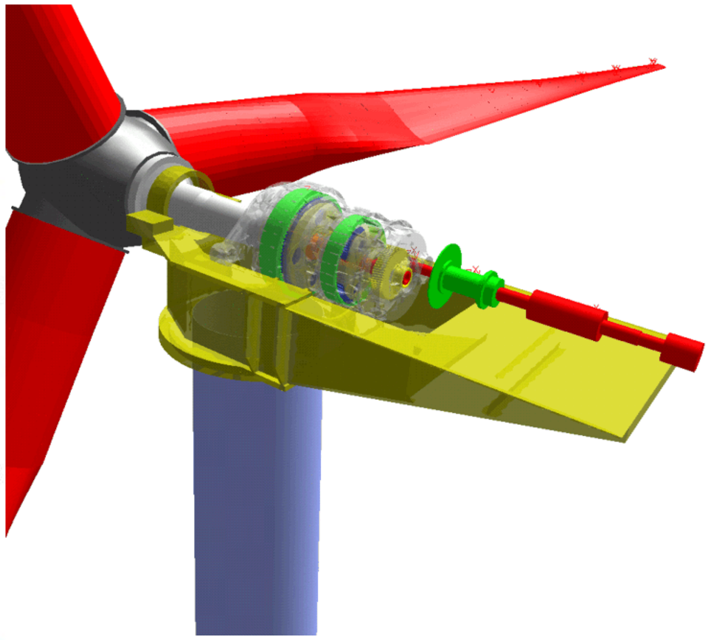




Simulation results – time domain

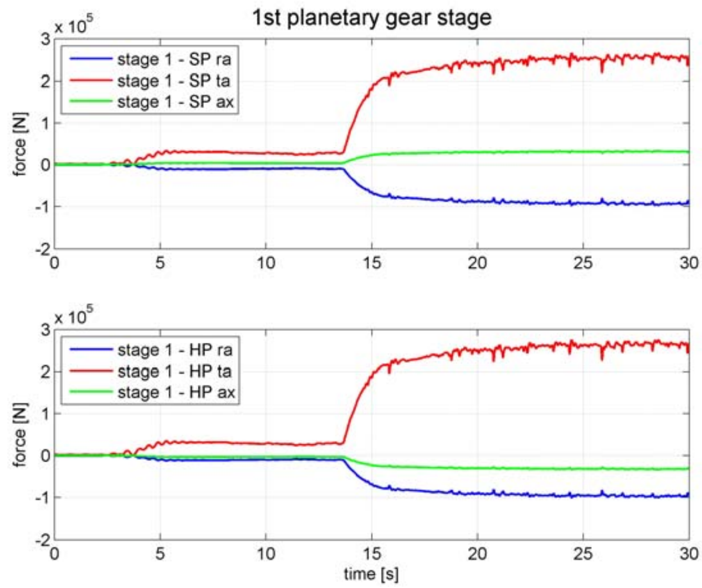
- Run up of a wind turbine
  - Pitching of the blades
  - Connecting of the generator

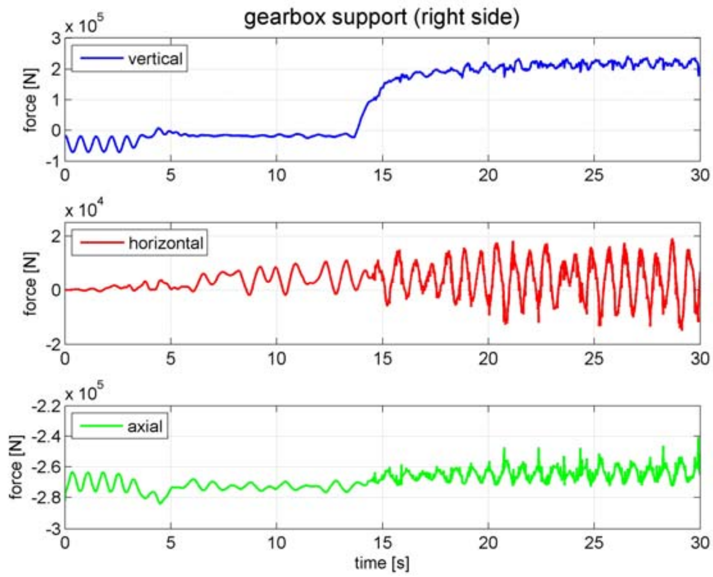




Simulation results – time domain

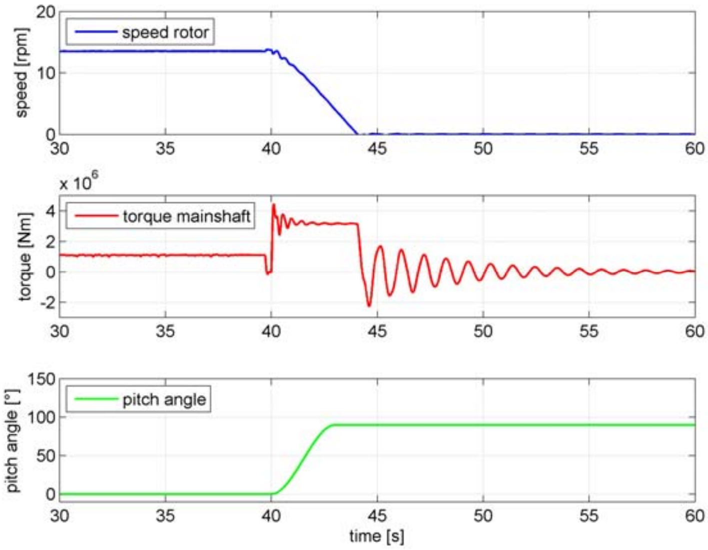
- Run up of a wind turbine
  - Forces in the gear stages and in the support of the gearbox

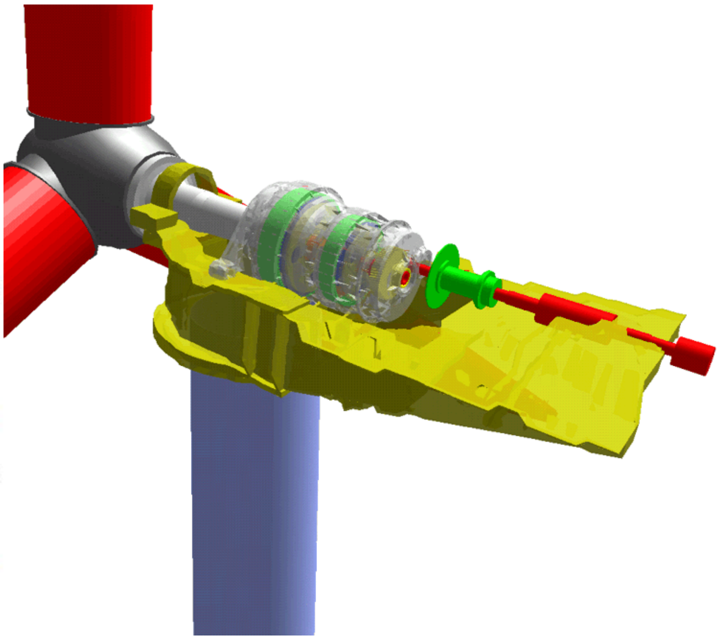




Simulation results – time domain

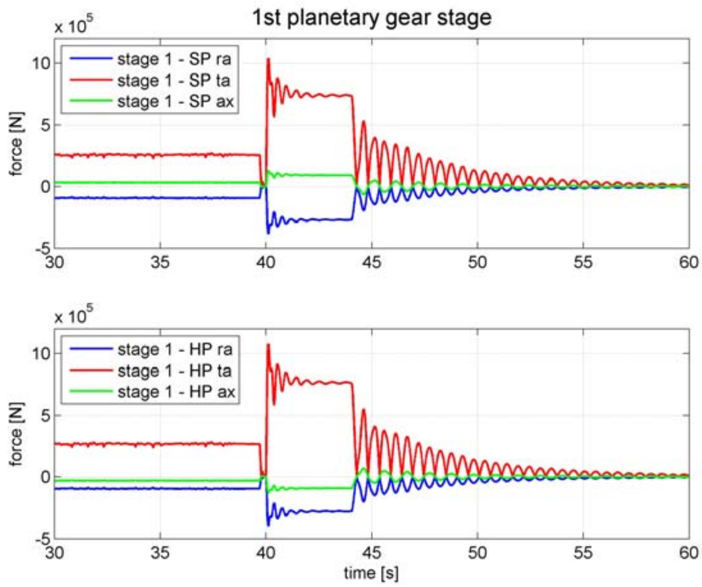
- Emergency stop of a wind turbine
  - Disconnecting of the generator
  - Pitching of the blades, breaking

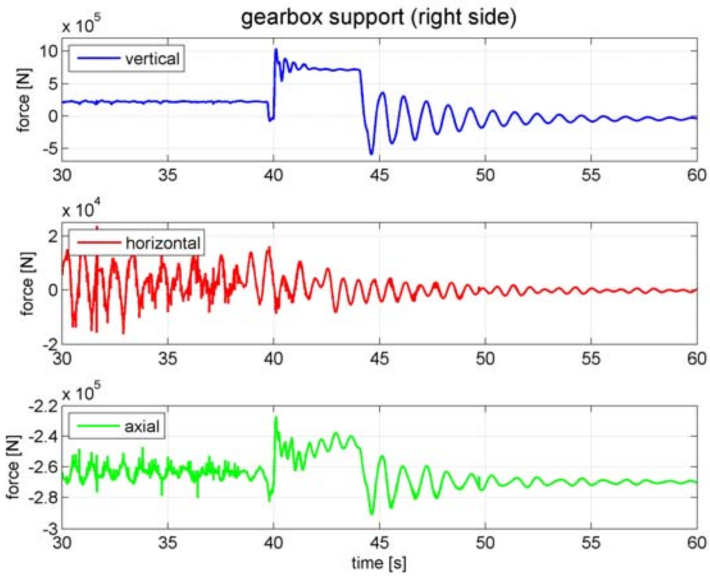




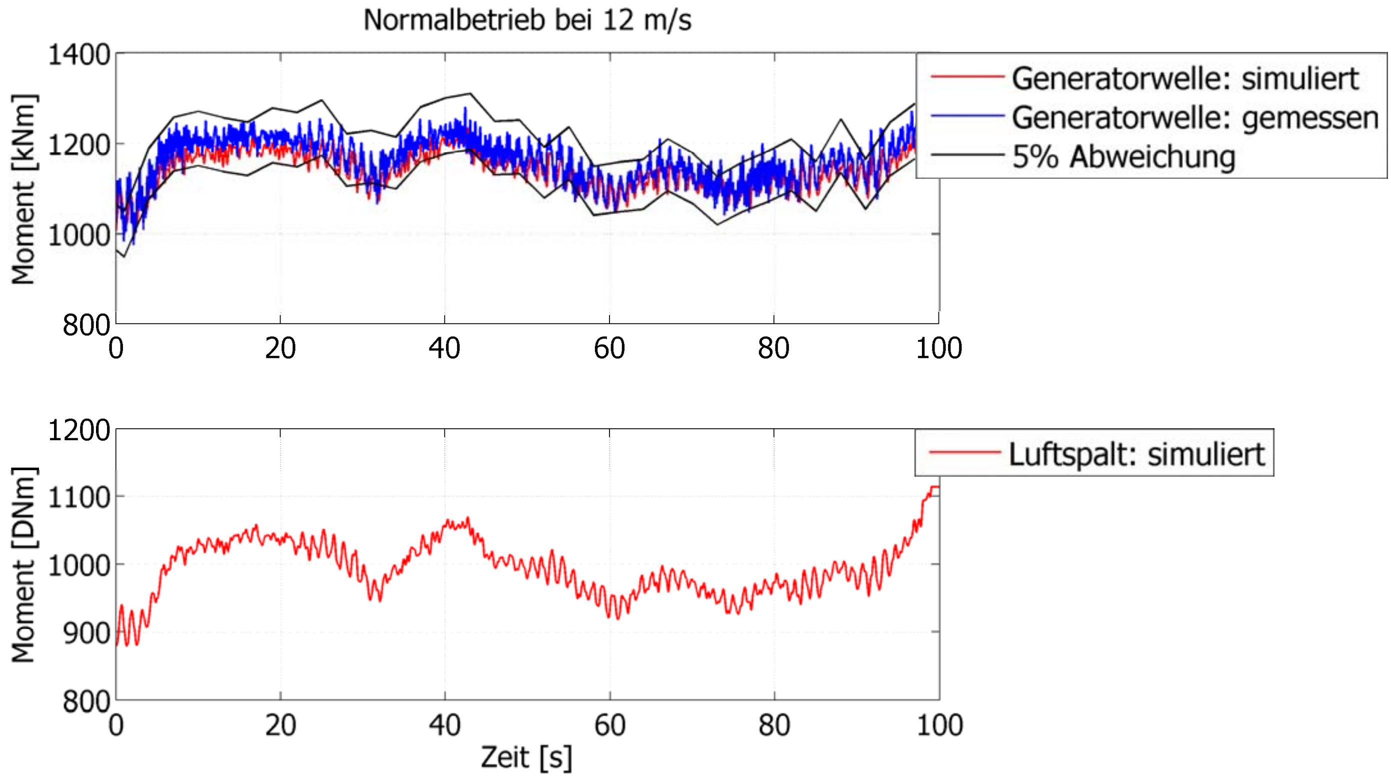
Simulation results – time domain

- Emergency stop of a wind turbine
  - Forces in the gear stages and in the support of the gearbox

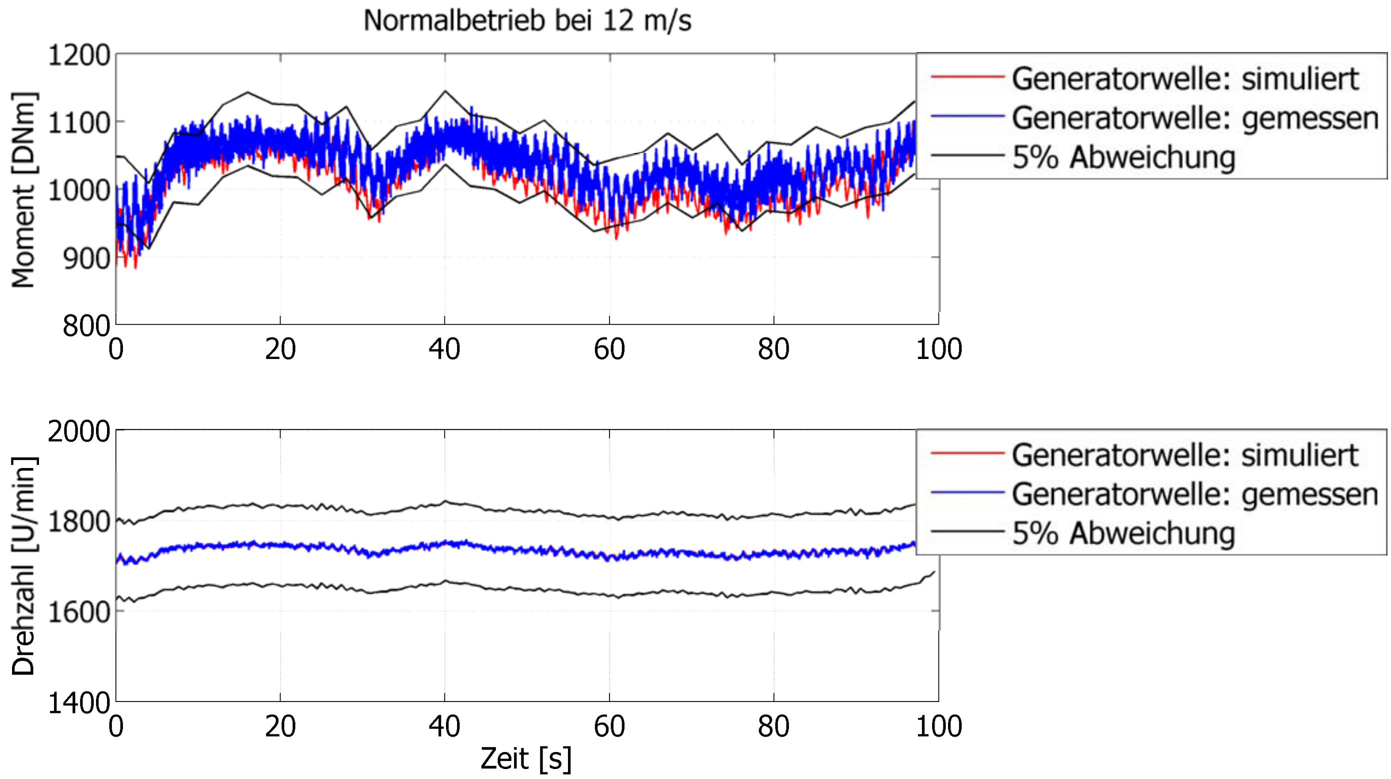




Simulation of wind turbines



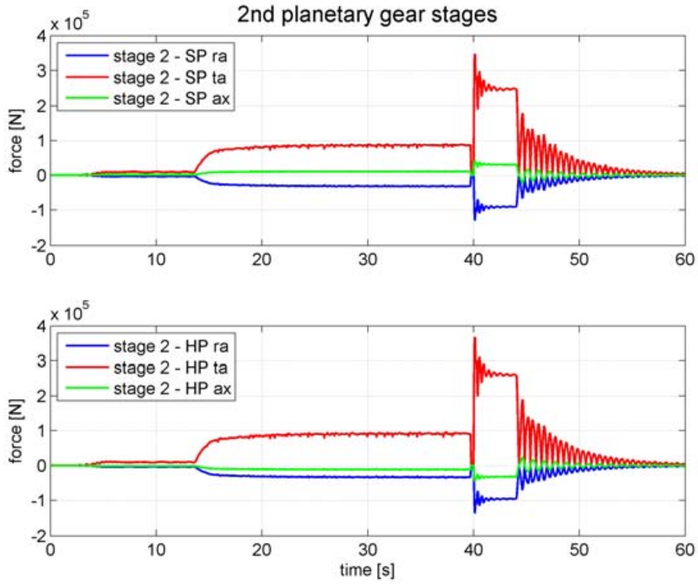
Simulation of wind turbines



Simulation results – time domain

- The simulation of measured loads cases allows the determination of
  - Displacements, speeds and acceleration of the drive train components
  - Forces and torques in shafts and clutches
  - Bearing and gearing forces

  which could not or only with a large effort be determined during measurement campaigns.



Content

- Motivation, state of the art
- Basics of drive train simulation
- Field of application for the MBS-method
  - Wind turbines
- Summary

Summary

- The MBS simulation can be a helpful tool during the design phase of large drive trains in heavy machinery applications

- It is an absolutely must to have the knowledge of all relevant natural frequencies of the drive train

- The Cosimulation offers a comfortable way to model the essential interactions and influences between the electrical and mechanical components of the system

- The simulation is much more cheaper than big measurement campaigns or the repair of drive train components

Thank You for Your Attention

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Chair of Machine Elements

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VibPower

The small test structure

Paul Klinge 2008-09-04

Business from technology

VibPower-project

- Goals
  - To develop practical measurement techniques for experimental estimation of mechanical source strength and transmitted mechanical power from the source to the foundation
  - To develop corresponding practical calculation methods based on FEM that can be used with measured data
    - At least at lower frequencies

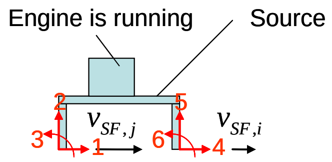
Simplified methods A-F

- The formulas are derived as for a single point contact
  - Cross-couplings are ignored = terminals are assumed independent
  - Error gets smaller towards higher frequencies
- There are 3 translations and 3 rotations at every contact point
  - Rotations are difficult to measure => they are ignored =>
  - The power transmitted by rotations is ignored

Method A

- No knowledge of the excitation forces are needed
  - The internal excitation mechanisms of the source are assumed not to be influenced by coupling to the receiver
- The source and the receiver measured (or calculated) separately
- No need to measure the coupled structure
- **Prediction of the transmitted power before the source is mounted**
  - Selection of the best suited engine
  - Modifying the base
  - Data library for different engine types?
    - The engine would be measured only once

Method A - Coupling source and receiver



- Compatibility conditions

$$F_{S,i} + F_{R,i} = 0$$

$$v_{S,i} = v_{R,i} = v_{T,i}$$

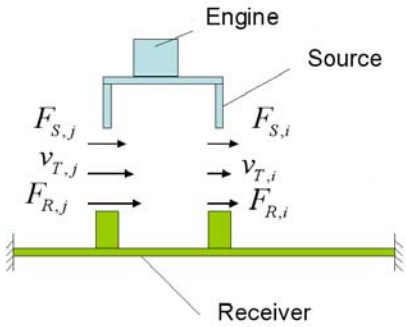
$$v_{S,i} = v_{SF,i} + Y_{S,ii} F_{S,i}$$

$$v_{R,i} = Y_{R,ii} F_{R,i}$$

$$\Rightarrow \quad F_{R,i} = \frac{v_{SF,i}}{\left(Y_{R,ii} + Y_{S,ii}\right)}$$

$$P_{R,i} = \frac{\bar{v}_{SF,i}^2 \operatorname{Re}\left(Y_{R,ii}\right)}{\left|Y_{S,ii} + Y_{R,ii}\right|^2}$$

$$\bar{v}_{SF,i}^2 = \frac{1}{2}\left|v_{SF,i}\right|^2$$



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Full mobility matrix methods G-L

- The formulas are derived without any simplifying assumptions => accurate in theory
- But there are 3 translations and 3 rotations at every contact point
  - Rotations are difficult to measure => they are ignored =>
  - The power transmitted by rotations is ignored

Method G

- No knowledge of the excitation forces are needed
  - The internal excitation mechanisms of the source are assumed not to be influenced by coupling to the receiver
- The source and the receiver measured separately
- No need to measure the coupled structure

- **Prediction of the transmitted power before the source is mounted**

Method G - Coupling source and receiver

- Compatibility conditions

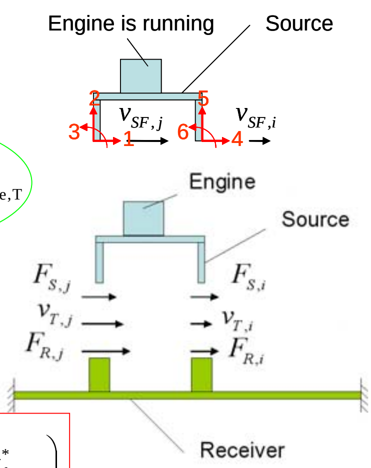
$$\mathbf{f}_{S,T} + \mathbf{f}_{R,T} = \mathbf{0}$$

$$\mathbf{v}_{S,T} = \mathbf{v}_{R,T} = \mathbf{v}_T$$

$$\mathbf{v}_T = \mathbf{v}_{free,T} - \mathbf{Y}_{S,TT}\mathbf{f}_T$$

$$\mathbf{v}_T = \mathbf{Y}_{R,TT}\mathbf{f}_T$$

$$\Rightarrow \mathbf{f}_T = \left(\mathbf{Y}_{S,TT} + \mathbf{Y}_{R,TT}\right)^{-1}\mathbf{v}_{free,T}$$



$$P_R = \frac{1}{2}\mathrm{Re}\left(\mathbf{v}_{free,T}^{T}\left(\mathbf{Y}_{S,TT} + \mathbf{Y}_{R,TT}\right)^{-1}\mathbf{Y}_{R,TT}^{*}\left(\left(\mathbf{Y}_{S,TT} + \mathbf{Y}_{R,TT}\right)^{-1}\right)^{*}\mathbf{v}_{free,T}^{*}\right)$$

VTT small test structure

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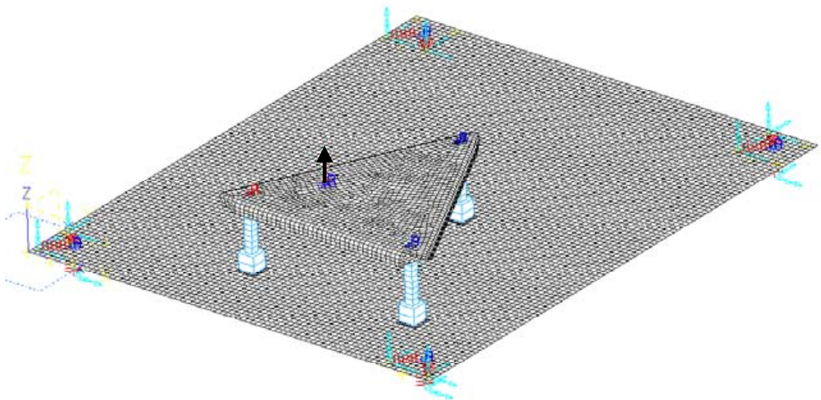
The FE model



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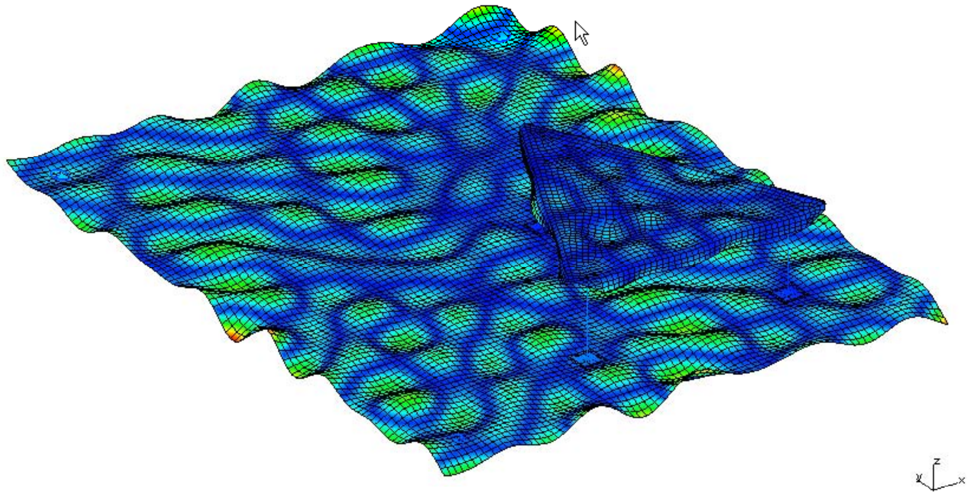
Mode Shape 256 Frequency<Hz> = 3484.019



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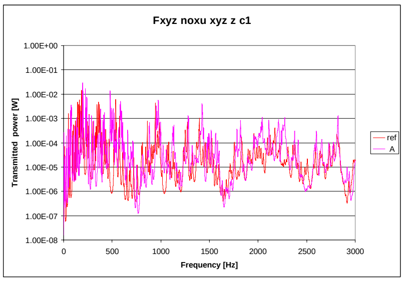
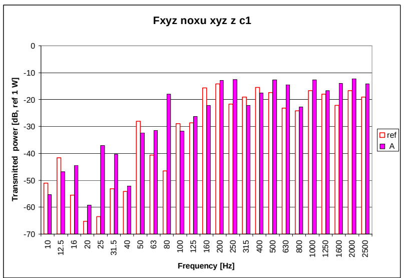
Method A

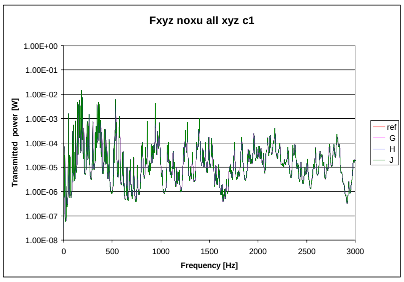
- The estimated transmitted power follows the reference in general well
- The frequency of the peaks is often somewhat off
- The method performs clearly better when only translations are used instead of all degrees of freedom
- The accuracy is better at frequencies over 100 Hz

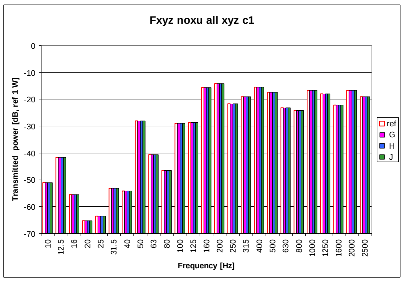




Full matrix methods

- Full matrix methods are accurate when all dofs (G, H, I) and enough far field velocities (J, K, L) are used

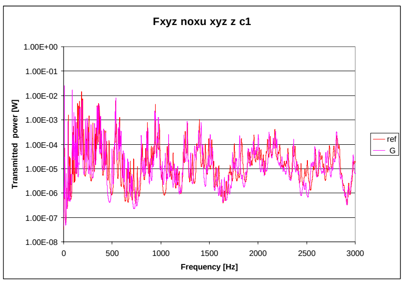


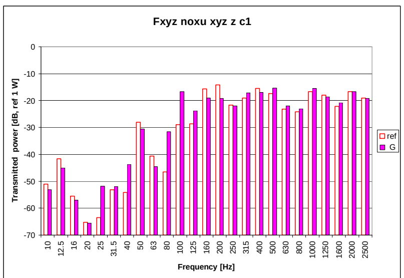


- In the following only the results calculated without rotations are considered

Method G

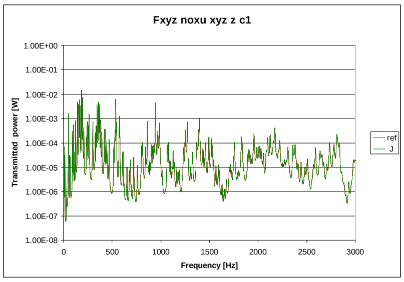
- The estimated transmitted power follows the reference well
- The accuracy is better at frequencies over 200 Hz

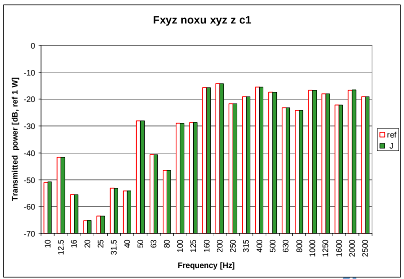




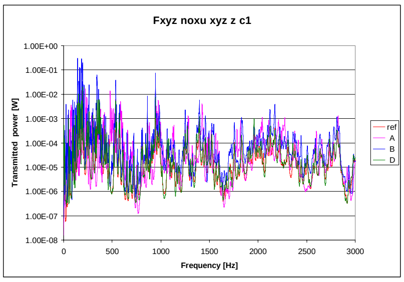
Method J

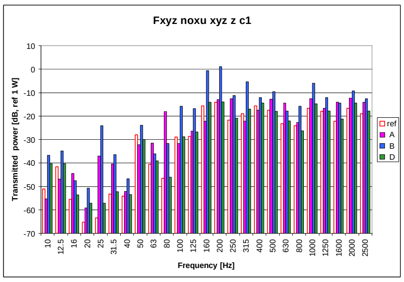
- The estimated transmitted power seems to follow the reference accurately when enough far field velocities are used, even when only normal velocity is considered
- The effect of the number of far field velocities beeing smaller than the number of terminals can be seen. However, it is small and evenly distributed over the spectrum.

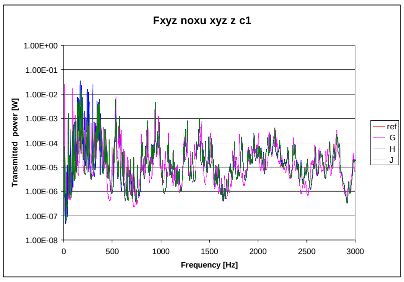


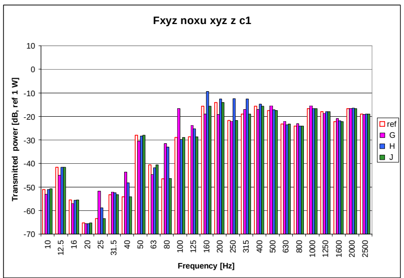


Performance of the methods









Summary

- The calculations showed that the full matrix methods give accurate transmitted power when all dofs are used. The methods proved to be robust and give accurate estimation also when only translations are used.
- The simplified methods were less accurate than the full matrix methods. Method D was clearly the best of the simplified methods. It was comparable in accuracy to full matrix methods.
- Method J was the most accurate of the methods.
- Methods A and G can be used to estimate the transmitted power before mounting of the engine.
- A Matlab program, VibPower, was created to calculate the transmitted mechanical power from source to the receiver. With it calculation of transmitted vibration power is fast and easy.

VTT

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Drive train dynamics: Certification requirements and modelling possibilities

Milan Ristow, milan.ristow@gl-group.com
www.gl-group.com/glwind

Germanischer Lloyd

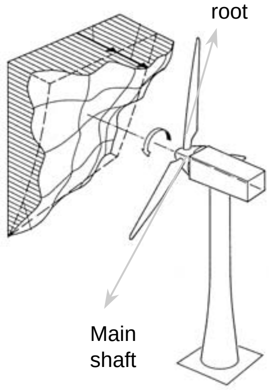
Content

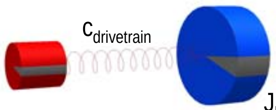
- Importance of drive train analysis
- Certification requirements
- Analysis within the Certification process
- Modelling possibilities and effects
- Future prospects

Source: Winergy

Importance of drive train analysis

- Load assumptions for the design of drive train components are based on simulations of global model
- Dynamic properties and internal loads are neglected
- Verification of design loads
- Validation of assumptions for global load simulation (e.g. stiffness, mass)





Certification requirements

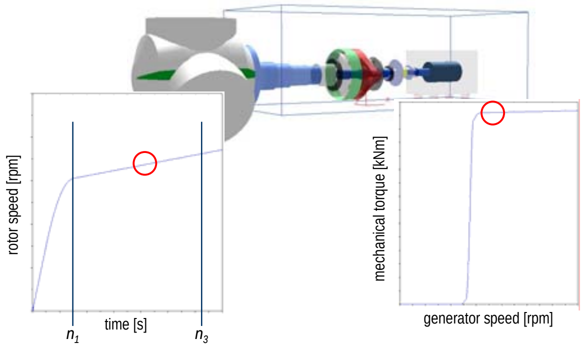
- GL Guideline for the Certification of Wind Turbines (Edition 2003 with Supplement 2004)
- GL Wind Technical Note 068: *“Requirements and recommendations for implementation and documentation of resonance analysis”*

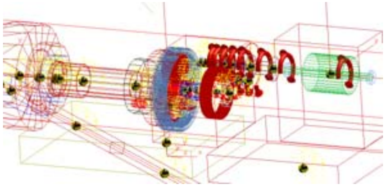
Aim of analysis:

- Analysis of the dynamic behaviour of the drive train using a detailed simulation model
- Verification of model parameter assumptions representing the drive train in global model

Analysis within the Certification process (1)

- Model set up
- Start-up szenario of drive train
- Torque speed curve
- Linerization point
- Modal analysis





04/09/08

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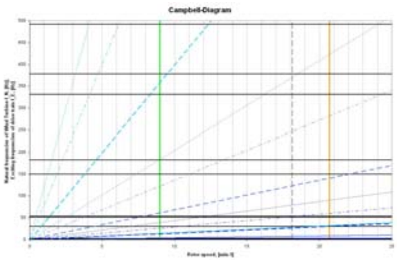
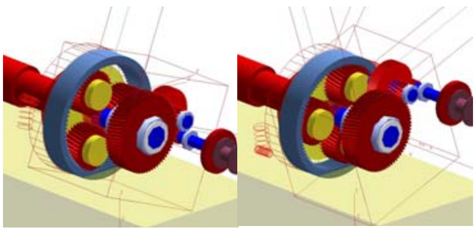
Analysis within the Certification process (2)

- Evaluation of mode shapes and energy distributions in connection with excitation frequencies



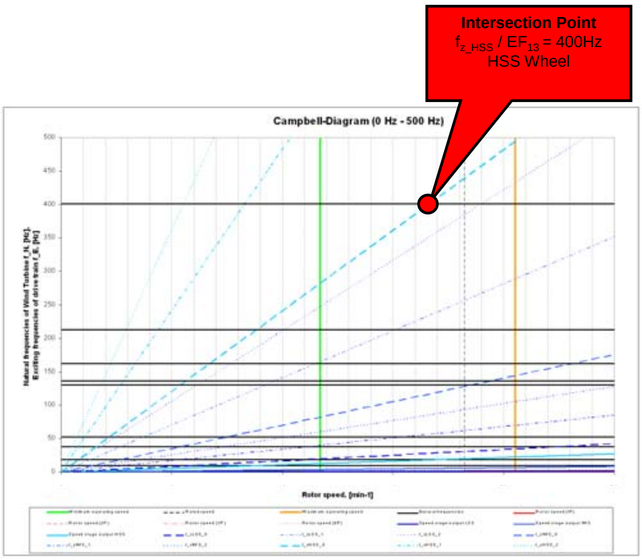


Potential resonances? → Evaluation of results from time domain simulation

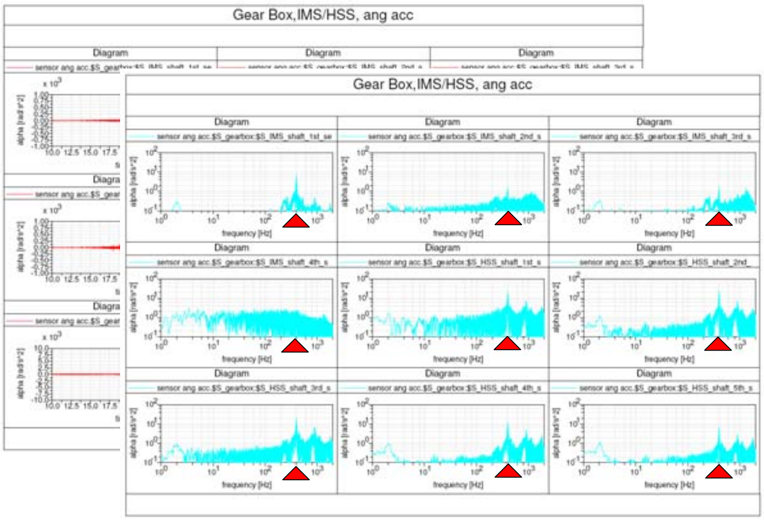
04/09/08

Germanischer Lloyd

Analysis within the Certification process (3)

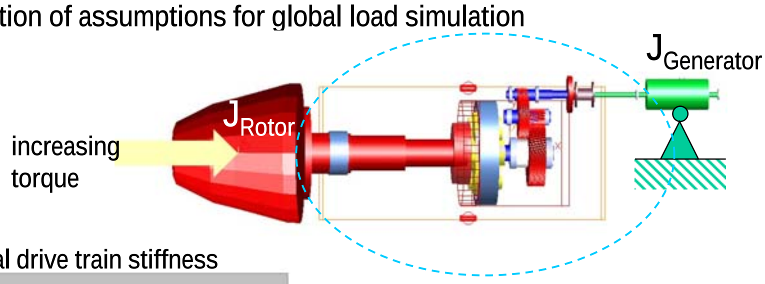


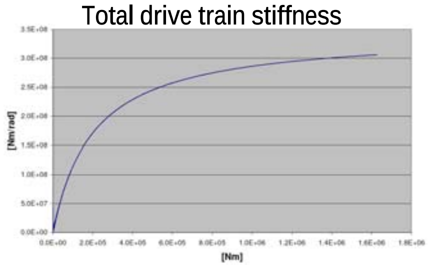
Analysis within the Certification process (4)



Analysis within the Certification process (5)

Verification of assumptions for global load simulation



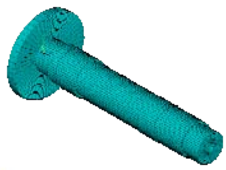


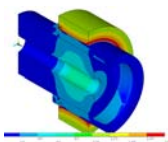
04/09/08

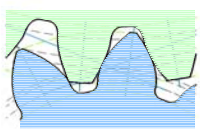
Germanischer Lloyd

Modelling possibilities and effects

- Modelling of shafts
- Modelling of shrink fit
- Modelling of gears
- Modelling of rotor blades





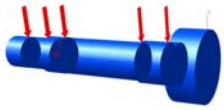


04/09/08

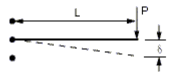
Germanischer Lloyd

Modelling of shafts

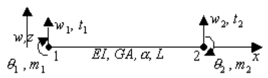
1. Shafts represented by rigid bodies connected by spring damper elements



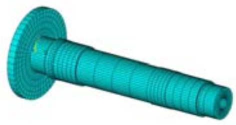
2. Elastic beam elements (Bernoulli)



3. Timoshenko beam elements

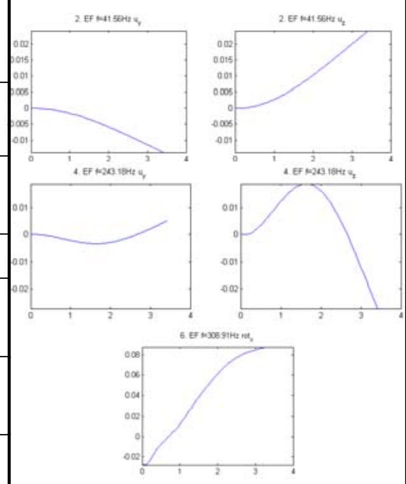


4. Structural solid elements



Modelling of shafts - comparison

	Bernoulli beam	Timoshenko beam	Structural solid
1st bending	41.6 Hz	40.8 Hz	38.7 Hz
2nd bending	243.2 Hz	219.4 Hz	213.2 Hz
1st torsion	309 Hz	309 Hz	300 Hz
1st elongation	402 Hz	402 Hz	393 Hz
3rd bending	653 Hz	532 Hz	526 Hz
2nd torsion	776 Hz	776 Hz	740 Hz



Modelling of shafts - conclusions

- No notch effects of beam elements with respect to stiffness
- Shear deformation effects have an impact on bending modes
- When the main focus is put on torsional modes: rigid bodies and spring damping elements are sufficient.
- Inclusion of axial modes: Bernoulli beam.
- Consideration of shear effects and bending modes: Timoshenko beam elements should be the first choice
- The use of solid elements is very complex and not common practice for multi body simulation.

$$J = \frac{m}{2} \cdot \left[\left(\frac{D}{2}\right)^2 + \left(\frac{d}{2}\right)^2 \right]$$

$$k_{Ti} = \frac{G \cdot I_p}{l}$$

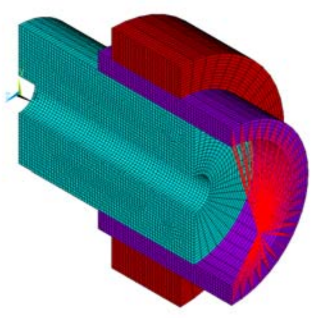
04/09/08 Germanischer Lloyd

Shrink fit (e.g. mainshaft / planet carrier)

analytical solution:

$c=1/(1/c_{main\ shaft} + 1/c_{planet\ carrier})$

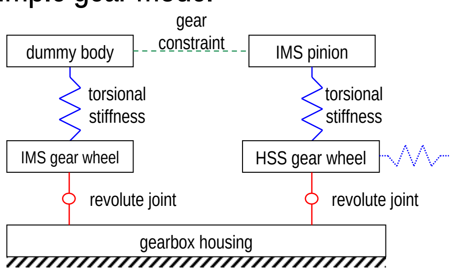
No	$C_{rot,\ analytical}$	$C_{rot,\ FEM}$	C_{ratio}
	[10^{12} Nm/rad]	[10^{12} Nm/rad]	
1	0.2044	0.2452	0.83
2	0.1521	0.1773	0.88
3	0.1687	0.1903	0.89
4	0.1314	0.1427	0.92



04/09/08 Germanischer Lloyd

Modelling of gears

Simple gear model



- transmission ratio
- constant stiffness

→ adequate for simulation in frequency domain

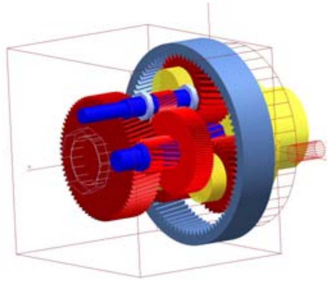
→ rotational DOF

Sophisticated gear model

- variation in tooth meshing stiffness
- change in axle distance
- change in axial direction

→ advisible for simulation in time domain

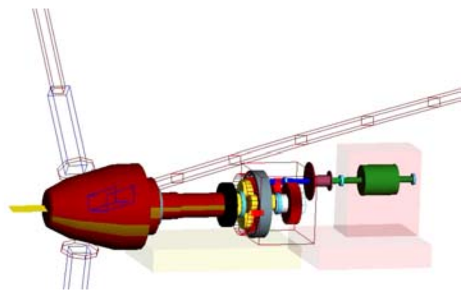
→ detailed modelling (1...6 DOF)



Influence of rotor blades on drive train frequencies

Same drivetrain – two different sets of rotor blades

	Blade A (1 body, 1 eqv. stiff.)	Blade A (fine discretization)
1.	1.6 Hz	1.6 Hz
2.	12.2 Hz	12.2 Hz
3.	21.9 Hz	21.9 Hz
4.	46.5 Hz	46.5 Hz
5.	67.3 Hz	68.4 Hz
6.	121.6 Hz	157.3 Hz
7.	170.2 Hz	170.1 Hz
8.	225.4 Hz	225.3 Hz
9.	...	...
10.	798.6 Hz	793.2 Hz
11.	1033.3 Hz	1033.3 Hz



→ Modes related to hub or mainshaft are shifted

Classification: Internal Status: Draft

IEA ”expert meeting”#57 Wind turbine drivetrain dynamics & reliability

Klaus Kr. Haglerød

StatoilHydro

Agenda

- 1. StatoilHydro in the wind industry
- 2. Hywind concept
- 3. Sheringham Shoal
- 4. Havøygavlen Wind Park

StatoilHydro

Hywind

..and we invented the Hywind concept

- Gas turbine father: Ægidius Elling.
  - Floating concrete sub-structure
  - "Off-the-shelf" offshore wind turbines
  - Water-depths >100 m
  - Inshore construction and assembly
  - Towed to site
  - Moored by three lines
- Designed for extreme conditions
  - H_s > 14m
  - U_{10} > 40 m/sec
- Potential
  - Power to offshore installations
  - Power to grid, Norway and internationally

StatoilHydro

Capacity turbine: 2,3 MW·

Weight turbine: 138 tonn·

Høyde på turbin: 65 m·

Rotor diameter: 82,4 m·

Depth below sea level: 100 m·

Total weight: 5300 tonn·

Diameter turbine tower at sea level 6 m

Thickness tower wall: 80 mm

Diameter floating element: 8,3 m·

Sea level: 120-700 meter·

Anchors: 3

2 years test program

Project cost: approx 450 mill NOK

(56 mill EUR)

- Contracts: WTG: Siemens
  - Technip: Structure and installation
  - Nexans: Cable to shore
  - Haugaland kraft: Grid operator

StatoilHydro

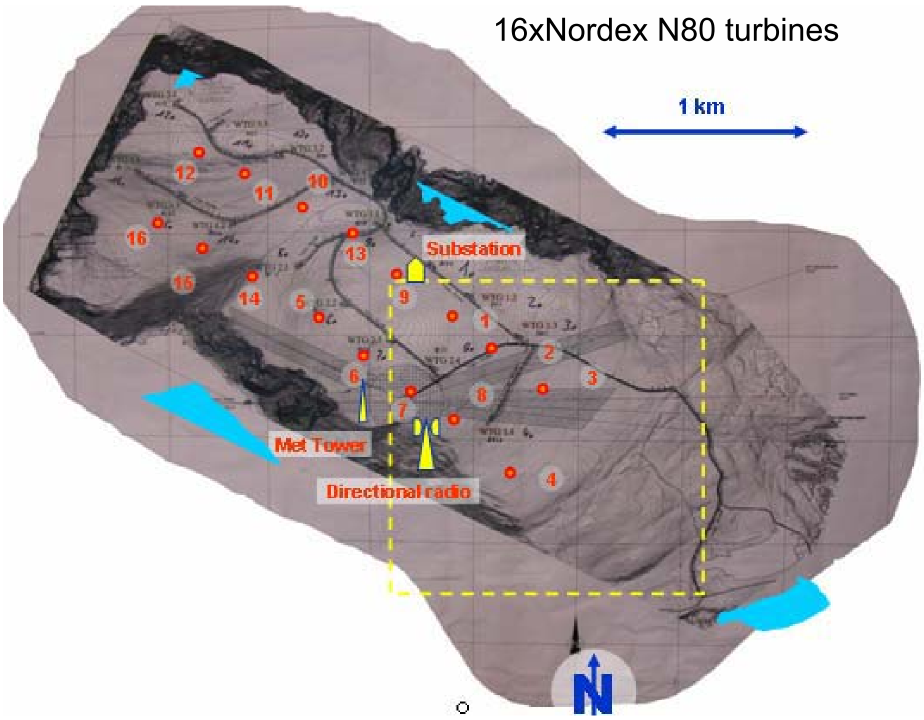
Sheringham Shoal

88x3,6 MW Siemens Start up 2011

StatoilHydro

HAVØYGAVLEN

16xNordex N80 turbines

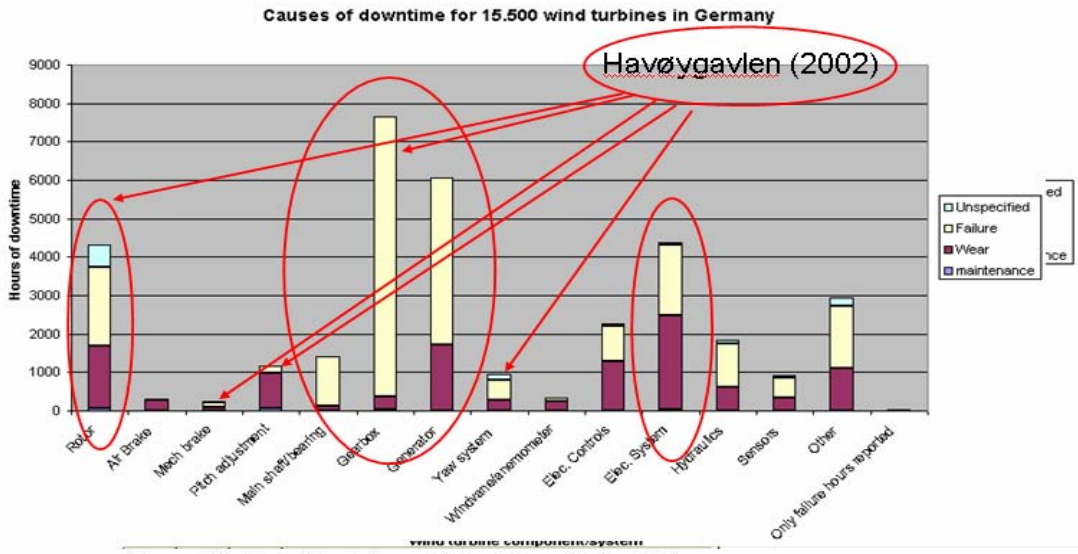


StatoilHydro

HAVØYGAVLEN

2. Wind turbine generator fundamentals

Failure statistics



Source: Windstats Newsletter vol. 17 no.2 Issue Spring 2004

StatoilHydro

Gearboxes

- All Eichoff gearboxes are exchanged (13 gearboxes)
- None complete new and four repaired in Germany

	Original	2004	2005	Replaced
WTG 1	E1		E2	2005-06-08
WTG 2	E1		E2	2005-06-14
WTG 3	E1	F		2004-09-27
WTG 4	E1		E2	2005-06-05
WTG 5	F			
WTG 6	F			
WTG 7	F->E1	E1	F	2005-06-29
WTG 8	E1	E2		2004-10-24
WTG 9	E1		E2	2005-06-21
WTG 10	E1	E2		2004-10-25
WTG 11	F			
WTG 12	E1		E2	2005-07-20
WTG 13	E1		E2	2005-08-03
WTG 14	E1	E2		2004-10-24
WTG 15	E1		E2	2005-08-10
WTG 16	E1	E2		2004-10-03

StatoilHydro

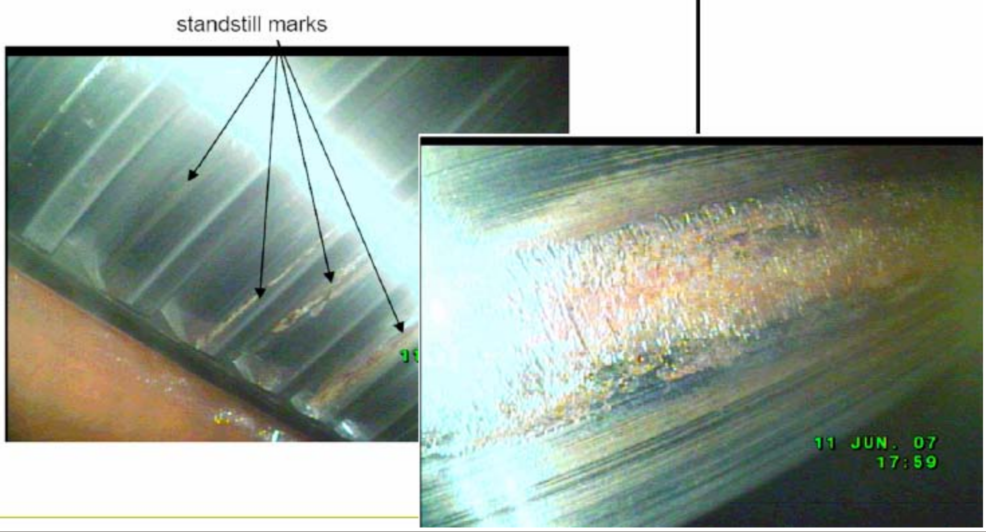
Main bearing

- No detected problems
- Needs a lot of grease and therefore a big maintenance object

- Bearing exchanged from spherical ball bearing to roller bearing

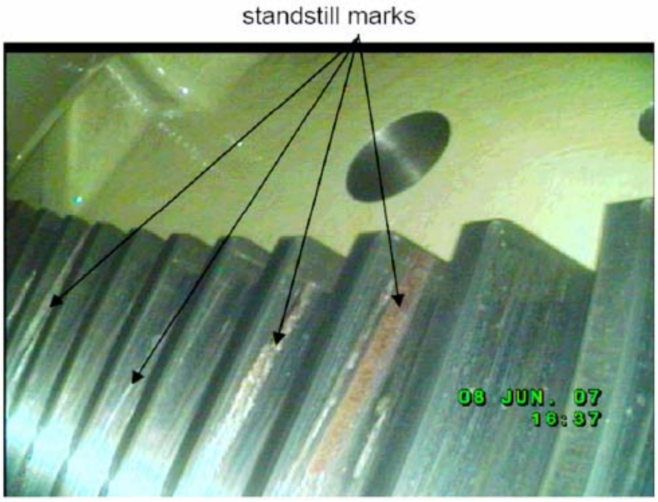
Example from WTG 3

On the gearing of the internal gear there are noticeable problems in the form of very distinct marks caused by standstill. The intended operating time will not be possible with these standstill marks. We recommend periodical checks to get a development trend.



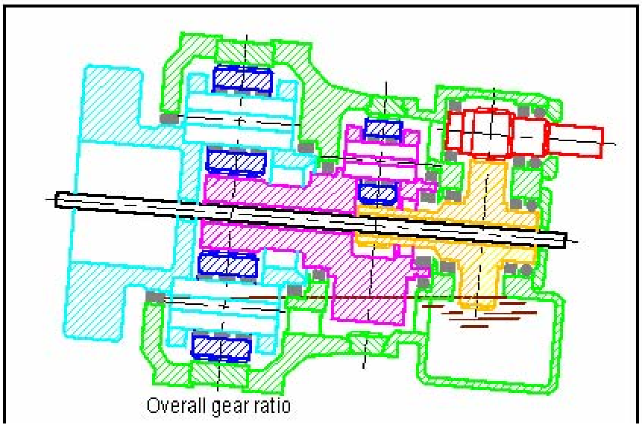
Example from WTG 9

On the gearing of the internal gear there are noticeable problems in the form of distinct marks caused by standstill. We recommend periodical checks to get a development trend.



Wind Turbine Gearbox

- Low input speed, 15-20 rpm→ Very high input torque
- High speed ratio, typical 1:70
- Low size - low weight is essential for WTG
- Extremely demanding task



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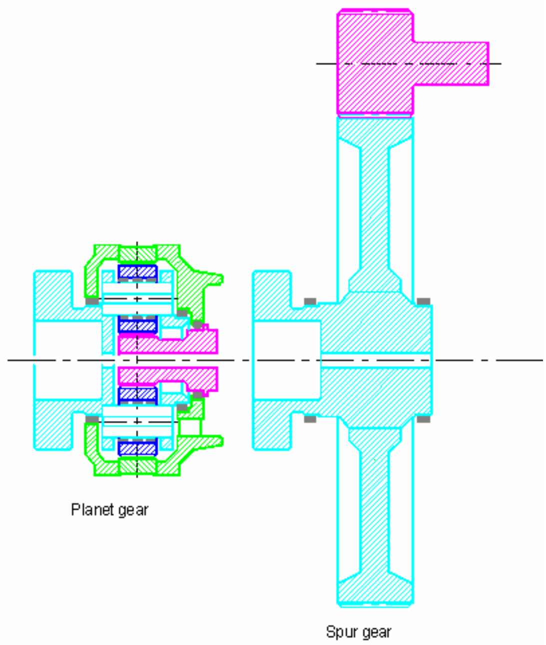
Why use planetary gears in WTGs?

- Planetary gears offer an excellent combination of low weight and size together with high speed ratio.
- See comparison with spur gear of same speed ratio and tooth loading.
- Less sized wheels since the high torque is distributed on three or four planetary wheels.
- No radial bearing force component caused by torque.



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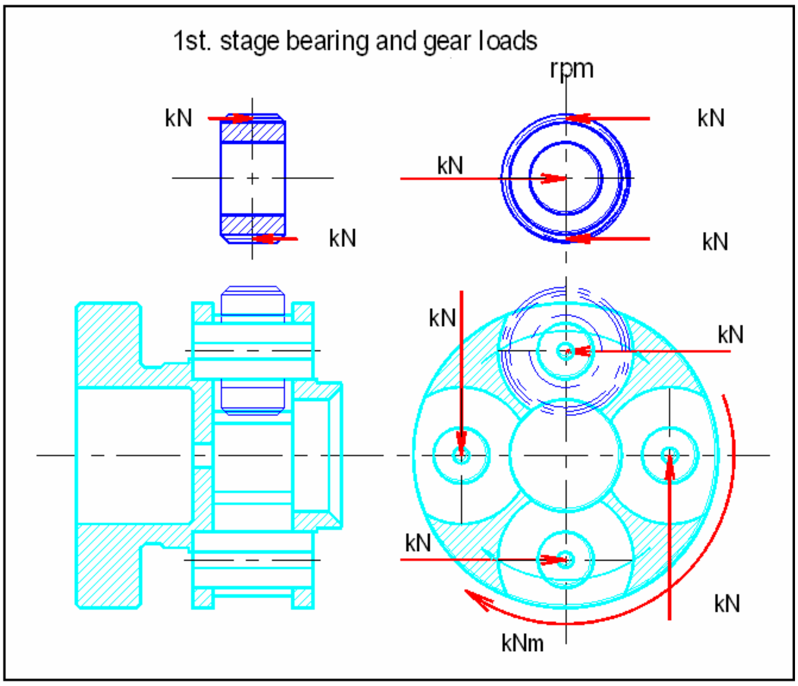
Load distribution in 1st. stage planetary gear.

- tons bearing force for each planetary wheels.
- Tilt moment on planetary wheels due to helical teething.
- Planetary tooth radial forces is balanced.
- No radial bearing force on planet carrier due to torque.



StatoilHydro

2002

2008

Thank you for your attention!

StatoilHydro

DS

IEC TC88/ ISO TC60 Joint Working Group

Standard for the Design of Gearboxes for Wind Turbines
IEC 61400-4 Edition 2
(ISO 81400-4)

Briefing for IEA Wind Experts Meeting

On Drivetrain Reliability and Dynamics

DS

DOCUMENT HISTORY

- ANSI/ AGMA/ AWEA 6006
  - US national standard completed in 2003
  - significant involvement from many countries
  - Written as application standard for developing specification
  - Converged (somewhat) US and German gear rating
- ISO 81400-4:2005
  - DK issued a New Work Item Proposal 2003
  - Developed equal peer level cooperation IEC TC88/ ISO TC60
    - ISO TC28 (lube) and ISO TC4 (bearings) as non-peers
  - used “fast track” process to publish 6006 as ISO standard
- Concurrently develop IEC 61400-4 Edition 2 under IEC (DK)

JOINT WORKING GROUP (JWG)

- Developed format to work jointly IEC/ ISO
- Meetings commonly 40 to 50 experts
  - DK, US, UK, DE, BE, ES, CH, FI, JP
  - Wind turbine manufacturers, consultants and researchers
  - Gear manufacturers, lubricant manufacturers, bearing manufacturers
  - Certification agencies
- 12 meetings to date

DIFFERENCES - Edition 1 to Edition2

- Not exactly an application standard
- Guidance for certification (via WT01)
- Attempt to harmonize reliability
- Loads clause
- Test and validation clause - more requirements
- More O&M and manufacturing considerations
- Broader lubrication requirements and guidance
  - Cleanliness, properties, monitoring
- Dodged dynamic analysis

CURRENT SCHEDULE

• editorial committee incorporate WD2 comments	May 08
• WD3 distributed to JWG	June 2008
• comments from NC/MB received at DS	August 08
• aggregated WD3 comments distributed	August 08
• meeting in Tokyo	Sept 08
• meeting in Switzerland	Nov 08
• meeting in US	Feb 09
• Develop Committee Draft	May 2009

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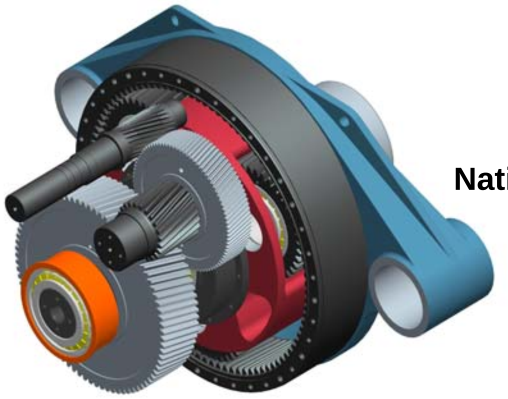
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Introduction to discussion



Sandy Butterfield
Chief Engineer
National Wind Technology Center

NREL

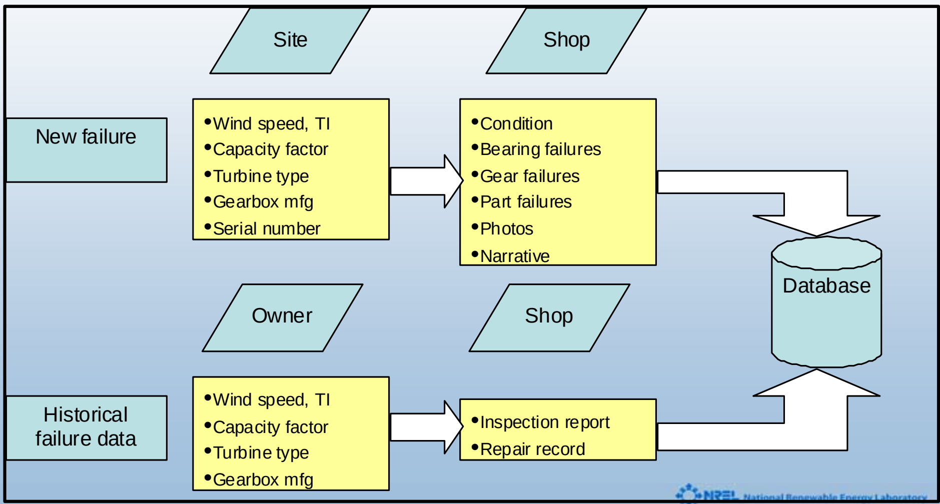
NREL is operated by Midwest Research Institute • Battelle

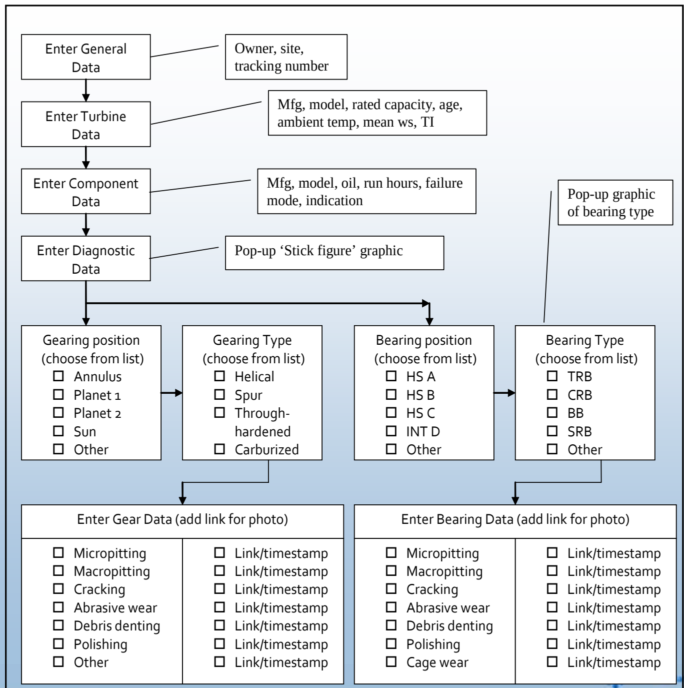
Gearbox Failure Database

- Need a unambiguous failure data base to focus research accurately.
- Inspection training is crucial
- Data input software to aid inspection, data consolidation and consistency
- Aid in bearing failure interpretation
- Participation welcome
- Partners get access to data base after sanitization

NREL National Renewable Energy Laboratory

Failure Data Process Flow





IEA Gearbox Reliability Annex?

- Model comparisons / verifications
- Study transient load case (and others) impact on bearing life
- Supply test data for design process validation (Utgrundan?)
- Develop new gearbox design load cases for standard
- Provide guidelines for gearbox design

- GRC could supply information to broader scope
- IEA provides convenient agreement mechanism to control dissemination of information and data
- This committee can define the scope of work
- Must honor existing GRC agreements
- Ultimately GRC reference data set will be published

NREL National Renewable Energy Laboratory

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Summary of IEA RD&D Wind – 57th Topical Expert Meeting on

WIND TURBINE DRIVETRAIN DYNAMICS AND RELIABILITY

September 2008, Jyväskylä, Finland

Brian McNiff, McNiff Light Industry

Background

The intention with this meeting was to facilitate an in depth discussion of both research and application engineering of the current state of the art of drive train systems for wind turbine applications.

Participants / Presentations

The meeting was very well attended with 47 registered participants, representing nine different countries, Denmark, Finland, Germany, South Korea, Norway, Sweden, the Netherlands, UK and the USA. The participants represented wind turbine manufacturers, sub suppliers, utilities and research organizations.

The following presentations were given:

1. Introductory Note
   E. Peltola, et. al.
2. Gearbox Reliability Collaborative – Overview
   S. Butterfield
3. Gearbox Reliability Collaborative - Test Engineer's Views
   B. McNiff
4. Gearbox Reliability Collaborative - Analysis Round Robin
   F. Oyague
5. The EC funded project PROTEST (PROcedures for TESTing and measuring wind energy systems)
   H. Braam, L. Rademakers
6. Measurement of drive system dynamics
   C. K. Christensen
7. Wind Turbine Drivetrain Modelling at DONG Energy
   S. A. Eisen
8. Drivetrain Event ECR Introduction
   T R Morgan, N. Brinkworth
9. Introducing GE Transportation
   M. Sirak
10. Wind Drive Train Dynamics and Reliability
    AW Giammarise
11. Wind Turbine Drivetrain Dynamic & Reliabilty – SKF Capabilities
    P. Malmberg

12. OVAKO driveline – RCA (Root Cause Analysis)
Hans Kjellberg

13. MACOM Machine Condition Monitoring
M. Hunt, N. Brinkworth

14. The Effect of Gearbox Flexibility on Wind Turbine Dynamics
E. Bossanyi, R. Dorling, R. Haines, N. A. Zaidi, A. Poon

15. Influence of Housing and Carrier Flexibility on Gear and Bearing Loaded Contact
A. Crowther, J. Coultate

16. Modelling of loads and dynamics of wind turbines
E. Peltola, P. Antikainen, T. Wallenius

17. Ricardo Wind Turbine Drivetrain Overview
G. Hundleby

18. Research in Dynamics & Vibration Future directions for wind-energy
D. Rixen

19. Strategy for user orientated simulation of wind turbines to calculate realistic load conditions
B. Schlecht, T. Rosenlöcher

20. VibPower - The small test structure
P. Klinge

21. Drive train dynamics: Certification requirements and modelling possibilities
M. Ristow

22. Wind turbine drivetrain dynamics & reliability
K. Kr. Haglerød

23. IEC TC88/ ISO TC60 Joint Working Group Standard for the Design of Gearboxes for Wind Turbines
B. McNiff

24. Introduction to discussion
S. Butterfield

Distillation

- analytical capabilities are strong as indicated by the talks at this meeting, challenge is applying these capabilities appropriately
- Butterfield thinks group should meet one more time focusing analytical capabilities using dynamic analysis validated by field data
- Validation using field data was also echoed as very important
- What can owner/ operator provide? Is just torque and some limited measurements of turbine enough? They would like guidance in what testing and data format is needed.
- TU Dresden and Delft TU think the models need more than just gearbox information in order to be accurate. Need whole system models with more involved validation. Could get simpler later.
- Observation that turbine design normally progresses from rotor to generator, but also need to look from generator back due to electrical considerations such as effect of EOn ride through requirements.
- What measurements needed to validate:
    - Frequency, modes, damping
    - Perhaps there should be a discussion of what measurements are needed

  - Would be good to be consistent
  - What sampling frequency?
  - Important to define a set
- Vattenfall is setting up measurement campaigns, but how to evaluate?
- Issues with data of two forms
  - Need modeling data such as masses
  - Need data from instrumentation
- McNiff says that you should start a test with questions or goals to guide any testing
  - Then your measurement campaigns and instrumentation details come from that
  - Shouldn't just collect buckets of data without focus
  - The US Gearbox Reliability Collaborative (GRC) is doing all this
- Need model sensitivity analysis (eg, is damping important, do you need exact stiffness or are simplifications enough?)
- Romax is concerned about model of transients? Are they being modeled correctly and are they being included properly. Doesn't think using just Load Duration Distribution is enough.
- UPWIND project from EU is open to input. There is a meeting soon where others can suggest testing goals.
- Braam thinks there are design load cases that are missed that need to be considered.
- Gilkes thinks the aero elastic models of the turbine are sufficiently accurate and inclusive but component manufacturers are asking the right questions of the data. What do we want to see.
- There was a long dialogue of whether to believe the main assumption of Miner's Rule should be questioned. That assumption is that it doesn't matter the sequence of loading in estimating damage. Should Miner's rule be validated for gears and bearings?
- Most fatigue testing is in laboratory conditions with uniaxial loading on small elements. Difficulty is in scaling up.
- Convenor refocused discussion onto what research suggestions are there?
- Delft TU suggests rubber joints characterization and system damping characterization
- Ray Hanson described new planned dynamometer facility in the UK. Email will be sent around regarding this

Options for Continuation

1. do nothing, go home
2. more meetings of this type
3. develop new task within IEA Wind
4. Contact and input to UPWind
5. Recommend new EU research

Sandy Butterfield suggests: - IEA Gearbox Reliability Annex??

- model comparisons/ validation
- Study transient load cases (and others) impact on bearing life
- Supply test data for design process validation (Utgrunden?)
- Develop new design load cases for the standard
- Provide guidelines for gearbox design
- Look at reformatting how loads, displacements and conditions are presented to gear and bearing designers
- GRC could supply information to broader scope
- IEA provides convenient agreement mechanism to control dissemination of information/data
- GRC data set will be published at some point in the future

Models available in the room:

- Romax
- TU Delft
- TU Dresden
- Ricardo
- NREL
- SKF

Suggestion – develop some common minimum measurements and data set formats for people collecting field data at present

Suggestion – we also develop some pass fail tests to use in new design prototyping tests in a dynamometer. There are many dynamometers being planned and coming on line in Europe at gear manufacturers, WTG manufacturers, and research facilities.

Question – what about the failure database? Can the GRC database work with others in the room to define a common format.

Question – how do we draw the wind turbine manufacturers into the process?

Suggested meeting subjects;

1. Explain load cases to gearbox designers
    a. Bring your favorite load case
    b. Simulations and measured data
2. Database of failures – how to do this
3. How to make a gearbox smart
    a. as per Winergy mechatronic idea
    b. may want to tie this into modeling
4. Measurement campaigns and requirements for model validation

Details of Forming a New Task or Annex

- need a core group willing to organize the task and meetings
- a proposal would be needed to describe task and the results of task efforts
- for instance, there may be a report for code validation, how it was done

Loads and validation seem to be the main topics.

GH and Romax would be willing to make a starting point on the load cases.

Sirak suggest we expand the task or meetings to be INPUTS - MODEL – OUTPUTS

Next ExCo of IEA is in Boston in 2 weeks, so a proposal couldn't be ready for that meeting. Could be available for the next meeting in 6 months if there is interest.

Question – some university researchers need money to continue participation or research applied to the subject. -- IEA does not have money to support these things. If we start a task, the companies and research groups are self funded or funded via national R&D budgets.

Email will go out soliciting support or input via Sandy.

List of participants

IEA R&D Wind Task 11, Topical Expert Meeting
Gearboxes and Drive Train Dynamics
Jyväskylä, Finland
4-5 September 2008

The following persons registered

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