Summary of Content:

0. **IST-Company Profile**

1. **Introduction into TOWER-MKS**
   - Overall Concept
   - User-Interface SIMPACK
   - Demonstration Application

2. **Hydrodynamics Theory**
   - Methods
   - Mixed Friction
   - Elasto-Hydrodynamics (EHD)

3. **Application of Hydrodynamics**
   - Hydrodynamics Input Parameters
   - Evaluation with XPost
The ‘IST GmbH’ was found in 1997 as spin-off of the ‘RWTH Aachen’ and of the ‘Universität Kassel’ headed by Prof. Knoll. The IST is an engineering association with core competences in the development of computer-assisted simulation software as well as its application on structure dynamics/elastohydrodynamics coupled engine components. Areas of application are dimensioning, weak point analysis and system optimisation of tribological, structure dynamical and acoustical problems. An extensive cooperation exists at present with engine manufacturers and their suppliers. Furthermore, the IST is responsible for the maintenance of software that was developed as part of the FVV research projects of the ‘Institut für Maschinenelemente und Konstruktionstechnik’ of the University of Kassel.
Universal tool for sleeve bearing calculations

Calculation method
- Characteristic diagram-method
- Quasi-static EHD-method
- Full-dynamic EHD-method

Solution of the Reynolds differential equation for rough surfaces in each period

Optional bearing geometries

Consideration of the oil supply

Mixed friction (flow factors, contact pressure)
PIMO3D

- Solution of the complete *Reynolds* equation in each period
- Piston- and bold hydrodynamics
- Multi body system for illustration of large rigid body motions
- Complex production- and contour in operation
- Contour cover
- Partial filling status in the piston flow clearance
- Mixed friction model based on flow simulations (flow factors, contact pressure)
FIRST

- Structure dynamic multiple body simulation
- Integration in the period (non-linear)
- Complex FEM structures (~1.e6 FHG)
  static/modal reduction (~150 FHG)
- Rigid body dynamic (big motions)
- Open model generation
  systems, drives, FD elements, loads, ...
- Hydrodynamics: integrated TOWER-module
  mixed friction, cavitation, grooves, ...
- EHD with substructure technique (engine compound)
Summary of Content:

0. **IST-Company Profile**

1. **Introduction into TOWER-MBS**
   - Overall Concept
   - User-Interface SIMPACK
   - Demonstration Application

2. **Hydrodynamics Theory**
   - Methods
   - Mixed Friction
   - Elasto-Hydrodynamics (EHD)

3. **Application of Hydrodynamics**
   - Hydrodynamics Input Parameters
   - Evaluation with XPost
TOWER-MBS Overview

MKS-Programm

Bewegung

Userforce-Schnittelle

MKS-Schnittelle

TOWER-MKS

Impedanz-Methode
- Kurze Rechenzeit

Online-FEM
- Sondergeometrien (Nuten, Zitronenspiel etc.)
- Mikrohydrodynamik (Kontakt- Flußfaktoren)

Axiale Führung
- Axiale Hubbewegungen
- Erfordert Online-FEM

Radiallagerung
- Zapfenrotation
- Impedanz oder Online-FEM

Druck

Umfang

Köre

Strukturanalyse
Tribologie

IST

SIMPACK User Meeting, TOWER-MKS, November 2004
MBS – Hydrodynamics Module TOWER MBS

Time Integration $t$

**Input Parameter**
- Position / Velocity (Shaft, Bearing)

**Output Parameter**
- Bearing Forces
- Minimum Gap
- Maximum Pressure

**MKS-Program**
- Structure
- • kinematics
- • kinetics
- • elasticity
- External Loads
- Integration

**Gap Function and Derivative with Respect to time**

**Interpolation Impedance Charts**

**Hydrodynamics Module TOWER MBS**

**Hydrodynamic Forces**

**Calculation Procedure: Example Impedance Method**
MBS – Hydrodynamics Module  

**Time Integration** $t$

<table>
<thead>
<tr>
<th><strong>Input Parameter</strong></th>
<th><strong>Output Parameter</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Position / Velocity (Shaft, Bearing)</td>
<td>Bearing Forces, Minimum Gap, Maximum Pressure</td>
</tr>
</tbody>
</table>

**MK5-Program**

- **Structure**
  - Kinematics
  - Kinetics
  - Elasticity

- **External Loads**

- **Integration**

**Hydrodynamics Module TOWER MBS**

**Calculation Procedure: Example Online-FEM-Procedure**

**Gap Function and Derivative with Respect to time**

Solution of the *Reynolds* differential equation to each period:

$$
\frac{\partial}{\partial x} \left( \frac{\rho h^3}{12 \eta} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left( \frac{\rho h^3}{12 \eta} \frac{\partial p}{\partial z} \right) = \frac{1}{2} (u_1 + u_2) \frac{\partial}{\partial x} (\rho h) + \frac{\partial}{\partial t} (\rho h)
$$
Summary of Content:

0. IST-Company Profile

1. Introduction into TOWER-MBS
   - Overall Concept
   - User-Interface SIMPACK
   - Demonstration Application

2. Hydrodynamics Theory
   - Reynolds differential equation
   - Mixed Friction
   - Impedance Method
   - Online-FE-Method
   - Summary of all Methods

3. Application of Hydrodynamics
   - Hydrodynamics Input Parameters
   - Evaluation with XPost
<table>
<thead>
<tr>
<th>Global Elasticity</th>
<th>Locale Elasticity (EHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impedance Method</strong> <em>(characteristics diagram solution)</em></td>
<td></td>
</tr>
<tr>
<td>- interpolation in characteristic diagrams (very quick)</td>
<td></td>
</tr>
<tr>
<td>- limited model generation (only cylindrical, no tilting, grooves, ...)*</td>
<td></td>
</tr>
<tr>
<td><strong>Online FEM-Method</strong></td>
<td></td>
</tr>
<tr>
<td>- solution of the <em>Reynolds</em> equation in each period</td>
<td></td>
</tr>
<tr>
<td>- optional shell geometry (oil grooves, holes, etc)</td>
<td></td>
</tr>
<tr>
<td>- variable gap in axial direction (tilting )</td>
<td></td>
</tr>
<tr>
<td><strong>Offline-EHD (TOWER)</strong></td>
<td></td>
</tr>
<tr>
<td>- Input: shaft tilting and force from MBS</td>
<td></td>
</tr>
<tr>
<td>- <em>rear EHD-analysis</em> (without reaction)</td>
<td></td>
</tr>
<tr>
<td><strong>Online-EHD</strong></td>
<td></td>
</tr>
<tr>
<td>- compact single body (e.g. connection rod )</td>
<td></td>
</tr>
<tr>
<td>- main axis reduction for bores</td>
<td></td>
</tr>
<tr>
<td><strong>Online-EHD with substructure technique</strong></td>
<td></td>
</tr>
<tr>
<td>- complex engine compound with bearings</td>
<td></td>
</tr>
<tr>
<td>- substructures with main axis reduction</td>
<td></td>
</tr>
<tr>
<td>- interface modes with SVD (boundary modes)</td>
<td></td>
</tr>
<tr>
<td>- high locale precision in each bearing bore</td>
<td></td>
</tr>
</tbody>
</table>
Hydrodynamic Lubricant Film Reaction

Reynoldssche Dgl.

\[
\frac{1}{r^2} \frac{\partial}{\partial \varphi} \left( \Phi \frac{h^3}{\eta} \frac{\partial p}{\partial \varphi} \right) + \frac{\partial}{\partial z} \left( \Phi \frac{h^3}{\eta} \frac{\partial p}{\partial z} \right) = 6 \frac{\partial h}{\partial z} W_i + 6 W_i \sigma^A \frac{\partial \Phi}{\partial z} + 12 \frac{\partial h}{\partial t}
\]

Micro hydrodynamics or rough surfaces

\[\Phi^P = \frac{q_{\text{rauh}}}{q_{\text{glatt}}} \left( \frac{\bar{h}}{h} \right)^3\]

\[\Phi^s = \frac{q_{\text{rauh}}}{\bar{u} \sigma}\]

h / \sigma
Läppen
Honen
Funkenerosion

ISO-Rauheitskennzahl N6
R\text{a} = 0.8 \mu m

Strukturanalyse
Tribologie

Micro Hydrodynamics on different Editing
Gesamtdruck

\[ p_{\text{ges}} = p + p_c \]

Hydrodynamische Schmierfilmreaktion

Reynoldssche Dgl.

\[
\frac{1}{r^2} \frac{\partial}{\partial \phi} \left( \Phi_p h^3 \frac{\partial p}{\partial \phi} \right) + \frac{\partial}{\partial z} \left( \Phi_p h^3 \frac{\partial p}{\partial z} \right) = 6 \frac{\partial h}{\partial z} W_i + 6 W_i \sigma \frac{\partial \Phi^s}{\partial z} + 12 \frac{\partial h}{\partial t}
\]

Festkörperkontakt

Normalkraft

\[ F = F_{\text{Hyd}} + F_c \]

Reibung

\[ F_r = f F_{\text{Hyd}} + \mu c F_c \]

Kontaktdruck integral

Streubereich Greenwood/Tripp

Kontaktmodell IMK

Spaltweite h

3D-Oberfläche Kontaktadruck lokal
Contact Pressure Characteristic Diagram $p_c(h^*)$

Test block experiment dragged:
- $F = 50\text{N/mm}^2$
- $n = 1500 \text{ 1/min}$
- $T = 90 \text{ °C}$

New Condition
- $R_a=0.75[\mu\text{m}]$
- $R_a=0.61[\mu\text{m}]$
- $R_a=0.54[\mu\text{m}]$
1. Bearing coupling (gap function $h$)

**Cone:**
- coupling node on the rotation axis
- interpolated spline

**Shell:**
- coupling node in the bore
- "least square fit" of a rigid cylinder (bore)

2. Force coupling

**Cone:**
- local pressure forces on adjacent coupling nodes

**Shell:**
- optimal force distribution (singular-value decomposition)

► Exact resulting loads
► Approximation of the pressure distribution
Coupling with rigid body

Coupling with flexible body

locale forces

locale gap course
Summary Of Content:

0. **IST-Company Profile**

1. **Introduction Into TOWER-MBS**
   - Overall Concept
   - User-Interface SIMPACK
   - Demonstration Application

2. **Hydrodynamics Theory**
   - Methods
   - Mixed Friction
   - Elasto-Hydrodynamics (EHD)

3. **Application Of Hydrodynamics**
   - Hydrodynamics Input Parameters
   - Evaluation with XPost
Hydrodynamic-Input File (complete)

- *bearing, name = impedance
  - bearing definition = standard-bearing
- *bearing def., name = standard-bearing
  - impedance file = /home/reynolds.imp
  - bearing segment = seg
  - hydrodynamics data = standard
- *bearing segment, name = seg
  - shell clearance = 1.d-3
- *hydrodynamic data, name = standard
  - bearing diameter = 30.0d-3
  - bearing width = 20.0d-3
  - reference viscosity = 0.0057
Input File:
- chart orientated
- hierarchic
- super positioned

**Input File Structure**

<table>
<thead>
<tr>
<th>Parameter Type</th>
<th>Kürzel</th>
<th>Beispiel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer</td>
<td>i</td>
<td>Integrationsgrad = 2</td>
</tr>
<tr>
<td>Double</td>
<td>d</td>
<td>Lagerdurchmesser = 45.e-3</td>
</tr>
<tr>
<td>Character</td>
<td>c</td>
<td>Druckrandbedingung = reynolds</td>
</tr>
<tr>
<td>Logical</td>
<td>l</td>
<td>Spaltverlauf plotten = ja</td>
</tr>
</tbody>
</table>
Basic Bearing Geometries
**Basic Bearing Geometries Specification**

- **Sleeve bearing with cylindrical clearance**
  - *bearing segment, name=cylindr*
  - phi-start = 0
  - phi-end = 360
  - shell clearance = 2.e-3

- **Sleeve bearing with elliptical clearance**

\[
\psi_S = \frac{R_S - R_W}{R_W} \quad \psi_B = \frac{R_B - R_W}{R_W}
\]

- **bearing segment, name=up**
  - phi-start = 0
  - phi-end = 180
  - phi-m = 90
  - shell clearance = 2.e-3
  - minimum clearance = 1.e-3

- **bearing segment, name=down**
  - phi-start = 180
  - phi-end = 360
  - phi-m = 270
  - shell clearance = 2.e-3
  - minimum clearance = 1.e-3
**Crush relief**

- *crush relief, name = crush-right*
  - angle = 0 # [°]
  - width = 10.e-3 # [m]
  - depth = 20.e-6 # [m]

- *crush relief, name = crush-left*
  - angle = 180 # [°]
  - width = 10.e-3 # [m]
  - depth = 20.e-6 # [m]

**Groove in the top-shell**

- * crush relief, name = groove*
  - phi-start = 45 # [°]
  - phi-end = 135 # [°]
  - width-start = -2.e-3 # [m]
  - width-end = 2.e-3 # [m]
  - depth = 1.5e-3 # [m]
Basic Bearing Geometrie Specification

Input – Contour File

<table>
<thead>
<tr>
<th>Breitenrichtung [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
</tr>
<tr>
<td>0.000</td>
</tr>
<tr>
<td>170.000</td>
</tr>
<tr>
<td>180.000</td>
</tr>
</tbody>
</table>

Umfangsrichtung [°]

Output

3-d Contour File <prefix>-.gap-3d / <prefix>-.gap-3de

2-d Contour File
- <prefix>.gap-mid
- <prefix>.gap-mid-seg
- <prefix>.gap-negative
- <prefix>.gap-positive
Pressure boundary conditions on bearing boundaries

Hydrodynamic pressure on asymmetric
Pressure boundary condition

Hydrodynamic pressure on symmetric
Pressure boundary condition

*pressure boundary condition, name=rbd-1
  width-start = -1
  width-end = -1
  pressure = 5.e5

*pressure boundary condition, name=rbd-1
  width-start = -1
  width-end = -1
  pressure = 0.e0

* pressure boundary condition, name =rbd-1
  width-start = 1
  width-end = 1
  pressure = 0.e0

* pressure boundary condition, name =rbd-1
  width-start = 1
  width-end = 1
  pressure = 0.e0
Oil supply groove in the bearing shell

Axial section in the bearing shell

Unwound bearing oil supply

*Bearing

*Bearing Definition

*Hydrodynamic Data

*Bearing Segment

*Crush Relief

*Pressure Boundary Conditions

*Oil Supply

*Roughness Chart

**oil supply, name = zb
phi-start = 0
phi-end = 180
width-start = -5.d-3
width-end = 5.d-3
pressure = 5.d5

Oil Supply (Pressure Boundary Conditions)
Consideration of Roughness per Measurements

Influence of micro hydrodynamics ~ $h/\sigma < 10$

→ Flow tensors
→ Integral roughness effect

Modified *Reynolds* differential equation

$$\frac{\partial}{\partial x_i} \left( \Phi_{ij}^p \frac{p \bar{h}^3}{12 \eta} \frac{\partial p}{\partial x_j} \right) = \frac{v_{i2} + v_{i1}}{2} \frac{\partial (\rho \bar{h})}{\partial x_i} - \frac{v_{i2} - v_{i1}}{2} \sigma \frac{\partial (\rho \Phi_{ij}^s)}{\partial x_j} + \frac{\partial (\rho \bar{h})}{\partial t} ; \quad i \neq 3$$
Consideration of Roughness according to Greenwood and Tripp

\[ R_q = \sqrt{\frac{1}{\Omega} \int_\Omega \delta_{x,y}^2 \, d\Omega} \]

- \( \delta \): Profile deviations
- \( \Omega \): Roughness reference area

### Geometric roughness average value

\[ p_c = K \cdot E' \cdot 4.4086 \cdot 10^{-5} \cdot \left( 4 - \frac{h^*}{\sigma} \right)^{6.804} \]

- \( \sigma \): Standard deviation (= \( R_q \))
- \( h^* \): nominal gap width
- \( K \): Factor (common size \( 1 \times 10^{-3} \))
- \( E' \): here: Steel on both bodies

*hydrodynamic data, name = contact
- contact pressure factor = 2.1e9 # calculate on contact pressure
- standard deviation shell = 1.e-6 # [m] according to \( R_q \)
- standard deviation shaft = 1.e-6 # [m] according to \( R_q \)
- friction value = 0.05 # friction value according to Coulomb
Program XPost

XPost V6.0
**Program XPost**

Graphic interactive evaluation

<table>
<thead>
<tr>
<th>of integral result dimensions:</th>
<th>and local result dimensions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Shifting course</td>
<td>- Pressure distribution</td>
</tr>
<tr>
<td>- Min. gap</td>
<td>- Gap function</td>
</tr>
<tr>
<td>- Max. pressure</td>
<td>- Oil output (hole def.)</td>
</tr>
<tr>
<td>- Friction capacity</td>
<td></td>
</tr>
</tbody>
</table>

| curve operations:                                                                          | 2D-animation of the hydrodynamic      |
|---------------------------------------------------------------------------------------------| pressure distribution                 |
| - Scaling                                                                                   |                                        |
| - Integration/Differentiation                                                               | programmable serial-evaluation       |
| - Addition/Subtraction                                                                      |                                       |
| - FFT-Analysys                                                                              |                                       |
XPost: Curves Creation and Plot-Windows
XPost: Curve Index and Curve Operations
XPost: FEM-Data Export

- ASCII Daten
- MSC/Nastar Verschiebungen
- Abaqus Verschiebungen
- IDEAS Zeitdaten
- I-DEAS FFT-Daten
- I-DEAS Verschiebungen
XPost: Animations Creation, Animator3 Interface
# XPOST Demonstration-Script

xp_reapprj first.prj

xp_setkw 720 1440

xp_makkur shaft:kw_v2:1 shaft:kw shaft:v2:1

for each k {1 2 3 4 5} {
    xp_makkur shaft:fa2:${k} shaft:kw shaft:fa2:${k}
    xp_makkur shaft:fa3:${k} shaft:kw shaft:fa3:${k}
}

for each k {1 2 39 40} {
    xp_makkur block:kw_x1:$k block:kw:$k block:x1:$k
    xp_makkur Block:kw_x2:$k Block:kw:$k Block:x2:$k
    xp_makkur block:kw_x3:$k block:kw:$k block:x3:$k
}

for each l {bear-1 bear-2 bear-3 bear-4 bear-5} {
    xp_makkur $l:epsx_epsy$l:epsx $l:epsy
    foreach var {hmin pmax prei} {
        xp_makkur ${l}:kw_${var} ${l}:kw ${l}:${var}
    }
}

xp_makkur bearing-1:kw_k2z_p:bearing centre
    bearing-1:kw bearing-1:k2z:bearing centre
    bearing-1:p:bearing centre

exit

forces on crank shaft FHG evaluation
velocity on crank shaft FHG evaluation
project file importation
output period specification
deflection of engine block FHG evaluation
shifting course of basic bearings
integral hydrodynamics-results of Basic bearings (H_{min}, P_{max}, friction)
Waterfall diagram generation for the hydr. pressure in the bearing centre
### Summary

- **Hydrodynamic Slider**
  - Online-FEM Solution

- **Hydrodynamic Bearing**
  - Impedance-Solution (fast)
  - Online-FEM Solution
  - Offline-EHD Solution (TOWER)

- **Enhanced Model Generation**
  - Valve Steam Direction
  - Camshaft positioning
  - Basic Bearing
  - Connecting-rod Bearing

### Perspective

- Online-EHD (without Substructure Technique)