Research in the Area of Ultra-High Rotational Speeds

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Agenda

ETH Zurich
Power Electronic Systems Lab.

General Research Approach

Performance & Technology Trends for Electrical Drive Systems

40'000'000 rpm Spinning Ball Motor

Conclusion

Acoustic Levitation
Departments of ETH Zurich

<table>
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<tr>
<th>Department</th>
<th>Description</th>
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<tr>
<td>ARCH</td>
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21 Nobel Prizes
413 Professors
6240 T&R Staff
2 Campuses
136 Labs
35% Int. Students
110 Nationalities
36 Languages
150th Anniv. in 2005
Energy Research Cluster @ D-ITET

- Power Systems
- Advanced Mechatronic Systems
- Power Semiconductors
- High Power Electronics
- High Voltage Technology
- Power Electronic Systems

► Balance of Fundamental and Application Oriented Research
Energy Research Cluster @ D-ITET

Balance of Fundamental and Application Oriented Research
PES Research Scope

- Airborne Wind Turbines
- Micro-Scale Energy Systems
- Wearable Power
- Exoskeletons / Artificial Muscles
- Hybrid Systems
- Pulsed Power

Actuators / EL. Machines

Cross-Departmental
- Mechanical Eng., e.g. Turbomachinery, Robotics
- Microsystems
- Medical Systems
- Economics / Society
General Research Approach

Design Challenges

Mutual Coupling of Performances
Power Electronics Converters Performance Trends

Performance Indices
- Power Density [kW/dm³]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h⁻¹]

Environmental Impact...
- [kg_{Fe} / kW]
- [kg_{Cu} / kW]
- [kg_{Al} / kW]
- [cm²_{Si} / kW]

State-of-the-Art

Future

Time-to-Market

Losses

Weight

Volume

Costs

Failure Rate
Multi-Objective Design Challenge

- Counteracting Effects of Key Design Parameters
- Mutual Coupling of Performance Indices → Trade-Offs

→ Large Number of Degrees of Freedom / Multi-Dimensional Design Space
→ Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization
Abstraction of Power Converter Design

Performance Space

- Efficiency
- Power Density
- Costs
- Reliability
- etc.

System
- Phase-Shift DC/DC Conv.
- Resonant DC/DC Conv.
- DC Link AC/AC Conv.
- Matrix AC/AC Conv.
- etc.

Components
- Power Semiconductor
- Interconnections
- Inductors, Transf.
- Capacitors
- Control Circuit
- etc.

Materials
- Semiconductor Mat.
- Conductor Mat.
- Magnetic Mat.
- Dielectric Mat.
- etc.

Performance Space

- Evaluation Formulas
- Lifetime Models
- Cost Models
- etc.

- Specifications
- Operation Limits
- Converter Topology
- Modulation Scheme
- Control Concept
- Operation Mode
- Operating Freq.
- etc.

- Doping Profiles
- Geometric Properties
- Winding Arrangements
- Magnetic Core Geometries
- etc.

→ Mapping of “Design Space” into System “Performance Space”
Mathematical Modeling and Optimization of Converter Design

→ Multi-Objective Optimization — *Guarantees Best Utilization of All Degrees of Freedom (¶)*
Technology Sensitivity Analysis Based on $\eta$-$\rho$-Pareto Front

- Ensures Optimal Mapping of the “Design Space” into the “Performance Space”
- Identifies Absolute Performance Limits $\Rightarrow$ Pareto Front / Surface

$\Delta p / \Delta k$ to Improvements of Technologies
$\Rightarrow$ Trade-off Analysis
Electrical Drives: General Trends
**Development of Motion Control Systems**

- **Exponential Development**
  - < 1900  Mechanical
  - 1900  Mechanical + Electrical
  - 1950  Mechanical + Electrical + Electronic  ➔  **Electronic Motion Control**
  - 1975  Mechanical + Electrical + Electronic + Computation  ➔  **MECHATRONICS**
  - 1985  Mechanical + Electrical + Electronic + Computation + Information/Communication
Innovation in Mechatronics and Electric Drives

Key Components Available Today

- Ultra-Compact & Efficient Power Converter
- Precision Sensors
- Ultra-Compact & Efficient Electrical Machines
- High-Speed Digital Signal Processing
- High-Performance Mechanical Actuators

Extremely Wide Application Areas

- Machining
- Handling and Assembly
- Transportation (land, sea, air)
- Gas, Oil and Mining
- Water, Wastewater
- Consumer Electronics
- Computers
- Home Appliances
- Defense
- Medical
- Space Exploration
Electrical Drives: Performance Trend

Power Density
Increasing Power/Torque Density

- Esson’s Scaling Law for Electrical Machines

1) Mechanical Power
   \[ P_m = \omega T \]

2) Machine Torque
   \[ T = c l_a d_r^2 \]

- Machine Torque Density
- Machine Size
- Rotor Diameter
- Axial Length of Machine
- Utilization Factor
  - Machine topology
  - Materials
  - Manufacturing methods
  - Cooling
Increasing the Machine Utilization Factor (1)

- Degrees-of-Freedom for Improved Utilization
  - Manufacturing methods
  - Materials
  - Cooling

  - **Cast coils:**
    + Very high filling factor
    + Low-cost
    + Aluminum or copper
    + High power densities
    - High-frequency losses

Source: GM
Cevrolet Volt 2016
Increasing the Machine Utilization Factor (2)

- Degrees-of-Freedom for Improved Utilization
  - Manufacturing methods
  - Materials
  - Cooling

- **Soft magnetic composites (SMC):**
  + 3-D electrical insulation
  + Low eddy-current losses
  + Transversal- or Axial-Flux Machines
  - Mechanical strength
  - Low magnetic permeability

Source: Bauer, Kleimaier
Observer Based Sensorless Predictive Hysteresis Control of a Transverse Flux Machine
Increasing the Machine Utilization Factor (2)

- Degrees-of-Freedom for Improved Utilization
  - Manufacturing methods
  - Materials
  - Cooling

- Integrated cooling (slotless machines)
  - Smart design:
    - Fast empirical models for cooling
    - Magnetic ↔ Mechanical ↔ Thermal
  - > 40 °C hotspot temp. reduction

Increasing the Power Density

Dimensional Scaling Factor $x_d$
Ratio of Dimensions Remains Constant

Machine Radius

Machine Length

Surface Area
$A_M = 2\pi r_M^2 + \pi r_M l \propto x_d^2$

Volume
$V_M = \pi r_M^2 l \propto x_d^3$

Mechanical Power
$P_m = \omega T \propto x_d^{2.5}$

$\omega = v_c / r_f \propto 1 / x_d$

Copper Losses
$P_1 = RI^2$ with $R = \rho l / A_I \propto \frac{1}{x_d}$

$P_1 \leq Q_c \downarrow$

$\Rightarrow I \propto x_d^{1.5}$

Power Density
$p_m = P_m / V_M \propto x_d^{-0.5}$
Industry Trend: High Rotational Speed for High Compactness

High-Speed Drives have Numerous Applications Across Industries

Emerging Applications

Source: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009
High-Speed Micro-Machining Applications

- **Rotational Speed:** 250'000 – 1’000’000 r/min
  - Smaller Feature Size (μ-vias for Consumer Electronics)
  - Higher Precision in Manufacturing
  - Accelerated Manufacturing Process
  - Higher Productivity

Source: Kolar et. al., Beyond 1 000 000 rpm Review of Research on Mega-Speed Drives, COBEP 2007
High-Speed Turbocompressor for Portable Fuel Cell

- Reduced Weight/Volume
- Increased Pressure Ratio

<table>
<thead>
<tr>
<th>Comercially available compressors</th>
<th>Speed (r/min)</th>
<th>Pressure ratio</th>
<th>Mass flow (g/s)</th>
<th>Weight (kg)</th>
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<tr>
<td></td>
<td>280 000</td>
<td>1.6</td>
<td>15</td>
<td>0.6</td>
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<tr>
<td></td>
<td>18 000</td>
<td>1.4</td>
<td>15</td>
<td>4</td>
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Ultra-Compact Turbocompressor for «Solar Impulse»

- Cabin Pressurization in Solar-Powered All-Electric Aircraft
  - Compact machine design with 150 W

Rotational Speed  500’000 r/min
Machine Power       150 W
Mass Flow           1.2 g/s
Compression Ratio   1.8
1’000’000 r/min - World Record Drive System

- Demonstration of Machine Design Principles with 100 W / 1’000’000 r/min Drive System
  - $P_{\text{loss}}$ 9W (excl. bearings)
  - $d$ Rotor PM 3 mm
  - Ball Bearing Losses 44 W (!)

Source: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009
Advanced Bearing Systems for High-Speed-Drives

Lifetime of Ball Bearings Limits Rotational Speed of Electric Machine

Active Magnetic Bearings
- No Wear, Long Lifetime
- Control of Rotor Dynamics
- Limited Load Capacity
- High Bandwidth / Complex Control
- Accurate Displacement Sensing

Space Application: Satellite Attitude Control

- Reaction Wheels are Widely Used for Satellite Attitude Control
- Currently Ball Bearings are Used Despite Disadvantages

- Magnetic Bearings Allow for
  - Less Microvibrations
  - Higher Speed: Smaller Reaction Wheel Size

Source: nasa.gov
World Record Magnetic Bearing with 500’000 r/min

Demonstration of Active Magnetic Bearing Concept at World-Record Speed

Source: Baumgartner and Kolar, Multivariable State Feedback Control of a 500 000-r/min Self-Bearing Permanent-Magnet Motor, IEEE Transactions on Mechatronics 2015
Technology Trends for High Rotational Speeds

Emerging MEMS and Power MEMS Technology

Adapted from: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009
Example 1: MEMS Brushless-DC Micromotor

- **Main Application:** Watch Industry
- **Stator Manufactured in Clean Room** (CMOS technology)
- **310 nW at 300 r/min**
- **42% Efficiency (Open-Loop Drive)**

Source: Merzaghi et. al., Development of a Hybrid MEMS BLDC Micromotor, IEEE Transactions on Industry Applications 2011
Example 2: Microfabricated Axial-Flux Generator

- **Intended Application:** Portable Power Generation
- **Permanent Magnet Rotor**
- **Stator Manufactured in Clean Room** (CMOS technology)
- **2.5 W Power Conversion at 120,000 r/min**
- **43% Efficiency**

Technology Selection for Ultra-High-Speed Rotation

- Difficult Manufacturing of Inductive Components Using CMOS Processes
- Significantly Higher Energy Density with Magnetic Fields at Millimeter Scale
- Active Magnetic Bearings well Suited for Ultra-High-Speed Rotation

Strategic Research Project

40’000’000 rpm Spinning Ball Motor
Exploring the Limits of Ultra-High-Speed Rotation

- Demonstrator System for Highest Recorded Rotational Speed for Electric Machines
- Development of Underlying Technologies for Future Drive Systems
**History of Ultra-High-Speed Rotation**

- Highest Rotational Speeds of Such Systems Date Back 70 Years
- Recently Evolved MEMS and NEMS Limited to < 3 Mrpm
## Highest Rotational Speed of an Electric Motor

- **J. W. Beams and J. L. Young: 37.98 Mrpm, 1947**
  - R. Katano and S. Shimizu: 12.64 Mrpm, 1979
  - A. Boletis and H. Bleuler: 2.88 Mrpm, 2005

- **Not Reproduced or Exceeded Since, Despite Other Attempts**

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**Experimental Setup Used in 1947**

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**Fundamental Limit: Mechanical Rotor Stability**

- **Withstanding Ultra-High Centrifugal Loads**
  - Steels Have Highest Specific Strengths
  - Optimal Shape Depends on Material/Failure Criterion

  Mechanical Stress: \( \sigma_{\text{max}} = C_s \rho \omega_r^2 a^2 \)

- **Rotor Diameter < 1mm Required**

- **Dynamic Rotational Stability**
  - Rotation is Only Stable Around the Axis with the Largest Moment of Inertia

- **Suitable Material Properties for Magnetic Suspension**
**Magnetic Suspension: Principle**

- **Levitation of the Rotor Without Mechanical Contact**

- **Stabilization of the Rotor in all DOF**
  - Insufficient Horizontal Damping Due to Low Friction

**Active Magnetic Damping**

- **Active Magnetic Suspension**
Windage Losses

- **Dependent on Nature of Gas Flow**
  - Determined by Ratio of Geometry Dimensions and Mean Free Path
  - **Different Modeling Procedures**

Reynolds Number

- laminar
- turbulent

Continuum Flow

- Slip Flow
- Free Molecular Flow

Operation Under Free Molecular Conditions Necessary to Achieve Ultra–High Rotational Speeds
Analytical Drive Model

- Solution Based on Magnetic Vector Potential
  - Conductive Sphere in Rotating Magnetic Field
    - Solid Rotor Induction Machine

\[
\begin{align*}
    f &= 100 \text{ kHz} \\
    f &= 1 \text{ MHz} \\
    f &= 10 \text{ MHz}
\end{align*}
\]

\[
\begin{align*}
    a &= 0.5 \text{ mm} \\
    B_0 &= 1.5 \text{ mT}
\end{align*}
\]

**Stator Design**

- **Drive Field Generation by Phase-Shifted Currents**
- **Air Coils**
  - Optimization for High Flux Density
    - Conical Design
- **Ferrite Core Designs**
  - Lower Losses at High Frequencies Than Conventional Materials
    - Manufacturing Constraints

- Ferrite Core Designs Yield Significantly Lower Losses
Position and Speed Sensors

- Rotor Shadow Projected on 2D Position Sensitive Device
  - Distance >> Rotor Size
  - Optical Effects of Glass Vacuum Tube

- Modulation of Light Reflected from the Rotor
  - Rotor is Marked Prior to an Experiment
  - High Bandwidth Optical Receiver Circuit
  - Real-Time Signal Analysis Using FFT
Digital Control

- Controllers & Filters Implemented on FPGA (VHDL)
  - Cascaded PID Control Structure for Axial Suspension
  - Active Radial Damping
  - Superposition of Drive and Radial Bearing Currents
  - PC Interface via DSP
Power Amplifiers

- **H Bridge Switching Amplifiers**
  - Nonlinearities due to Dead Time
  - Compensated Digitally
  - Switching Frequency up to 1.5 MHz
  - Current Sensing via Shunts for Axial Suspension

![Diagram of H Bridge Switching Amplifiers]

▲ Fundamental Frequency Modulation of the Drive Currents
Experimental Setup

- Integrated Two-Stage Vacuum System
  - ISO KF DN 40 Vacuum Tubes
  - Final Pressure ~ \(10^{-4}\) Pa
- Adjustable Centering Core Height and Motor Platform
- Individual Horizontal Adjustment of Components
- Vibration Decoupling
Magnetic Suspension Performance

- Prototype Hardware Realization:

Axial Suspension Coil
Centering Core
Rotor
Drive and Radial Bearing Coil

LED
Position Sensor

Radial Damping Increased by Factor >100

\[ x(t) = x_0 e^{-at} \]

Time t (s)

0 1 2 3

0 0.5 1 1.5

-1.5 -1 -0.5 0 0.5 1 1.5

Rotor position x (mm)

0 20 40 60 80 100

0 0.5 1 1.5

0 0.5 1 1.5

Time t (s)
Torque Characteristics and Rotor Temperature

- Experimental Results in Good Agreement with Models
  - Higher Deviations at Low Slip Frequencies due to low Absolute Torque Level
  - Rotor Temperature Approaches Ambient Temperature at High Speeds
  - Main Energy Transfer by Radiation
Achieved Rotational Speeds

- Highest Rotational Speed Achieved with an Electrically-Driven Rotor to Date
  - Circumferential Speed 1047 m/s
  - Centrifugal Acceleration $4.5 \times 10^8 \ g$
### Failure Analysis

- **Rotor Explosion**
  - Recorded at 100,000 fps
  - Spatial Resolution 23 μm
  - No Detectable Deformation

- **Microscopic Analysis**
  - 3D Imaging Using Laser Confocal Microscope
  - Brittle Failure without Apparent Voids/Defects
Project Outcomes

- Technologies for Micro Magnetic Beatings
- Stator Designs for Megahertz Magnetic Drive Fields
- Insights for Future Ultra-High Speed Drive Systems

Highest Rotational Speed Achieved with an Electrically-Driven Rotor to Date: 40’260’000 rpm
- Reproduced and Exceeded World Record from 1947
- Statistically Significant Number of Bursting Experiments
High Complexity of Active Levitation

- **Active Magnetic Levitation**
  - Sensing Difficult for Small Rotors
  - High Bandwidth / Complex Control

- **Passive Magnetic Levitation**
  - High Eddy Current Losses

- **Passive Acoustic Levitation**
  - Particle < Wavelength
  - Acoustic Pressure Field
  - Ultrasound Transducers
  - Passively Stable
  - Low Losses
  - Low Load Capacity

Source: https://www.instructables.com/id/Acoustic-Tractor-Beam/
Strategic Research Project

Acoustic Levitation
Transducer Arrangements and Modelling

- Individual Excitation of Many Transducers
  - Manipulation of all Degrees of Freedom Possible
  - Achievable Force/Torque Dependent on Transducer Arrangement

\[ p = \sum_{j=1}^{N} p_j \]

\[ p_j = e^{i\phi} M_j \]

\[ M_j = P_0 J_0(kr \sin \theta) \frac{1}{d} e^{ikd} \]

Rotational Speed \( \leq 210 \text{ r/min} \)

Source: Marzo et. al., Holographic acoustic elements for manipulation of levitated objects, Nature Communications 2015
Types of Acoustic Traps

- **Twin Trap**
  - Provides sufficient load capacity and radial stiffness
  - Spatial rotation of trap

Source: Marzo et. al., Holographic acoustic elements for manipulation of levitated objects, Nature Communications 2015

Vortex Trap

Bottle Trap

Pressure in $xz$-plane

Pressure in $xy$-plane
Levitation Height and Particle Shape

- Balance of Acoustic and Gravitational Force
  - Negative Force Gradient Required for Stability
  - Multiple Stable Levitation Points

- Rotor Shape Limited by Manufacturing Constraints
  - Soft Polystyrol Material
Design for High Rotational Speeds

- Rotational Speed Limited by Drag

- Transducer Arrangement
  - Short Distance to Levitated Particle
  - Low Reflections
    (difficult to assess analytically)
Transducer Properties and Excitation

Transducer Equivalent Circuit
- Reactive Power
- Resonance Frequency ≈ 40 kHz

- 24 Transducers Excited by Rectangular Wave
  - Full-Bridge Converter Topology
  - 64 V peak-peak, I ≤ 25 mA
  - FPGA-Based Switching Signal Generation
System Implementation

Twin Trap
- Approx. Constant Suspension Forces by Non-Linear Phase Shift
- Stability over Wide Speed Range
Achieved Rotational Speed

Highest Rotational Speed: 55’410 r/min
- Limited by Power Losses
- Audible Sub-Harmonics

- Increased Power in Sidebands
  - High Transducer Losses
  - Consideration of Transducer Properties Necessary for Higher Rotational Speeds

- Increased Acoustic Pressure at Rotor for Higher Rotational Speeds
  - Second Transducer Arrangement from Top
Conclusions
Summary

- Multi-Objective Design Approach Required for Power Converters and Electric Drives

- Ongoing Trend Towards High Power Density at High Rotational Speeds
  - Miniaturization of Electric Machines
  - Alternative Bearing Concepts
  - Integration of Power Electronics
  - System-Level Optimization

- Rotational Speeds of Several Million r/min Possible
  - High System Complexity/Control Effort
  - Future Micro Magnetic Bearings & Ultra-High-Speed Drive Systems

- Passive Levitation and Manipulation of Particles Possible Using Ultrasound
  - Various Materials/High Flexibility
  - Applications in Medical Systems, Small Robots, Material Handling, etc.

«Innovation Potential Only Limited by Laws of Physics & Imagination»
Thank You!