Coupled Fluid-Thermal-Structural Modeling of Motorized Spindle to Reduce Thermal Distortion

Mallinath N. Kaulagi[1] Srinivas N. Grama[2]
Ashok N. Badhe[3] J. Sharana Basavaraja[4]

[1,4]B. M. S. College of Engineering, Bengaluru, KA, India
[2,3]Dr. Kalam center for innovation, Bharat Fritz Werner Ltd., Bengaluru, KA, India

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Outline

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Motorized spindle reduces transmission loss but compounds thermal effects

- Manufacturing industries - aiming at reducing production time and increasing productivity
- Conventional spindles (power transmission loss) are replaced by motorized spindle
- Thermal issues in motorized spindle because of built-in motor
- Needs external cooling to reduce thermal issues

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The problem statement is two fold: heat characterization and spindle coolant channel optimization

The aim of present work is to

- Estimate heat generation rate of motorized spindle in an experimental-numerical framework.
- Analyze the motorized spindle in coupled fluid-thermal-structural simulation framework and optimize the coolant flow channel for minimizing the thermal distortion

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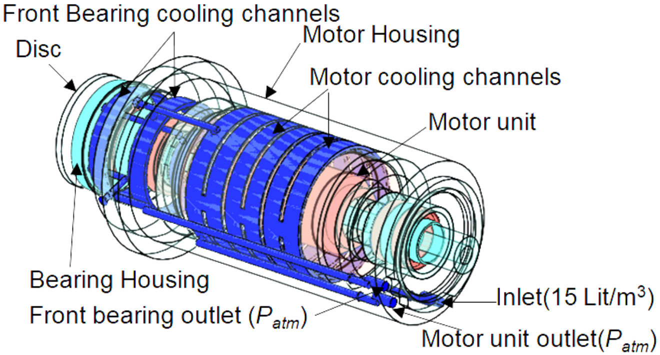
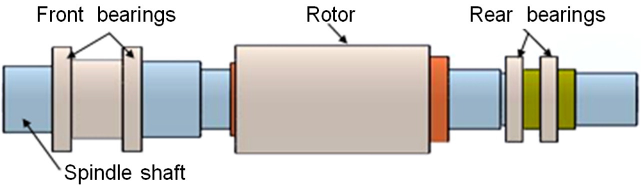
External forced Coolant flow channel is used to reduce the temperature of spindle

Navier-stokes equation is used for fluid model



Forced air convection heat transfer coefficient(h_1) based on empirical relation [4]



$$\boxed{\text{Rotation(rpm)} \longrightarrow \text{Re(laminar or turbulent)} \longrightarrow \text{Nu} \longrightarrow Nu = \frac{h_1 \times L}{k}}$$

Free air convection h_2=10 W/m^2K

[4] G.G. Raghavendra, M.Tech.Thesis, VTU (2017)

Thermal contact conductance (TCC) coefficient at contact interface based on empirical relation

The TCC at contact interface is given by [4]

$$R = \frac{\delta_{race}}{k_{race}} + \frac{\delta_{gap} - (T_{race} - T_h) \times \gamma \times r_h}{k_{air}}$$

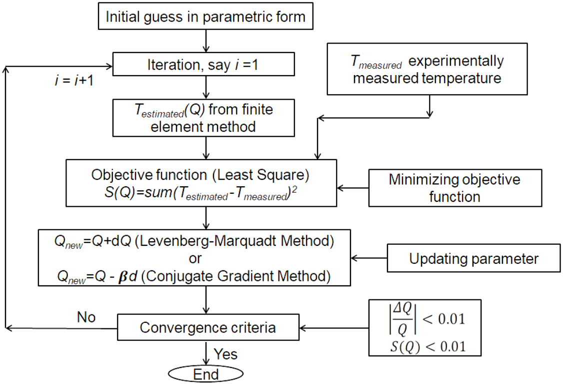
$$C = \frac{1}{R}$$

TCC between outer race of bearing and housing

TCC between inner race of bearing and shaft

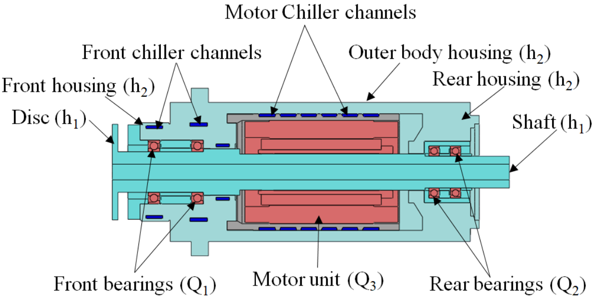
[4] G.G. Raghavendra, M.Tech.Thesis, VTU (2017)

Iterative technique involved in Inverse Methodology [3]



[3] Ozisik, Inverse heat transfer, CRC Press (2000)

Inverse Algorithm Validation for Spindle problem



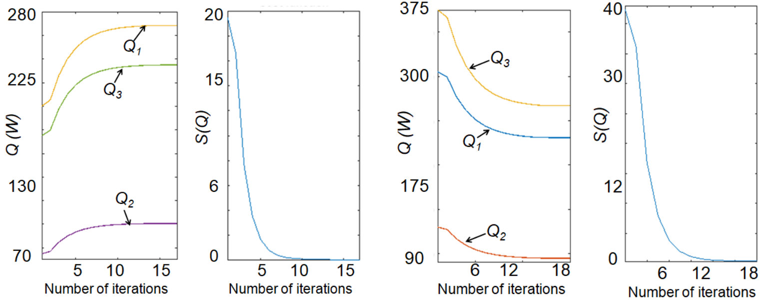
Knowing sensor point temperature(T_i) and initial guess value (Q_i) Inverse Methodology is used to estimate Heat sources

T_1, T_2 are outer race temperature of front & rear bearing, T_3 is motor surface temperature

Solution converges to true value

Levenberg Marquadt Method:Irrespective of initial guess value, solution is converging towards true value with maximum error of 7.64%

True heat sources $Q_1 = 250\,W$ $Q_2 = 100\,W$ $Q_3 = 250\,W$



Lower initial guess value Higher initial guess value

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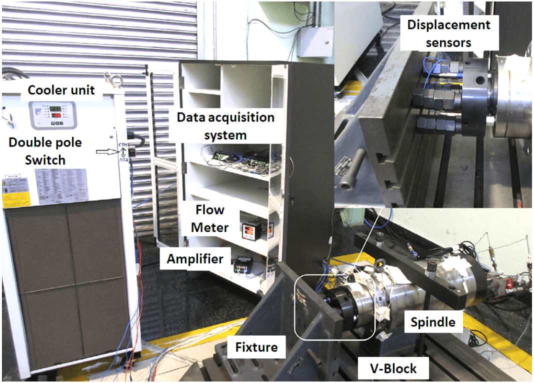
Actual experimental setup [2]



[2] Grama et al, IJMTM, 132, 3–16 (2018)

Heat generation rate from spindle unit are estimated under steady state condition

Based on experimental temperature heat sources are estimated

4,500 rpm	15,000 rpm
Q_1 = 111.28 W	Q_1 = 238.44 W
Q_2 = 37.1 W	Q_2 = 125.96 W
Q_3 = 66.76 W	Q_3 = 132.69 W

Higher heat generation is observed for higher spindle speed.

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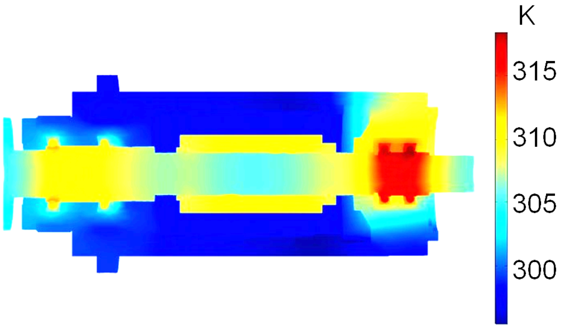
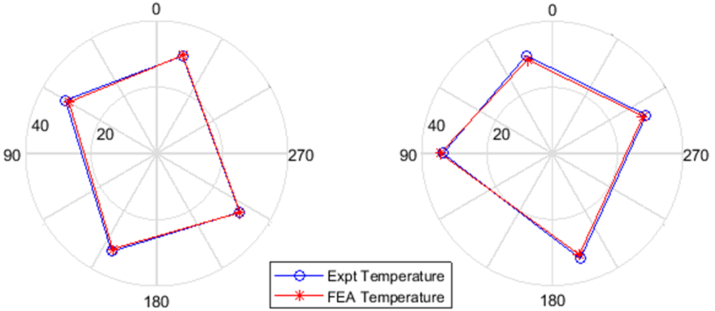
Higher temperature is observed near rear bearing as it is not cooled

Temperature distribution of motorized spindle at 15,000 rpm



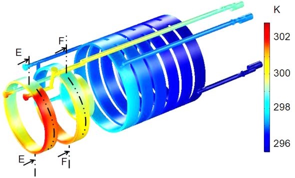
Coupled fluid-thermal analysis of spindle is validated from experimental temperatures measured near front bearing

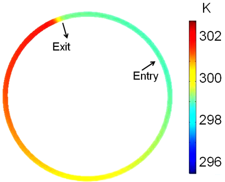


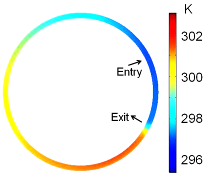
Non uniform temperature distribution observed in current fluid channel at front bearing region

Spindle and coolant channel analysed using COMSOL multi-physics

Maximum temperature variation across sections E-E and F-F for current spindle design is 2.98°C & 4.26°C



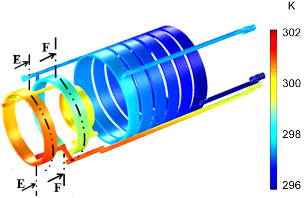


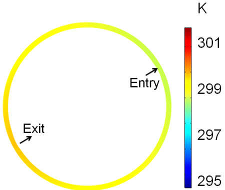


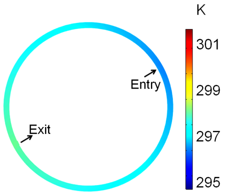
Optimization of coolant channel leads to almost uniform temperature distribution near front bearings

The coolant entry and exit angles near the front bearings are made diametrically opposite

Maximum temperature variation across sections E-E and F-F for optimized spindle is 0.87°C & 1.4°C

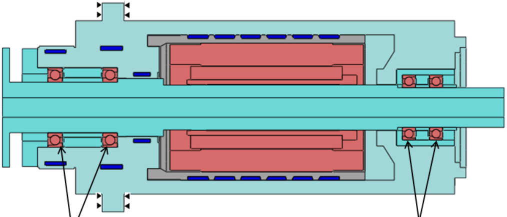






Boundary condition for structural analysis are provided through bearing stiffness and fixing collar of housing

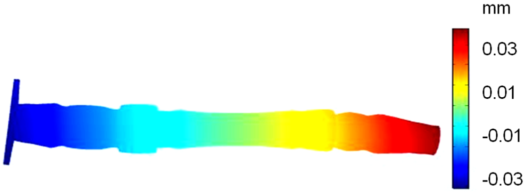
For current preload condition, radial stiffness is twice that of axial stiffness [1]



For front & rear bearings, K_a=146.7x10^6 & 121.6x10^6 N/m respectively, for 25° contact angle, $K_r = 2\times K_a$

[1] FAG manual, Schaeffler technologies (2010)

Optimized spindle shows reduced angular distortion through analysing coupled fluid-thermal-structural framework using COMSOL multi-physics



Distortion	Current spindle	Optimized spindle
Axial (μm)	26.49	25.44
Angular (μrad)	12.8	3.23

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Summary

- Heat generation characterization using Levenberg-Marquardt method.
- Non-uniform temperature distribution near front bearings has been reduced from 2.5°C to around 1°C by coolant channel optimization.
- Spindle angular deformation is reduced from 12.8 to 3.23μrad in the optimized design.

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Acknowledgements:

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Thank you for your attention

Outline

Iterative Steps involved in LMM

- Direct heat transfer:-analyse the model with initial guess value Q^T = $[Q_1, Q_2, Q_3]$ are vector of unknown parameter
- Objective function, $S(Q) = \sum_{i=1}^{M} [T_{estimated} - T_{experimental}]^2$
- Sensitivity matrix, $J(Q) = \left[\frac{\partial T^T(Q)}{\partial Q}\right]$
- The ΔQ for Levenberg-Marquadt method is calculated by

  $$[(J^k)^T \times J^k + \mu^k \times \Omega^k] \times \Delta Q^k = (J^k)^T \times [T_{experimental} - T_{estimated}(Q^k)]$$

  where k represent iteration. μ^k=damping parameter, ρ^k=diagonal matrix
- New value of parameter, Q^{k+1}=Q^k + Δ Q^k

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Boundary conditions

Fourier law of heat conduction is used for solid heat transfer problem

- The three dimensional governing equation for steady state heat transfer

$$\frac{\partial}{\partial x}\left[\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[\frac{\partial T}{\partial z}\right]+\frac{Q_1}{k}+\frac{Q_2}{k}+\frac{Q_3}{k}=0$$

  Q_1, Q_2, Q_3 are heat generation at front bearing, rear bearing and motor respectively.

- heat transfer at contact interference (Q_c)

$$Q_c = C \times (A \times \Delta T)$$

  C = Thermal contact conductance, A = Contact area, ΔT = Temperature drop at the contact interface

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- Convection heat transfer (Q_{out}) equation is

$$Q_{out} = h \times (T(x, y, z) - T_{\infty})$$

Q_{out} = Heat dissipation due to convection,
h = Convective heat transfer coefficient,
$T(x, y, z)$=Temperature of spindle,
T_{∞} = Surrounding temperature

- Radiation heat dissipation is neglected in the analysis

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