Special Interest Group Meeting on Thermal Issues
Laboratory for Machine Tools and Production Engineering (WZL) of
RWTH Aachen, Germany, February 2020
www.euspen.eu

A rapid thermal characteristic modelling approach of machines tool spindles based on bond-graph method

Yun Yang [1] Feng Xiaobing[1] Du Zhengchun[1]✉ Yang Jianguo [1]

[1]School of Mechanical Engineering, Shanghai Jiao Tong University, No.800, Dongchuan Road, Shanghai 200240, China

✉ zcdu@sjtu.edu.cn

Abstract
The thermal issue of spindles obviously has a great influence on the quality of machined work-piece. This paper focuses on a typical spindle in a vertical machine center and proposes a novel rapid thermal characteristic modelling approach without detailed mechanical structure information and precise parameter calculation. Firstly, the structure of this spindle is simplified and then divided into different detailed thermal components. According to thermal characteristic analysis, the network of thermal capacitances and thermal resistances is presented. Consequently, a thermal characteristic model describing the heat transfer in this spindle based on bond-graph method is established. The thermal properties in the spindle are briefly estimated, and further calibrated by experiment data. Finally, a verifying experiment is designed to testify the temperature variation in different rotation speed. The results show that the predicted thermal behaviour matches the experiment very well, which indicates the practice of the bond-graph based thermal characteristic model of spindle.

Bond-graph method; Lumped mass method; Thermal characteristic model; Spindle of Machine tool;

1. Introduction

Thermal issue of spindles have been a vital issue of machine tools [1]. Most approaches are based on heat transfer theory, including the thermal capacitances and thermal resistances network [2, 3] and the Finite Element Analysis methods [4, 5]. However, these theory based approaches require detailed structure information and thermal properties [6, 7]. Other measured data based approaches need large amounts of measured data with time consuming experiments [8].

The bond-graph method[9] is convenient and effective in analyzing the transfer of energy, including heat transfer. In the analysis of thermodynamics, the original bond-graph method has been reduced as the pseudo-bond-graph method[10], with the transfer of heat flow instead of entropy flow. Kim [11] firstly used pseudo-bond-graph method t in prediction of the thermo-elastic behavior of a spindle–bearing system.

This paper focus on proposing a reduced modelling approach in prediction of thermal behaviors of spindles with simplified structure information and briefly estimated thermal properties.

Chapter 2 shows the thermal characteristic analysis of a typical spindle system. Chapter 3 shows the thermal modelling process. In chapter 4, a calibration experiment and a verifying experiment are conducted.

2. Thermal characteristic analysis

Thermal characteristics is determined by the mechanism structure. Figure 1 shows the structure of the spindle in V850 vertical machine centers produced by SMTCL. The locknuts and the spacers rotate with the shaft. The flanges, the end cap and the housing are stationary parts.

As Figure 2 shows, the structure model is simplified based on lumped mass method. Bearings in two groups are parallel connected. The rotating parts are simplified as a shaft and then divided into 5 components. Similarly, the stationary parts are simplified as a housing and then divided into 3 components.

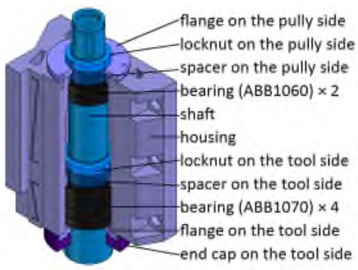

Figure 1. Structure of the spindle

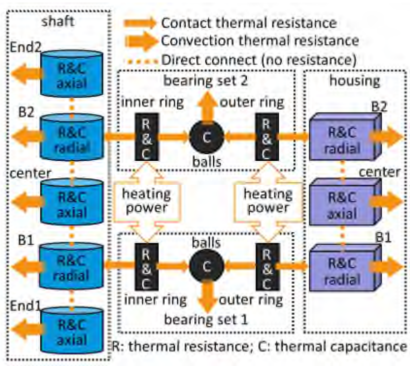

Figure 2. Thermal capacitances and resistances network of spindle

3 Reduced thermal modelling

3.1 Bond-graph model

The bond-graph model of thermal characteristics in the spindle, as Figure 3 shows, can be obtained according to the above thermal characteristic analysis and the modelling rules of bond-graph method.

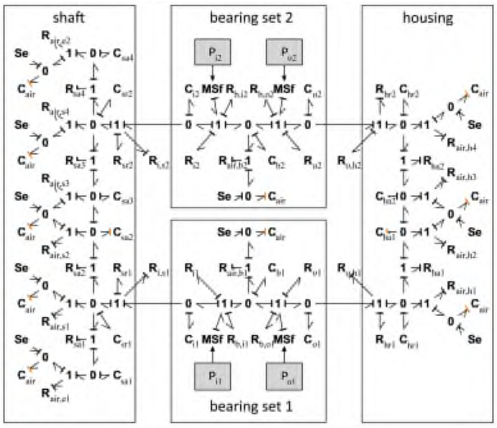

Figure 3. the bond-graph model

3.2 Estimation of properties

Heating power of bearings can be confirmed based on an empirical formula. **Thermal capacitance and thermal resistance** of each component can be estimated according to the shape, mass and material [12]. **Convective thermal resistance** of natural heat convection of the housing and the forced heat convection of the shaft are estimated based on the analogy of a long straight plate [13]. **Contact thermal resistance** are estimated based on experience.

4 Experiments

Due to the estimation in properties' confirmation, the thermal model needs to be calibrate. A verification experiment is also conducted to make sure correctness of prediction. In experiments, the thermal sensor was placed at the flange on pulley side. In comparison, the temperature of "housing B2" was simulated, as Figure 4 shows.

In calibration experiment, the spindle rotated at 4000 r/min for 10000s. The convective resistance and the thermal capacitance of housing components were adjusted to ensure the simulated data matching with the measured data, as shown in Figure 5.

Figure 6 shows the verification experiment. In the verification experiment, the spindle rotated at 4000 r/min for 6000s, and stopped for 4000s, then rotated at 6000 r/min for 4000s, and finally stopped and cooled naturally. The predicted temperature is mostly consistent with the experiment data. However, the simulated cooling speed is a little faster, probably because of the thermal resistances of bearing balls can no longer be ignored, when the spindle stopped.

6 Conclusion

In this paper, a novel rapid thermal characteristic modelling method of spindles based on bond-graph method is presented. The structure of a typical spindle system is simplified and then divided into different components with lumped mass. The bond-graph method based thermal model is established according to the thermal mechanism. Thermal properties are estimated and then calibrated. The verification shows that the prediction of thermal behaviors matches the measured values well.

Acknowledgement

This work was supported by National Key R&D Program of China (2018TFB1701204), and the National Natural Science Foundation of China (51975372 & 51705262).

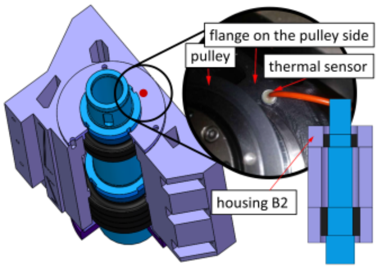

Figure 4. Settings of experiments and simulation

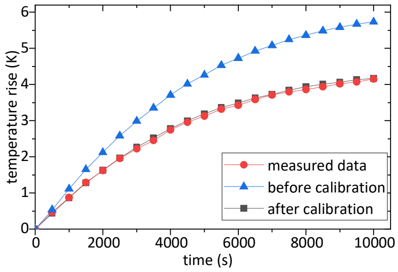

Figure 5. Measured and simulated data before/after calibration

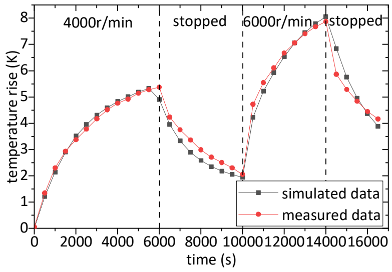

Figure 6. Measured and simulated data in verification of model

References

[1] Li Y, Zhao W H, Lan S H, Ni J, Wu W W and Lu B H 2015 *J. Int. J. Mach. Tools Manuf.* **95** 20-38

[2] Bossmanns B and Tu J F 1999 *J. Int. J. Mach. Tools Manuf.* **39** 1345-66

[3] Liu Z F, Pan M H, Zhang A P, Zhao Y S, Yang Y and Ma C Y 2015 *J. Int. J. Adv. Manuf. Technol.* **76** 1913-26

[4] Choi J K and Lee D G 1998 *J. Int. J. Mach. Tools Manuf.* **38** 1017-30

[5] Chen D J, Bonis M, Zhang F H and Dong S 2011 *J. Precis. Eng.-J. Int. Soc. Precis. Eng. Nanotechnol.* **35** 512-20

[6] Li Y, Zhao W H, Wu W W and Lu B H 2017 *J. Int. J. Adv. Manuf. Technol.* **90** 2803-12

[7] Zivkovic A M, Zeljkovic M V, Mladjenovic C D, Tabakovic S N, Milojevic Z L and Hadzistevic M J 2019 *J. Thermal Science* **23** 2117-30

[8] Liu K, Sun M J, Zhu T J, Wu Y L and Liu Y 2016 *J. Int. J. Mach. Tools Manuf.* **105** 58-67

[9] Gawthrop P J and Bevan G P 2007 *J. IEEE Control Syst. Mag.* **27** 24-5

[10] Bouamama B O, Medjaher K, Samantaray A K and Staroswiecki M 2006 *J. Control Engineering Practice* **14** 71-83

[11] Kim S M and Lee S K 2001 *J. Int. J. Mach. Tools Manuf.* **41** 809-31

[12] Incropera F P, Lavine A S, Bergman T L and DeWitt D P 2007 *Fundamentals of heat and mass transfer* (Hoboken: Wiley)

[13] Tan F, Yin Q, Dong G H, Xie L F and Yin G F 2017 *J. Int. J. Adv. Manuf. Technol.* **91** 2549-60