euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Evaluation of an Invar shaft for a high speed spindle

Byron Knapp, Dave Arneson, Dan Oss

Professional Instruments Company, Hopkins, Minnesota, USA

Email: bknapp@airbearings.com

Abstract
Diamond micro-machining processes are used to manufacture optics with sub-micrometer form error. These processes typically require high speed spindles with nanometer-level error motions and thermal stability during cuts that can take several weeks. The increasing demands for accuracy led to the evaluation of a low expansion material (Super Invar) for a new the spindle rotor. Critical material property ratios are used to assess the impact on performance. A finite element model of the rotor and air bearings is created and validated using experimental modal analysis results. The refined model is used to predict the spindle dynamics based on rotor material selection.

Keywords: Thermal spindle growth, spindle dynamics, modal analysis, finite element model updating

1. Introduction

The selection of materials for precision systems should include consideration of the properties that dictate static and dynamic behavior. These properties can be conveniently compared using a few material property ratios [1]. For high speed spindles, the stiffness and thermal properties are critical. In this work, the relevant static and dynamic property ratios are used to compare a 420 stainless steel shaft to a Super Invar shaft of a high speed spindle. The effect on performance is predicted using property ratios. A finite element model of the rotor and air bearings is used to confirm the predicted effect on spindle dynamics.

2. Material property ratios

There are two common precision design approaches to handling disturbance effects—minimum response (compensation) and minimum disturbance (elimination) [1]. This evaluation considers only the properties which govern the response of the spindle while force and thermal inputs are considered constant between the two design alternatives. Therefore, static stiffness, dynamic stiffness, static thermal response and transient thermal response are considered.

2.1. Static stiffness (specific stiffness)

One of the most familiar material property ratios is the specific stiffness, or stiffness to weight ratio, shown in Equation (1),

$$K_{static} = {}^{E}/_{\rho} \tag{1}$$

where K_{static} is the specific stiffness, E is the Young's modulus, and ρ is the density. For a given geometry, minimize elastic deflections such as self-weight loading by choosing large K_{static}.

2.2. Dynamic stiffness

Systems that experience vibration disturbances should also consider the wave speed in Equation (2),

$$K_{dynamic} = \sqrt{{}^{E}/_{\rho}} \tag{2}$$

where $K_{dynamic}$ is the wave speed, E is the Young's modulus, and ρ is the density. If the geometry is fixed, as is the case for the high speed spindle, choosing a material with a higher $K_{dynamic}$ will lead to a higher first natural frequency and, in general, less dynamic deflection. Although $K_{dynamic}$ is not independent of the specific stiffness, it is included in this comparison because the square root diminishes the benefits as will be shown later.

2.3. Static thermal distortion

Thermally sensitive designs often only consider the coefficient of thermal expansion. In cases where a constant heat flow is disturbing the system, the important material properties are minimum dimensional change under steady energy load [1]. This results in a property ratio of the coefficient of expansion and the thermal conductivity shown in Equation (3),

$$D_{static} = {}^{\alpha}/_{\lambda} \tag{3}$$

where D_{static} is the static thermal distortion, λ is the thermal conductivity, and α is the thermal coefficient of expansion. A lower value of D_{static} for a given geometry and heat source leads to less dimensional change.

2.4. Dynamic thermal distortion

The required time for a material to dimensionally stabilize following a thermal disturbance is a ratio of the coefficient of thermal expansion and thermal diffusivity [1]. The property ratio is shown in Equation (4),

$$D_{dynamic} = {}^{\rho C_p \alpha}/_{\lambda} \tag{4}$$

where $D_{dynamic}$ is the dynamic thermal distortion, ρ is the density, and C_p is the specific heat capacity, α is the coefficient of thermal expansion, and λ is the thermal conductivity. A lower value of $D_{dynamic}$ will result in lower thermal distortion for dynamic heat loads on the system.

3. Material comparisons

The spindle shaft for material evaluation is shown in Figure 1. Axial and radial air films of the spindle are 7 µm providing high stiffness but creating heat due to shearing (250 W at 50,000 RPM). In addition, the core losses of the brushless servo motor are approximately 50 W at 50,000 RPM. The spindle housing is aluminum to prevent thermal runaway and is temperature-controlled using integrated water-cooling around the bearings and motor.

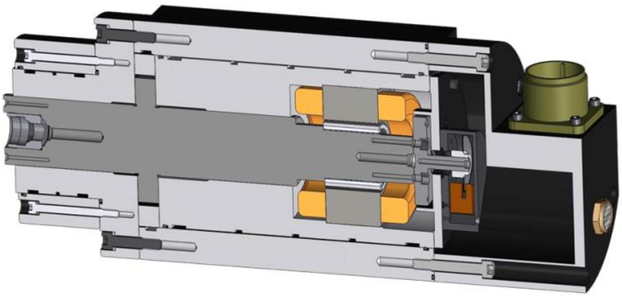

Figure 1. Cross-section of the high speed air bearing spindle.

Comparisons of 420 stainless steel and Super Invar are shown in Tables 1 and 2. Although their densities are similar, the lower Young's modulus of Super Invar results in a K_{static} that is 30 % lower than 420 stainless steel. The impact is not as severe with respect to $K_{dynamic}$ due to the square root, but it is still 17 % lower for Super Invar. Both stiffness indices lead to selection of 420 stainless steel over Super Invar. However, both thermal distortion ratios are many times larger for 420 stainless steel than for Super Invar. This result is expected, as the primary advantage of Super Invar is its low thermal expansion. Notwithstanding, the negative impact on stiffness is problematic.

Table 1 Comparison stiffness ratios of candidate shaft materials. Higher values are better.

Material	K_{static} $10^6 m^2 s^{-2}$	$K_{dynamic}$ $10^3 ms^{-1}$
420 SS	25.6	50.6
Super Invar	17.8	42.2
Al 6061-T6	25.5	50.5

Table 2 Comparison thermal ratios of candidate shaft materials. Lower values are better.

Material	D_{static} $10^{-6} Wm^{-1}$	$D_{dynamic}$ $sm^{-2} {}^\circ C^{-1}$
420 SS	0.41	1.48
Super Invar	0.06	0.26
Al 6061-T6	0.14	0.34

4. Model updating using experimental results

A finite element model of the shaft and air bearings is created to predict the first two natural frequencies. Stiffness of the air films is modeled using elastic support. Radial and axial frequency response functions of the spindle assembly are shown in Figure 2. Tilt and axial modes are extracted from the experimental data and shown in Table 3. The stiffness matrices of the shaft and bearing models are updated using these experimental test results. $K_{dynamic}$ indicated a decrease of 17 % in the first mode and the FEA predicts a 13 % reduction demonstrating the usefulness of this approach.

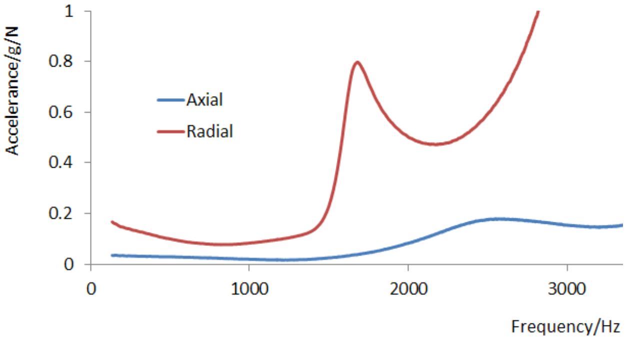

Figure 2. Frequency response function of the spindle with steel shaft.

Table 3 Summary of model updating and Super Invar shaft prediction.

Spindle Mode /Hz	Steel shaft experimental	Steel shaft FEA	Super Invar shaft FEA
Mode 1: Tilt	1680	1680	1490
Mode 2: Axial	2580	2580	2480

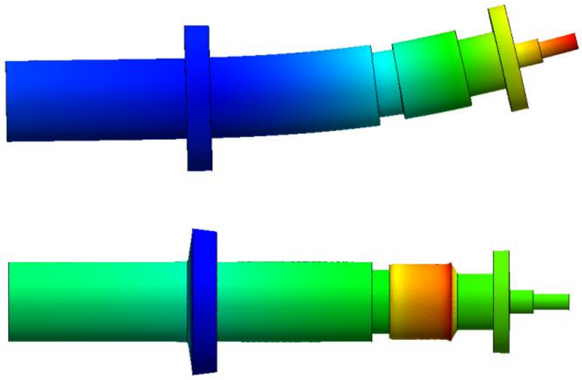

Figure 3. FEA results showing first two mode shapes.

5. Conclusion

Material selection for a shaft of a high speed air bearing spindle used for micro-machining processes is evaluated. Material property ratios indicating static and dynamic behavior are considered. Compared to a 420 stainless steel shaft, the first natural frequency of a Super Invar shaft is predicted to have a 17 % reduction. The thermal behavior is estimated to improve by a factor of 6-7 times. A finite element model of the rotor and air bearings is used to verify the material property ratio prediction.

References

[1] Chetwynd DG 1987 Selection of structural materials for precision devices. *Precision Engineering*. **9**(1): 3-6.