Interferometry for the Next Generation of Nanopositioning and Nanomeasuring Machines

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Abstract

Modern interferometry at high precision levels requires advanced techniques in order to be effective when utilized for nanopositioning and nanomeasuring machines. The state of the environment in which the devices are situated has a significant and direct influence on the achievable measurement results. This means that a reduction in measurement uncertainty requires careful control of that environment, which for example includes the possibility of using the machine in a vacuum. This article discusses the various design challenges with respect to heat transfer and other design aspects suitable for a vacuum environment.

1 Introduction

Improvements in the measurement uncertainty of interferometers are continuously being investigated in order to meet the needs for the next generation of ultra-precision nanopositioning and nanomeasuring machines (NPMMs). A large number of precision measuring machines currently exist with nanometer capability, including the Molecular Measuring Machine [1], the Sub-Atomic Measuring Machine [2], the Isara 400 [3], the Nano-CMM [4] and the 3D-CMM (F25-Zeiss) [5]. One such device, the Nanopositioning and Nanomeasuring Machine NMM-1 developed in Ilmenau, can achieve a resolution of 0.1 nm in a measurement range of 25 mm x 25 mm x 5 mm. Step-height measurements (2 mm nominal step height, ISO-5436) in a controlled air environment have been done which attained a measurement uncertainty of about 3 nm at k = 2 [6].

In a controlled, stationary air environment, correction of the index of refraction is limited to the order of 10^{-8} [7]. However, these corrections usually cannot account for additional changes induced by such factors as air fluctuations or turbulence. Efforts have been undertaken to reduce the uncertainty in ambient air by shielding or measuring the refractive index. Another possibility is using the NPMM in a helium atmosphere, which can improve the stability of the index of refraction by about one order of magnitude (to 10^{-9}) [8, 9]. However, these measures are no longer sufficient for NPMMs with greater measuring ranges in the hundreds of millimeters, if these devices are to achieve uncertainties on the order of 30 nm.

2 Challenges in a vacuum environment

Naturally, the primary method of further reducing the air's influence is to work in a vacuum environment. This article discusses some of the necessary measures to handle interferometry in a vacuum in order to achieve the ambitious level of resolution and uncertainty necessary for NPMMs with large measuring volumes. In a vacuum environment the refractive index becomes almost constant, therefore other factors play a major role.

When using interferometer in vacuum the overall constraints of the mechanical design must be adapted to these new conditions. The materials used should have low outgassing rates and the mechanical design should follow basic rules for vacuum setups to avoid virtual leaks or the like [10].

A particular aspect under examination includes temperature control, the importance of which increases because of the non-existent thermal convection, which results in a significant change in heat transfer. For this reason, electronics which are especially close to the metrological components of the interferometer are monitored, with a necessary tradeoff between good signal-to-noise ratio and low induced heating.

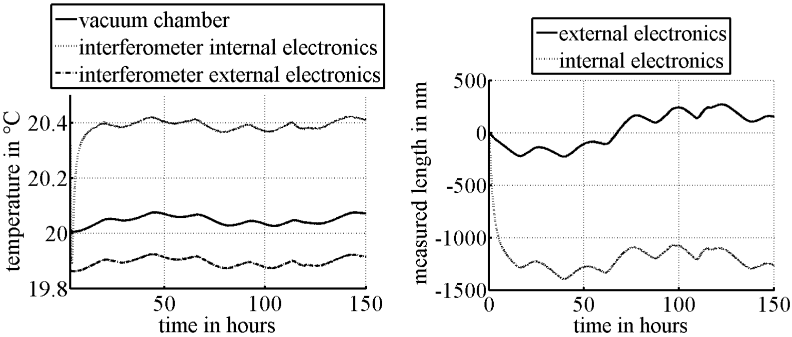

Figure 1: Comparison of two interferometers (using internal and external electronics, respectively)

Two interferometers were compared during our investigations, the results of which are shown in figure 1. The first interferometer setup uses internal electronics for signal amplification as is normally used in an ambient air environment. The second setup involved placing these electronics externally in order to reduce heat input into the optical interferometer components. Both setups were installed in a vacuum chamber, the pressure of which was 1.0 ± 0.3 mbar. The temperature was measured on the solid invar body of the reference beam. As was expected the internal electronics represented a significant heat source when the system was powered up. This change is visible as a rise in temperature of about 0.5 K and a change in the displayed length value as compared to the interferometer with external electronics. The measured temperatures und lengths exhibited a strong dependency, demonstrating that the simple introduction of heat into the reference beam body contributes significantly to measurement uncertainty.

3 Conclusion and outlook

For future interferometer designs the heat sources must be decoupled from metrologically important parts. The primary step is to assure a large clearance between the optical and electronic parts; secondarily the heat can be dissipated for example by solid body heat conduction, heat pipes or a tempering fluid. For solid body heat transfer the heat has to be guided by materials with low thermal resistance and shielded by some with high thermal resistance. These kinds of designs have rather large space requirements. Heat pipes need a temperature difference of at least a few kelvins to assure the phase transition of the internal media. The temperature difference in an interferometer should be kept much lower, so in most cases the use of a heat pipe is not possible. When the heat is dissipated using a fluid, the mechanical design can be a rather small one, but the design must be kept from introducing external vibrations into the interferometer from the moving fluid.

In summary working in a vacuum affects the movement of heat because of a lack of air convection, leaving radiation and convection as the only modes of heat transfer. The results confirm that the mechanical design must take this into account when the intended use is a vacuum environment.

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