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To cite this article: E. Bainbridge *et al* 2022 *J. Phys.: Conf. Ser.* **2380** 012070

In-built resonant structures for precision assembly of X-Ray Optics for 4th Generation Light Sources

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Abstract. As the Diamond Light Source embraces the move towards becoming a fourth generation light source it will require its optics to perform under increasingly demanding conditions. Foremost amongst these conditions will be the increasing powers they are subjected to and the reducing real estate they must perform in. With these new challenges comes the need for greater understanding of how optics are assembled and how consistently this activity is carried out. In this paper, the concept of using passive resonant structures as part of a precision assembly approach for such optics is introduced. Numerical simulation of a passive resonant device comprising tines which are compressed as clamping force is increased is presented, revealing a frequency shift from intermediately fastened to fully tightened. This approach has the potential to provide a robust, game changing improvement to the accuracy of assembly of X-ray optics and subsequently a significant improvement in their performance.

1. Introduction

Diamond is moving toward the Diamond-II upgrade, a coordinated programme of development that combines a major machine upgrade with new instruments and complementary improvements to optics. When assembling optical devices such as monochromators, it is essential that a reliable, repeatable approach is taken to achieve predictable performance during service on the beamline. Distortion of the optical surface of the crystal due to incorrect assembly or thermal strain can result in higher beam divergence and a reduced capacity to focus the beam [1]. To meet required tolerance in terms of monochromaticity and collimation of the diffracted beam, optical surfaces with sub-nanometre figure errors are typically required [2]. At present, optics are typically assembled using calibrated spring arrangements and torque wrenches to set preloads. Optics are clamped, measured, and re-clamped in a time-consuming iterative process to minimise distortion of the optical surface. Docker investigated different clamping regimes for the first crystals for the I20 monochromator experimentally, revealing a 20% inaccuracy associated with this conventional approach [3].Numerous studies have investigated the effect of heat load on distortion of the optical surface [4-7]. However, comparatively little research has been focused on the effect of clamping arrangements on distortion of the optical surfaces [8-10].

In this paper, the effect of the clamping of the first crystals for the I20 monochromator on the subsequent performance under conditions representative of beamline operation is investigated numerically.The potential for incorporation of passive resonant devices to allow enable greater precision in the assembly of X-ray optics is discussed.

2. Importance of clamping

Numerical simulations were used to determine the effect of clamping on the distortion of the optical surface of an indirectly cooled monochromator used on the I20 beamline at Diamond under environment conditions representative of operation on the beamline.

2.1. Finite element model development

A one-way coupled thermal-mechanical simulation of the first crystal for the I20 monochromator was developed in ANSYS. The assembly consists of a silicon crystal in a copper heat exchanger as shown in Figure 1 (a), with the beam propagating in the *x,z* plane.. Liquid nitrogen flows through internal channels in the side panels shown in Figure 1 (b). Indium foil is sandwiched between the silicon crystal and copper side panels on both sides to improve thermal contact, modelled here using surface bodies. The assembly is held together by two stainless steel bolts which are threaded through the center of the crystal, modelled as line bodies and used to apply clamping force in the form of bolt pretension. Cone structures at either end are used to provide a more uniformly distributed force across the contact faces.

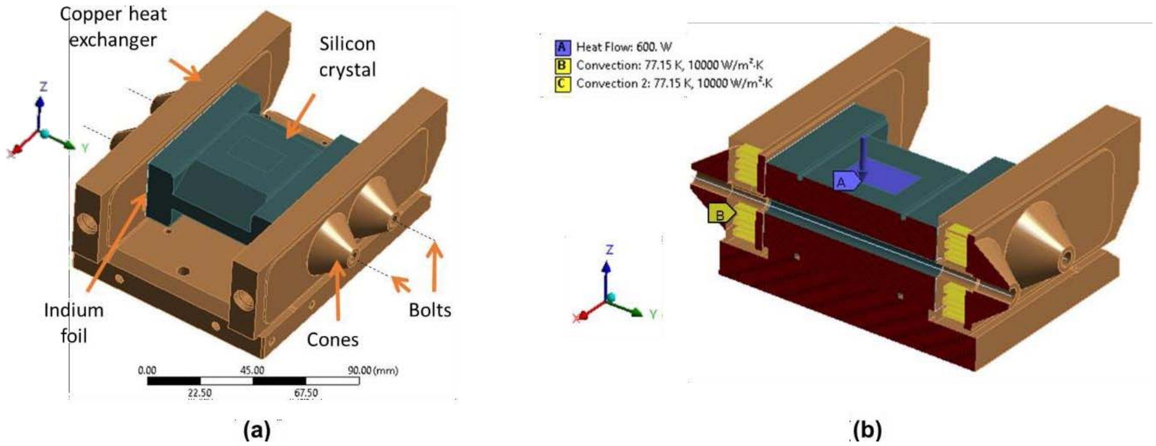

Figure 1. Schematic diagrams of (a) monochromator assembly and (b) section view of assembly showing thermal boundary conditions.

Temperature dependent values for the thermal expansion coefficient and thermal conductivity for copper and silicon over a range of 0 K to 300 K were taken from the NIST database and literature, with the temperature dependency of Young's modulus and Poisson's ratio for copper considered [11]. Built-in anisotropic stiffness coefficients for the Si(100) crystal plane in ANSYS were used.

Thermal and structural boundary conditions were chosen to effectively simulate: i) the assembly process and ii) subsequent conditions in the beamline during service. The base of the heat exchanger was fixed. A bolt pretension of 190 N was applied to each of the two line bodies representing the steel through bolts, with cylindrical supports applied to the inner cylindrical faces of the through holes. Frictionless contact formulation was specified at the silicon-copper-indium interfaces, as well as at interface the base of the crystal with the copper base plate.

For the thermal simulation, convective heat transfer was applied to all inner faces of the cooling channels in the copper heat exchanger, with a heat transfer coefficient of 10000 W/m^2 and an external temperature of 77.15 K. A heat flow of 600 W was applied to a 14.17 mm x 21.5mm area on the center of the optical surface, representative of a typical total power loading and projected beam footprint on the I20 beamline. The structural analysis consisted of two steps. In the first step, the bolt pretension was applied at the environment temperature of 295.15 K. The bolts were then locked and the imported temperature load from the thermal simulation was activated to simulate beamline conditions.

2.2. Effect on distortion of optical surface

The effect of clamping force on distortion of the optical surface during operation on the beamline was determined numerically. The imported temperature load from the thermal simulation along with the resulting distortion across the centerline of the optical surface of the crystal in the sagittal and meridional directions for a clamped and unclamped assembly are shown in Figure 2.

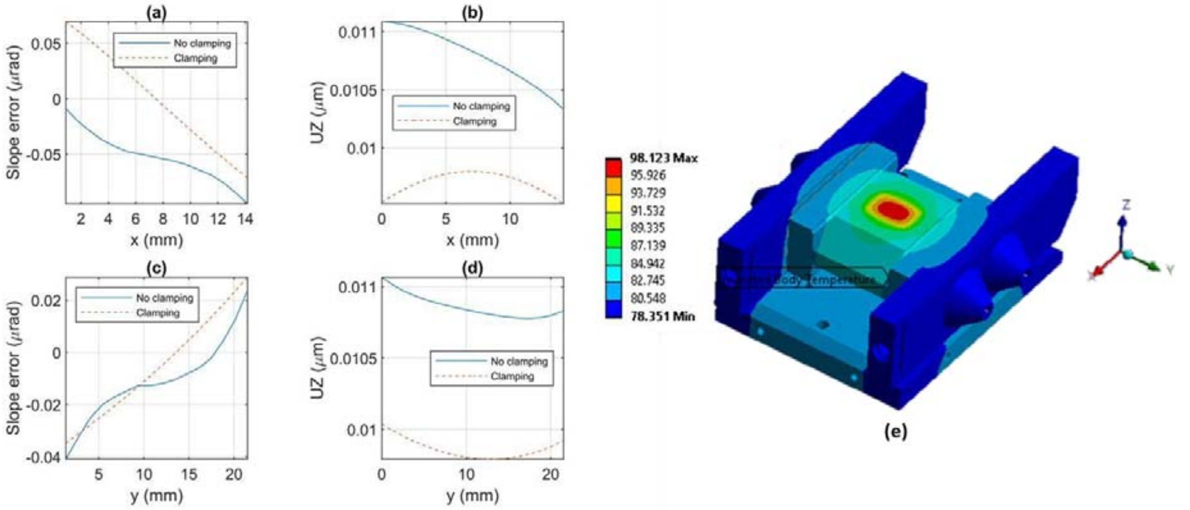

Figure 2. Distortion of the optical surface under thermal load with (a, c) slope errors in the meridional and sagittal directions, respectively, (b, d) vertical displacement UZ in the meridional and sagittal directions, respectively and (e) the temperature distribution in the assembly in Kelvin.

Figures 2 (b-d) reveal an increase in the thermal distortion of the optical surface in the absence of clamping forces for the imported temperature load shown in Figure 2 (e). This is reflected in the meridional and sagittal slope errors shown in Figures 2 (a-c), which were obtained by taking height profile derivatives in the meridional and sagittal directions.

3. Passive resonant structures

There is significant scope for the incorporation of high-sensitivity, passive resonant structures for non-destructive evaluation of clamping forces during assembly. Such devices should be i) compact enough to fit within the footprint of the existing mounts and ii) sufficiently sensitive to the applied clamping forces. One such device, incorporating simple slender members which are compressed with increasing clamping force is shown in Figure 3 (e). The tines are compressed as the bolts are tightened, inducing compressive stresses which shift their resonant frequency. The tines were designed to resonate in audible frequency range. The multiple components could be machined by wired electrical discharge machining to sufficient precision [12]. Options for excitation of the tines include impulse hammer or alternatives such as laser impulse or surface mounted piezoelectric transducer. Measurement could be done by acoustic sensor, laser vibrometer or surface mounted accelerometer.

The frequency shift for this device as the bolts are tightened under ambient laboratory conditions was predicted numerically using the structural simulation detailed in Section 2, incorporating the novel device. The applied bolt pretension was determined on the basis of ensuring comparable contact pressure between the crystal and heat exchanger with the simulation without the device and was found to be 185 N. A full, pre-stress harmonic response analysis was used to determine the frequency response under impulse, as shown in Figure 3 (a-d) for two load conditions: fully tightened (bolt pretension of 185 N) and intermediately fastened (bolt pretension of 92.5 N).

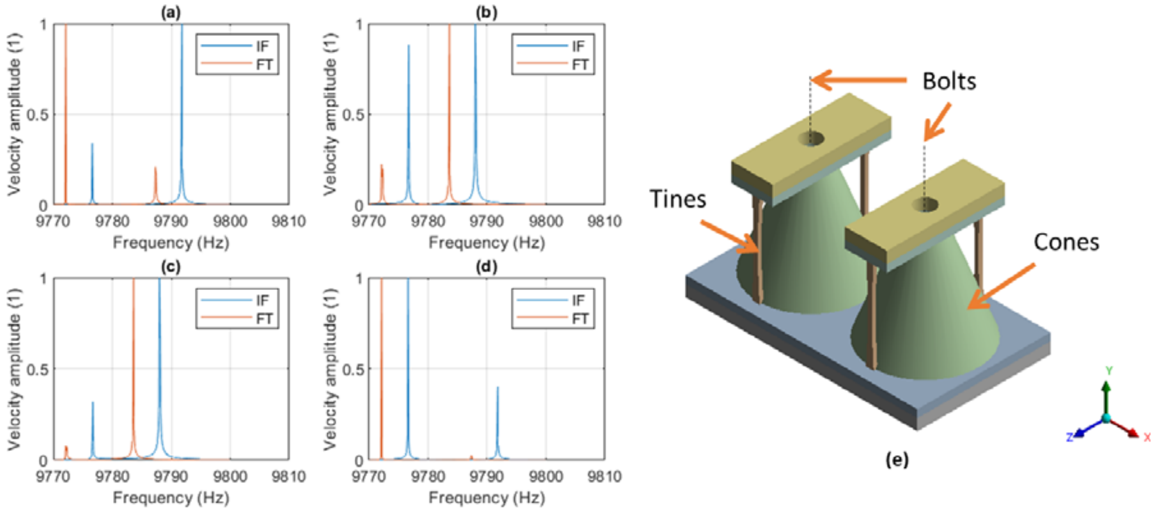

Figure 3. Frequency response of the passive resonant structure under load with (a-d) velocity amplitude response of each of the four tines in the structure when intermediately fastened (IF) and fully tightened (FT), and (e) a schematic diagram of the passive resonant device.

Figures 3(a-d) show that, as bolt pretension is increased, the tines are compressed, resulting in a frequency shift of approximately 4.5 Hz. This is consistent across all four tines in device. These peaks corresponded to simple out of plane bending modes for the tines

4. Conclusions

In this paper, the effect of the clamping on distortion of the optical surface of the first crystals for the I20 monochromator under conditions representative of beamline operation was investigated using numerical simulations. Clamping was shown to reduce the slope error across the centerline of the optical surface in the sagittal and meridional directions, minimizing the effect of thermal strain. The potential for incorporation of passive resonant devices to allow enable greater precision in the assembly of X-ray optics was demonstrated through numerical simulation of a passive resonant device incorporating simple slender members which are compressed with increasing clamping force. A frequency shift of approximately 4.5 Hz was predicted between intermediately fastened and fully tightened states of assembly of the monochromator, demonstrating the potential for use in precision assembly. Precision in assembly is essential to enabling optics to perform to greater accuracy with reduced tolerances. There is also the potential for monitoring during service, as the resonant devices will remain in place, providing information relating to any changes in assembly throughout the optics lifetime. Challenges include how to measure this frequency shift accurately and determining how best it can be used to aid precision assembly of such assemblies in real time.

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