DESIGN AND CERTIFICATION OF CFRP CHOPPER DISKS FOR THE NEAT II TOF SPECTROMETER: A LESSON LEARNED

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Abstract

Chopper disks are commonly used in neutron Time-of-Flight spectroscopy. They are disks with one or more cut-outs rotating around an axis parallel to the neutron beam, reaching operational speeds of up to 366.66 Hz, correlating with accelerations of up to 200 000 g at the edge of the disk. The NEAT II TOF spectrometer utilizes a set of seven carbon fiber-reinforced polymer (CFRP) chopper disks with an outer diameter of 700 mm and different window configurations with a maximum window depth of 135 mm. A relatively thick (1.5 mm) absorber coating is required, together with a maximal operational speed of 333.33 Hz. When the Institute of Lightweight Structures (LLB) of the Faculty of Mechanical Engineering at Technical University of Munich (TUM) was asked to design and produce the set of disks for the instrument, the major challenge seemed to be that of achieving the operational speed in accordance with the given requirements. In particular, the large area with the boron coating, adding a non-structural weight in a highly loaded area, appeared to be the most challenging design parameter. A common cross section that could sustain the load for all the different window configurations, was manufactured for all the disks. A hub was designed which fitted the system and fulfilled the given requirements. Due to recurring vibrations at a rotational speed of about 260 Hz during the certification test, it proved impossible to achieve the required rotational speed with the original configuration, although all parts of the system seemed to work properly and no initial failure had occurred. This paper presents all the steps that led to the improved design of the system, consisting of disk and hub, which allowed the certification for the desired operational speed.

1. Introduction

The NEAT chopper disk system is located at the neutron source Helmholtz Zentrum Berlin (BER II). The chopper disk system comprises seven disks, the first of which subdivides the neutron beam into discreet packets of neutrons. At the second chopper disk, neutrons in this discreet packet that have not the requested speed are obstructed [1–3]. The remaining disks are used for different filtering of the neutron beam. The rotational speed during operation is planned to be 333.33 Hz. The outer diameter of the disks is 700 mm. The cut-outs are relatively large, compared to other chopper disks. They have a maximum opening angle of 34° and a maximum depth of 135 mm. The combination of the very high rotational speed together with the large cut-outs lead to different structural and dynamical problems. A sketch of the NEAT chopper disk system with its seven disks is shown in figure 1. A general sketch of a chopper disk is shown in figure 2. The chopper disk is mounted in the central drilling on a hub, which is then connected to the shaft. The inner plateau is designed to attach the disk to the hub and the outer plateau to get a planar surface for the drilling of the balancing holes [4]. These holes are needed to add weight to the disk for static and dynamical balancing.

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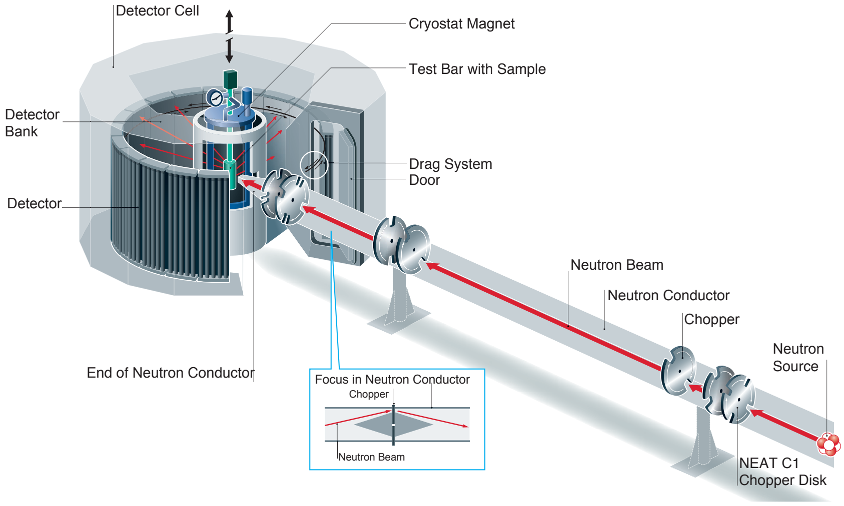

Figure 1. Schematic plan of the TOF spectrometer NEAT II [5].

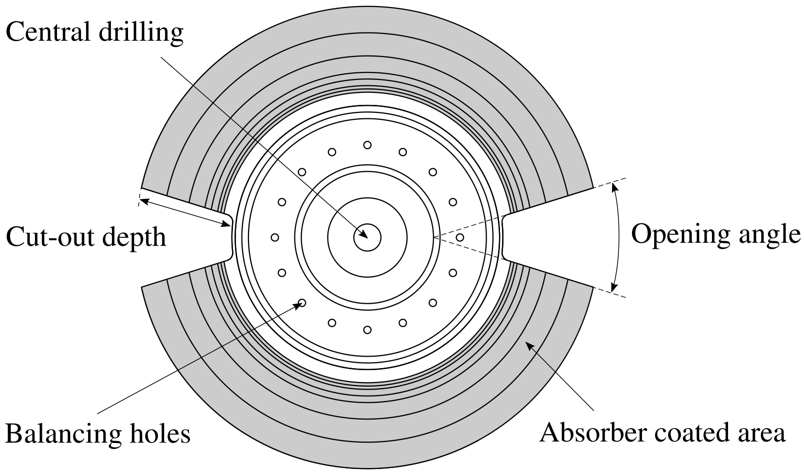

Figure 2. Optimized thickness distribution for lower radial displacement at the central drilling.

2. Analysis of the chopper disk system

The first prototype of the NEAT chopper disk has been designed mainly from the point of view of strength. The operational speed of 333.33 Hz leads to very high centrifugal forces. The acceleration at the edge of the disk is up to 200 000 times the gravity of earth [6–10]. The cross-section of the disk is designed as a constant stress disk profile [11, 12]. The area bearing the highest stress is the one around the corners of the cut-outs. Nevertheless, the stress peaks are below a failure index of 1. During a first spinning test, a strong vibration occurred at a rotational speed of 260 Hz. These vibrations were reproducible within a range of the rotational speed of 220 Hz to 265 Hz. The vibrations are measured at the shaft drive. The plot of the vibrations is shown in figure 3. The vibration scale is set between 0 and 1. 1 represents the maximum allowable deflection of the drive shaft of 0.2 mm in radial direction. Area I in figure 3 shows the pass of the second natural frequency of the shaft, area II shows a frequency range, where the vibrations are at a constant level of 30 % and area III shows the strong vibration. To avoid these vibrations and to reach the operational speed of 333.33 Hz, the disk and the hub were redesigned and optimized with regard to structural dynamics.

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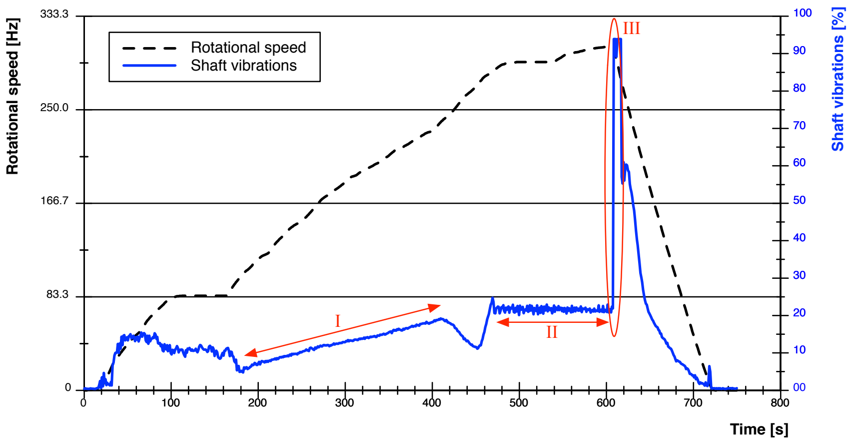

Figure 3. Spinning test of the first prototype [13].

3. Optimization of the chopper disk system

The vibration problem of the first prototype disk was assumed to be a pass through a natural frequency or a detachment of the disk from the hub. In order to counteract these problems, two finite element (FE) models were created. The first one is used for a numerical optimization of the cross-section of the disk. Goal of the optimization is a minimization of the widening of the disk and hence a detachment of the disk from the hub at a higher rotational speed. A typical radial displacement or widening is shown in figure 4. The widening of the central drilling at a rotational speed of 380 Hz is between 0.20 mm and 0.22 mm. At the outer edge of the disk the radial displacement rises to 1.4 mm.

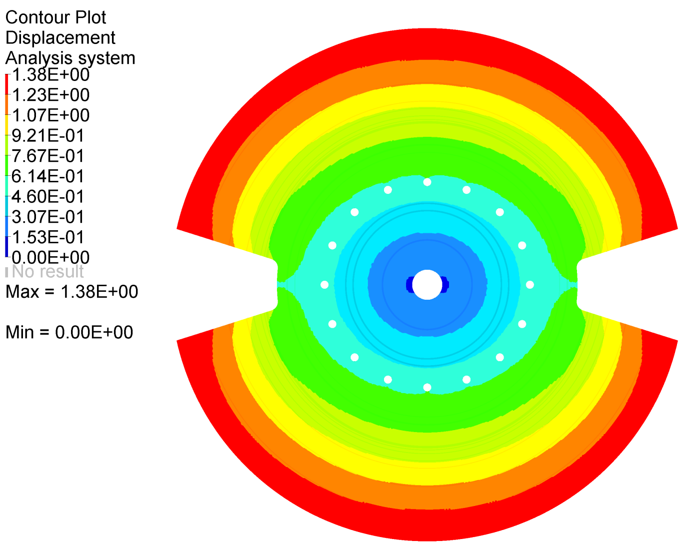

Figure 4. Radial displacement of a chopper disk at a rotational speed of 380 Hz.

The results of the numerical optimization for lower radial displacement at the central drilling are shown in figure 5. At a discreet radius r_E there is a jump in the thickness distribution from 40 mm to 18 mm. For $r < r_E$ it is beneficial to thicken the disk. Additional layers placed in this area lead to less widening of the central drilling. For $r > r_E$ it is unprofitable to add additional layers due to the fact that the additional weight of the added layers leads to higher centrifugal forces and more widening of the central drilling.

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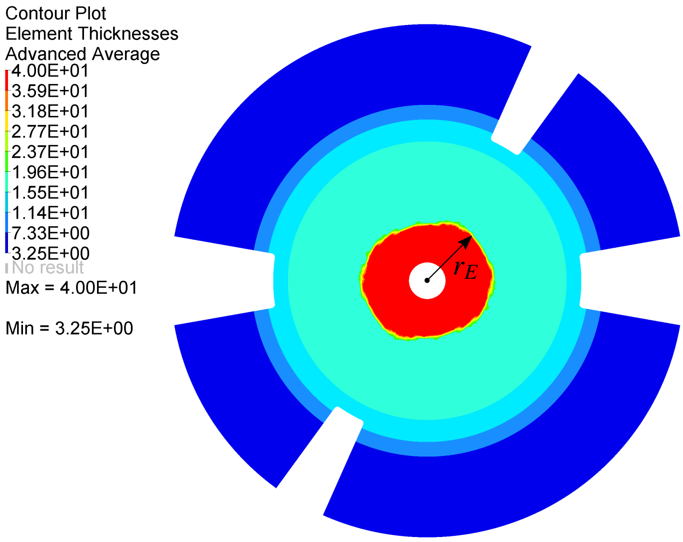
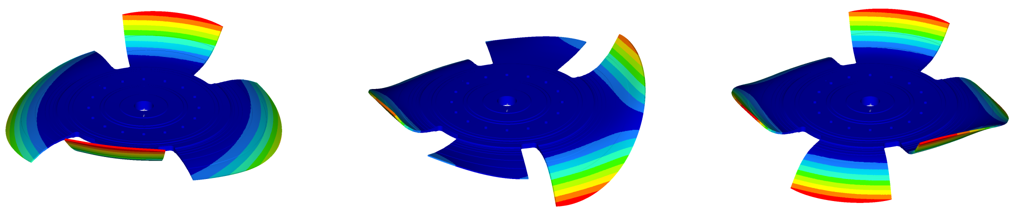


Figure 5. Optimized thickness distribution for lower radial displacement at the central drilling.

With the second FE model, the disk is optimized for higher natural frequencies. The shapes of the first three eigenmodes of the chopper disk are shown in figure 6. The first eigenmode is the bending mode of the edges of the chopper disk. The second eigenmode is a torsion mode of the wings of the copper disk. The third eigenmode is a coupling of both, the bending and the torsion of the wings [14]. Rotordynamic effects occur during rotation, which lead to a shift of the natural frequencies to higher values. This is caused by a membrane stiffening of the disk due to the centrifugal forces [15]. The numerical optimization is defined as a maximization of the sum of the first three natural frequencies with a weight factor of 1 for each natural frequency. This assumption of a unweighted multi objective optimization is valid because of the narrow range of the three different natural frequencies.



Mode 1: 214.4 Hz Mode 2: 223.8 Hz Mode 3: 229.8 Hz

Figure 6. First three eigenmodes of the chopper disk.

The results of the optimization for higher natural frequencies are shown in figure 7. In the area around the central drilling the thickness of the disk is at its maximum value of 40 mm. There is a linear decline in thickness from a radius of $r \approx 100$ mm to the edge of the disk. The minimum value at the edge of the disk is 1.28 mm, which corresponds with 8 layers of the carbon fiber prepreg material. The tendency of the thickness distribution is similar to the one of the optimization for lower radial widening. This is advantageous because both results can be combined to a new design with less radial widening and higher natural frequencies. The final design depends on the weighting of the two different optimizations. For the improved design a mixture between the result of the lowest radial widening and the highest natural

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frequencies is chosen and manufacturing constraints are considered for the decision.

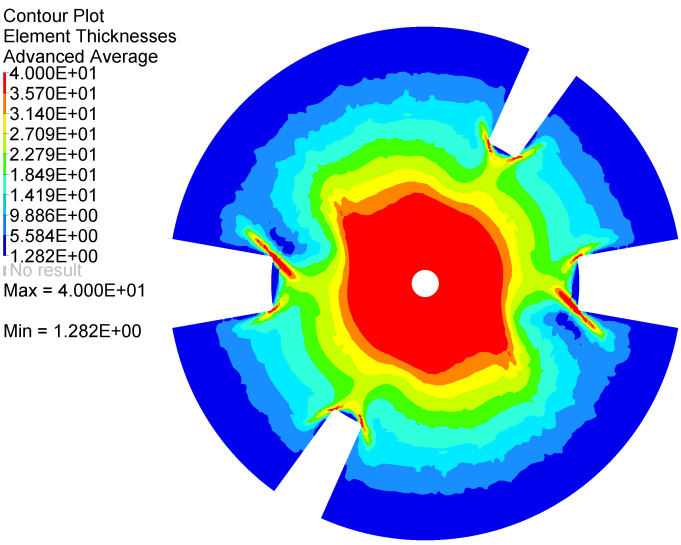

Figure 7. Optimized thickness distribution for higher natural frequencies.

4. Verification

The new design of the chopper disk is verified with a strength test of the disk. The operational speed of the chopper is 333 Hz, the certification speed is 350 Hz and the design speed is 380 Hz. At a rotational speed of 380 Hz the failure index in the areas around the cut-outs reaches 1. Due to the higher natural frequencies of the disk and the lower widening around the central drilling neither a triggering of the disk by the rotational frequency nor a detachment of the disk from the hub is expected. At the spinning strength test, the disk failed at a rotational speed of 380.5 Hz, which matches precisely with the predicted value. Due to the complete destruction of the disk, which is shown in figure 8, it was not possible to clarify if the initial failure was caused by a delamination of the CFRP or a vibration input by a detachment of the disk from the hub.

Figure 8. Destroyed chopper disk after spinning strength test.

5. Conclusions

The initial design of the chopper disk showed strong vibrations at a rotational speed of 260 Hz. The disk was redesigned in order to avoid these vibrations and to reach an operational speed of 333.33 Hz respectively 380 Hz for the strength spinning test. In order to get an indication of those areas where an increasing in thickness leads to positive results, two numerical optimizations were carried out. The first optimization minimizes the radial widening around the central drilling. The result of this optimization shows a discreet value of the radius to which it is beneficial to thicken the disk. The second optimization for higher natural frequencies of the disk shows a linear decrease of the thickness. With these results, an optimized disk is designed with a first natural frequency of 274 Hz and a radial widening of the central drilling of 0.16 mm at a rotational speed of 380 Hz. This represents a percentage improvement of the initial design by 26 % for the natural frequencies and 24 % for the radial widening of the central drilling. Both enhancements lead to an optimized design, which fulfills the requirements of an operational speed of 333.33 Hz. The spinning strength test of the optimized design confirmed the prediction of the failure of the disk at a rotational speed of 380.5 Hz. It can be noted that designing a chopper disk only from the point of view of strength is not sufficient for large disks with high rotational speeds. In addition to the strength criterion, rotordynamic effects have to be considered in the design process.

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