Safety of the NCal rotor for O4.
VIR-1327A-21

Eddy Dangelser, Dimitri Estevez, Hubert Kocher, Benoit Mours, Antoine Syx

IPHC-Strasbourg

December 03, 2021

Contents

1 Introduction

The risk associated with the rotation of the O3 NCal system was described in the VIR-0270A-18 Virgo note. The primary concern was the dislocation of the rotor that is spinning at a relatively high speed. With a simple analytical model, the maximum stress was estimated to be 12 MPa when spinning at 100Hz, much less that the 470 MPa elastic limit of the aluminum 7075 used. This result was confirmed with a full 3d ANSYS simulation of the rotor, showing maximum stress on the covers and external ring of the 03 rotor, but still very far from the elastic limit.

The rotor design is evolving for O4. Figure 1 shows the layout of the O3 rotor on the left, and the planned version for O4 on the right. The O4 design is much simpler. The external ring has been suppressed as well as the covers. We are left with only two sectors, and therefore, the evaluation of the stress could be simply done with an analytical model, without the need of a confirmation with an ANSYS simulation.

This note will first present this evaluation of the expected maximum stress on the rotor. It will show that again, the O4 design is safe. Then, a test performed on a modified rotor will be discussed. The purpose of this test is to demonstrate that indeed, there is a large safety factor in the design of the O4 rotor and the risk of rotor dislocation are extremely small.

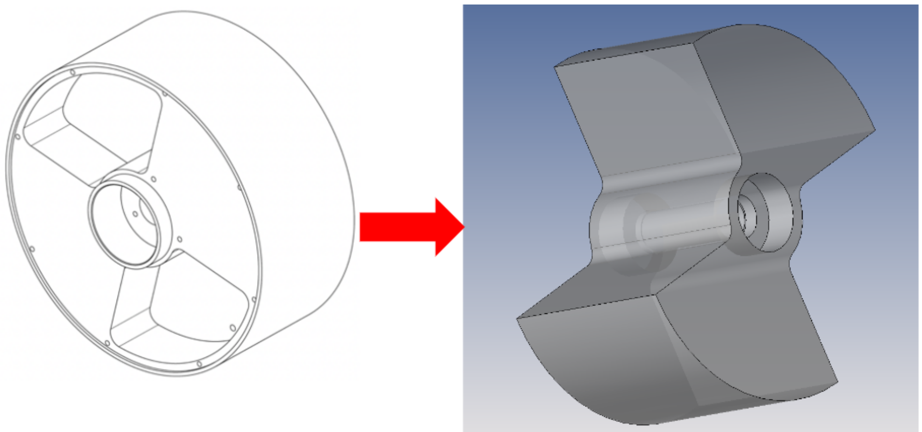

Figure 1: On the left is the O3 "NCal-200" rotor and on the right is the foreseen O4 rotor.

2 Analytic estimation of the stress for the O4 rotor

We will compute the stress applied on the surface between a rotor sector and the central rotating axis for a O4 rotor shown on figure 2. This surface being where the stress is expected to be maximal. Since there are two similar areas we will only compute one of them.

The equation 1 is used to compute the stress:

$$\mathrm{d}\sigma = \frac{\mathrm{d}F_{cent}}{\mathrm{d}S} = \frac{\omega^2\, r\, \mathrm{d}m}{\mathrm{d}S} \tag{1}$$

- $\mathrm{d}F_{cent}$ being the centrifugal force of the infinitesimal rotor sector
- $\mathrm{d}S$ is the infinitesimal surface where the stress is applied at radius r_S
- $\mathrm{d}m$ is the mass of the infinitesimal sector
- $\omega = 2\pi f$ is the angular velocity of the rotor
- and r is the radius to the center of gravity of the infinitesimal object considered

Considering the problem in cylindrical coordinates and the height and angle opening of the surface and sector are the same. The infinitesimal surface $\mathrm{d}S$ can be expressed as:

$$\mathrm{d}S = r_S\, \mathrm{d}\theta\, \mathrm{d}z \tag{2}$$

For the O4 rotor shown in figure 3, assuming the density ρ is constant, we have the mass $\mathrm{d}m$:

$$\mathrm{d}m = \rho\, r\, \mathrm{d}r\, \mathrm{d}\theta\, \mathrm{d}z \tag{3}$$

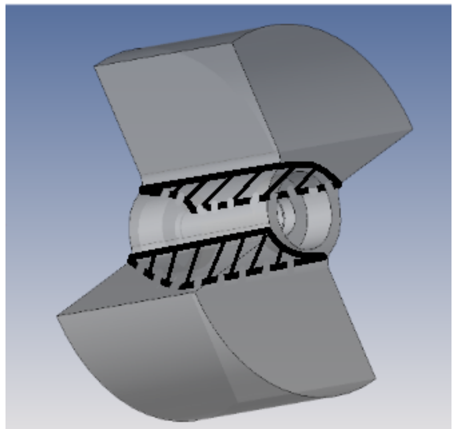

Figure 2: Surface stress on O4 rotor shown in black hatched areas.

We then have the infinitesimal stress using equation 1:

$$\begin{aligned} d\sigma &= \frac{\rho\,\omega^2 dr d\theta dz}{d\theta dz}\frac{r^2}{r_S} \\ &= \rho\,\omega^2\frac{r^2 dr}{r_S} \end{aligned} \tag{4}$$

Since R the radius of the sector $(0.1025m)$ is much larger than r_S the radius to the surface stress $(0.029m)$, we can neglect the r_S^3 term while computing the integral over r, and therefore the stress is:

$$\sigma = \frac{1}{3}\rho\,\omega^2\frac{R^3}{r_S} \tag{5}$$

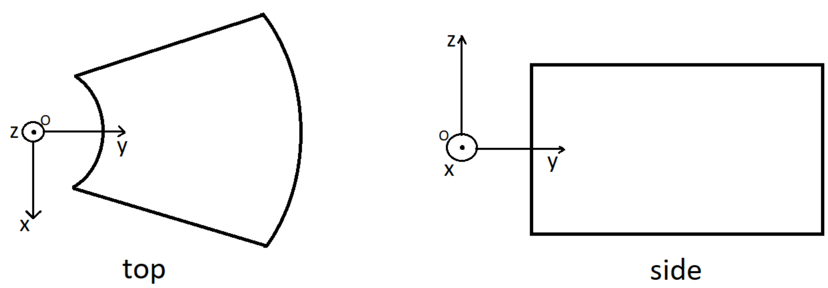

Figure 3: Outline of one of the sectors of the O4 rotor. Left is a top view, right is a side view.

Using the following parameters in table 1:

Parameters \ NCal	O4 NCal
ρ $(kg.m^3)$	2770
ω (s^{-1})	628.31
R (m)	1.025×10^{-1}
r_S (m)	2.9×10^{-2}

Table 1: Parameters considered for the O4 rotor stress computation.

We now compute the stress for the approximated O4 rotor rotating at a frequency of 100Hz that is the expected maximum rotation speed frequency:

$$\sigma_{100} = 13.5 \text{ MPa}$$

This result is not very different from the analytic computations of the previous safety note about the O3 rotor since the main difference is a slight increase of the external radius. The stress induced by the rotation of the O4 rotor is far below the elastic limit of the material of 470 MPa with a safety factor of about 35.

There is no need to confirm this result with a full FEM modelling like ANSYS, since the O4 rotor is much simpler than in O3 (no external ring for instance), and since the O3 ANSYS study confirmed the analytical results for O3.

3 Test of the safety factor

To demonstrate that the safety factor is very large, one of the O3 rotor was machined to simulate the O4 rotor geometry, with a much larger stress. To increase the stress on the rotor, the connection between the sectors and the central part of the rotor was machined to reduce the surface S (from equation 5) on which the centrifugal force is acting. The red arrow on figure 4 shows the small amount of material left (less than $11mm$ of thickness) compared to the initial $82.4mm$. This modification increases the stress by a factor $82.4/11 = 7.5$.

Since we were using an O3 rotor for this test, the external radius was $102.5mm$ instead of the foreseen $104mm$, reducing the stress by a factor 1.04 compared to the expected O4 geometry.
Overall, this geometry increases the stress by a factor $7.5/1.04 = 7.2$. Therefore, the expected stress is $13.5 * 7.2 = 97.2$ MPa, still about a factor 5 away from the elastic limit.

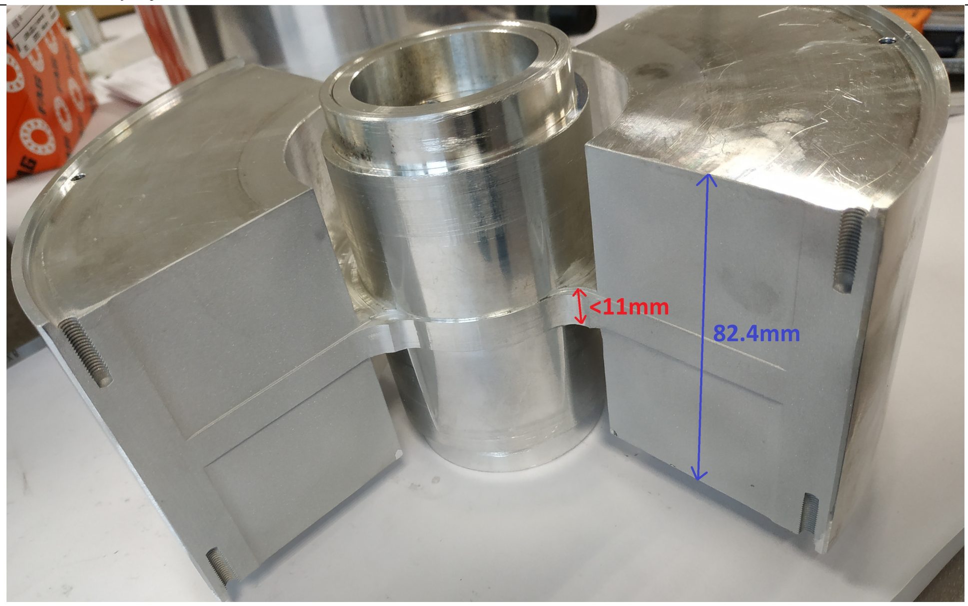

Figure 4: Weakened O4 rotor.

3.1 Experimental test of the weakened O4 rotor

The rotating test involving the weak O4 prototype has been made at IPHC on November 22, the goal was to increase the rotating speed as much as possible and check that the rotor would not break appart.
Figure 5 shows the FFT in time during the test (about 1300s) of this weakened NCal. As described on the figure, the two pannels show different frequencies, the top pannel shows the frequency of the horizontal accelerometer corresponding to the rotor frequency reaching a peak at 96Hz for about 3 minutes while the bottom pannel shows the output frequency from the light pulse going through the rotating NCal. The rotor being composed of two full sectors, the frequency retrieved is then twice the real value (about 192Hz).

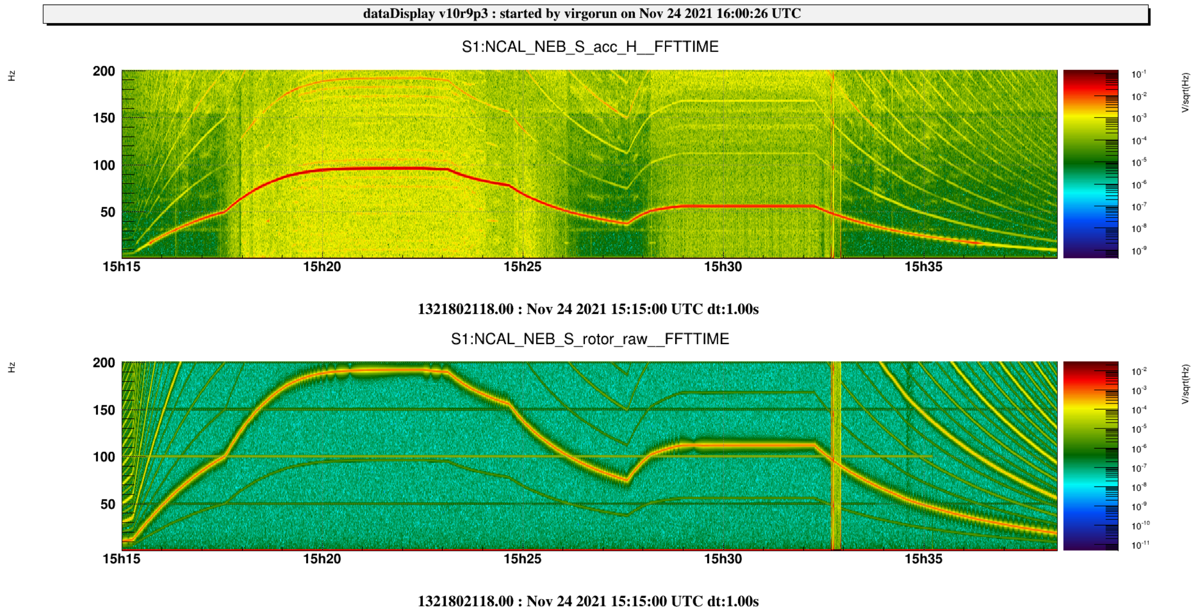

Figure 5: On top the FFT of the horizontal accelerometer over the testing time and on the bottom is the FFT of the rotor output frequency over the testing time.

3.2 Converting the 96Hz result to a 100Hz rotation

Since the rotor could only reach 96Hz during the experimental test and not 100Hz as for the O4 design, the stress was a factor $(100/96)^2$ weaker than the expected value. Therefore, taking into account the reduction of the central surface, the slight change of the rotor diameter and the maximum rotation speed reached during this test, the stress was enhanced by a factor $7.5/1.04 * (96/100)^2 = 6.6$.
In other words, since the rotor was not damaged, this test demonstrates that the safety factor is at least 6.6.

As a side comment, using equation 4 we can compute the stress for the approximated weak O4 rotor rotating at a frequency of 96Hz:

$$\sigma_{96} = 93.4 \text{ MPa}$$

Which is well below the elastic limit, as confirmed by the success of the test.

4 Conclusion

We have first shown that the maximum stress expected is 13.5 MPa, well below the elastic limit of 470 MPa. Then we have prepared an O4 like rotor where the stress was increased by cutting material and making the rotor more fragile. We operated this rotor up to 96Hz, without any damage, demonstrating that our safety factor is a least a factor 6.6 when operating at its maximum speed.

It is comforting to notice that the elastic limit of 470 MPa considered is below the breaking stress of 535 MPa, which makes the O4 rotor a safe system to use.