Characterization of Narrow-Angle-Baffle’s damping system in KAGRA

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related Documents: https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=8693

1. Introduction

The Narrow-Angle-Baffles (NAB) are located each ~15m away from the test-masses toward the arm (4 test-masses → 4 NABs) inside the, so called, A-chambers (see Figure 1). They are supposed to work under ultra-high vacuum conditions. As for convention, “NAB” shall be used here to denominate the baffle plus its suspension.

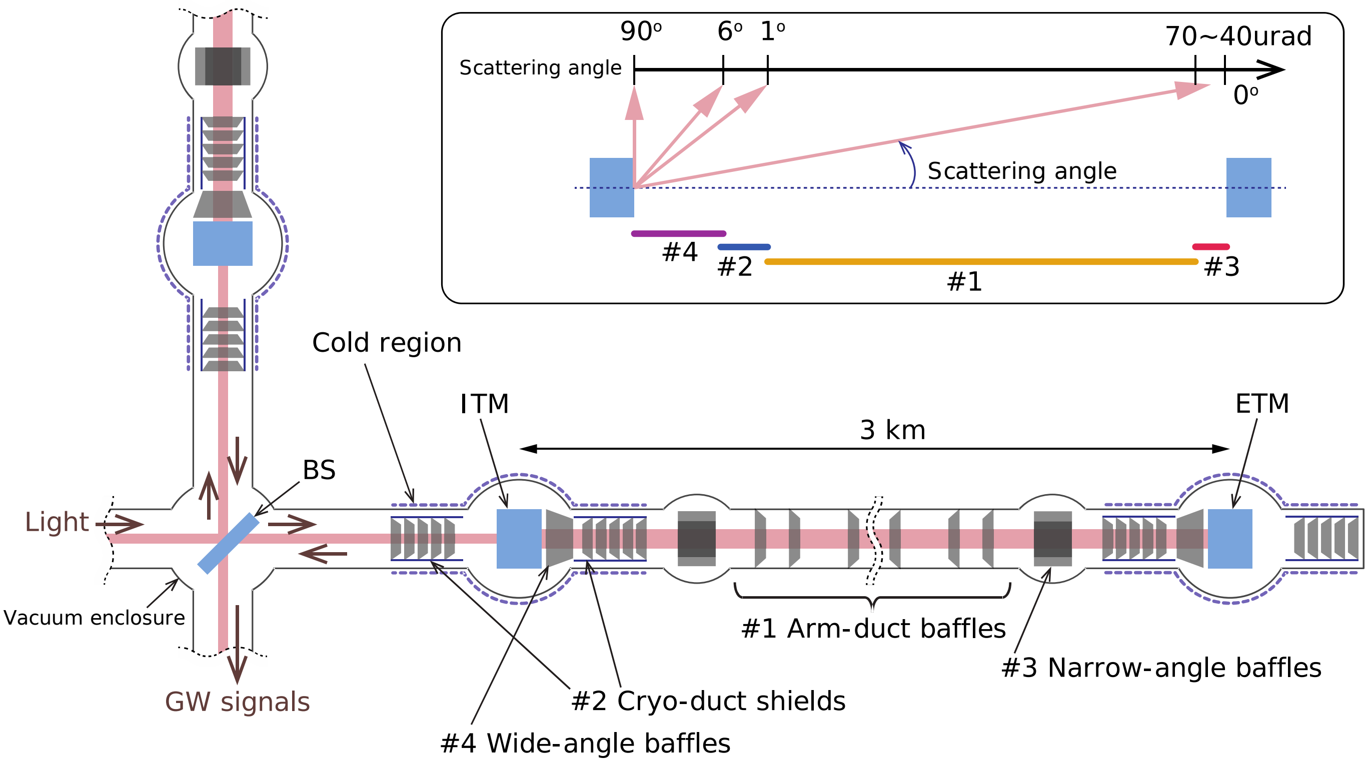


Figure 1: Sketch of the basic position for each type of baffle within the main interferometer. Basically shown is only the, so called, X-arm. The configuration in Y-direction is the same.

The structure of a NAB as it is installed inside the chamber can be seen from Figure 2. The NAB itself (and its whole suspension system) is placed inside a “tower” made of stainless steel. The tower is fixed to the optical-table on the ground of each A-chamber.

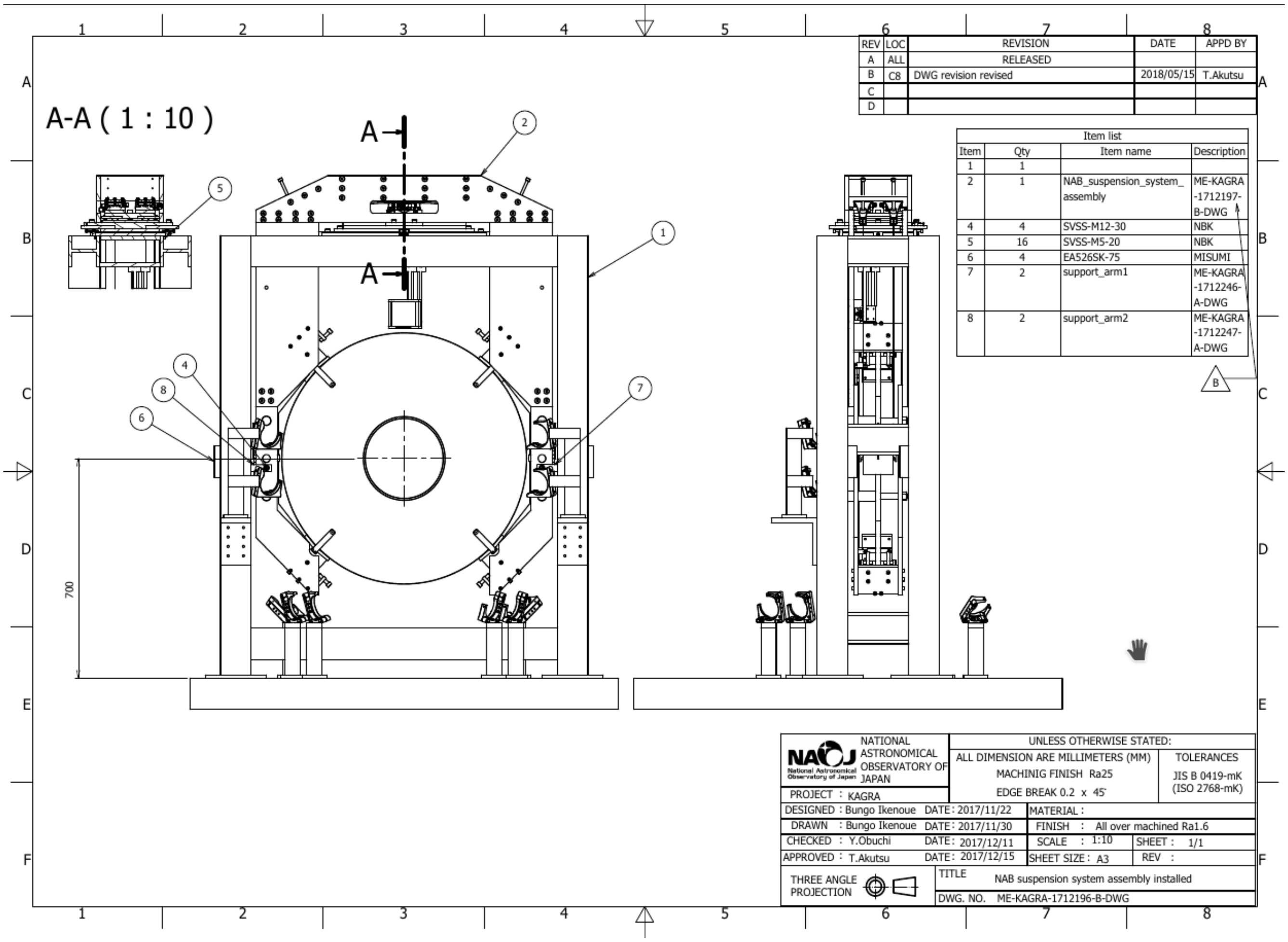


Figure 2: DWG drawing of the NAB installed into the tower-holder

Note: Each NAB has a dedicated direction!
The front-view in Figure 2 is showing the NAB as it is looking toward the arm-cavity (easily recognizable from the 4 photo-diodes and their respective holders that partly lay over the baffle’s main surface).

The baffle is covered with black NiP plating (Solblack) and will not be cooled down (in contrast to the wide-angle baffles).

2. Suspension

2.1. General Notes

The NAB has each a pendulum-spring suspension at 4 points on the horizontal plane-of-gravity of the baffle itself. Each point has a distance of ~42cm from the baffle's point of gravity. As the baffle itself is merely a cylindrical structure, the basic symmetries are relatively simple.

The spring-blades which we are using are made of Phosphor-Bronze and have a thickness of ~4mm, while the wires for the pendulum are made of Tungsten with a thickness of ~1mm.

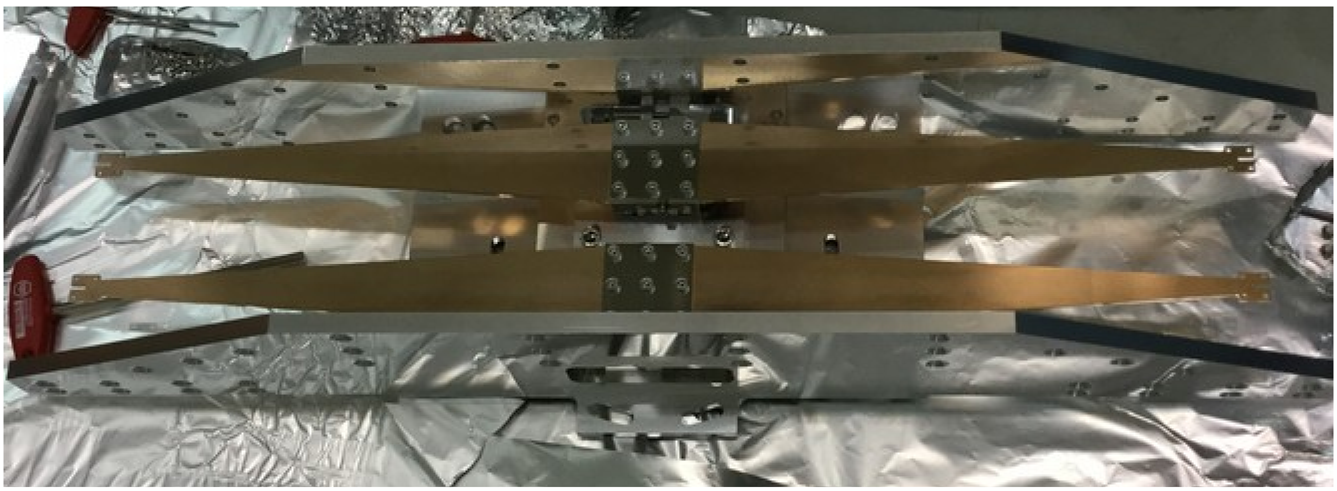
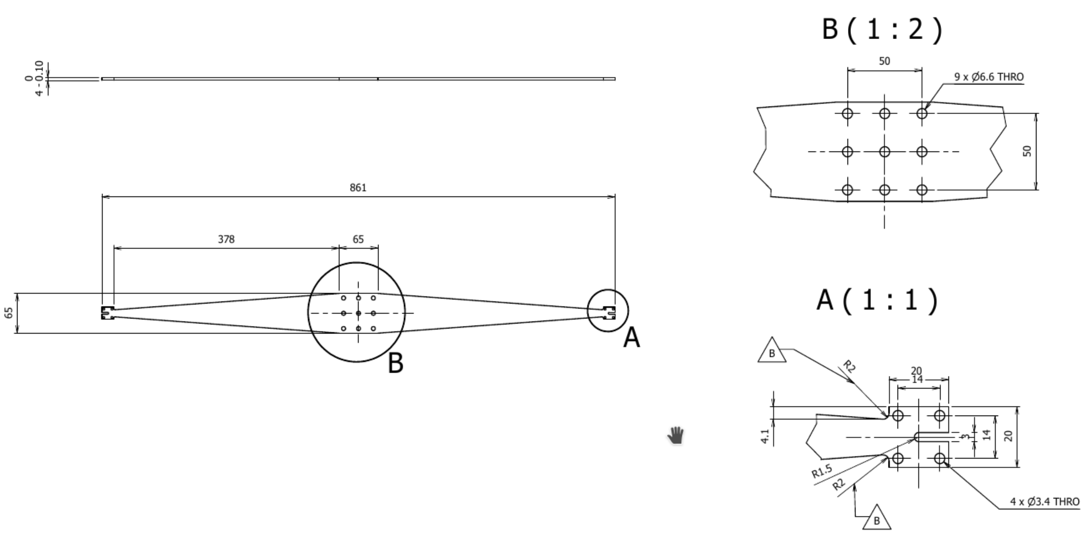


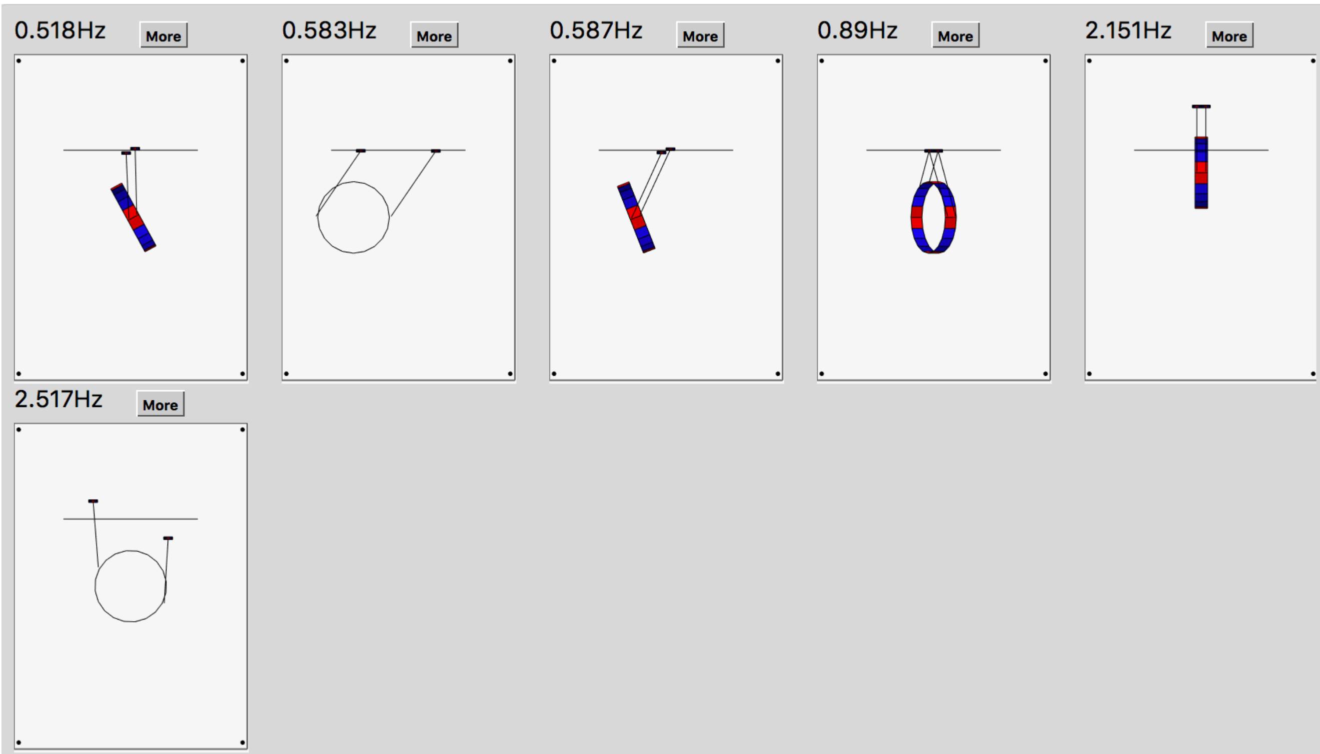
Figure 3: The spring-blades during the assembly of the suspension.

Each blade is 861mm long and is technically a merge of 2 blades as having 2 suspension points at either end of the blade. During the assembly, each blade will be fixed to a X-Y-translator stage in their center (see Figure 3).



Unfortunately, we discovered very soon that the company which provided us the blades could not manufacture them having the same flatness. In fact, we got quite differently shaped blades (having deviations of up to 5 ~ 7mm at the tips when laying over each other). This led to insufficiently balanced baffles and often to an offset in pitch which we had to re-balance with additional masses on top and bottom of the baffle!

According to a SUMCON analysis, the eigenfrequencies of the NAB oscillations are as follows:



We can denominate the modes as:

- Pitch – 0.518 Hz
- Transversal oscillation – 0.583 Hz
- Longitudinal oscillations – 0.587 Hz
- Yaw – 0.89 Hz
- Vertical oscillation – 2.151 Hz
- Roll oscillation – 2.517 Hz

Note, that the modes were calculated without any damping or additional influences like air-pressure or balance masses.

2.2. Damping

The baffle is, however, passively damped as to avoid an endless swinging baffle within the chambers. In case of the NABs, this is realized by “Eddy-current” damping via strong Nd magnets facing Cu-plates attached to the baffle in a distance of 5 ~ 10mm (actual distance is depending on the NAB as there are also factors like fine-tuning of the baffle's position in the chamber to be taken into account). Within this range of distance, we have obtained the best results in terms of the Quality-factor (see below) and still have a reasonable freedom for the baffle to move.

Our first tests with this type of damping have shown that using 4 Eddy-current dampers are at least necessary to get satisfying results especially for damping the vertical and the pitch mode. The very first design has involved only two dampers, placed in the horizontal plane-of-gravity. But due to this, the pitch-movement did not create enough velocity for the Cu-plates moving along the magnetic-field to produce a counter-force strong enough to damp the baffle-movement sufficiently. This phenomenon can be seen in Figure 4 where the OpLev signal of a mirror (placed on the baffle-ear) for each an actuation of pitch and yaw is shown.

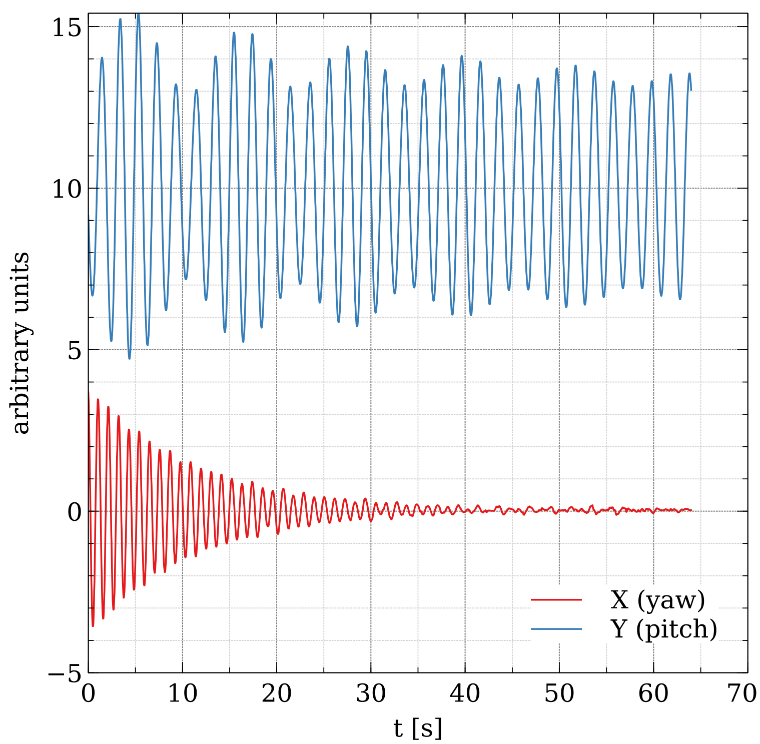


Figure 4: Graph picturing the damping-effect on the pitch and the yaw-mode for the NAB with 2 Eddy-current dampers in the plane-of-gravity.

While the yaw-movement experiences some damping, oscillations in pitch are persistant.

Due to these, we revised the design for damping the NAB and put 4 dampers out of the horizontal plane-of-gravity (see Figure 5 and 6).

Note: In Figure 4, the shown graph for pitch indicated a coupling with another mode (probably the longitudinal one). Therefore, the amplitude itself shows an additional variation in ~0.1 Hz frequency.

As we know that the longitudinal mode showed a damping behavior similar to the yaw-mode by measurements with laser-displacement sensors, we can say that the undamped mode in the above graph is indeed the pitch-mode.

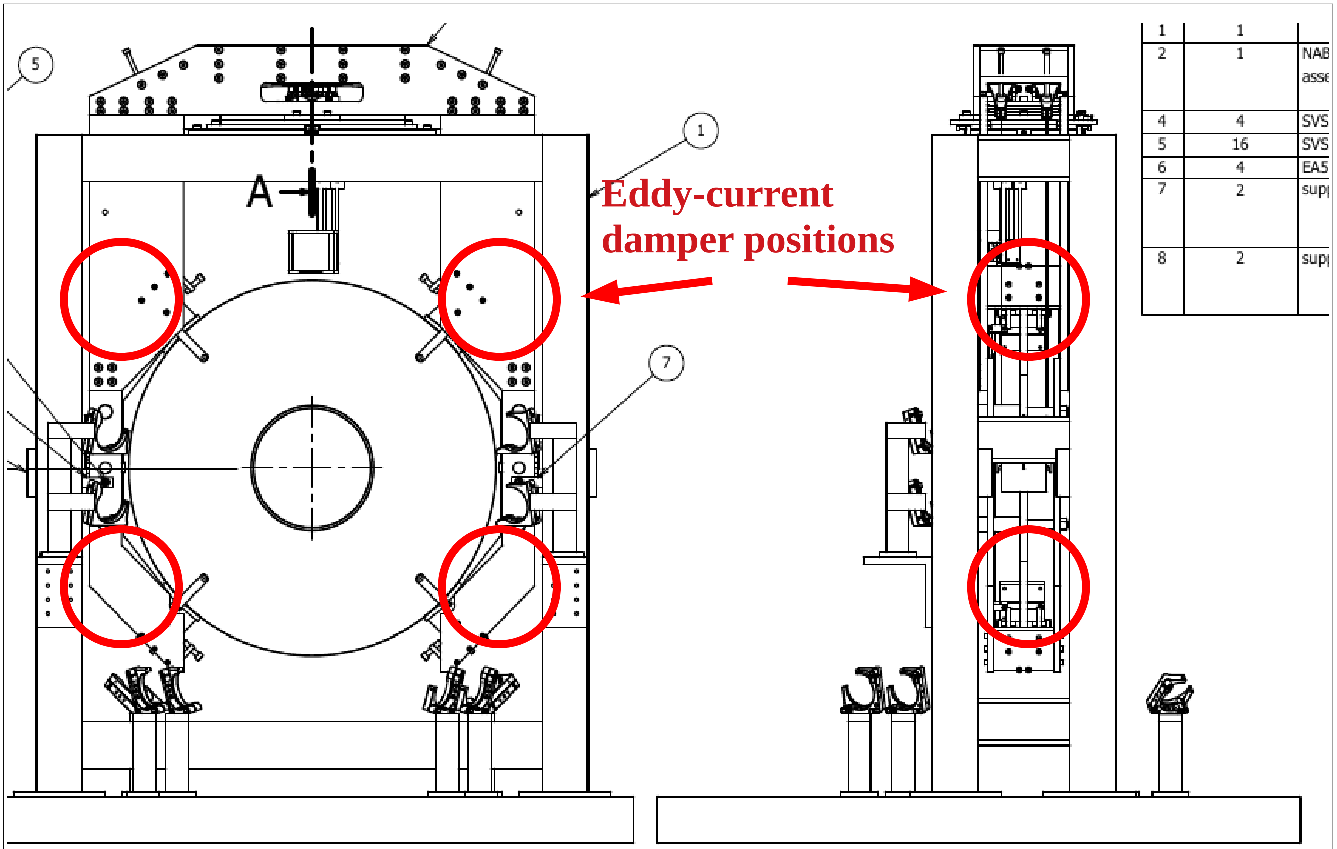


Figure 5: Positions of the Eddy-current dampers around in the (final) NAB design.

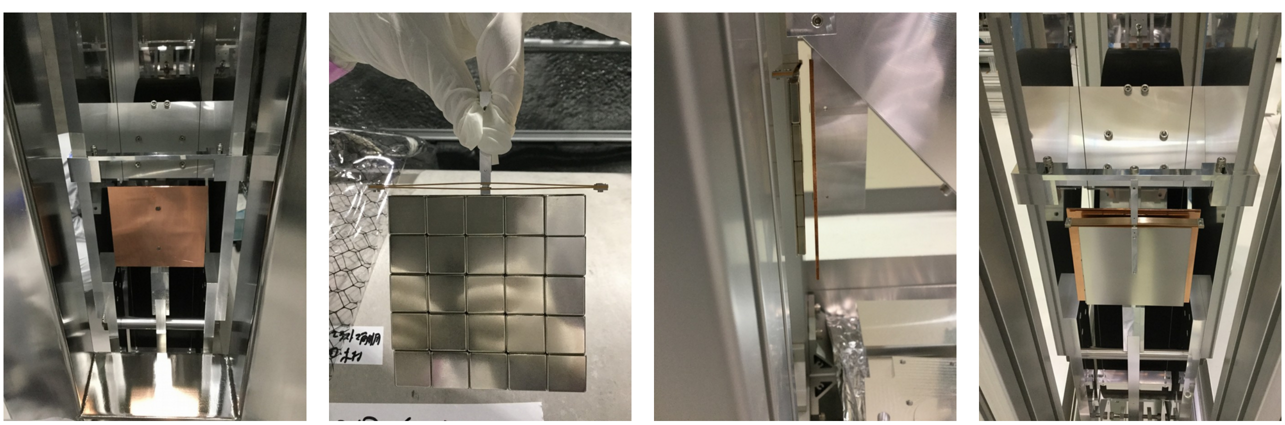


Figure 6: From left to right: (1) the Cu-plate of one of the dampers attached to the baffle-ear; (2) the magnet-holder with its suspension; (3) side-view of Cu-plate and magnet-holder in the assembled state; (4) front-view of the assembled damper

As can be seen from Figure 6, we completely covered the surface of the magnet-holder plate (SUS) with 20x20x4mm Nd-magnets. Therefore, we needed 100 magnets per NAB to realize a sufficient damping of the baffle.

That the damping is indeed sufficient can be seen in Figure 7. In contrast to the solution with only 2 dampers, especially the motion in pitch is rapidly damped. Also the damping-factor for the yaw-mode increased.

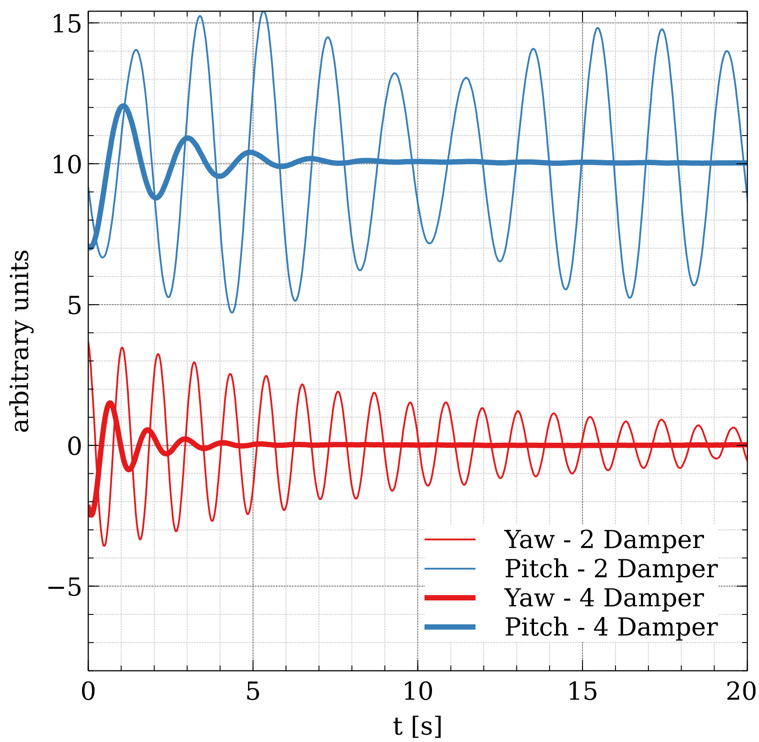


Figure 7: Comparison of a 2-damper and a 4-damper solution. Obviously, with the given configuration of 4-dampers, the damping-factor especially for the pitch-mode increased a lot.

Theory

A damped oscillation may be described with the following formula:

$$y(t)=\Re\{A\cdot\exp(-2\pi f[d+i\sqrt{1-d^2}]\cdot t+i\,\phi)\}$$

Here, y is the elongation while A, f, d, and φ are the amplitude, frequency (undamped), damping-ratio, and the phase, respectively. This formula is used for all the fit-calculations to characterize the damping.

Alternatively, we can write:

$$y(t)=\Re\{A\cdot\exp(-\pi f[Q^{-1}+i\sqrt{4-Q^{-2}}]\cdot t+i\,\phi)\}$$

with Q being the quality factor of the oscillation. Although the fits have been made with the first formula, we will refer to the quality factor in the following characterizations.

3. KAGRA NABs

In Table 1, the eigenmode parameters frequency (f) and quality-factor (Q) as taken right after the assembly in the Advanced Technology Center (ATC) of NAOJ are presented. As the air-flow inside the clean-room where the assembly has been done is relatively strong, it may be that the parameters were altered to a certain extend. So, the values should be taken with care. Also, it was not always possible to clearly actuate some of the modes, and so we we could not get sufficient data (see the roll-mode for NAB@IXA or the pitch-mode for NAB@EYA).

In the further subsections, more particular information on each NAB during the installation and the measurements done at KAGRA are presented.

As main measurement device (for both Mitaka and KAGRA measurements), we used laser-displacement sensors from NAOJ's ATC (→ refer to Uraguchi-san). We had 3 sensor-heads available.

Specification:

- "KEYENCE" - LK-H085 (sensor heads)
- "KEYENCE" - LK-G50000V (Controller)

In addition to that, when doing measurements at KAGRA, we installed an optical-lever (OpLev) to measure the pitch and yaw movements. The OpLev instrument is basically the same as used for the main mirrors of KAGRA (see respective documents at the JGW document-server). As we can measure pitch and yaw also with the laser-displacement sensors, the OpLev measurements were done as a supplement.

	NAB@IXA		NAB@IYA		NAB@EXA		NAB@EYA	
	f	Q	f	Q	f	Q	f	Q
longitudinal	0.59	7.2	0.58	5.2~6.1	0.56	5.3	0.59	8.3
transversal	0.65	3.2	0.6	2.8	0.59	3.1	0.59	4.6
vertical	2.02	20	2	18	2.05	22.2	2	29
yaw	0.98	1.6(?)	0.88	2.7~2.97	0.88	3.1	0.88	4.6~4.9
pitch	0.56	4.76	0.59(?)	4.26(?)	0.5	4.1	-	-
roll	-	-	2.3	7.8	2.21	6.2	2.3	11~12

Table 1: frequency and Q-factor from the fits to the measurements of each mode, done in the clean-room at Mitaka (before shipping). Note that for some modes it was not possible to actuate them sometimes or to differentiate from other modes. Also, the air-flow in the clean-room altered some mode parameters likely.

3.1. IXA

This was the first NAB to be assembled and installed.

As for the suspension system, we had here also our first encounter with the above mentioned issues of having blades with different flatness. Our strategy to overcome the offset in pitch (~ 5°) was to shorten the Tungsten wires on one side. This, however, proved to be quite complicated as the shortened wires itself changed the balance additionally with their mass-loss. We reached a kind of sufficient solution in the end but decided to change the strategy toward balance-masses for the other NABs.

The also above mentioned upgrade of the dampers had been done for this NAB after its installation in the IXA chamber (see report No. 5693 and 5856 below), as we firstly designed the NAB with the old damper-structure and it took us a while to find a proper solution.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5216

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5218

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5241

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5255

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5693

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5751

http://klog.icrr.u-tokyo.ac.jp/osl/?r=5856

In Figure 8, a summary of the data taken with laser-displacement sensors for different actuation of the baffle are shown. As we did not put two sensors for sensing coherent movements on different places but only one, we had difficulties to clearly detect certain eigenmodes. In addition to this, we had difficulties in actuating the roll and yaw modes for which we didn't get any reliable result with the laser-displacement sensors. However, measurements done with an OpLev later (on Aug. 30th 2018) showed the existence of at least the yaw-mode. The results of these measurement are also shown in Figure 8 (amplitudes of pitch and yaw data are reduced by a factor 1/2). Unfortunately, the data taken for the yaw-mode are heavily coupled with the longitudinal mode. Therefore, in the graph's legend, parameters for both modes are given.

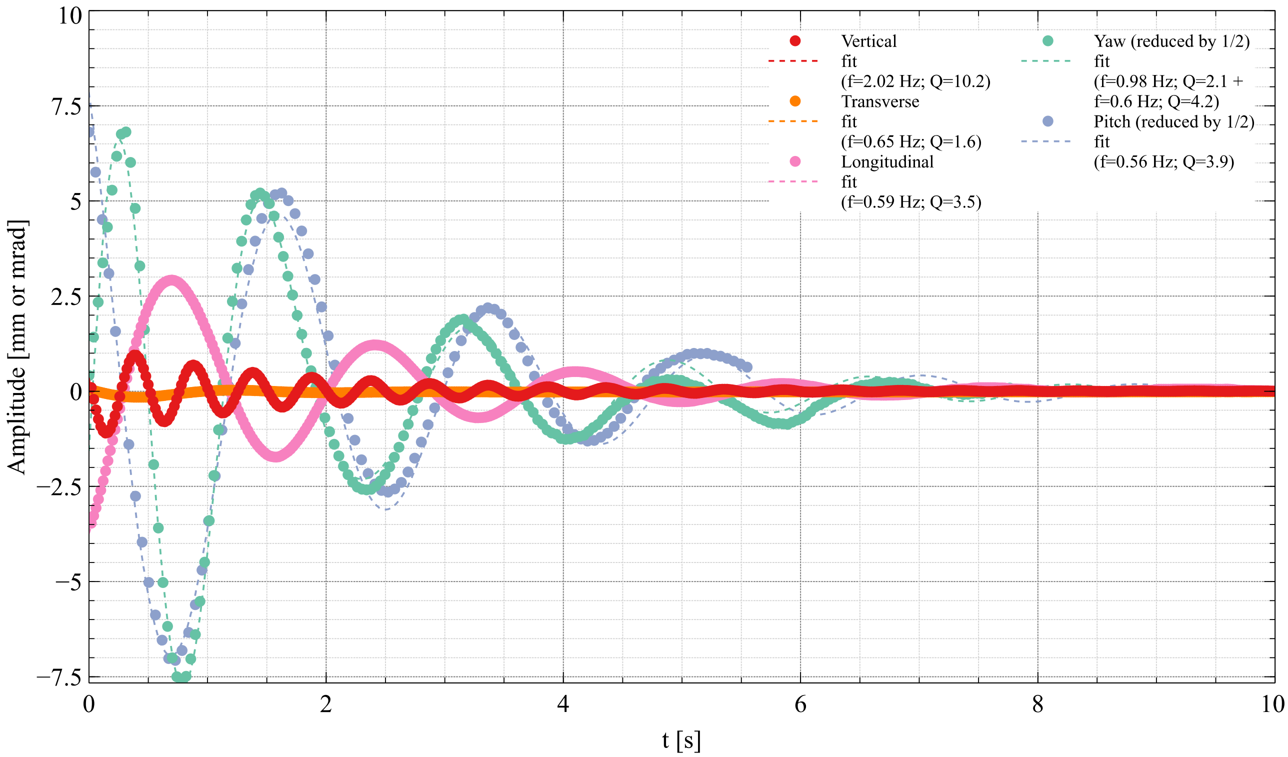


Figure 8

3.2. IYA

This was the second NAB to be assembled and installed. However, the assembly took place almost at the same time as the third NAB and we shipped both at the same time from Mitaka to Kamioka in early November of 2018.

The difficulty for the installation of this NAB was that we had to bring it from the entrance at Y-end along the 3 km arm toward IYC because the center-area was not accessible for such large devices at that time. The NAB survived the transport quite well, although we found some loosened screws for fixing the suspension (see the klog-entries below).

This was the first NAB where we used balance-masses instead of shortening the wires. We put 800g of those masses symmetrically on 4 points around the baffle initially and tuned these masses after the PD-attachment was done down to 400g in total.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6873

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6885

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6916

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6953

http://klog.icrr.u-tokyo.ac.jp/osl/?r=6985 http://klog.icrr.u-tokyo.ac.jp/osl/?r=7008

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7126

In Figure 9, the measurements taken on-site on the installed baffle are shown (from Nov. 16th 2018). This time, we had (only) in the beginning some problems in confirming the parameters from the Mitaka-measurements. It turned out that the PD-wires were set too stiffly and therefore induced a strong additional damping. After the wire-issue was fixed, the parameters went back to be in the expected range.

We were not able to actuate the pitch-mode sufficiently and could not get satisfying results with the laser-displacement sensors. Therefore, the pitch-mode has been remeasured later with the OpLev (Nov. 27th 2018). However, the data showed again a strong coupling with the longitudinal-mode (also indicated in the legend of Figure 9). Anyway, we think that pitch-mode is at least somehow recognizable with the respective fit, but the parameters should be taken with care as the error is probably quite high.

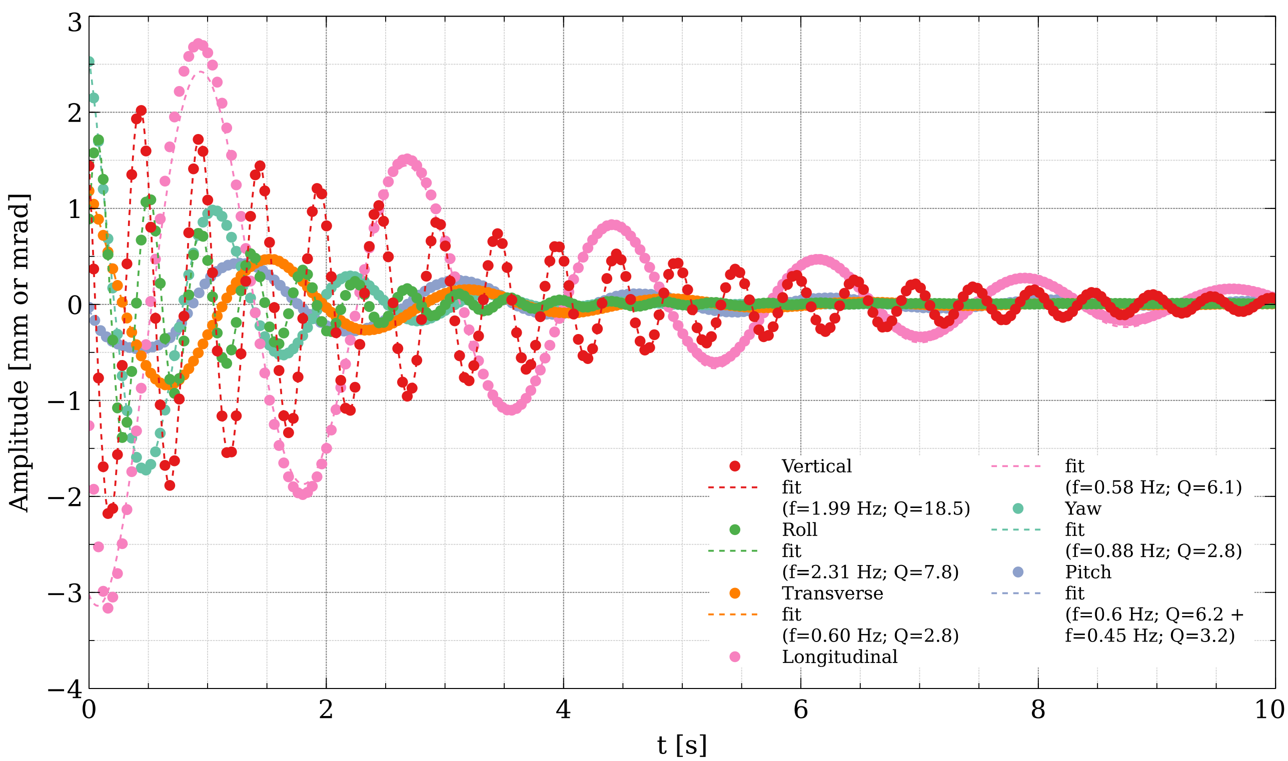


Figure 9

3.3. EXA

This was the fourth (and last) baffle to be assembled and installed.

By the time of assembly, we contacted the company responsible for the spring-blades already and reported about the issues with the planarity. They have done some investigations of their own and provided us additionally treated blades from which we chose the most promising ones. Indeed, it turned out that we did not have to use balance-masses for this baffle!

The shipment and the installation took place in February 2019. Similar to the second NAB (@IYA), we had to transport the NAB 3 km along the x-arm to its destination at EXA chamber. By that time, however, we could use the central entrance (Atotsu) and used a fork-lifter for transport (actually, x-arm is wider due to missing drainage-pipes).

The actual installation took place within 2 days and another day was needed for the characterization. Please refer to the following links for the installation and test reports:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8061

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8062

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8063

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8064

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8076

http://klog.icrr.u-tokyo.ac.jp/osl/?r=8098

In Figure 9, the results of the measurements we took are shown. All data have been taken with the laser-displacement sensors and we had surprisingly no problems in actuating and detecting all eigenmodes (maybe we had already enough training by that time).

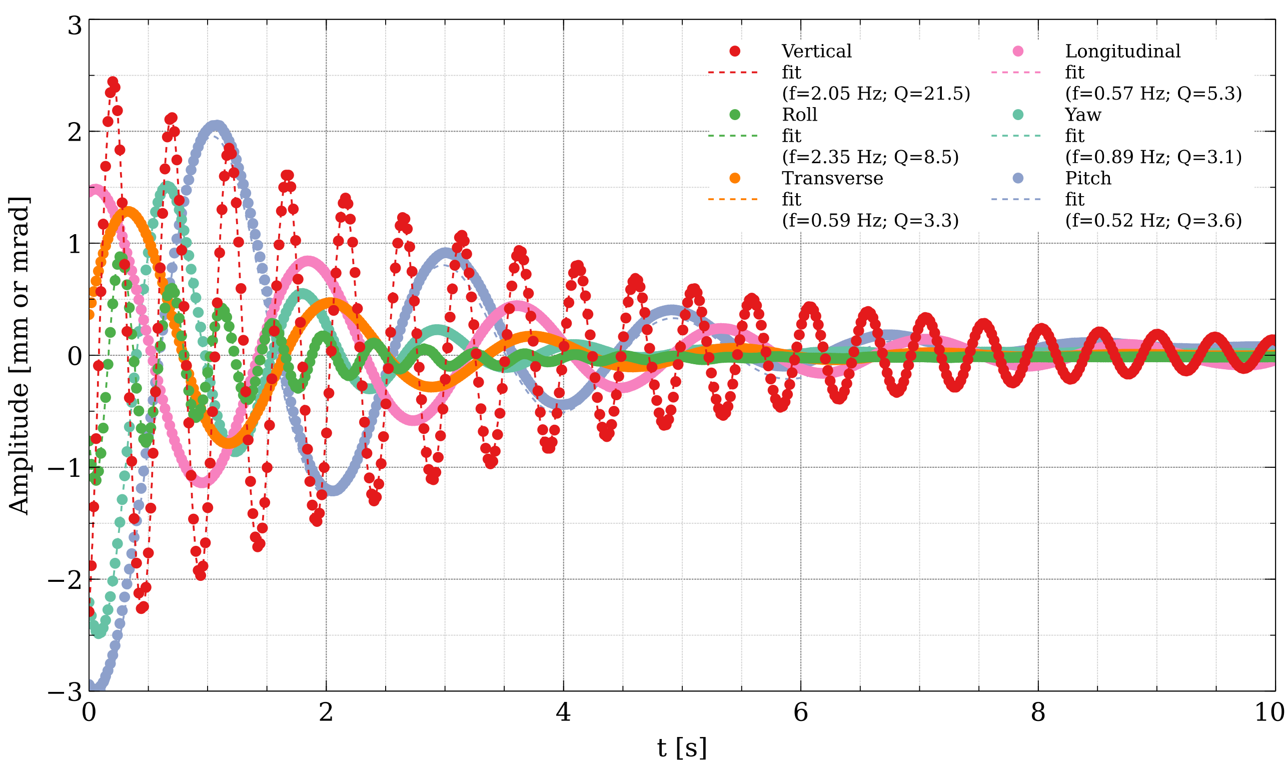


Figure 10

3.4. EYA

This was the third NAB to be assembled and installed. However, the assembly took place almost at the same time as the second NAB and we shipped both at the same time from Mitaka to Kamioka in early November of 2018.

As we entered the Y-end area via the Mozumi-entrance with both NABs at that time, we did not have to go along the Y-arm with the NAB. However, the NAB had to pass EYC before reaching EYA chamber.

The installation itself took place between Nov. 19th and 22nd 2018. An important notion is that due to the already mentioned issues with the spring-blades and the PD-holder installation, we had to add in total 1.2 kg of balance-masses. Which was a challenging part as we had to use some more hidden screw-holes for fixing the masses on the baffle.

Below, you can find links to the installation and test reports on-site:

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7036

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7062

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7079

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7100

http://klog.icrr.u-tokyo.ac.jp/osl/?r=7130

Measurements on the eigenmodes and their damping were done on Nov. 22nd 2018. Unfortunately, we had again difficulties with the pitch-mode and could not acquire sufficient data for a fit. Also, there have been no OpLev measurements until now. Therefore, we can not say anything about that mode. However, giving the parameters found for the other modes, it is very likely that the pitch-mode is in a similar range for frequency and quality-factor as for the NAB at EXA.

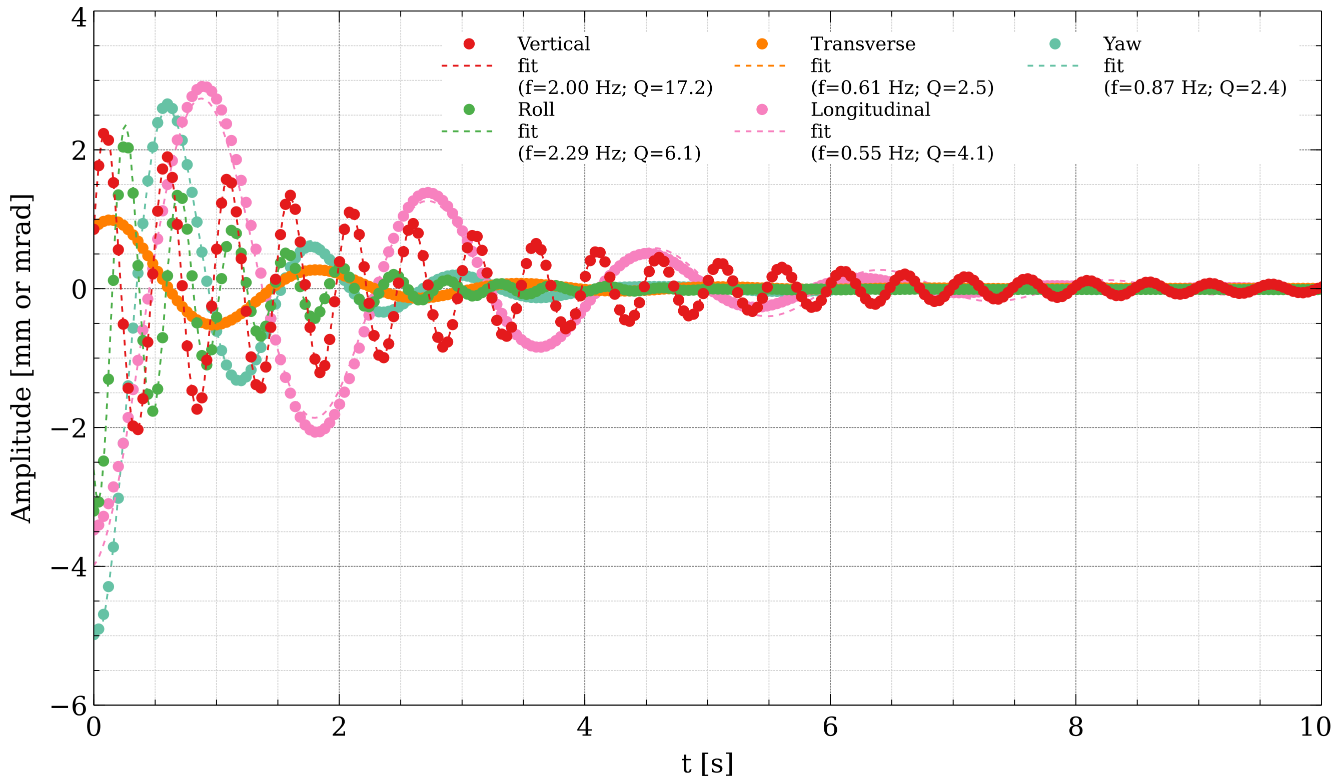


Figure 11

3.5. Remarks

We often had problems in actuating especially the pitch-mode. Apparently only for the last NAB we found a proper procedure to actuate and measure the pitch-mode (lifting and pushing the spring-blades on front/back only in the proper resonance). By that time, however, the other NAB-containing chambers were already closed and so we could not transfer our experience to the other NABs.

Also, the measurements were taken not always by the same people and so the exact procedure may differ from NAB to NAB.