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Sensing and Driving Matrices for Alignment of the Arms of AdV+ phase I

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1 Introduction

The goal of this work is to profit from the advanced status of the commissioning of AdV+ to provide an up to date measurement the alignment sensing and driving matrices, especially interesting concerning the arms. The considered lock for this measurement is a long lock obtained on February 18th, UTC:21:00:00.

2 Current Sensing and Driving Matrices

We begin by measuring the optical gain of the considered error signals for the plus modes of the arms. B1p_QD2_56MHz_I has been long used in the commissioning as the error signal for DIFFp, while B7_QD1_DC is used to control the beam tilt in the North cavity. Finally, the minus modes are controlled through the local controls of the mirrors.
The sensing matrix is measured in a single mirror base: to obtain the optical gain of signal for each mirror, we measure the transfer function between the signal and the correction applied to the marionetta of that mirror then compensate with the transfer function between these corrections and the tilt of the mirror. Of all these transfer functions, we select the value at the frequency of the relevant dithering line:

$$OG\left[\frac{\mathrm{mW}}{\mu\mathrm{rad}}\right] = \frac{\mathrm{Signal}}{\mathrm{MAR\_CORR}}\left[\frac{\mathrm{mW}}{\mathrm{V}}\right]\cdot\frac{\mathrm{MAR\_CORR}}{\mathrm{MIR}}\left[\frac{\mathrm{V}}{\mu\mathrm{rad}}\right] \tag{2.1}$$

This choice ensures that the measurement of the optical gain is always supported by a high coherence at the frequency of the dithering lines.
From these measurements we can compute the elements of the sensing matrix, given in mW/μrad.
The minus modes are monitored by a combination of the optical levers of the single mirrors. In this circumstances, the sensing matrix becomes, for TX:

$$\begin{pmatrix} B1p\_QD2\_V\_56MHz\_I \\ B7\_QD1\_V \\ Sc\_NA\_NE\_Ctx \\ Sc\_WA\_WE\_Ctx \end{pmatrix} = \begin{pmatrix} -0.407 & 0.448 & 0.356 & -0.494 \\ 0.255 & -0.261 & 7.39 & -12.2 \\ -1.06 & -0.367 & -50.7 & -64.7 \\ -36.9 & -45.3 & 0.3646 & -0.623 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{2.2}$$

and TY:

$$\begin{pmatrix} B1p\_QD2\_H\_56MHz\_I \\ B7\_QD1\_H \\ Sc\_NA\_NE\_Cty \\ Sc\_WA\_WE\_Cty \end{pmatrix} = \begin{pmatrix} -0.316 & 0.333 & 0.285 & -0.334 \\ -0.250 & 0.267 & -6.95 & 9.82 \\ 0.201 & 0.237 & -72.8 & -88.5 \\ -58.8 & -62.8 & -0.255 & -0.824 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{2.3}$$

In the sensing matrix, the elements of each row that are deemed negligible with respect to the others are faded. The current strategy is to use B7_QD1 to control the beam tilt in the North cavity ("NORTHp"). Since DIFFp is closed in full bandwidth, this takes care of the common tilt in the arms. The error signal for NORTHp is B7_QD1.
By normalizing row by row we transform each sensor in the corresponding degree of freedom. This assumes that the calibration of each sensor is such that 1 μrad of tilt correspond to 1 mW of difference in the power detected by the quadrant, inside the linear region of the signal. The result of the normalization is the following, TX and TY respectively:

$$\begin{pmatrix} DIFFp\_TX \\ NORTHp\_TX \\ NORTHm\_TX \\ WESTm\_TX \end{pmatrix} = \begin{pmatrix} -0.474 & 0.522 & 0.415 & -0.575 \\ 0 & 0 & 0.518 & -0.855 \\ 0 & 0 & -0.617 & -0.787 \\ -0.632 & -0.775 & 0 & 0 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{2.4}$$

$$\begin{pmatrix} DIFFp\_TY \\ NORTHp\_TY \\ NORTHm\_TY \\ WESTm\_TY \end{pmatrix} = \begin{pmatrix} -0.497 & 0.525 & 0.448 & -0.526 \\ 0 & 0 & -0.527 & 0.816 \\ 0 & 0 & -0.635 & -0.773 \\ -0.684 & -0.730 & 0 & 0 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{2.5}$$

Inverting this matrices yields the driving matrices for these degrees of freedom:

$$\begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} = \begin{pmatrix} -1.11 & 0.810 & 0 & -0.749 \\ 0.906 & -0.660 & 0 & -0.680 \\ 0 & 0.841 & -0.914 & 0 \\ 0 & -0.660 & -0.554 & 0 \end{pmatrix} \begin{pmatrix} DIFFp\_TX \\ NORTHp\_TX \\ NORTHm\_TX \\ WESTm\_TX \end{pmatrix} \tag{2.6}$$

$$\begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} = \begin{pmatrix} -1.01 & -0.743 & 0 & -0.727 \\ 0.947 & 0.696 & 0 & -0.689 \\ 0 & -0.835 & -0.882 & 0 \\ 0 & 0.686 & -0.569 & 0 \end{pmatrix} \begin{pmatrix} DIFFp\_TY \\ NORTHp\_TY \\ NORTHm\_TY \\ WESTm\_TY \end{pmatrix} \tag{2.7}$$

We have reconstructed the approach currently used in Virgo, thus summarized:

- to control **DIFFp** the actuation is on WE and WI due to the sensing asymmetry between DIFFp and COMMp.
- to control **NORTHp** (beam tilt in the North arm), the actuation is on all the test masses.
- to control **NORTHm** (beam shift in the North arm), the actuation is on the mirrors of the North arm.
- to control **WESTm** (beam shift in the West arm), the actuation is on the mirrors of the West arm.

While the elements of the driving matrix come from a measurement of the optical gains, this computation does not keep track of individual characteristics of actuators, circuitry, suspensions exc., for this reason, the elements of the driving matrix are tuned overtime to minimize the cross coupling and the control noise of the alignment loops.

3 Alternative Sensing and Driving Matrices

Let us propose a sensing/driving for COMMp. We start by looking at the optical gains of the quadrants in transmission of the arms, measured as explained in the previous Section. This minor of the sensing matrix is, for TX and TY:

$$\begin{pmatrix} B7\_QD1\_V \\ B8\_QD1\_V \\ B7\_QD2\_V \\ B8\_QD2\_V \end{pmatrix} = \begin{pmatrix} 0.255 & -0.261 & 7.39 & -12.2 \\ -2.74 & 0.509 & 0.321 & -0.379 \\ 0.225 & -0.212 & -3.37 & 1.65 \\ -8.87 & 7.16 & -1.23 & 1.24 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{3.1}$$

$$\begin{pmatrix} B7\_QD1\_H \\ B8\_QD1\_H \\ B7\_QD2\_H \\ B8\_QD2\_H \end{pmatrix} = \begin{pmatrix} -0.250 & 0.267 & -6.95 & 9.82 \\ -1.41 & 1.22 & -0.221 & -0.250 \\ -0.158 & 0.166 & -5.35 & 3.43 \\ -7.96 & 5.68 & -0.517 & -0.421 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{3.2}$$

We find that a combination of B7_QD1 and B8_QD2 would produce an adequate signal, since both quadrants resolve well the tilt of the respective test masses.
Since these are DC quadrants, the alignment signal is given by the movement of the spot on the quadrant itself rather than a wavefront sensing technique. This means that the misalignment of the bench on which the quadrant is mounted and the misalignment of the arms will produce the same effect on the alignment signal.
This complication is fixed for B7_QD1 by using the very low frequency portion of this signal to align the bench itself, under the hypothesis that the movement of the suspended bench is much slower than the movement of the beam in the cavity, that is between a few hundreds of mHz to a few Hz. In this case, the information on the beam tilt sacrificed by aligning the bench on the same sensor is small enough that the two loops can coexist.
The alignment of the West bench is managed by B8_QD1. This means that in principle the spot on B8_QD2 could drift far enough to start clipping on the border of the quadrant.
To at least validate this measurements, we need to verify that the spot was contained in the sensor during the considered data stretch.

Fig.1 shows the asymmetry signals (top half of the quadrant minus bottom half for V, left half minus right half for H) normalized over the total power impinging on the quadrant. This gives a percentile measurement of the miscentering of the spot on the quadrant.

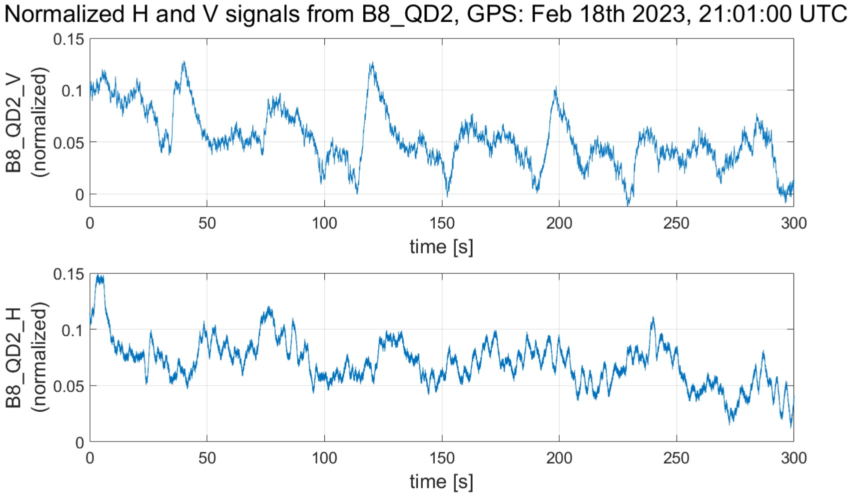

Figure 1: Asymmetry signals for B8_QD2 H and V, normalized over the power impinging on the quadrant. This provides a percentile evaluation of the miscentering of the spot.

We see in Fig.1 that the miscentering of the beam on B8_QD2 remains below $\approx 15\%$ for the five minutes of data taken for this measurement. We can trust our results, but if we decide to use B8_QD2 as an alignment signal, the alignment of the bench needs to be handed-off to this quadrant similarly to how it is for the North bench. We can then take the difference of B7_QD1 and B8_QD2 to obtain the sensing matrix with COMMp instead of NORTHp:

$$\begin{pmatrix} DIFFp\_TX \\ COMMp\_TX \\ NORTHm\_TX \\ WESTm\_TX \end{pmatrix} = \begin{pmatrix} -0.474 & 0.522 & 0.415 & -0.575 \\ 0.496 & -0.403 & 0.399 & -0.657 \\ 0 & 0 & -0.617 & -0.787 \\ -0.632 & -0.775 & 0 & 0 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{3.3}$$

$$\begin{pmatrix} DIFFp\_TY \\ COMMp\_TY \\ NORTHm\_TY \\ WESTm\_TY \end{pmatrix} = \begin{pmatrix} -0.497 & 0.525 & 0.448 & -0.526 \\ 0.509 & -0.358 & 0.451 & -0.639 \\ 0 & 0 & -0.635 & -0.773 \\ -0.684 & -0.730 & 0 & 0 \end{pmatrix} \begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} \tag{3.4}$$

From which we obtain the driving matrices by inversion:

$$\begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} = \begin{pmatrix} -0.595 & 0.563 & 0 & -0.694 \\ 0.485 & -0.460 & 0 & -0.725 \\ 0.537 & 0.586 & -0.881 & 0 \\ -0.421 & -0.459 & -0.580 & 0 \end{pmatrix} \begin{pmatrix} DIFFp\_TX \\ COMMp\_TX \\ NORTHm\_TX \\ WESTm\_TX \end{pmatrix} \tag{3.5}$$

$$\begin{pmatrix} WI \\ WE \\ NI \\ NE \end{pmatrix} = \begin{pmatrix} -0.571 & 0.515 & 0 & -0.663 \\ 0.535 & -0.482 & 0 & -0.748 \\ 0.494 & 0.578 & -0.814 & 0 \\ -0.406 & -0.475 & -0.624 & 0 \end{pmatrix} \begin{pmatrix} DIFFp\_TY \\ COMMp\_TY \\ NORTHm\_TY \\ WESTm\_TY \end{pmatrix} \tag{3.6}$$

Having eliminated the asymmetry between DIFFp and COMMp, we find that the driving for both of them is now spread out on all the test masses. The minus modes are still resolved on a single arm basis and actuated only on the respective test masses.

4 Conclusions

We have summarized the process of building the sensing and driving matrices for alignment degrees of freedom of the arms, and proposed an alternative that removes the asymmetry between DIFFp and NORTHp/COMMp. Keep in mind that this work does not keep into account the mechanics of the suspensions, or differences between sensors, so the actual elements of the matrices can vary in reality and will need to be tuned according to experimental data.