TAMA coil driver modification

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1 Introduction

The coil drivers are a crucial part of the TAMA interferometer. They are used to control the position and orientation of the suspended mirrors. Both the longitudinal and alignment control loops use them as their actuators. Low noise and high dynamic range are very important. As with many such circuits, stability of the circuit is not easy to obtain. The circuits were designed by K. Kawabe, who spent a long time in experimentally making the circuits stable. Recently, however, it has been discovered that some of them oscillate at some MHz. Therefore a new stability analysis has been done with LISO, the results of which are reported here.

2 Coil impedance

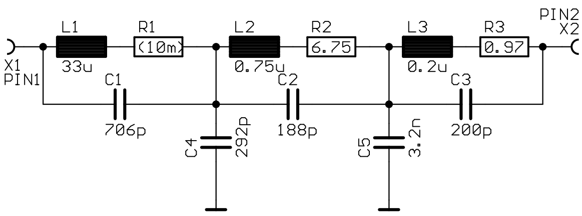

Figure 1: Impedance model for a typical TAMA coil.

Figure 1 shows a model for the coil impedance including the typical cable (approx. 2 m long). It was obtained by first measuring the impedance with a RF network analyzer, leading to the model without C4 and C5, and later refined as described below.

Figure 2 shows the measured data and fitted model, and Figure 3 shows the corresponding impedance of the coil.

As soon as an intermediate version of the coil driver circuit was built that was stable enough to measure transfer functions, the measured transfer function was used

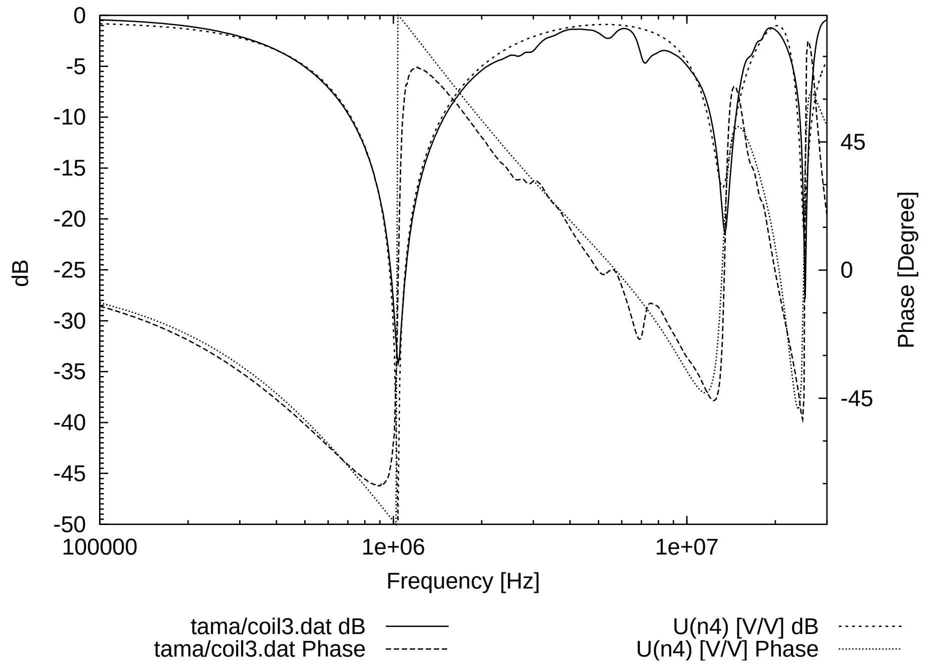

Figure 2: Measured data and fitted model for the coil impedance measurement. (transfer function with 50 Ohm source and load).

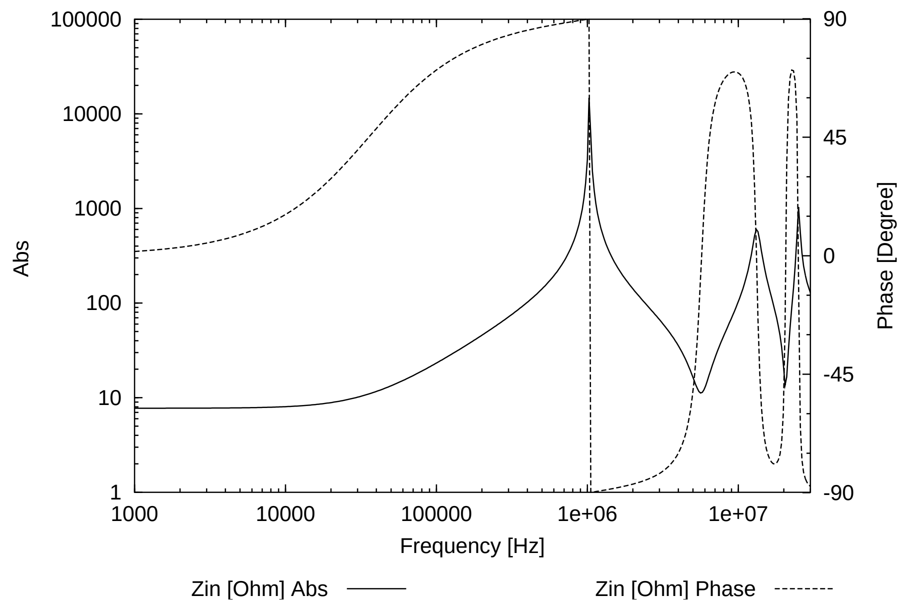

Figure 3: Impedance of a typical TAMA coil as determined from the above model.

to refine the model, in particular add capacitors C4 and C5.

Although the model is still not perfect, it was good enough for the calculations described in this document.

3 Coil driver circuit

Figure 4 shows the circuit of the coil driver. The circuit shown in Figure 4 with the

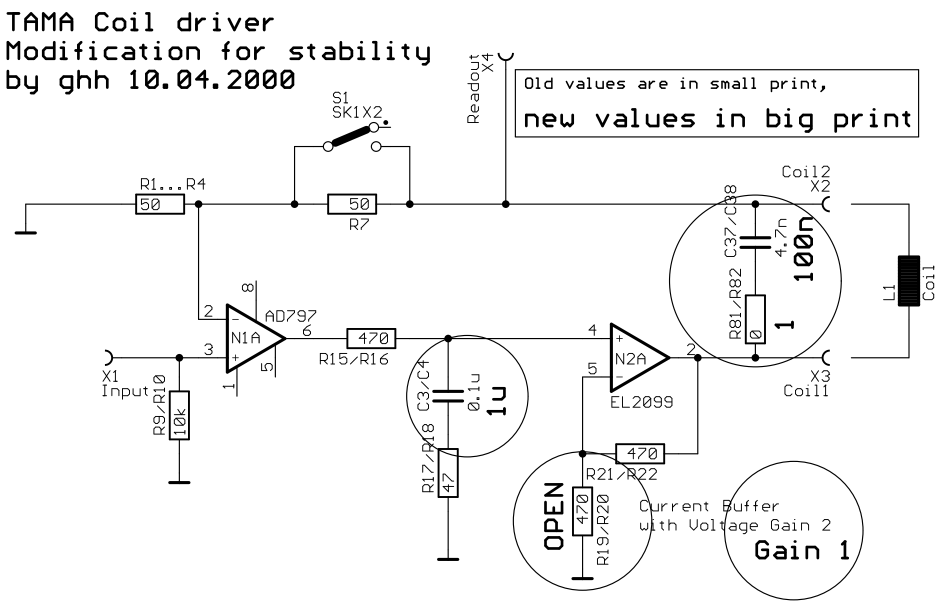

Figure 4: Circuit diagram of the TAMA coil driver.

component values printed in small typeface is the old circuit used up to now, while the component values printed in large typeface represent the new circuit (already installed).

It is essentially the standard voltage-to-current converter with the adjustable 50 Ω resistor $R_1 \ldots R_4$ as scaling resistor. The additional 50 Ω resistor R_7 does not change the current-to-voltage transfer function. It doubles, however, the voltage drop at the readout point X_4, making possible a readout of the coil current with slightly lower noise (see Section 6 below), at the expense of a reduced dynamic range.

The output current of the main op-amp (AD797) is boosted by the EL2099 Video op-amp, which is used in the noninverting configuration. While the old circuit used the EL2099 with a voltage gain of 2, the new circuit uses it as voltage follower (gain = 1). The 470 Ω feedback resistor $R_{21/22}$ is still necessary, because the EL2099 is a current-feedback amplifier.

There are two main stability problems in this circuit:

- Any voltage-to-current converter with an inductive load tends to have stability problems. This is especially true if the load has resonances at frequencies where the op-amps still have gain, as is the case here. The standard solution is to add a series RC 'snubber' circuit parallel to the load (R_{81}/C_{37} in Figure 4). The values of R and C can either be found experimentally, or by LISO (in complicated cases such as this one, an iterative process involving both approaches works best).
- The AD797 tends to have stability problems in many circuits, even with less problematical loads. These problems are enhanced in the circuit discussed here, because the current driver (EL2099) has a smaller bandwidth than the AD797, meaning that additional phase delays are introduced at frequencies where the AD797 still has gain. In the old circuit, the voltage gain of the current buffer made the situation even worse. The remedy is the lowpass-filter $R_{15}/C_3/R_{17}$, which reduces the open-loop gain of the op-amp's feedback loop at high frequencies.

4 Old circuit

The circuit shown in Figure 4 with the component values printed in small typeface is the old circuit which had been used up to now. Figure 5 shows its computed transfer function, both with and without the additional 50 Ω resistor (this transfer function could not be measured due to instability). The op-amp open-loop gain (Figure 6) has stability problems near 400 kHz, where the transfer function has a high-Q peak, and also at several frequencies between 1 MHz and 10 MHz.

5 New circuit

After some calculation and experimentation the new circuit (shown in Figure 4 with the component values printed in large typeface) was found.

The voltage gain of the current buffer was changed from 2 to 1 by removing R_{19}, and the compensation components C_3, R_{81} and C_{37} were changed.

Figure 7 shows its computed and measured transfer functions. The computed transfer function represents input voltage ⟶ coil current, while the measured one represents input voltage ⟶ voltage at readout point, the difference between the two being the scale factor (50 Ω) and the currewnt through the compensation network.

Figure 8 shows the computed op-amp open-loop gain (i.e. stability function) if the AD797 in this circuit, **without** the additional 50 Ω readout resistor. The unity-gain frequency is 3 MHz, with a phase margin of 50°. Without the resistor, it is 52° at 2 MHz. No oscillation was observed in the prototype of the new circuit, for any input signal and any combination of short cables/long cables and 50 Ω readout resistor/no

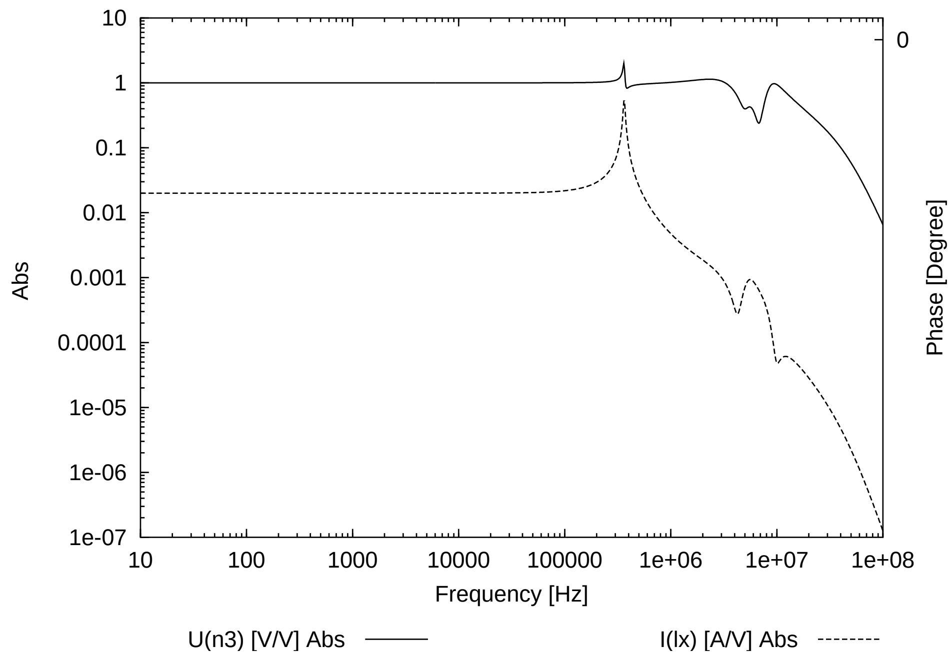

Figure 5: Transfer function of the old TAMA coil driver, from the input to the voltage at the EL2099's output ('n3') and to the coil current ('lx').

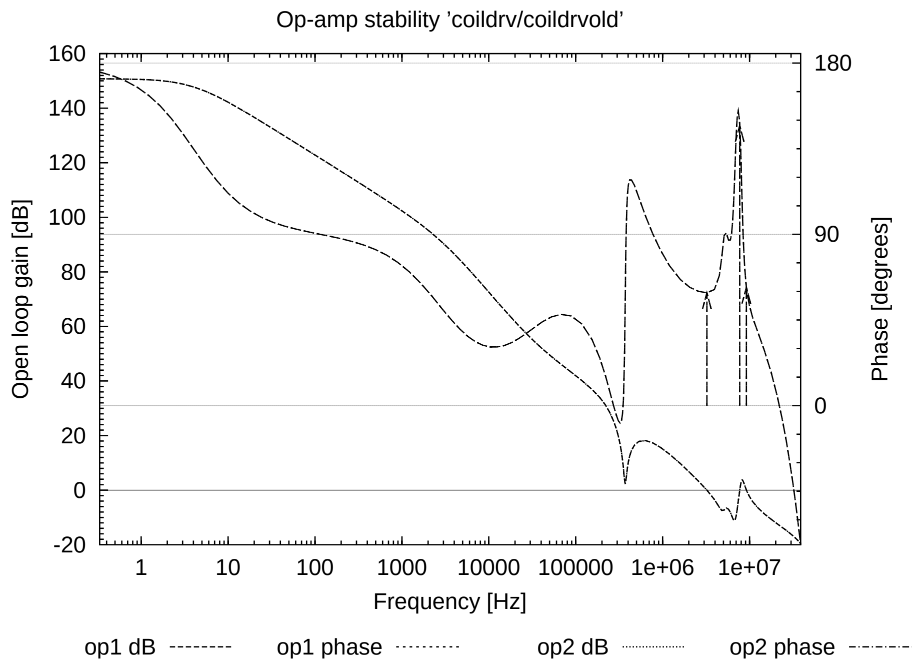

Figure 6: Open-loop gain of the old TAMA coil driver.

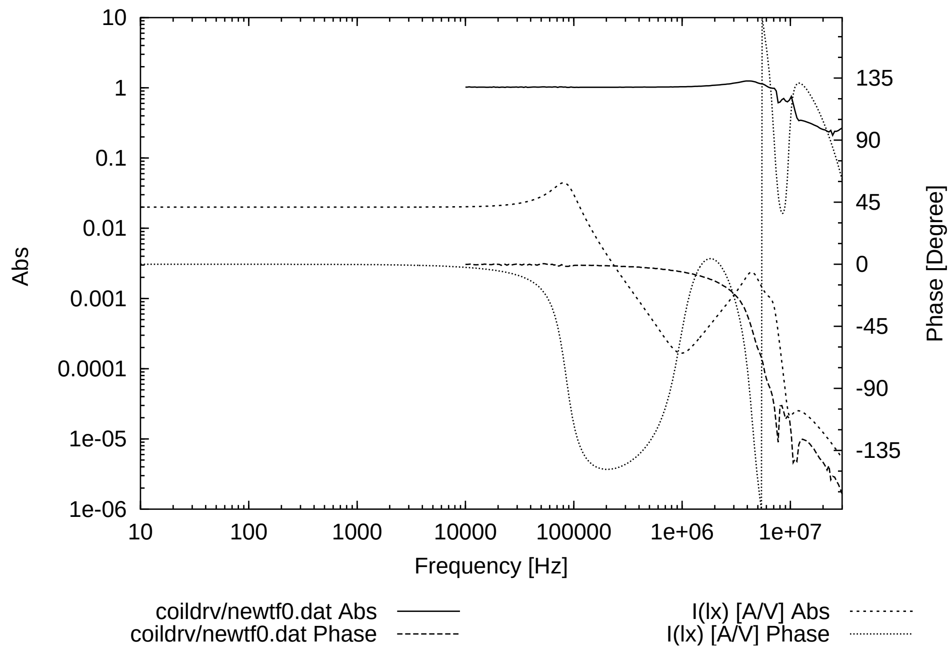

Figure 7: Transfer function of the new TAMA coil driver **without** the additional 50 Ω readout resistor. The curves starting at 10 kHz are measured transfer functions to the readout point, while the curves starting at 10 Hz are simulated to show the current through the coil (i.e. **excluding** the compensation network).

readout resistor. However, the stability is strongly dependent on the load, such that any change in the cable or even the grounding of the cable screen might change the situation and require a new analysis.

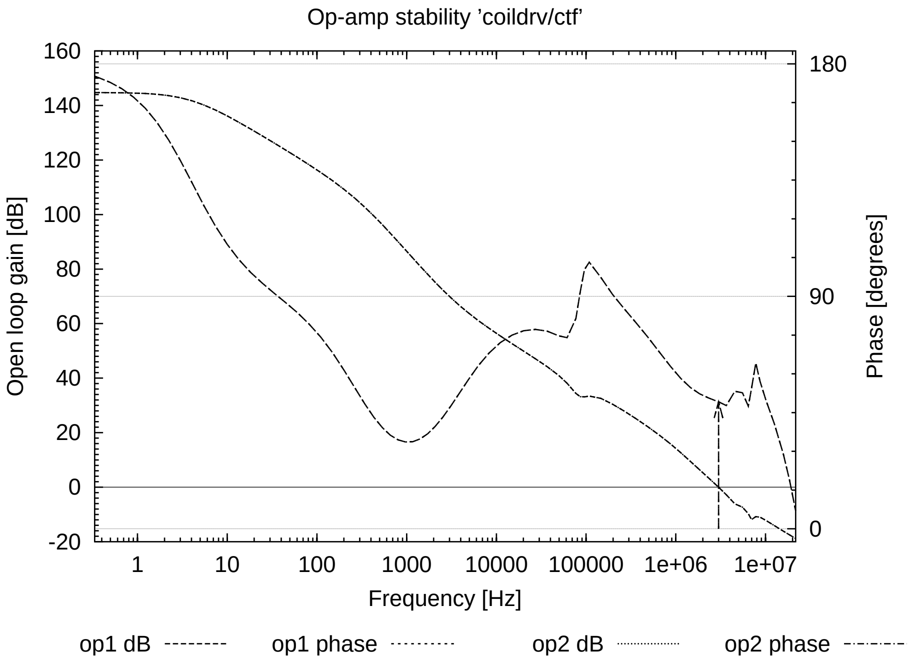

Figure 8: Open-loop gain of the AD797 op-amp in the new circuit.

6 Noise and readout system

Since the coil driver described in this document acts directly on the suspended mirrors of the interferometer, its noise is of utmost importance. Figure 9 shows the noise current through the coil, referred to the input (and hence expressed as equivalent $\mathrm{V}/\sqrt{\mathrm{Hz}}$ at the input). The two main contributors are also plotted, voltage input noise of the AD797 (dominant up to 3 kHz) and current input noise of the EL2099. The total noise at 1 kHz is $1.4\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, and it is dominated by the voltage noise of the AD797, a situation that can hardly be improved. The noise level at the input of the coil driver will almost always be much bigger than this.

In future there may be situations where the $1.4\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ added by the coil driver are a measurable contribution to the overall interferometer noise. If the open-loop gain of the relevant longitudinal control loop (i.e. L_-) is still > 1 at measurement frequencies, the noise can be further reduced by reading out the coil current directly.

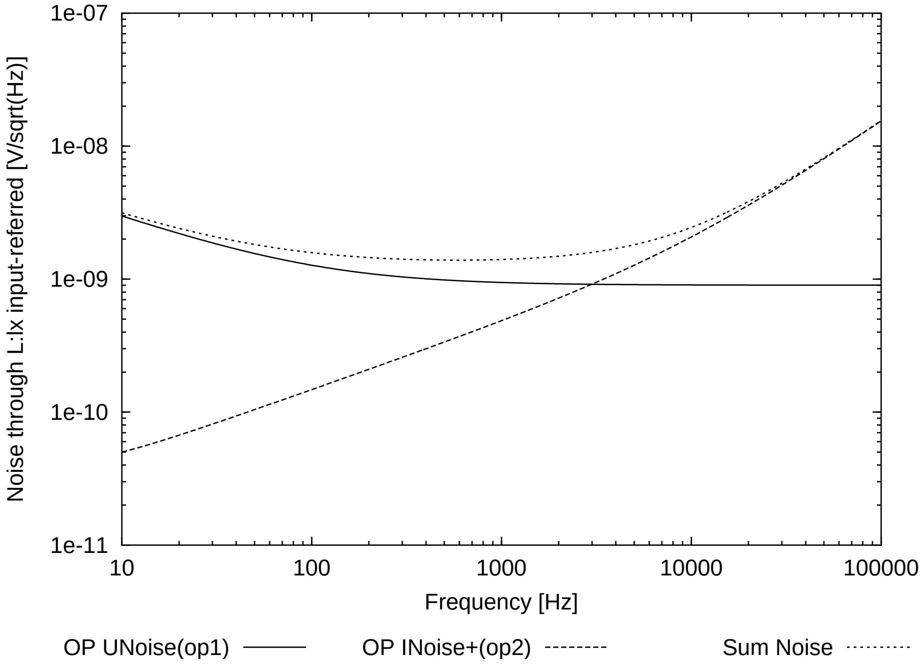

Figure 9: Noise of the coil driver circuit (see text).

In this situation, the noise added by the coil driver will be suppressed by the open-loop gain. However, the read-out amplifier will add extra noise of its own.

Figure 10 shows the circuit diagram of the readout amplifier (unchanged by the present author) and Figure 11 its transfer functions.

The two curves labeled 'a2' and 'a3' in Figure 12 show the **additional** noise generated by the readout amplifier, i.e. the noise generated by the components shown in Figure 10, again with and without the additional $50\,\Omega$ readout resistor. The noise at $1000\,\mathrm{Hz}$ is $1.85\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (without) and $0.92\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (with $50\,\Omega$), respectively. For comparison, the curve labelled 'a1' shows the total noise of the coil driver without the additional $50\,\Omega$ readout resistor (same as in Figure 9).

The noise reduction achievable by using the readout amplifier as compared to measuring directly at the coil drivers input is not very big. If necessary it may be possible to build a readout amplifier with lower noise by using an audio transformer. However, this will only be worthwhile when the coil driver noise is a significant contribution to the overall interferometer noise.

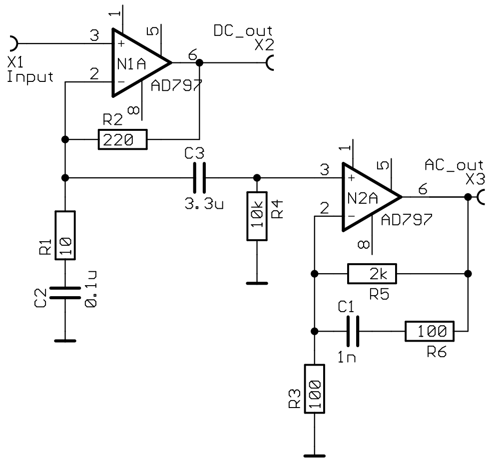

Figure 10: Readout amplifier.

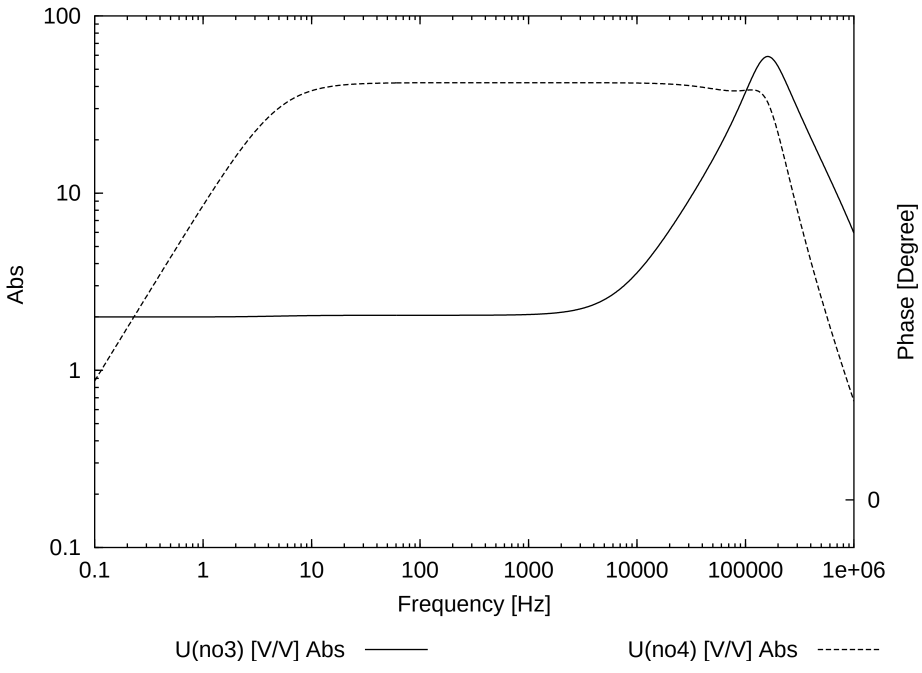

Figure 11: Transfer functions of the readout amplifier (DC and AC outputs, **with** additional $50\,\Omega$ readout resistor).

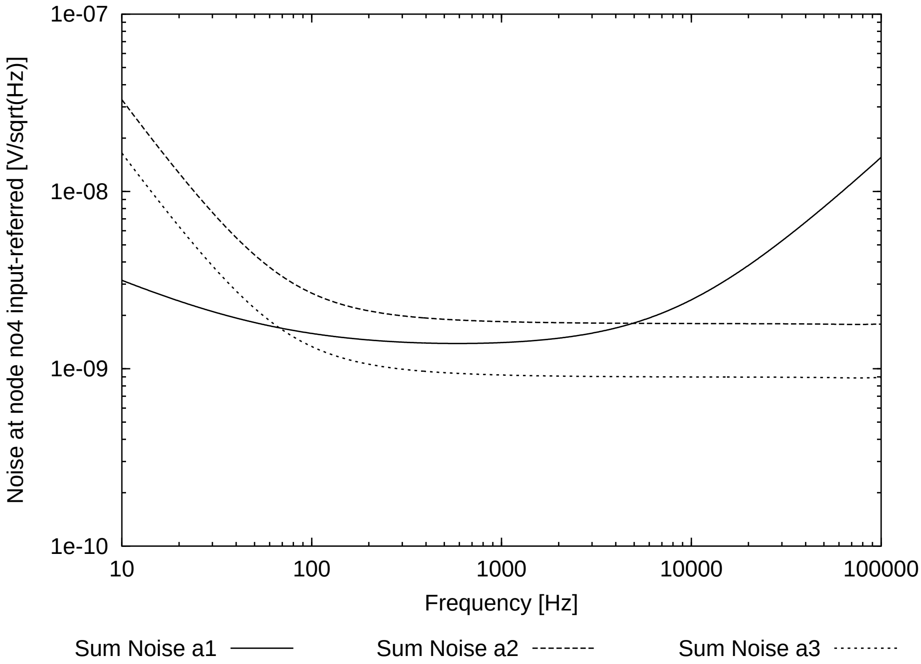

Figure 12: Noise generated by the readout amplifier ('a1' and 'a2' with and without the additional $50\,\Omega$ readout resistor, respectively) compared to noise of the coil driver ('a0').

7 Output impedance

In order to avoid damping of the pendulum, the output impedance of the coil driver should be high (ideally, a current source has infinite output impedance). Figure 13 shows the output impedance of the new driver circuit.

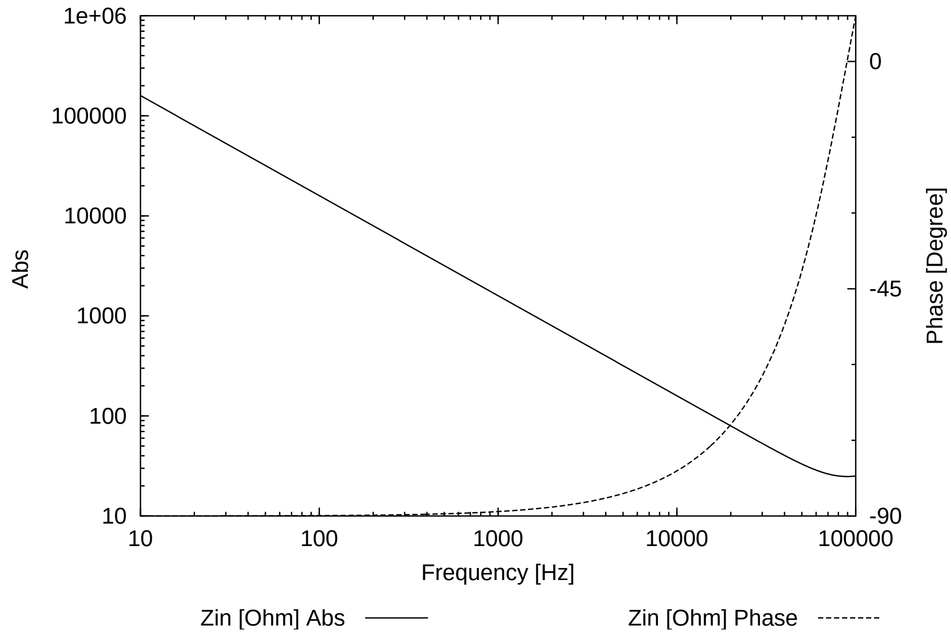

Figure 13: Output impedance of the coil driver circuit (see text).

For the damping of the pendulum the **real** part of the impedance is important. It is shown in Figure 14. At 1 kHz, its value is about 300 kΩ.

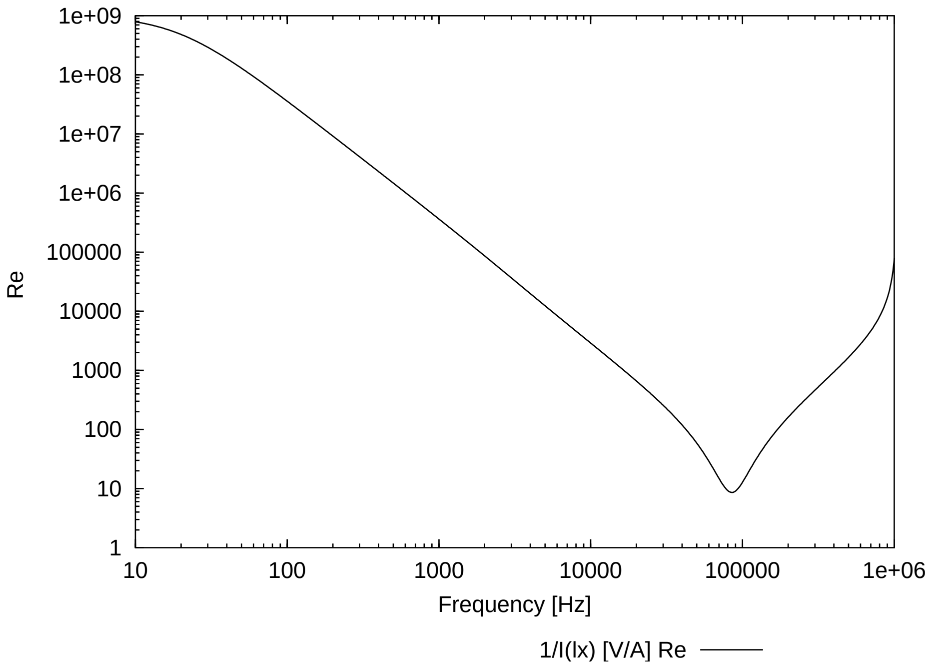

Figure 14: Real part of the output impedance of the coil driver circuit (see text).