Cancelling coil wire impedance to supercharge eddy current damping

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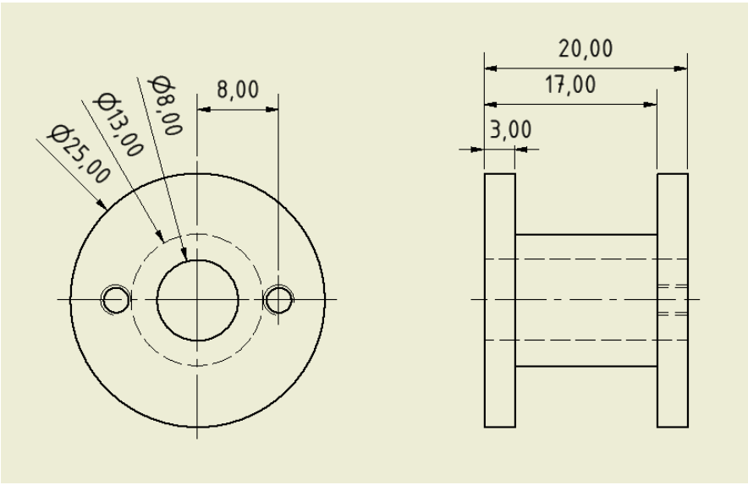
Eddy current damping

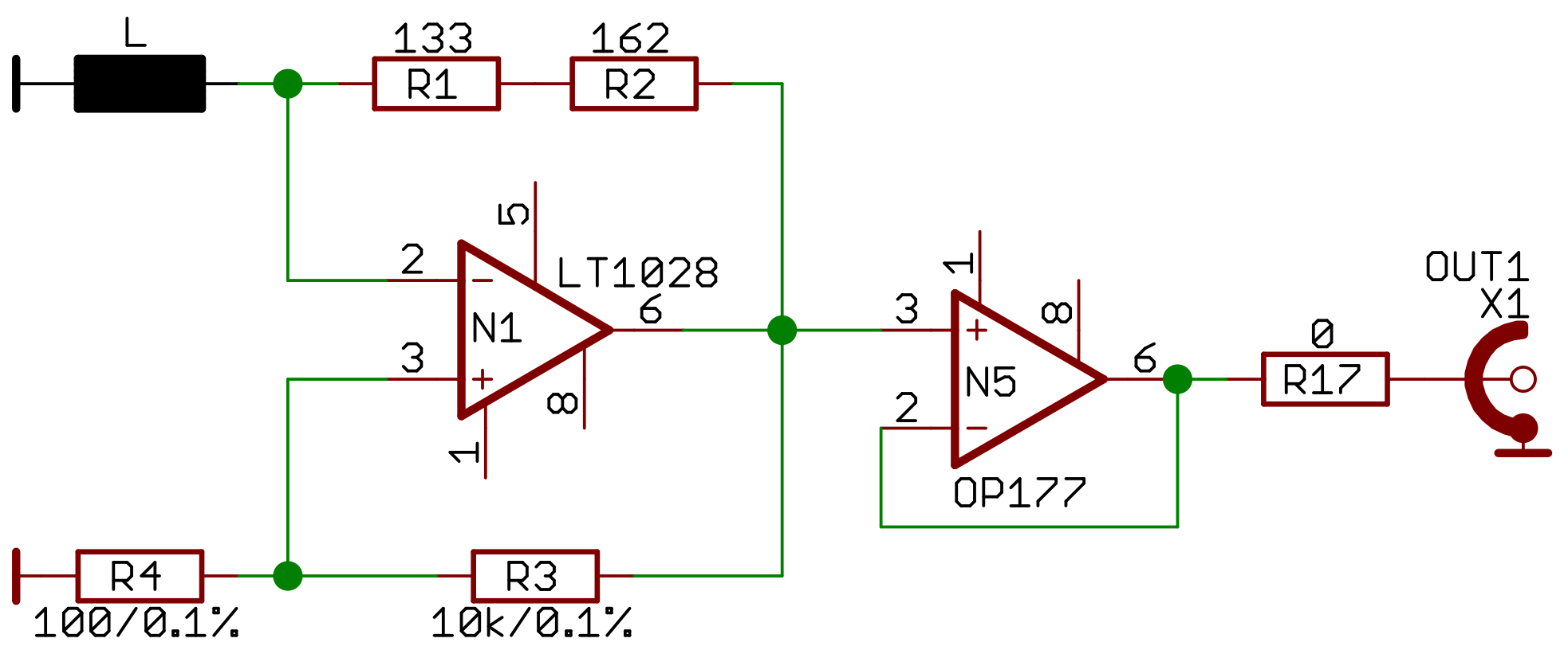
Multistage pendulum suspensions are used to attenuate test mass motion from environmental disturbances. Thermal noise from the suspension material influences the linewidth of the pendulum resonances via its quality factor (Q); this is typically minimised through the use of high-Q materials such as fused silica, but once excited at their mode frequencies, such materials have very long ringdown times. Eddy current dampers are typically employed to reduce the effective resonance Q-factors, consisting of high electrical conductivity cups around magnets attached to the test mass. Motion of the magnet relative to the cup induces eddy currents which are dissipated due to the resistance of the conductor, thereby extracting energy from the test mass. Voice coils are also typically wound around the cups to provide a means of actuation.

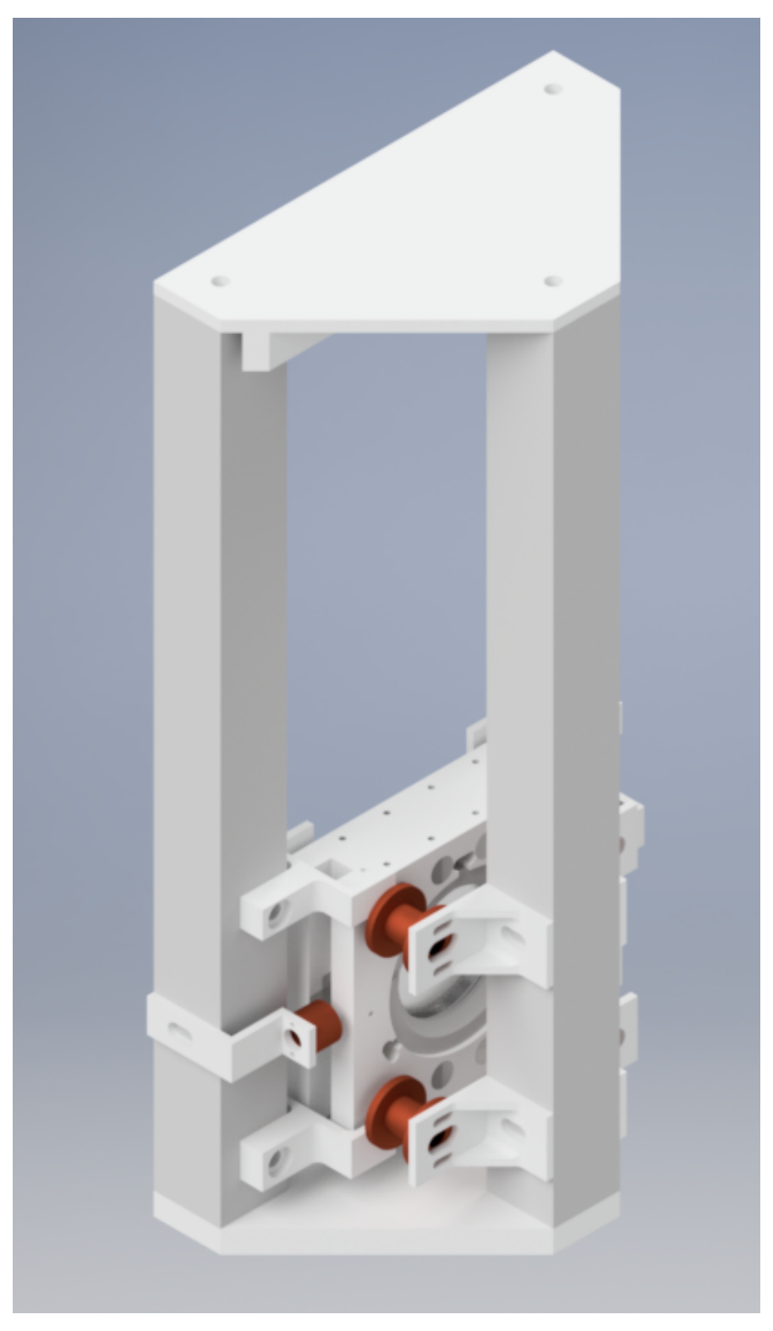
Eddy current damper design represents a trade-off between performance and noise coupling. Dampers bypass suspension filtering from suspension stages above, and the more turns that are used, the higher the available actuation but the higher the force noise due to the intrinsic resistance of the conductor (Johnson thermal noise). To resolve these competing goals, *switchable* eddy current damping has been introduced in the Glasgow Sagnac speed meter suspensions [1] to provide large damping during lock acquisition but low damping (and therefore noise) during measurements. The authors reported a reduction of the yaw mode Q-factor on a small suspension from 10,314 to 1,302. The damping performance of this system is still ultimately limited by the impedance of the coil wire. Here we consider a new approach using an active circuit to effectively cancel the coil wire impedance.

Experiment and initial results

A 2" suspended steering mirror designed for the AEI 10 m prototype was fitted with four polyoxymethylene coil formers wound with approximately 200 turns of 200 µm enamelled copper wire. The series resistance was around 5.4 Ω and inductance around 360 µH. The coils were connected to the circuit shown below.

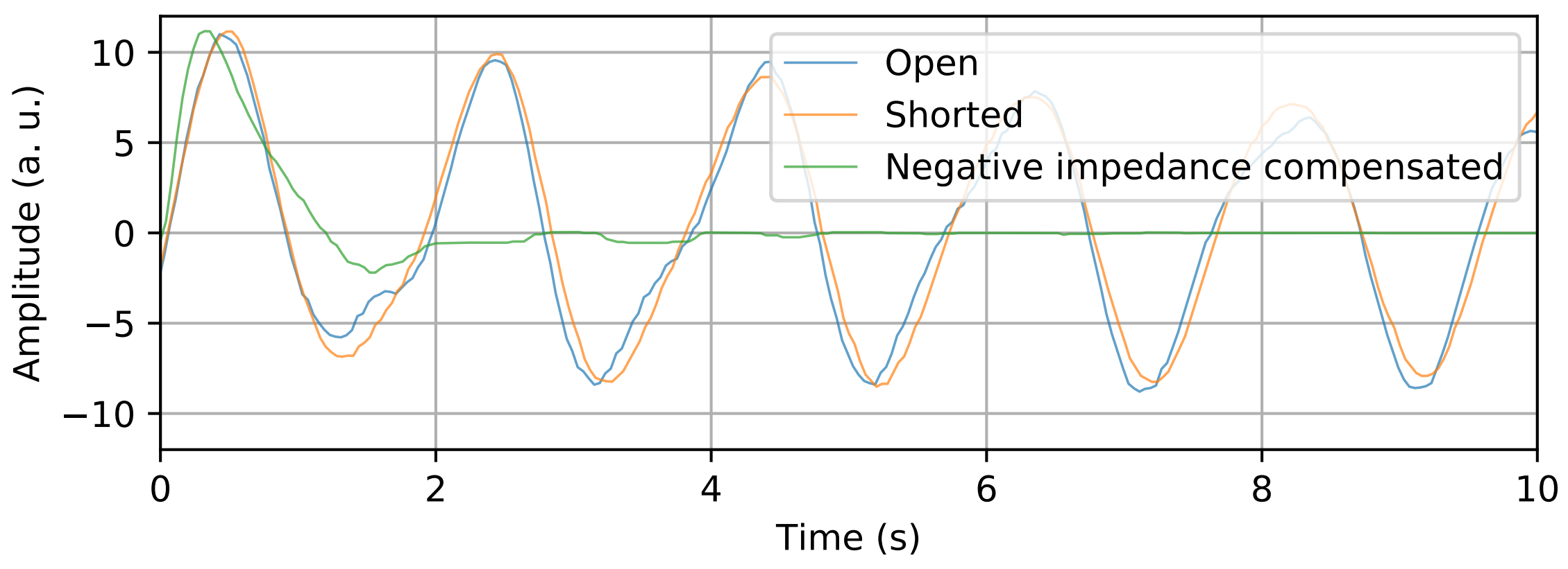


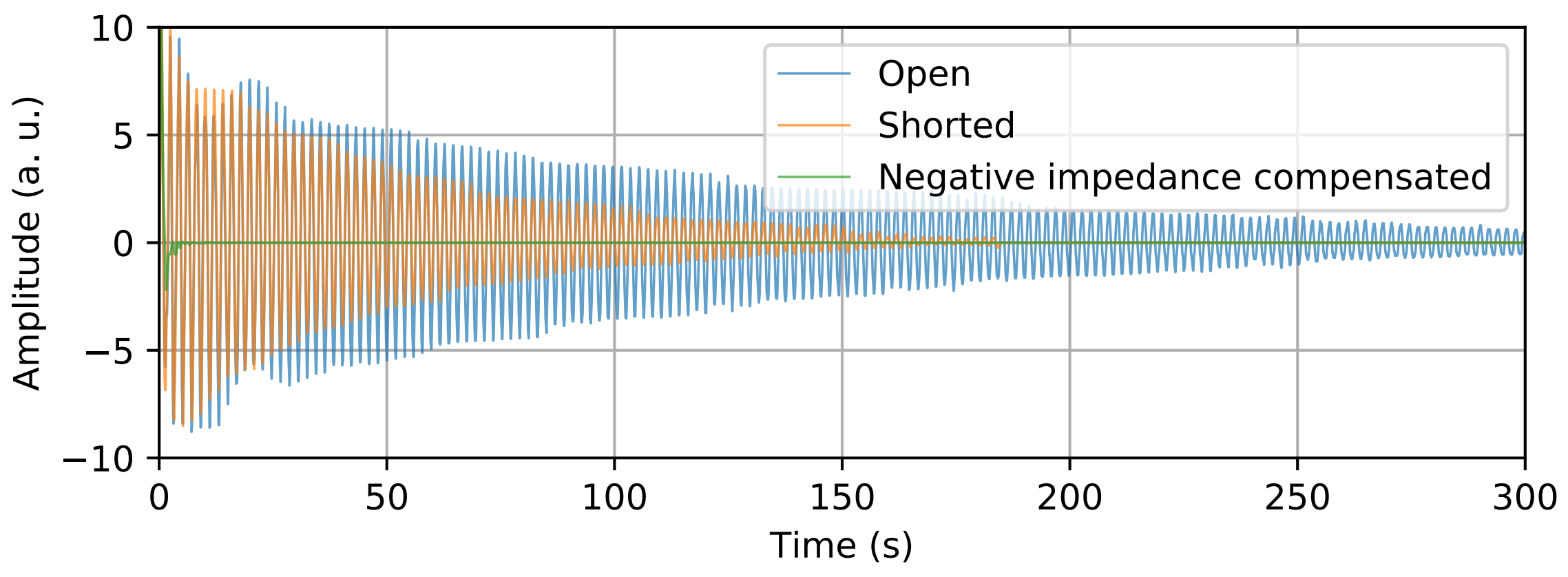




Copper eddy current dampers were installed on the sides of the mirror to damp all degrees of freedom except pitch. The mirror was then excited in pitch and the ringdown was observed with a camera. Video tracking software was used to estimate the ringdown times in three scenarios: circuit connected (representing negative impedance compensated coils), coils shorted (equivalent to ref. [1]), and coils open (no damping).

The negative impedance compensated coils are damped extremely quickly, with a time constant (1/e) of around **0.6 s**, compared to 50 s and 115 s in the case of the shorted and open coils, respectively.





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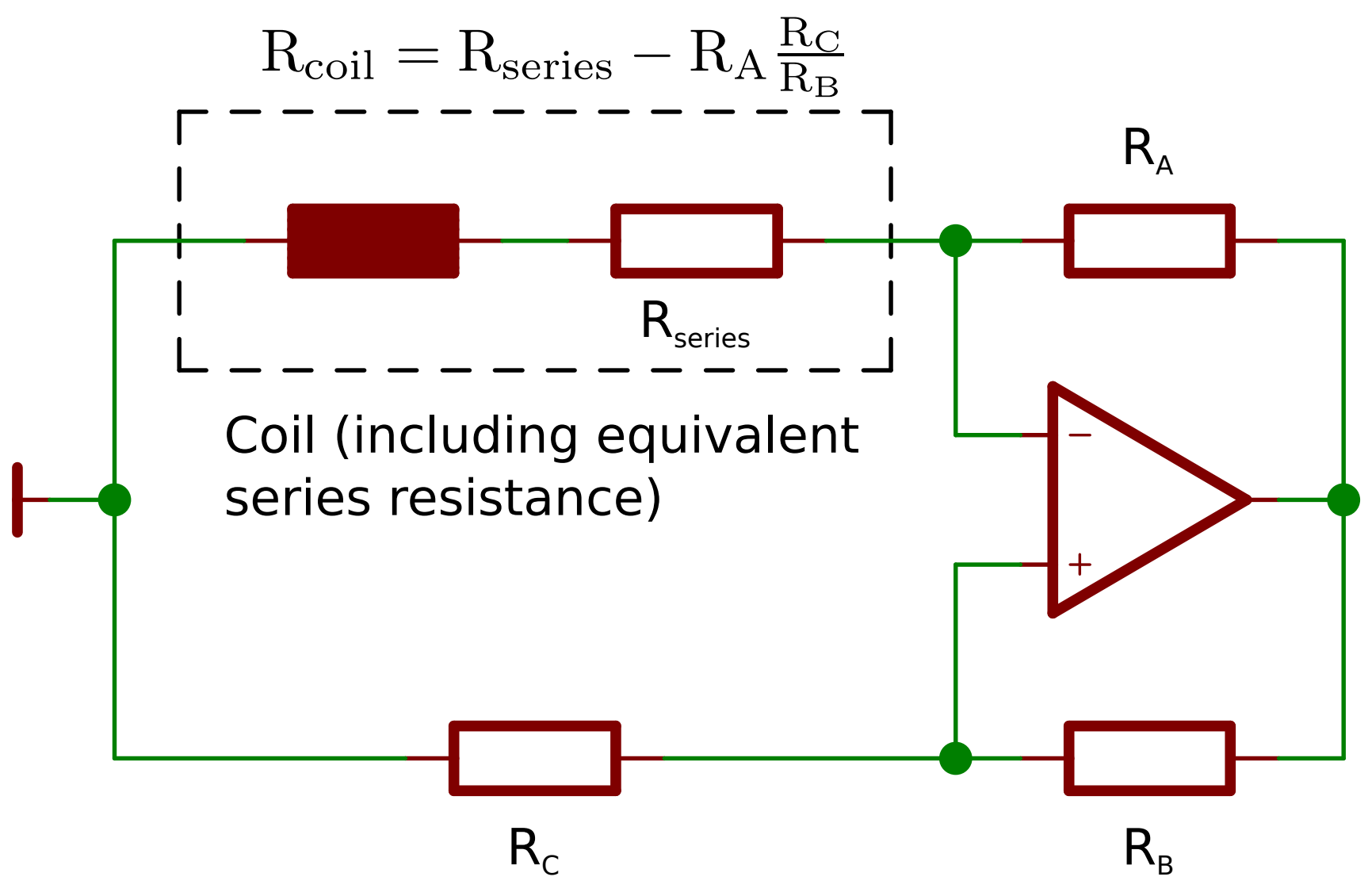
[1] Hennig et al., "*Demonstration of a switchable damping system to allow low-noise operation of high-Q low-mass suspension systems*", Phys. Rev. D **96**, 122005.

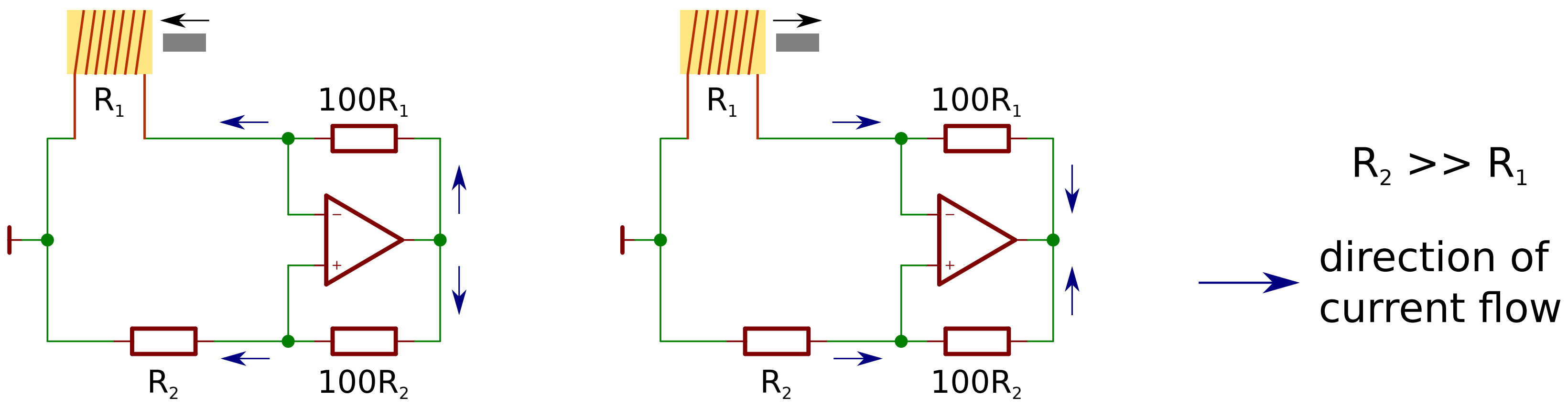
The presented work includes that of IREU summer student Isabella Molina.

Damping with negative impedance

Even greater damping performance compared to shorted coil wires while maintaining low noise can be achieved by reducing the effective coil impedance with an active circuit. The *negative impedance converter* op-amp circuit provides a means of reducing the effective resistance of a load by inducing an opposing voltage or current.



Negative feedback op-amp circuits output current to attempt to null the potential difference between the inverting and non-inverting inputs. The negative impedance converter works by providing an additional (in this case positive) feedback path to provide a current which must be additionally compensated by the negative feedback. With shorted coils, as in ref. [1], both sides of the coil wire "see" ground potential; however, with the negative impedance converter, one side of the coil sees a lower, negative potential due to the op-amp having to compensate for the positive feedback path. This is equivalent to the behaviour of a resistor in series with the coil with a negative magnitude, leading to the cancellation of the intrinsic coil impedance and therefore the ability to extract greater energy from the test mass.



By carefully tuning the ratio of the positive and negative feedback voltage dividers, very high damping can be achieved. The division ratio of the positive and negative feedback paths must be similar to achieve highest damping, with the positive path slightly lower than the negative path to avoid instability. The ratio between the resistors connecting the op-amp's output to its inputs sets the suppression. In theory, the positive feedback resistances should be much larger than the negative feedback resistances, but current and thermal noise considerations must be made when choosing values for a given op-amp.

The op-amp output provides a means of reading out the compensation signal. This provides a rudimentary sensor for the magnet's velocity, with the signal amplified by the inverse of the positive feedback resistors' division ratio. The positive feedback path can additionally be provided by an external input, allowing the readout and feedback to be filtered and rolled off at higher frequencies using e.g. CDS. The feedback path can also be used to apply offsets, allowing for dc and ac adjustment of the test mass position.

Conclusions and future work

The presented system is already successful as a means of damping suspensions after lock loss transients. It is, however, not yet clear whether the presented system will provide sufficiently low force noise to be used during data acquisition of low noise experiments. It is likely that optical readout systems (for example, BOSEMs) will still win in displacement noise terms, but this system provides the advantage that no in-vacuum hardware is required beyond voice coils, providing both simplicity and the possibility to retrofit negative impedance converters on existing auxiliary suspended optics.

Future work will investigate the displacement noise imparted onto the test mass by electronic noise through the use of an out-of-loop optical sensor, and the system will be further integrated into CDS to allow for reprogrammable filtering and integration with lock acquisition routines. Another topic of investigation will be calibration of the readout signal in terms of displacement, providing a potentially useful error signal for local control of suspensions.

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