Control and tuning of a suspended Fabry-Perot cavity using digitally-enhanced heterodyne interferometry

John Miller,* Silvie Ngo, Adam J. Mullavey, Bram J. J. Slagmolen, Daniel A. Shaddock and David E. McClelland

Centre for Gravitational Physics, The Australian National University, Canberra, ACT, 0200, AUSTRALIA

*john.miller@anu.edu.au

Compiled April 13, 2017

We present the first demonstration of real-time closed-loop control and deterministic tuning of an independently suspended Fabry-Perot optical cavity using digitally-enhanced heterodyne interferometry, realising a peak sensitivity of $\sim 10 \text{ pm}/\sqrt{\text{Hz}}$ over the 10–1000 Hz frequency band. The methods presented are readily extensible to multiple coupled cavities. As such, we anticipate that refinements of this technique may find application in future interferometric gravitational-wave detectors. © 2017 Optical Society of America

OCIS codes: 120.2230,120.3180.

Fabry-Perot optical resonators continue to play an important role as frequency references and displacement sensors across a variety of disciplines. Several established techniques exist for deriving resonator sensing and control signals, the most prevalent being the Pound-Drever-Hall (PDH) method [1]. However, all of these techniques suffer from the same shortcoming – useful signals are only realised in a small neighbourhood around resonance. This characteristic reduces sensing range and can make it difficult to bring a cavity to resonance from an initially uncontrolled state, a process known as lock acquisition.

Lock acquisition proved a particularly challenging problem for the first generation of gravitational-wave interferometers (GWIFOs) and, due to increased optical complexity, the solutions developed [2, 3] are not appropriate for contemporary instruments (e.g. [4]). Hence, this issue has been the subject of significant research interest in recent years, resulting in the development of acquisition schemes for second generation GWIFOs (e.g. [5]). More recently, tools have been developed to supplement these schemes in an effort to make the lock acquisition process more deterministic [6, 7]. However, these tools are limited to a single degree of freedom and may not be immediately compatible with proposed third-generation detectors (e.g. [8]). For these reasons, readouts based on the newly developed digitally-enhanced heterodyne interferometry (DEHI) technique [9] are of great interest to the gravitational-wave community.

DEHI augments the standard heterodyne interferometry technique with an additional radio-frequency binary modulation-demodulation stage to provide a number of additional features without compromising the underlying heterodyne sensitivity. Specifically, it allows high-dynamic-range multiplexed measurements to be performed whilst simultaneously suppressing noise due to electronics and scattered light.

The multiplexing capabilities of DEHI have been verified in fibre strain measurements [10] and its noise performance has been explored using a low-finesse fixed-mirror Fabry-Perot cavity [11]. We build upon this work to present the first demonstration of real-time control and tuning of an independently suspended Fabry-Perot optical cavity using DEHI. These results are of relevance to the problem of lock acquisition in future GWIFOs.

In order to measure the detuning of a Fabry-Perot optical cavity we employ DEHI in transmission to perform heterodyne measurements on two beams, one which passes directly through the cavity and another which undergoes a round trip before being transmitted. Both measurements are performed relative to the same reference beam so that the difference between the resulting phases is the round-trip cavity phase.

Reference Laser

Fig. 1. (Colour online) Schematic showing our cavity apparatus addressed by two measurement systems, DEHI and PDH. The DEHI reference laser doubles as the input source for PDH readout. Cavity length can be controlled by applying either PDH or DEHI signals to coil-magnet actuators on the resonator’s end mirror.
A schematic of our experimental setup is shown in Fig. 1. Our cavity was formed between two ‘Tip-Tilt’ suspension systems [12]. It was 1.3 m long and had a finesse of $\sim$300. The measurement laser was an Innolight Prometheus (1064 nm output). This source was offset phase-locked to a Lightwave 126 laser which provided both the DEHI reference beam and the input light for corroboratory PDH measurements. All digital signal processing was carried out using a commercial field-programmable gate array (Xilinx Virtex-5 LX110).

The measurement beam was first phase modulated with a pseudo-random noise (PRN) code of length $2^{15} - 1$. The chipping frequency was set to 115.3 MHz, matching the cavity’s free spectral range. In this way a signal which completes $n$ round trips through the cavity is delayed by $n$ chips.

The beam transmitted through the cavity was combined with the reference beam and detected by a wide-bandwidth photodetector (New Focus 1811). The photodiode output was sampled at 115.3 MHz and divided into two processing channels. The first channel was demodulated with the PRN code delayed by $\tau_1$ to isolate the straight-through beam. The second channel was demodulated with the PRN code delayed by $\tau_1 + \tau_2 = \tau_1 + n\tau_{PRN}$, where $\tau_{PRN}$ is the PRN code chip-period, to isolate the $n^{th}$ round-trip beam.

The demodulated signals were subsequently passed to independent digital phase meters. These phase meters continually modify their local oscillator to match its frequency to that of the input signal, integrating the frequency error to retrieve phase information. It is this closed-loop operation which endows DEHI measurements with their impressive dynamic range.

The outputs of the two phase meters were finally subtracted to yield a direct measure of the round-trip cavity phase. This difference was used as the error signal in a feedback loop controlling the cavity’s resonant state. Correction signals were applied to the cavity end mirror using coil-magnet actuators.

Of utmost importance to any interferometric sensing technique is its noise performance or sensitivity. This quantity was evaluated by locking the cavity on resonance using the DEHI system and employing a standard PDH sensing scheme as an out-of-loop sensor.

The results, presented in Fig. 2, show both the in-loop DEHI error signal and the out-of-loop PDH error signal. Together, these traces reveal that the DEHI scheme employed here is limited by white sensing noise at the 7 pm/$\sqrt{\text{Hz}}$ level with performance degrading toward lower ($\approx 20$ Hz) frequencies.

In a DEHI measurement signals arrive at the photodetector not only from the desired straight-through and round-trip beams but also from light which undergoes multiple round trips within the cavity. Since DEHI provides only finite attenuation of unwanted signals, these additional components limit sensitivity and give rise to the white noise observed.

The broadband nature of the DEHI noise floor may limit usefulness in noise-critical applications, especially in the context of multiply suspended optics. For example, based on Simulink modelling of the Advanced LIGO suspensions, we estimate that in order for DEHI to be useful as a lock acquisition tool the white noise floor must be reduced to $\sim 1$ pm/$\sqrt{\text{Hz}}$. This requirement is enforced to prevent saturation of the suspension actuators. Fortunately, however, the level of the DEHI noise floor scales as $\sqrt{\tau_{PRN}}$. This dependency allows one to leverage future advances in digital signal processing to improve performance. Based on currently available hardware we believe that sub-picometre noise levels are realistically achievable.

Below $\sim 20$ Hz, trace (i) in Fig. 2 represents an upper bound to the DEHI sensitivity. Low-frequency noise is introduced by the DEHI system but is associated with external factors. For instance, alignment fluctuations affect DEHI more strongly than PDH as DEHI is a non-resonant technique which does not benefit from the spatial mode filtering of the cavity. A standard auto-alignment system would substantially mitigate this problem. Acoustic couplings are also known to adversely affect our bench-top apparatus. Indeed, the prominent feature centred about 130 Hz is the acoustic resonance of the intra-cavity beam tube introduced to ameliorate this low frequency noise source. Vacuum operation would yield significant improvements in this area.

The unity gain frequency of the DEHI loop was set to $\sim 100$ Hz, where the free-swinging displacement noise intersected the DEHI noise floor, so that injected noise would not compromise the pendulums’ isolation. This choice explains the observed high-frequency roll-off.

DEHI offers excellent sensitivity, compatible with the vast majority of industrial and scientific measurements. Nevertheless, some extreme endeavours require performance which surpasses that presented here. In such cases...
DEHI can be used to acquire initial control before deferring to a second sensor. Mindful of this, we detail in Fig. 3 the transfer of control over our independently suspended optical cavity from the high-dynamic-range DEHI system to a lower-noise PDH readout.

![Graph](image)

**Fig. 3.** (Colour online) Automated acquisition of cavity length control using digitally-enhanced heterodyne interferometry. Top – DEHI error signal (i.e. round-trip cavity phase). Middle – Normalised Pound-Drever-Hall error signal. Bottom – Normalised reference laser cavity transmission. Data were sampled at \( \sim 200 \text{ Hz} \). The division of the axes is discussed in the main text.

Each stage of the transfer is now described according to the alphabetic labels in Fig. 3. a) Initially the cavity is freely swinging, its motion driven by environmental disturbances. b) The cavity is then locked at a predetermined offset from resonance, far from any higher-order modes or sidebands, using the omnipresent DEHI signal. c) The offset is reduced in a controlled manner until the cavity arrives within the linewidth of the desired carrier resonance. d) At this point the PDH signals become quasi-linear and control over cavity length is transferred from the DEHI loop to the PDH loop by simultaneously adjusting their respective gains (G in Fig. 1).

e) The cavity is now under sole control of the PDH-based feedback loop. At all stages of the transfer control signals were applied to the end mirror’s coil magnet actuators.

These data confirm that DEHI has the capability to produce useful sensing signals at any cavity detuning. This large dynamic range, combined with previous demonstrations of multi-mirror multiplexing [10], engenders confidence that the technique will perform as expected if applied to coupled-cavity interferometers.

Work is currently under way to extend the DEHI concept from longitudinal to angular control. This would result in a wide-range alignment sensor which does not have cavity resonance as a prerequisite to its operation. Such a system may be capable of replacing traditional optical levers. Techniques are also being developed to allow DEHI to operate in reflection and with improved sensitivity [13].

**Acknowledgements**

The authors thank Lisa Barsotti for valuable comments during the preparation of this manuscript. This work was supported by the Australian Research Council (ARC). JM is the recipient of an ARC Post Doctoral Fellowship (DP110103472). This paper has been assigned LIGO Laboratory document number LIGO-P1200100.

**References**

1. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Applied Physics B: Lasers and Optics 31, 97 (1983).
2. M. Evans, N. Mavalvala, P. Fritschel, R. Bork, B. Bhawal, R. Gustafson, W. Kells, M. Landry, D. Sigg, and R. Weiss, Optics Letters 27, 598 (2002).
3. F. Acernese et al., Astroparticle Physics 30, 29 (2008).
4. G. M. Harry and the LIGO Scientific Collaboration, Classical and Quantum Gravity 27, 084006 (2010).
5. R. L. Ward, Ph.D. thesis, California Institute of Technology (2010).
6. A. J. Mullavey, B. J. J. Slagmolen, J. Miller, M. Evans, P. Fritschel, D. Sigg, S. J. Waldman, D. A. Shaddock, and D. E. McClelland, Opt. Express 20, 81 (2012).
7. K. Izumi, K. Arai, B. Barr, J. Betzwieser, A. Brooks, K. Dahl, S. Doravari, J. C. Driggers, W. Z. Korth, H. Miao, J. Rollins, S. Vass, D. Yeaton-Massey, and R. X. Adhikari, J. Opt. Soc. Am. A 29, 2092 (2012).
8. M. Punturo et al., Classical and Quantum Gravity 27, 084007 (2010).
9. D. A. Shaddock, Optics Letters 32, 3355 (2007).
10. D. M. R. Wuchenich, T. T.-Y. Lam, J. H. Chow, D. E. McClelland, and D. A. Shaddock, Opt. Lett. 36, 672 (2011).
11. G. de Vine, D. S. Rabeling, B. J. J. Slagmolen, T. T.-Y. Lam, S. Chua, D. M. Wuchenich, D. E. McClelland, and D. A. Shaddock, Opt. Express 17, 828 (2009).
12. B. J. J. Slagmolen, A. J. Mullavey, J. Miller, D. E. McClelland, and P. Fritschel, Review of Scientific Instruments 82, 125108 (2011).
13. A. J. Sutton, O. Gerberding, G. Heinzel, and D. A. Shaddock, Opt. Express 20, 22195 (2012).
References

1. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, “Laser phase and frequency stabilization using an optical resonator,” Applied Physics B: Lasers and Optics 31, 97–105 (1983).

2. M. Evans, N. Mavalvala, P. Fritschel, R. Bork, B. Bhawal, R. Gustafson, W. Kells, M. Landry, D. Sigg, and R. Weiss, “Lock acquisition of a gravitational-wave interferometer,” Optics Letters 27, 598–600 (2002).

3. F. Acernese et al., “Lock acquisition of the Virgo gravitational wave detector,” Astroparticle Physics 30, 29–38 (2008).

4. G. M. Harry and the LIGO Scientific Collaboration, “Advanced LIGO: the next generation of gravitational wave detectors,” Classical and Quantum Gravity 27, 084006 (2010).

5. R. L. Ward, Ph.D. thesis, California Institute of Technology (2010).

6. A. J. Mullavey, B. J. J. Slagmolen, J. Miller, M. Evans, P. Fritschel, D. Sigg, S. J. Waldman, D. A. Shaddock, and D. E. McClelland, “Arm-length stabilisation for interferometric gravitational-wave detectors using frequency-doubled auxiliary lasers,” Opt. Express 20, 81–89 (2012).

7. K. Izumi, K. Arai, B. Barr, J. Betzwieser, A. Brooks, K. Dahl, S. Doravari, J. C. Driggers, W. Z. Korth, H. Miao, J. Rollins, S. Vass, D. Yeaton-Massey, and R. X. Adhikari, “Multicolor cavity metrology,” J. Opt. Soc. Am. A 29, 2092–2103 (2012).

8. M. Punturo et al., “The third generation of gravitational wave observatories and their science reach,” Classical and Quantum Gravity 27, 084007 (2010).

9. D. A. Shaddock, "Digitally enhanced heterodyne interferometry," Optics Letters 32, 3355–3357 (2007).

10. D. M. R. Wuchenich, T. T.-Y. Lam, J. H. Chow, D. E. McClelland, and D. A. Shaddock, “Laser frequency noise immunity in multiplexed displacement sensing,” Opt. Lett. 36, 672–674 (2011).

11. G. de Vine, D. S. Rabeling, B. J. J. Slagmolen, T. T.-Y. Lam, S. Chua, D. M. Wuchenich, D. E. McClelland, and D. A. Shaddock, “Picometer level displacement metrology with digitally enhanced heterodyne interferometry,” Opt. Express 17, 828–837 (2009).

12. B. J. J. Slagmolen, A. J. Mullavey, J. Miller, D. E. McClelland, and P. Fritschel, “Tip-tilt mirror suspension: Beam steering for advanced laser interferometer gravitational wave observatory sensing and control signals,” Review of Scientific Instruments 82, 125108 (2011).

13. A. J. Sutton, O. Gerberding, G. Heinzel, and D. A. Shaddock, “Digitally enhanced homodyne interferometry,” Opt. Express 20, 22195–22207 (2012).