7 Lock acquisition of Fabry Perot cavity

The cavity end mirror energy retains following relation.

$$\frac{1}{2}mv_0^2 \leq F\Delta L \tag{53}$$

m, v_0, F, and ΔL are test mass, test mass velocity, actuation force and sensing range. Therefore the key point for success of lock acquisition are

1. Reducing v_0
2. Strengthen actuation force
3. Widen sensing range (sensing range $\propto \frac{1}{Finesse}$).

In KAGRA, the cavities finesse are high about 1500 and if the larger actuator force has much actuator noise. Therefore idea for 1st item is needed.

In this section, as the part of RSE lock acquisition, here is the verification for effectiveness of one software method that is called Guided Lock for arm cavity to reduce the mirror velocity.

Guided Lock [5] is the method of deceleration of mirror velocity to possible one for lock acquisition. In this thesis it succeeds in raising the lock probability by critical actuation of the mirror. This critical guided lock is tested in TAMA300 [6] and the result is that effect of acceleration by the seismic motion would release the mirror position.

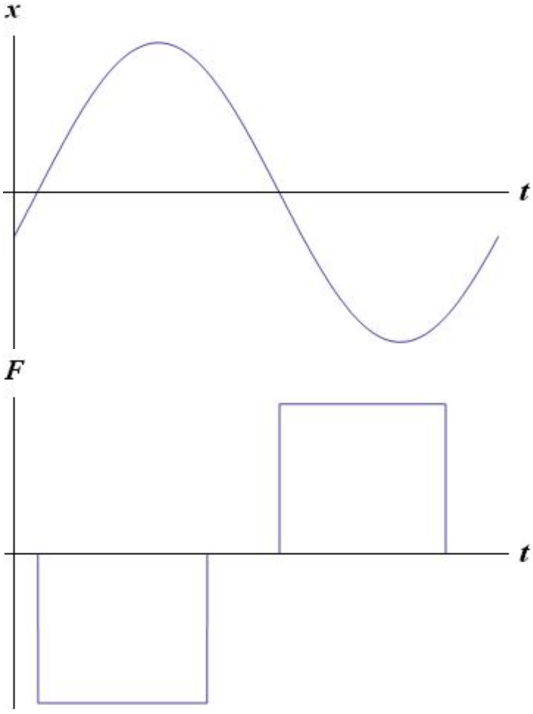

Figure 43: actuation to mirror for deceleration

7.1 Refined Guided Lock

In ground base detector, seismic motion is inevitable at low frequency and frustrates the stability of optical system. But the end mirror of Fabry Perot cavity has to be actuated for retaining the cavity length as resonance. Considering the mirror deceleration for locking, the crucial parameter is duration time of actuation.

Primary actuation is operated without any considerations about actuation duration. If the time is much long, the mirror has only inverted velocity from first resonance. But if it is too short, it takes much time to come back to the resonant point. In principal, there is optimal actuation duration to minimize the full time until acquiring lock of cavities.

Therefore actuation duration time should be optimized. In what follows, Guided Lock means Guided Lock with this new optimization. The actuation duration T is calculated as follow with deceleration

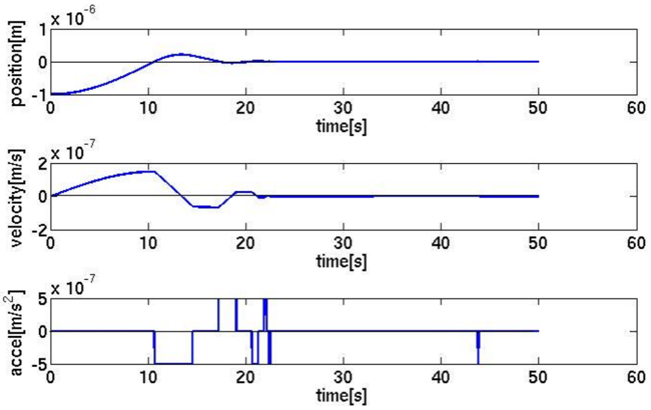

Figure 44: Guided Lock effect without any disturbance

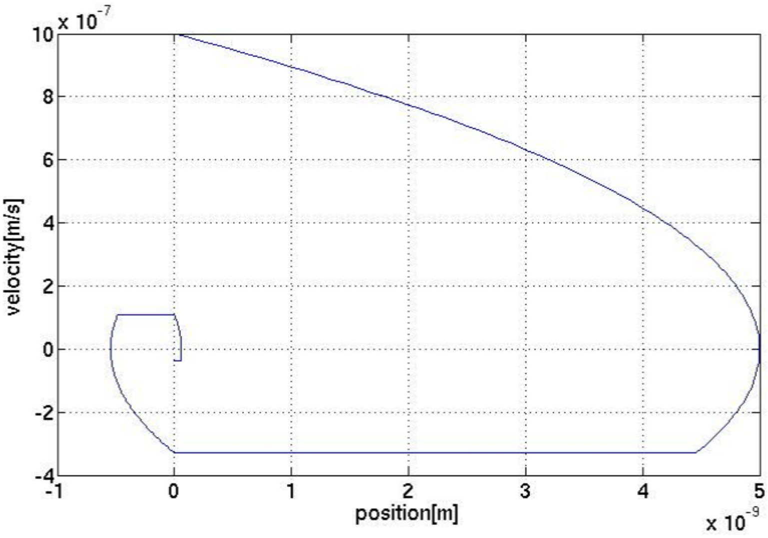

Figure 45: Guided lock effect

parameter β.

$$
\begin{aligned}
v_0 - accel\tau &= 0 \\
\tau &= \frac{v_0}{accel}
\end{aligned}
$$

$$T = \beta\tau \tag{54}$$

' τ ' is the duration time of deceleration to zero, 'v_0' is mirror first velocity at resonant point and ' accel ' is acceleration in m/s^2. (1$\leq \beta \leq$2)

- $\beta = 2 \rightarrow v = -v_0$: Therefore it's far from deceleration.
- $\beta = 1 \rightarrow v = 0$: It takes much time to come back to the resonant position.

Optimizing this β is what we call Guided Lock.

Guided Lock is executed repeatedly at every resonance until decelerated point to threshold velocity, which is possible mirror velocity to acquire lock.

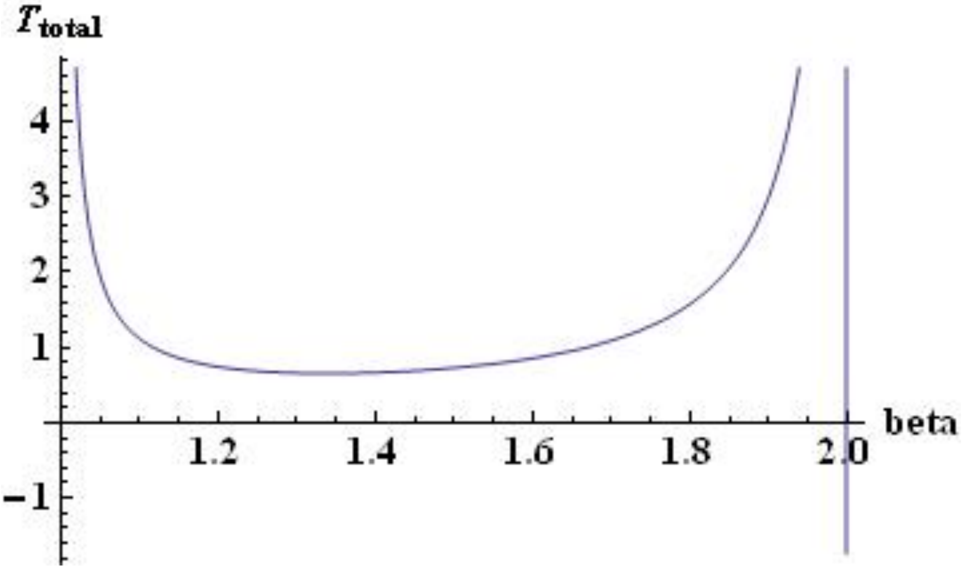

Figure 46: β-T_{total} optimization

Actuation duration is critical to soft landing for locking. Here is the calculation by matlab of optimal β.

$$T_{total} = \tau \cdot \frac{\beta^2}{2\beta - 2} \cdot \left(\frac{(\beta - 1)^N - 1}{\beta - 2} \right)$$
$$N = \frac{Log\left(\frac{v_{lock}}{v_0}\right)}{Log(\beta - 1)} \tag{55}$$

Calculated optimal β by matlab is 1.33. Figure43show the mirror swinging around resonant point and the force on mirror. In this system, mirror velocity is calculated crossing the near zero and according to this velocity' sign and value, the actuation force on the mirror for deceleration is determined. If the mirror velocity is down to threshold by Guided Lock actuation force, system switch to the filtered feeding back the error signal from cavity for acquiring the lock of cavity.

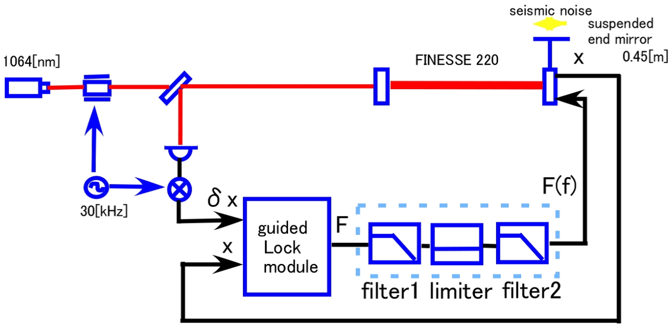

Figure 47: guideLock scheme

Parameter	Value
Mirror mass	10kg
Suspension length	0.45m
Cavity length	3995m
Modulation frequency	24.493MHz
Transmittance of ITM	0.028
Transmittance of ETM	6×10^{-6}
Mirror loss of ITM	7.5×10^{-5}
Mirror loss of ETM	7.5×10^{-5}
Finesse	220
β	1.33
Guided Force	0.9mN

Table 10: optical parameters for Guided Lock

7.2 setup on e2e

Figure47 is the diagram of the guide locking process simulation by end to end (e2e), the time domain simulator written by C++.

One arm Fabry Perot cavity, whose end mirror is suspended and its suspension point is excited by seismic motion, is locked by pre-modulation and demodulation with Guided Lock.

In this scheme, there is the 'Guided Lock' module as 'FUNC' module in the feeding back loop. The error signal, end mirror position and end mirror velocity are the input of 'Guided Lock' module, whose output is the force on mirror.

Above the threshold velocity, this module chooses the guided force

Switched filter	Pole	@100Hz (2)
	Zero	@1kHz (1)
	Gain	0.003

Table 11: Parameters of servo for error signal

filter1	Pole	2.7Hz (1)
	Zero	11Hz (1)
	Gain	3.7mN@11〜40Hz
filter2	Pole	40Hz (1)
	Zero	81Hz (1)
	Gain	7.4mN @81Hz〜
Limiter value	0.9mN	

Table 12: Parameters of filters for force frequency depended

for deceleration. If once the velocity were below the threshold, the module would choose the servo for error signal.

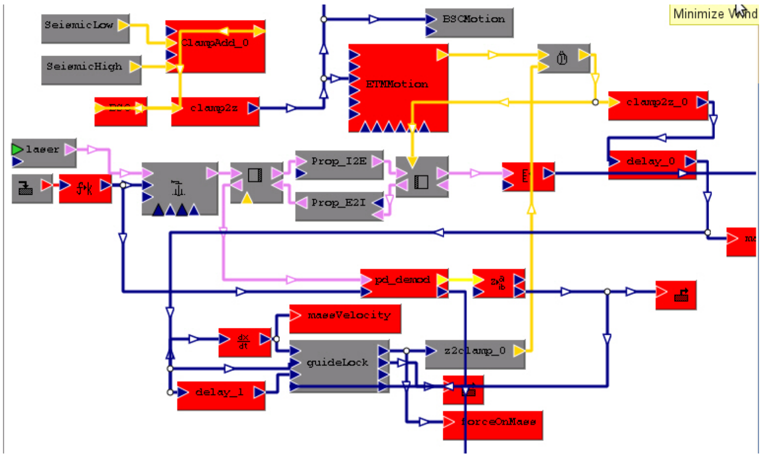

Figure 48: optical setup on alfi

This FUNC module (seeing in Appendix 1) is composed of 3 parts.

1. Measurement of the mirror velocity
    - For the later determination of actuation
        - Velocity is defined with delay module. By the time passing $10^{-10} m$ from resonance and the time on resonance, its velocity is calculated.
2. The determination of the mirror velocity
    - For switching whether it reaches threshold velocity to acquire the lock
        - The threshold velocity is one parameter.
3. Operation of the feedback force to end mirror according to that determination,
    - Guided force or servo using error signal is chosen by Boolean from step2.
        - Output of this calculation module is connected to the limiter that is 9mN and the force has frequency dependence by fileter1 and filter2.

The guided force is constant to get the velocity lower and the error signal is fed back at the temporary after the switching until acquiring lock.
Every simulation is executed

- Under the seismic motion and threshold velocity being variable
  - $\times \frac{1}{10}$, $\times \frac{1}{3}$, $\times 1$, $\times 3$, $\times 10$ of seismic motion at Hanford site
  - threshold velocity range is 1×10^{-5} to 1×10^{-8}
- Each is executed under the same condition by 10 different seeds.

The detail of parameters used in this simulation is table (7.1).

Seismic motion level	upper value
$\frac{1}{10}$Hanford	1×10^{-6}
$\frac{1}{3}$Hanford	3×10^{-6}
Hanford	4×10^{-6}
$3\times$Hanford	2×10^{-5}
$10\times$Hanford	3×10^{-5}

Table 13: Seismic level under the guide Lock simulation

7.3 Result of guided lock

When servo works at the end mirror being around resonant, the lock acquisition works well under the lower seismic motion. However at higher seismic level it needs to guided lock to decelerate end mirror velocity.

The guided lock effect is when the disturbance is 3 and 10 times of Hanford site. At lower disturbance, this system could get lock only by servo. The main reason of failure locking is that still trend remains.

8 Conclusion

RSE is the necessary to next generation ground detector. However it is challenging due to high finesse and high degree of freedom that RSE acquires the lock.

This scheme aim to validate the software method to lock RSE.

In first, it is attested to be effective to use multi-deceleration Guided Lock if there are some large disturbance with where only servo could not control by it own. The lock acquisition rate get improved by 1.3∼3 times.

And second, it is approved to constrain the moving end test mass by some signals with the central part lock holding. All of the ETMX and ETMY each and ETMX·Y could be constrained and make it possible to use the guided Lock.

This software method could be the backup plan for KAGRA.

Appendix

1. Programs in GuidedLock module

```
if(useGL)
  {
   if ( t >5 )
     {
      if ( (fabs(posIn)-1e-10)*(fabs(posIn2)-1e-10) <0 )
            //posIn is mirror position and posIn2 is one step delayed data.
            define the 1e-10m from resonance and that the time.
        {
         t1=t;
         x=posIn;
        }
      if (posIn*posIn2 < 0 )
            //define the time on resonance. calculates the mirror velocity.
        {
         t2=t;
         vel=-x/(t2-t1);
        if (fabs (vel) > thresholdVel ) //Give the boolean for switching.
         { useGL=true; }
        if ( fabs( vel ) <= thresholdVel )
         { useGL=false; }
        if ( vel <= 0 ) //determine accel direction.
         { curAccel = accel; }
        else
         { curAccel = -accel; }
        tilTime = t2 + beta * fabs( vel/ accel );
            //calcul ate the time duration to actuation.
        }
     }
  }
if ( useGL ) //Output feedback force according to the forward Boolean.
  { if ( t < tilTime )
    forceOut = curAccel * mass;
  else
    forceOut = 0 ; }
 else
    forceOut = FIL.filterApply( errorSig ) ; //FIL is defined as servo filter.
```

Acknowledgement

First of all I would like to appreciate to all of the related people in this thesis completed.

Professor Akio Sugamoto and Professor Seiji Kawamura always encourage me to enjoy science. Thank you for giving me all of the good chances to bring me growth in this researching activity and humanity.

Thank you for all the things that you have taught me. Prof. H. Yamamoto. Prof. K. Somiya.

Thank you for giving me lots of good chances. Prof. M. Fujimoto, Prof. K.Kuroda. Prof. Cho-Gi-Chol.

Thank you for teaching me physics. Prof. R. Takahashi. Prof. K. Arai, Assistant Professor S. Sakata, T. Akutsu, D. Tatsumi, and K. Yamamoto, Dr. K. Hayama Dr. K. Agatsuma Dr. K. Kokeyama. Ph.D. student K. Izumi, and T. Mori, Dr. N. Ohmae, AP A. Ueda, Prof S. Sato, Prof M. Ando, Prof. K. Tsubono, Prof. R. Desalvo, Prof. S. Ballmar, Prof. A. Freise, Prof R. Adhikari, Dr. F. Kawazoe, Dr. K. Niwa, Ishizaki san, Yamasaki san, torii san, Ukita san, Fukushima san.

Thank you for taking care for traveling or others stuff. Ochanomizu University, NAOJ, Tokyo University.

I would like to thank to my family that support me all the time. I won ’t be here without your hospitable cooperation.

References

[1] HJ Kimble, Y. Levin, A.B. Matsko, K.S. Thorne, and S.P. Vyatchanin. Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics. *Physical Review D*, 65(2):022002, 2001.

[2] *http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/Search*, (G1100441-v1).

[3] *http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/Search*, (G1100558-v5).

[4] J. Mizuno, K.A. Strain, PG Nelson, JM Chen, R. Schilling, A. Rüdiger, W. Winkler, and K. Danzmann. Resonant sideband extraction: a new configuration for interferometric gravitational wave detectors. *Physics Letters A*, 175(5):273–276, 1993.

[5] J. Camp, L. Sievers, R. Bork, and J. Heefner. Guided lock acquisition in a suspended fabry-perot cavity. *Optics letters*, 20(24):2463–2465, 1995.

[6] K. Izumi. Research of lock acquisition of fabry perot cavity for interferometric gravitational wave detector. *Master thesis*, page 102, 2009.