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Transfer function measurement of JIF triple pendulum suspension system in Glagow

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1 Triple Pendulum Suspension System

In both the GEO600 Hanover observatory and the 10-m prototype JIF lab in Glasgow, the similar design of triple pendulum suspension system is used. The local control servo with six actuator coils on the upper mass is installed to provide damping of the normal modes of the suspension pendulums. These include coil 1 and 2 on the rear of the upper mass control the longitudinal and yaw mode, coil 6 on the side control the sideway motion while coil 3,4,5 acting on the top control vertical motion plus roll and the unsymmetrical location of coil 3 and 4 provide the control for pitch mode[1].

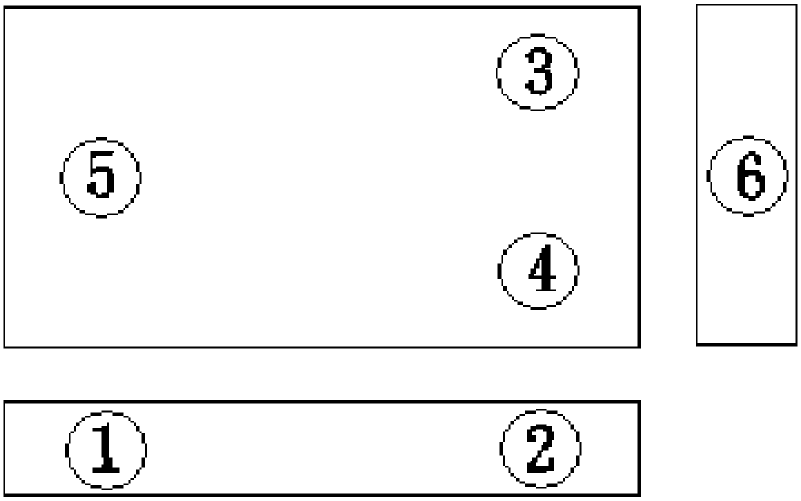

Figure 1: *Schematic view of the locations of the coils on the upper mass of the triple pendulum from the top (coil 3,coil 4 and coil 5),from the front (coil 1 and coil 2) and from side (coil 6).*

2 Cross Coupling

Due to the mechanical imperfections, perfect performance of the suspension system is deteriorated by the cross couplings. As we have seen on the intermediate mass, the sag points of the wires are not at the same horizontal plane where the center of the mass is. Together with the offset - difference between real and the theoretical center of the mass, we have enough reason to see the longitudinal/pitch coupling effects. The difference of the displacement of coil 3 and coil 4 relative to the symmetrical axis of the upper mass between them couples pitch to vertical motion of the pendulum. Also, when the side projection of the pendulum suspension is considered, there are two wires visible(one to the front of the upper mass and one to the back),a difference in the spring constants of these wires couples vertical motion to pitch.Similarly, we may see longitudinal/yaw coupling effect due to the asymmetry of the locations of coil 1 and coil 2 and roll/vertical coupling due to the imbalances among coil 3,coil 4 and coil 5. Among them, longitudinal/pitch coupling seems to be the dominant factor that may cause some problems for good damping of the suspension system. One locking problem noticed in the GEO600 Hanover site several months ago was suspected to be related with it. A strong tilt mode with poor damping was clearly seen when the feedback signal for damping was checked on BS(beam splitter)[2]. So some transfer function measurement on the 10m prototype interferometer suspension system can help us to have a better idea about the cross coupling effects and test the Matlab model that we use to simulate the triple pendulum suspension system.

3 Transfer Function Measurement

First, Close loop transfer functions of six channels are measured to test the parameter settings of the Matlab simulink model[3]. These six channels from 1 to 6 are related to six coils on the upper mass. The white noise input signal generated by the SR785 model signal analyzer is injected to the input end of each channel and the feed back signal to the same channel is measured, thus the frequency response of each channel with the suspension pendulums under damping is checked. We also check the response of channel 3,4 and 5 with vertical input,which means the same signal is injected to all these three channels to produce the vertical motion of the pendulum. Second, cross coupling effects are measured. With the input points at both channel 1 and channel 2 to provide the longitudinal input, the difference between the feed back signals from channel 3 and channel 4 measured as the output, we get the transfer function for longitudinal/pitch coupling. Transfer functions for the triple pendulum's motions of different freedoms are measured by changing the combination of input and output channels.The input and output points for cross coupling measurement are listed in Table 1.

Finally, pitch/longitudinal and yaw/longitudinal cross coupling due to the ground motion are measured with the input point given to the actuator on the top of the supporting frame. With the actuator, we can push the whole triple pendulum to move longitudinally. The optical lever

Coupling	Input point	output point
longitudinal/pitch	CH1 + CH2	CH3 - CH4
roll/vertical	CH3 + CH4	CH5
longitudinal/yaw	CH1	CH2
pitch/vertical	CH3	CH4

Table 1: *Cross coupling measurement. Same local control servo setting is designed for all channels.*

is set up to study the resulting test mass motion, which consists of two turning mirrors fixed in the ITM chamber and the photo detector, input laser box outside. Both the input and output laser beam pass through the same view port. And the photo detector has two channels: one for horizontal motion of the incoming laser beam and the other for the vertical motion.

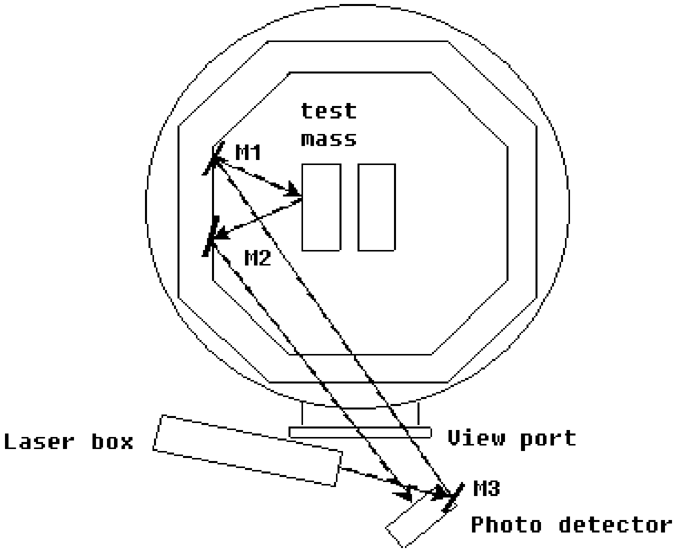

Figure 2: *schematic view of the set up of the optical lever in Chamber 7.*

4 Comparison Between The Modelling Result and The Experimental Result

Using the matlab file cit.m[4], normal mode frequencies of the triple pendulum parameterized by the file jbr_test.m[4] can be calculated. Table 2 lists all the prototype mode frequencies.

Figure 3 is the block diagram of the feed back control system of the triple pendulum,which is generated by the simulink model.We put a slightly different gain setting for channel 1 from other channels to better represent the real situation(the LED of coil 1 is dimmer than the others).

In the following figures, experimental measurement and modelling results are marked with blue and red lines separately.Frequency response measurement of the yaw, pitch, longitudinal and side motion shows reasonably good agreement with the simulink modelling results(In some figures of measurement, we can see a stack motion around 8 Hz.The rubber stack is used to

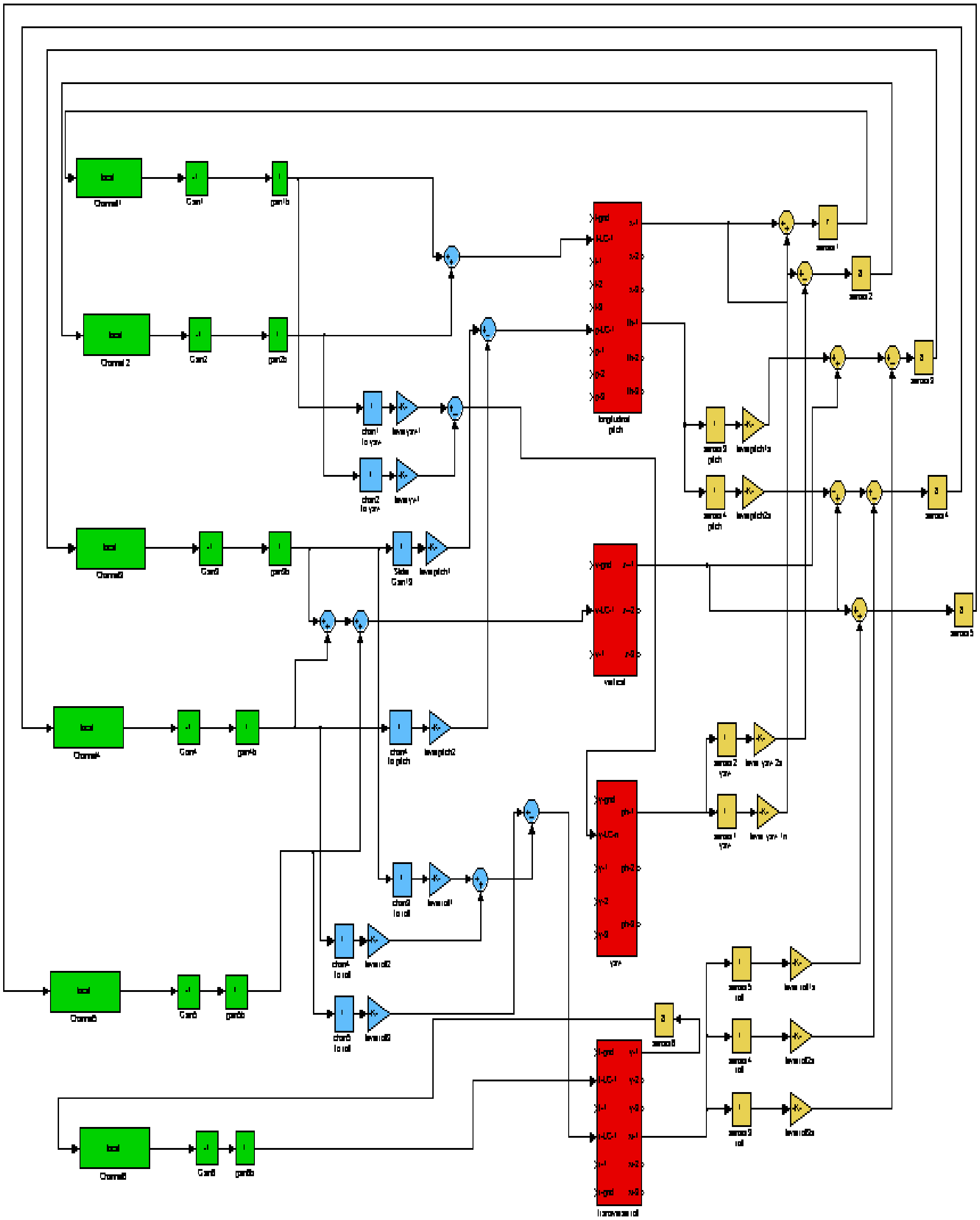

Figure 3: *The block diagram of the triple pendulum suspension feed back control system.*

Axis	Frequencies(Hz)
Longitudinal/pitch	4.63,2.95,2.19,0.95,1.33,0.55
Sideway/roll	37.8,4.2,2.8,2.2,1.3,0.55
yaw	2.5,1.5,0.79
vertical	27.98,4.95,1.30

Table 2: *Mode frequencies of the triple pendulum calculated using the cit.m matlab file written by Calum Iain Torrie.*

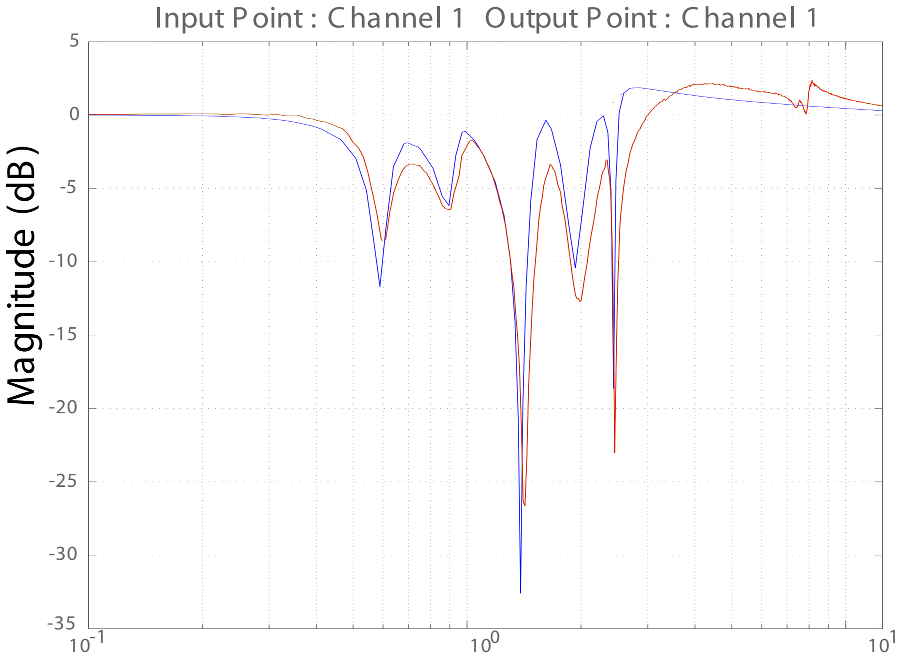

Figure 4: *Close loop transfer function of the damped triple pendulum with channel 1 as both the input and the output points. Frequency responses of yaw and longitudinal motion are expected to be seen.*

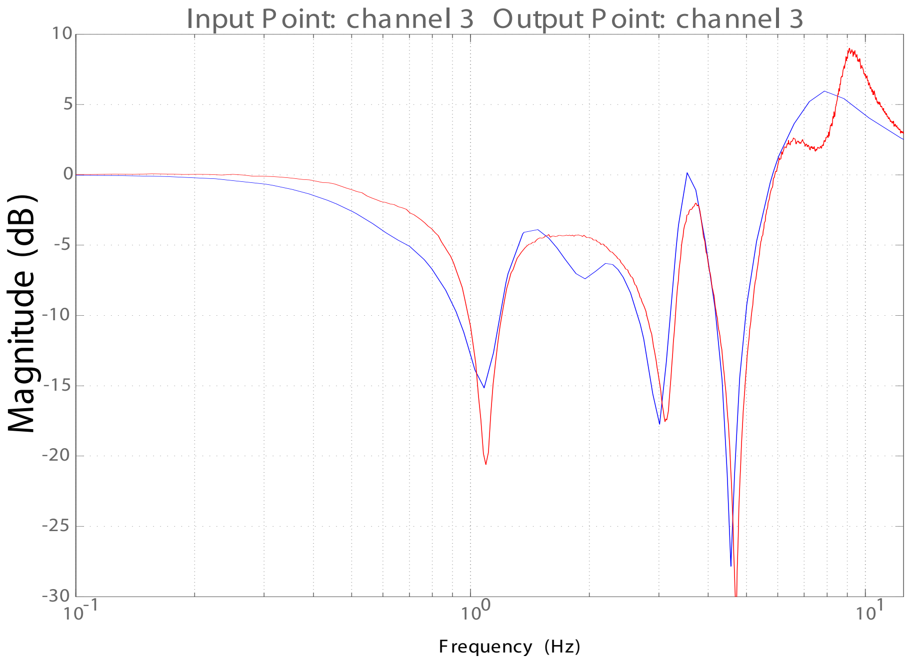

Figure 5: *Close loop transfer function of the damped triple pendulum with channel 3 as both the input and the output points. Frequency responses of pitch,roll and vertical modes are expected to be seen.*

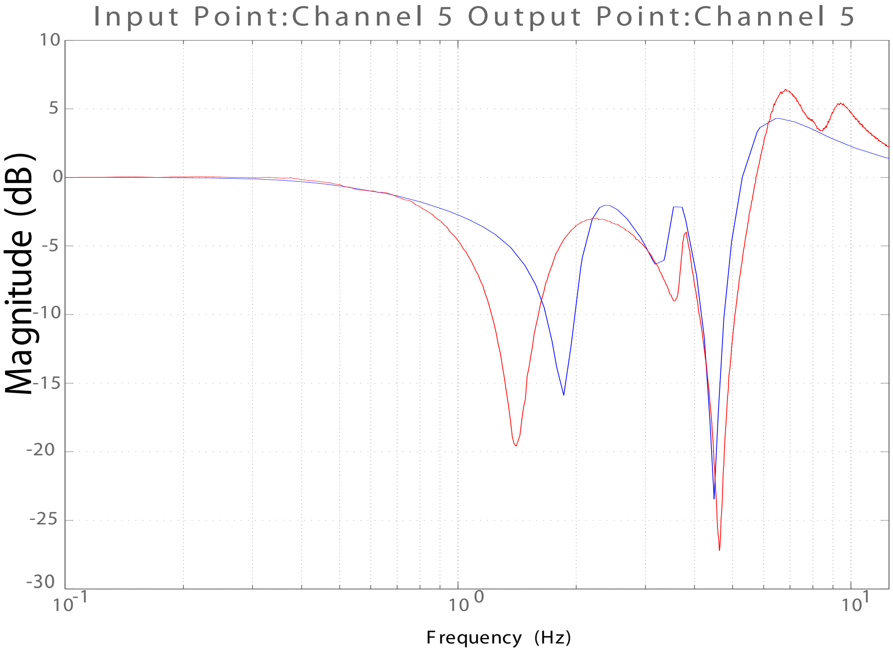

Figure 6: *Close loop transfer function of the damped triple pendulum with channel 5 as both the input and the output points. Frequency responses of roll and vertical modes are expected to be seen.*

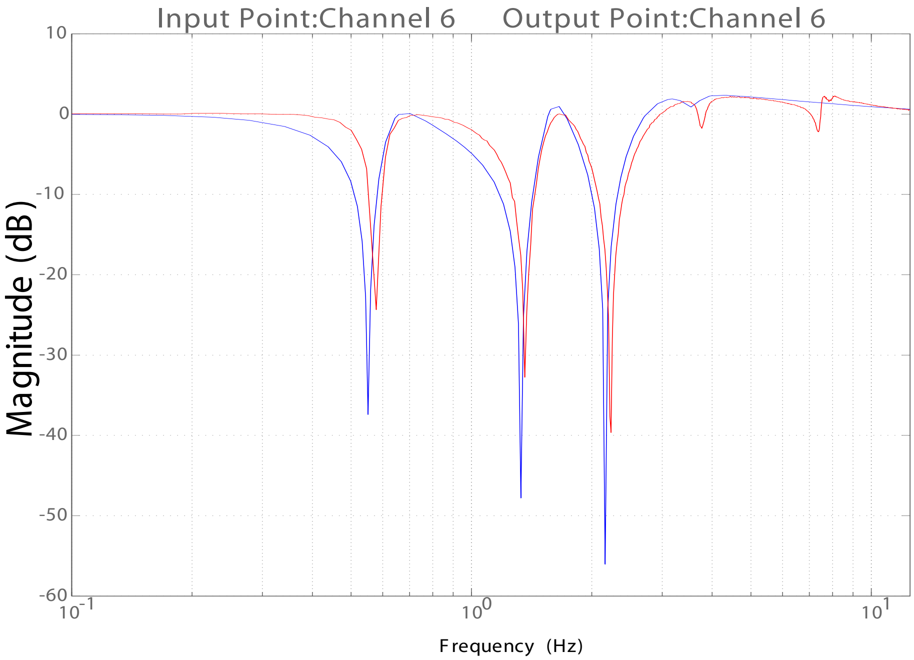

Figure 7: *Close loop transfer function of the damped triple pendulum with channel 6 as both the input and the output points. Frequency responses of sideway mode is expected to be seen.*

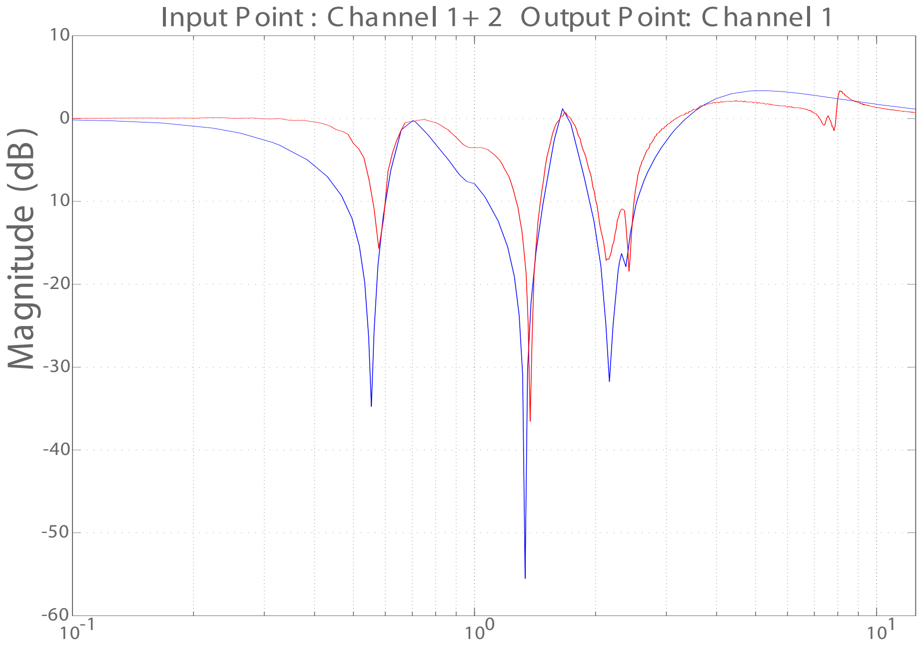

Figure 8: *Close loop transfer function of the damped triple pendulum with the same injection source from both channel 1 and channel 2 to provide the longitudinal motion. Feed back signal of channel 1 is measured.The gain setting for channel 1 and channel 2 are not balanced well,thus yaw modes are expected to be seen here.*

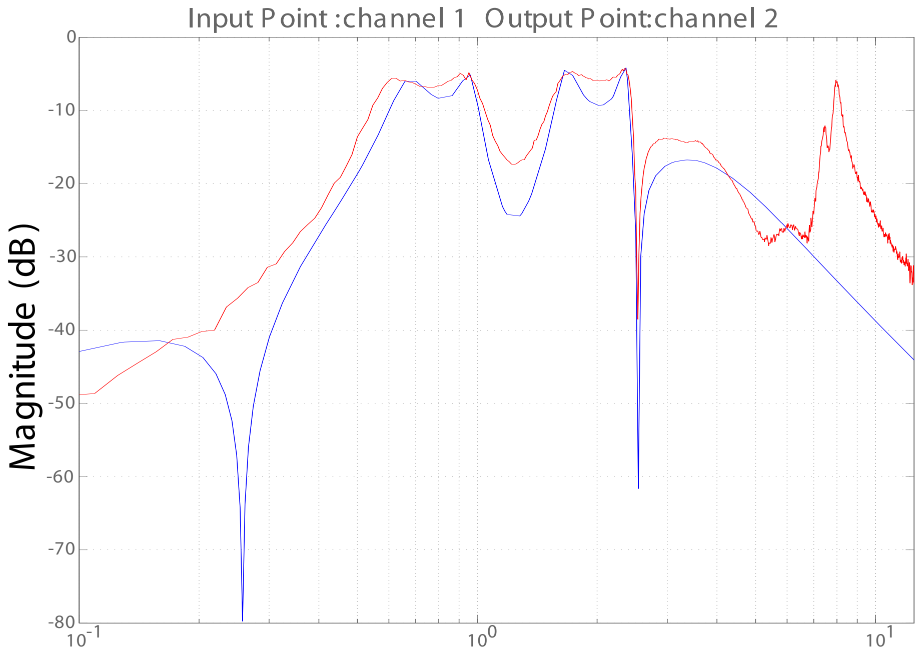

Figure 9: *Close loop transfer function of the damped triple pendulum with channel 1 as the input point and channel 2 as the output point. We expect to study longitudinal/yaw coupling effects by this way.*

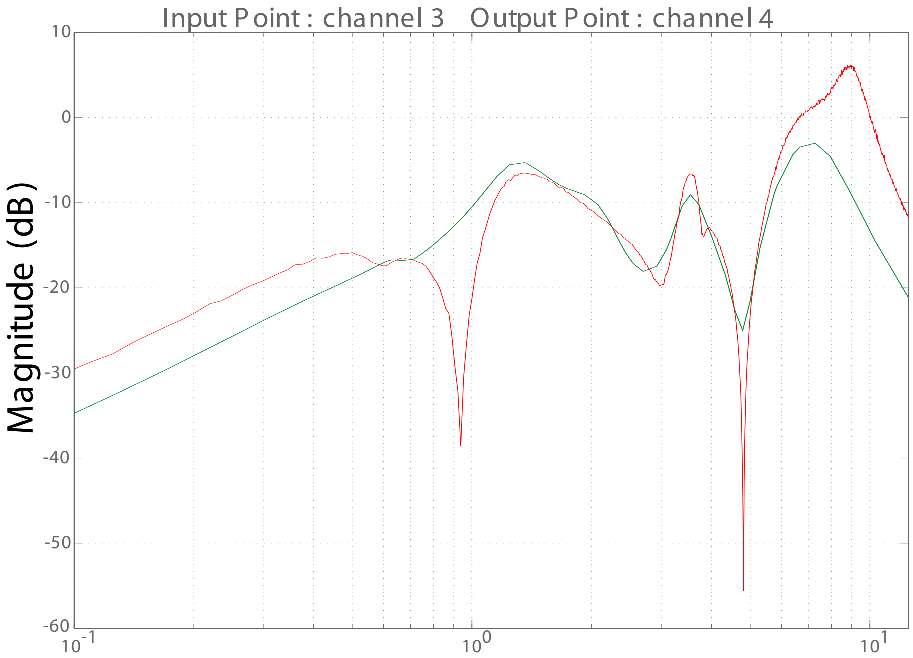

Figure 10: *Close loop transfer function of the damped triple pendulum with channel 3 as the input point and channel 4 as the output point. We expect to study pitch/vertical cross coupling effects by this way.*

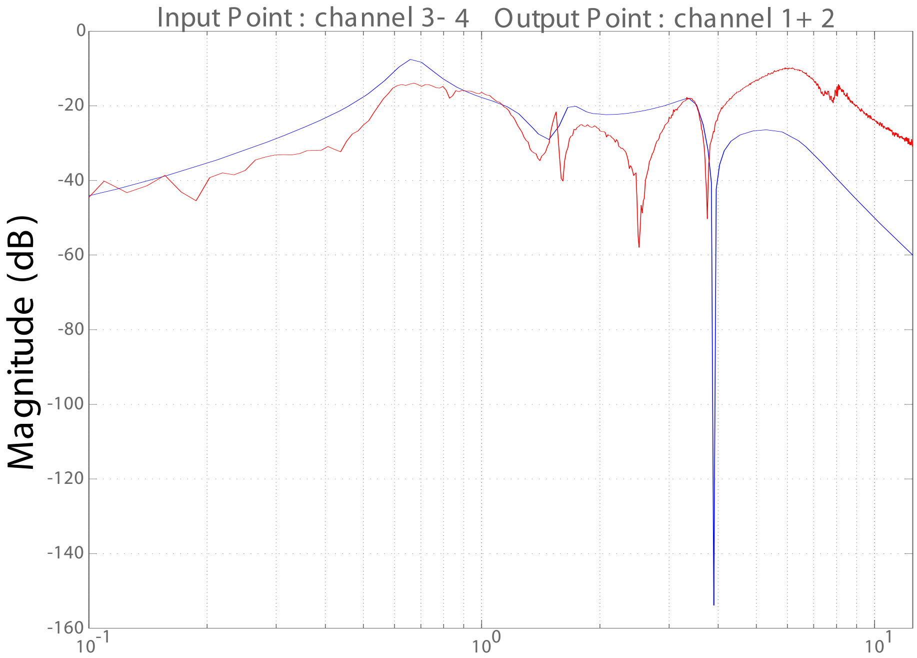

Figure 11: *Same amplitude but negative sign impulse injection to both channel 3 and 4 while feed back signal measured from channel 1 and channel 2 combined as the output,thus the pitch/longitudinal cross coupling effects is examined.*

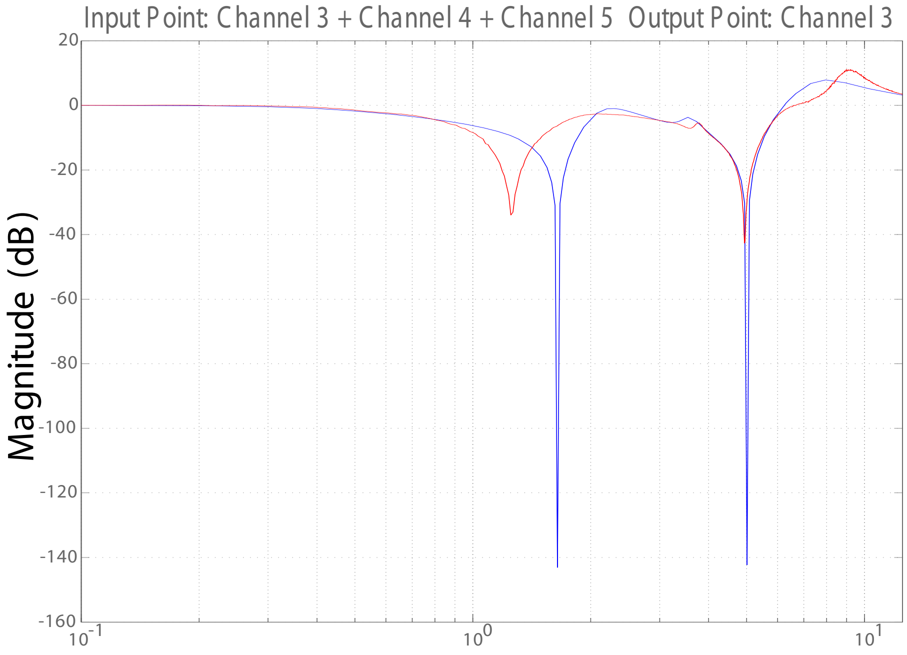

Figure 12: *Same impulse injection is given to channel 3,4 and 5 together to produce vertical vibration of the damped pendulum.Frequency response of the channel 3 is measured.*

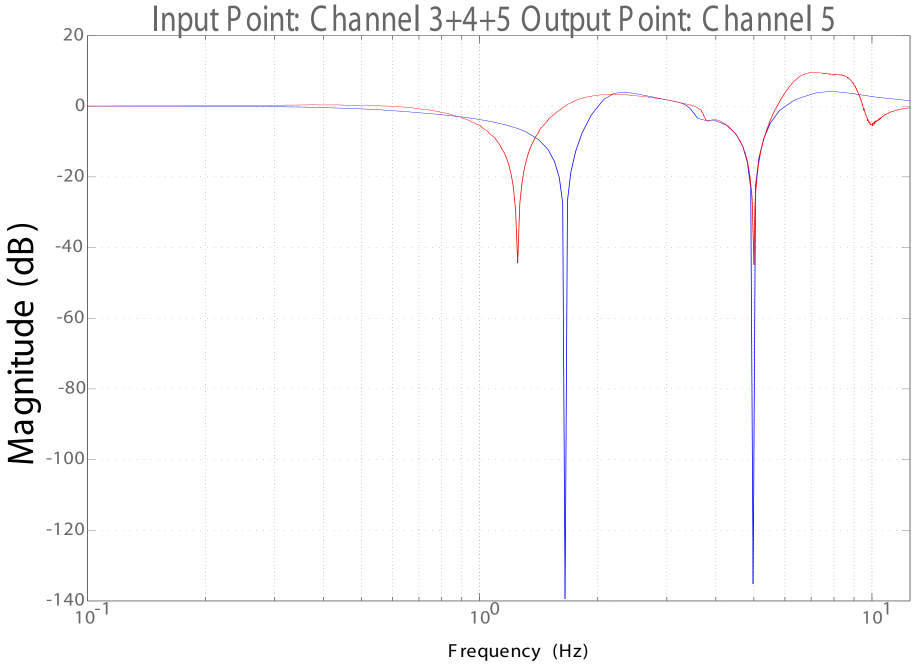

Figure 13: *Same impulse injection is given to channel 3,4 and 5 together to produce vertical vibration of the damped pendulum.Frequency response of the channel 5 is measured.*

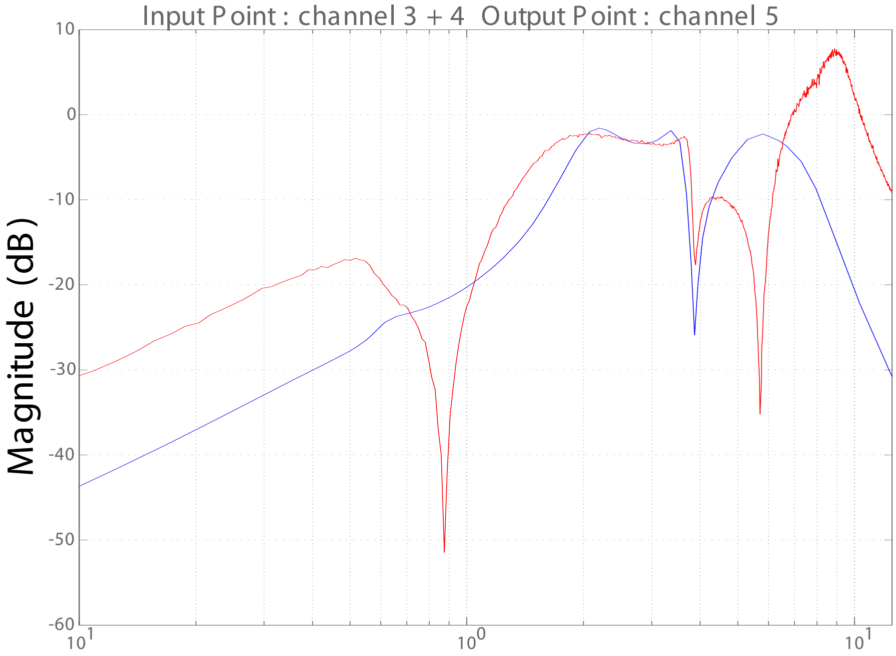

Figure 14: *Impulse injection is given to both channel 3 and channel 4 to produce yaw motion. Channel 5 is then examined for vertical/roll coupling.*

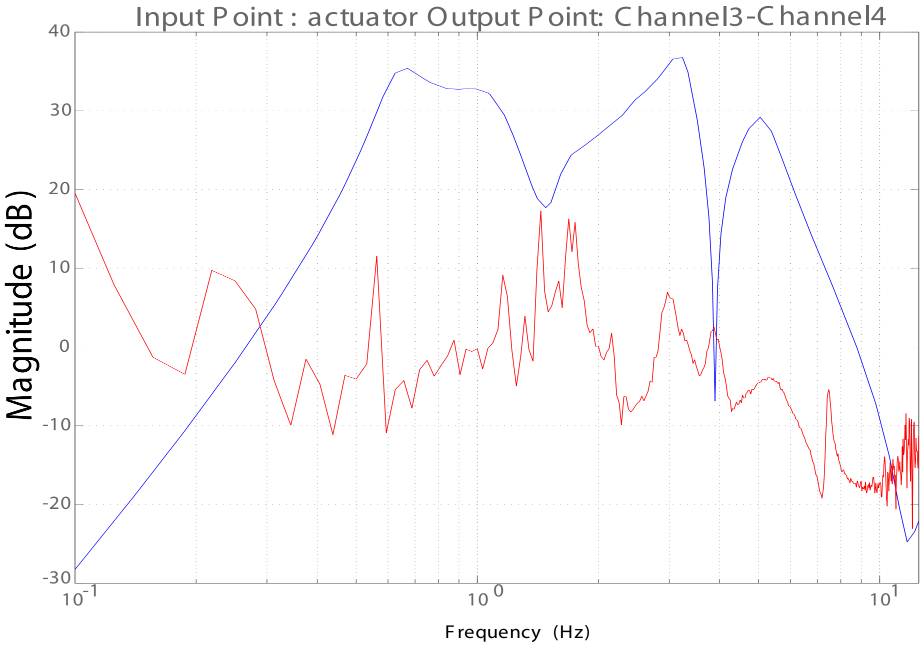

Figure 15: *Ground motion/pitch coupling close loop transfer function of the damped triple pendulum with the input injection given to the actuator and the difference between the feed back signal of channel 3 and channel 4 as the output.*

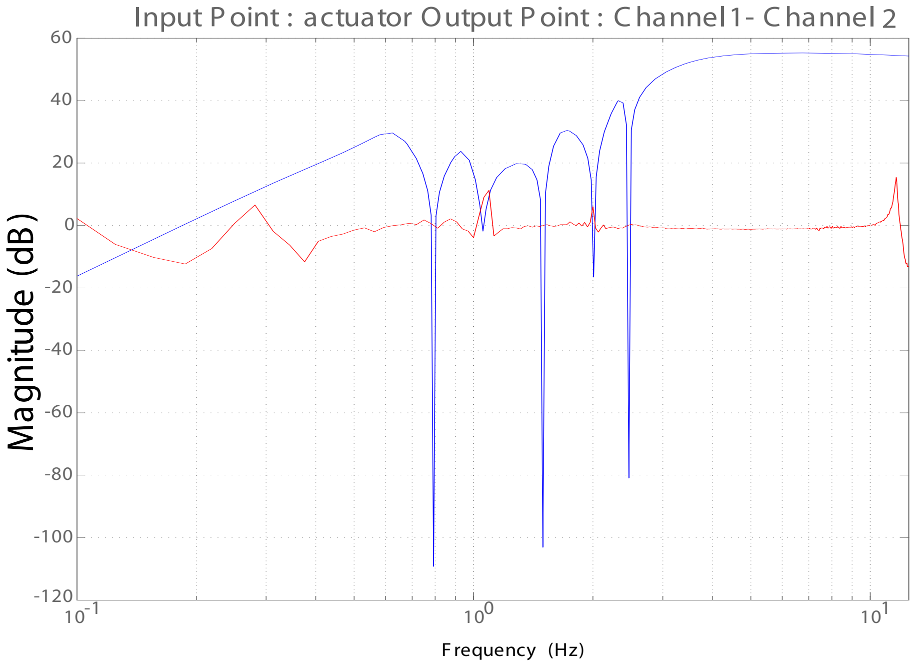

Figure 16: *Ground motion/yaw coupling close loop transfer function of the damped triple pendulum with the input injection given to the actuator and the difference between the feed back signal of channel 1 and channel 2 as the output.*

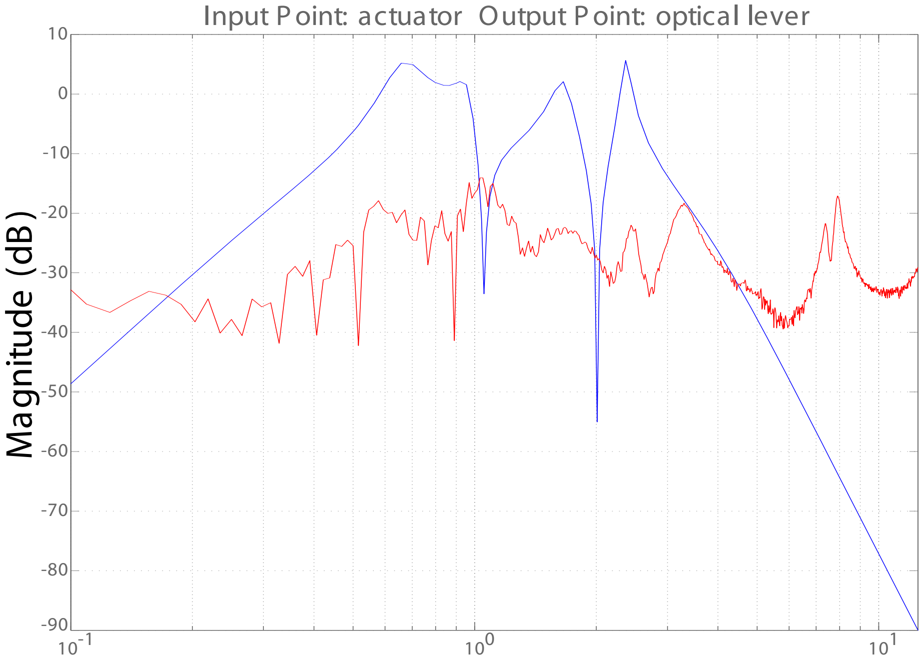

Figure 17: *The pendulum is excited from the actuator and the pitch motion of the test mass is detected by the optical lever.*

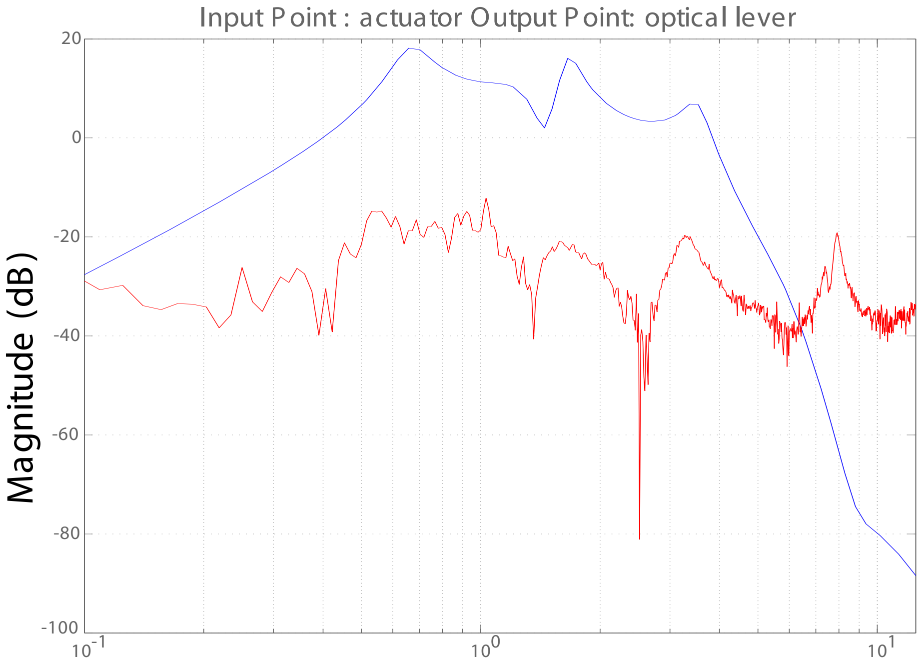

Figure 18: *The pendulum is excited from the actuator and the yaw motion of the test mass is detected by the optical lever.*

isolate the supporting frame from the seismic noise). This gives confidence that the dynamic model is accurate for future design work.However,there is an obvious difference between the modelling and the experimental frequency response measurement of channel 5.It is clearly seen in figure 6,figure 12 and figure 13 that frequency response notch in the measurement moves to the lower frequency range as compared with the notch predicted theoretically. We are not clear about what is behind this. My guess is that the Matlab model is built on the basis that the lines joining the wires are always in a horizontal plane while in reality the upper wires and the intermediate wires are attached to two separated cantilever blades that behave like springs. The disaccord of the behavior of the two blades in both upper and intermediate stages could result in the roll motion of the triple pendulum,which may be a big factor that causes the difference.

Totally, the ability of the Matlab model to predict the cross coupling is not so satisfactory. However, the dynamic model does give us a reasonably good prediction about the logitudinal/yaw and pitch/vertical coupling of the triple pendulum under damping.

Motion of the test mass detected using the optical lever does not give us a clear correlation with the pitch or yaw motion due to the ground/pitch and ground/yaw coupling predicted by the model.

References

[1] M.plissi,GEO 600 triple pendulum suspension system:seismic isolation and control

[2] H.Grote,H.Lck,K.Strain,M.Hewitson,GEO600 logbook

[3] C.Torrie,K.Strain,S.Killbourn, Triple suspension simulink model

[4] C.Torrie, PhD thesis