Minimizing Vibration Effects in Satellite Laser Communication

Shaikhul Arefin Khan and Mohammed Tarique

***Abstract*—A natural development in the space communication is the free space laser communication. The free space laser communication has greater advantage over traditional Radio Frequency (RF) communication. Some of the advantages are high data rate, low probability of detection and minimum interception. The major limitation of this optical communication is the noise introduced by the mechanical vibration of the satellites. This kind of vibration causes pointing problem and affects the performance of the inter-satellite link in terms of bit error rate. Hence a perfect tracking system is required for transmitting and receiving satellite. In this paper, a novel method to improve tracking system has been introduced. It has been shown that the vibration effects can be reduced to an acceptable level and hence the bit error rate can be reduced by using a feed forward compensation technique. The improvement in Bit Error Rate (BER) has also been presented in this paper.**

***Keywords*—Bit Error Rate, Feed Forward Compensation, Laser Link and PID Controller**

I. INTRODUCTION

Artificials earth satellites have been used in communication system for more than 35 years. It has become an essential part of the World's telecommunication infrastructure. There are many applications of satellite communication such as (a) communications systems, (b) broadcasting systems, (c) remote sensing, (d) global positioning and navigation, (e) search and rescue, (f) weather and pollution monitoring, and (g) surveillance. Although satellite communication is considered one of the most means of providing communication, it has some problems too. Some of the problems are (a) signal latency, (b) rain fade, (c) maintaining line-of-sight path, and (d) Fresnel Zone effects. Hence the designing of a satellite link is very challenging because it limits the performance on the high speed communication. Microwave link has been a popular choice since the early days of satellite link designing. Now-a-days free space optical communication is considered a good candidate for the satellite link. Some of the advantages of an optical communication system over microwave communication system in free space are: (a) smaller size and weight, (b) less transmitter power, (c) larger bandwidth, and (d) higher immunity to interference. The main complexity of satellite optical communication is the pointing system. The complexity of the pointing system derived from the necessity to point from one satellite to another over a distance of tens of thousands of kilometers with a beam divergence of microradians. Pointing system uses two complementary information sources in order to point the information beam in the right direction. The rough pointing is based on Ephemerides data (the position of the satellite according to the orbit equation). The fine pointing is based on an electro-optics tracking system. Free space optical communication between satellites networked together can make possible high speed communication between different places on the Earth. The basic free space optical communication network includes at least two satellites. In order to communicate between them, the transmitter satellite must track the 'beacon' of the receiver satellite and point the information optical beam in its direction. The pointing systems for the laser satellite communication suffer during tracking from vibration due to electronic noise, background radiation from interstellar objects such as Sun, Moon, Earth, and Stars in the tracking field of view, and mechanical impact from satellite internal and external sources. The signal received at the satellite receiver is affected by the vibration of the receiver. This effect limits the system bandwidth for given bit error rate (BER).

II. THEORETICAL BACKGROUND

The concept of communication satellite networks was introduced in [1]-[4]. The concept of optical intersatellite link has been described in [4]-[7]. Some results of on board measurements of the vibration spectra of communication satellites OLYMPAS and LANSAT are specified in [8]-[11]. The impact of random pointing and tracking errors on the design of coherent and incoherent optical intersatellite communication link has been analyzed in [13]. The root mean square (rms) standard deviation of the pointing error distribution and the burst error of the communication system have been presented in [14]. More analysis of the effects of vibration on satellite optical communication can be found in [15]-[17]. A detail description of the performance limitations

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of free-space optical communication satellite networks due to vibration has been presented in [18], [19]. Some possible solutions of decreasing the effects of vibration on the performance of the optical communication network have been reviewed in [20]. Some of the solutions mentioned therein are bandwidth adaptation, beamwdith adaptation, power control, coding technique, channel diversity, vibration isolation and self-tuning feed forward compensation. The basic idea of bandwidth adaptation is to adapt the bandwidth and the receiver parameters according to the change of the received power due to transmitter vibrations. This kind of adaptive system is a very good solution for short-period vibrations of the optical satellite. The main reason of beam width adaptation solution is to dissipate minimum power and to obtain minimum BER.

This aim is achieved with very small transmitter divergence angles to assure maximum received power. The main disadvantage of this solution is that too narrow divergence angle increases the chance of missing the receiver satellite. According to the power control solution enough link power margin need to be maintained so that even if the received power scintillates, the BER still meet the requirement. The effects of vibration can also be minimized by choosing an appropriate coding scheme. The channel diversity scheme suggests that by using a number of independent paths for transmitting the same information. Using a number of channel increases the probability that at least one channel will ensure sufficient signal quality. The vibration isolator is a system that reduces the transmission of vibrations from the spacecraft body to the communication system. Two basic isolators are used namely active and passive. The passive isolator includes a mechanical low-pass filter of a spring-mass system. The active isolator includes a vibration control system, force actuator, and displacement sensor. The passive isolator is designed to reduce the vibration disturbances in the high frequency region. On the other hand, the active isolator is used to dampen low-frequency high amplitude vibrations. The self-tuning feed forward compensation technique has been introduced in [21], [22]. The proposed method uses a miniature accelerometer to monitor the vibration characteristics. The vibration and the disturbance propagating along the mechanical path are monitored and electrically compensated for before they affect the communication system.

This paper presents a feed-forward compensation technique that minimizes the vibration effects. This paper presents an approach to analyze the performance of optical communication system in the presence of satellite vibration and BER mathematical model has been derived. A feed forward compensation model under fine tracking mode is developed in MATLAB/Simulink to investigate how to decrease the vibration effects. The simulation results presented in this paper shows that the noise due to vibration effects can be reduced significantly and hence the BER can be reduced significantly by the proposed method. The satellite optical system model, pointing error model has also been presented.

III. SATELLITE OPTICAL COMMUNICATION SYSTEM

In this section, a brief review of the components of satellite optical communication system is explained. The main components of the system are transmitter, receiver and tracking system.

The transmitter model for on On-Off keying (OOK) is shown in Fig. 1. The transmitter consists of a laser transmitter, a telescope, and random attenuation. When the message arrives in the form of electrical signal at the input of the transmitter, the transmitter converts the electrical signal into optical signal using the laser. The telescope sends the laser radiation in the receiver satellite direction.

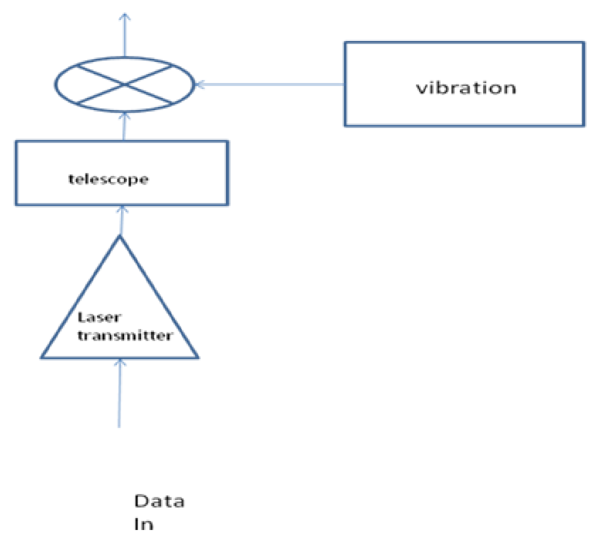

Fig. 1. Transmitter scheme

The receiver model for OOK includes a telescope, an optical bandpass filter, input insertion losses, an optical amplifier, a photodiode, an electrical filter, and a decision circuit. The receiver telescope focuses the received optical radiation onto the optical filter to filter out the background radiation. The radiation then amplified by the optical amplifier. The output of the amplifier also contains noise.

The optical filter prevents the amplifier noise from propagating through the system. The radiation is then converted to an electrical signal by a photodiode. The electrical signal is then filtered by using an electrical filter. The electrical signal is then processed by a decision device. The decision device then estimates about the kind of information that was sent from the transmitter.

To ensure the accurate signal reception at the receiver it is imperative that the transmitter and the receiver must be properly aligned during the entire communication. The satellites use the Ephemerides data for tracking and the pointing system. The popular methods of pointing and tracking between satellites include use of a beacon signal on one satellite and a quadrant detector and tracking system at the other satellite. The elevation and azimuth angle of the

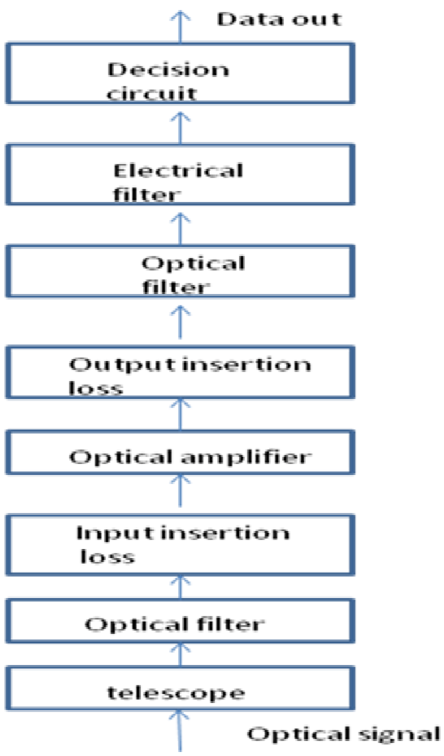

Fig. 2. Receiver scheme

pointing system estimates the pointing direction from the output signal of the quadrant detector. The main components of satellite tracking system are shown in Fig. 3. The radiation from the beacon on one satellite is received by the telescope on the other satellite. The telescope focuses the received radiation onto the quadrant detector. The pointing and control unit calculates the telescope pointing direction according to the quadrant detector signal.

The tracking system is very similar to electro-optic communication systems. Therefore, the tracking system suffers from the same various noise sources, such as laser relative intensity noise, Johnson (thermal) noise, dark current shot noise, signal shot noise, and background shot noise. The signal from the tracking system enters the control system. The control system points the transceiver to the other satellite. Noises from the control system are added to the pointing signal. All of these noise sources cause vibration of the pointing direction. Due to vibrations of the transmitter beam to the receiver satellite, the communication system performance is degraded. The simplest expression for tracking noise (standard deviation) is given by:

$$\delta = \frac{1}{SF\sqrt{SNR}} \quad (1)$$

where, SF is the angular slope factor of the angle-to-voltage transfer function expressed in units per radian and SNR is the signal-to-noise ratio in the tracking system bandwidth. The value also has been referred to as the noise equivalent angle (NEA) of the tracking system [25].

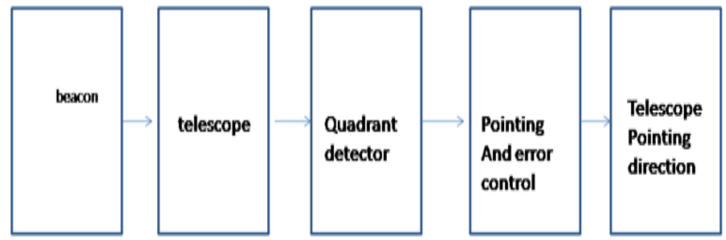

Fig. 3. Tracking system

IV. PERFORMANCE ANALYSIS OF TRACKING SYSTEM

In the analysis presented in this paper Intensity Modulation/Direct Detection (IM/DD) ON/OFF keying is adopted. The receiver includes an optical detector and converts the optical power to electronic signals with conversion ratio of *R*. The receiver integrates the signal and determines whether the signal is ON or OFF. Here, define the relative electronic signal as *y* before making decision. In addition, assume that the noise is independent of the received signal, with zero mean and variance σ_n^2. The signal *y* corresponds to the following conditional densities when the bit is ON or OFF:

$$P(y/on,\theta) = \frac{1}{\sqrt{2\pi\sigma_n}}\exp\{-\frac{[y-RP_t(\theta)]^2}{2\sigma_n^2}\} \quad (2)$$

$$P(y/off) = \frac{1}{\sqrt{2\pi\sigma_n}}\exp\{-\frac{y^2}{2\sigma_n^2}\} \quad (3)$$

The likelihood Function is given by:

$$\Lambda(y,\theta) = \frac{P(y/on,\theta)}{P(y/off)} = \exp\{-\frac{-2yRP_r(\theta)+[RP_r(\theta)]^2}{2\sigma_n^2} \quad (4)$$

Take the natural logarithm of both sides of equation (4), cancel the common factors and the following is gotten:

$$L\Lambda(y,\theta) = y - RP_r(\theta)/2 \quad (5)$$

The BER is described as follows:

$$BER = \int_0^\infty [P(on)P(off/on,\theta) + P(off)P(on/off,\theta)]f(\theta)d\theta \quad (6)$$

Where, P (off/ on,θ and P (on/ off,θ) are given by:

$$P(off/on,\theta) = \int_{L\Lambda(y,\theta)\triangleleft 0} P(y/on,\theta)dy \quad (7)$$

$$P(on/off,\theta) = \int_{L\Lambda(y,\theta)\triangleright 0} P(y/off)dy \qquad (8)$$

Calculating equations (7) and (8) with equations (2) and (3) and then substituting equations (7) and (8) into equation (6)

$$P_r(\theta) = P_t G_t \eta_t L_R G_r \eta_r \exp(-G_t \theta^2) \qquad (9)$$

and the following is the final expression for the BER

$$BER = \int_0^{\infty} [\frac{1}{2} - \frac{1}{4} erf(C\exp(-G_t\theta^2))] \frac{\theta}{\sigma^2} \exp(-\frac{\theta^2}{2\sigma^2}) d\theta \qquad (10)$$

where, P(on)=P(off) = 1 / 2, C is a constant factor, and erf(●) is error function. Here, define a new variable, $u = \frac{\theta^2}{2\sigma^2}$, so equation (10) is changed to

$$BER = \int_0^{\infty} [\frac{1}{2} - \frac{1}{4} erf(C\exp(-2G_t\sigma^2 u))] \exp(-u) du \qquad (11)$$

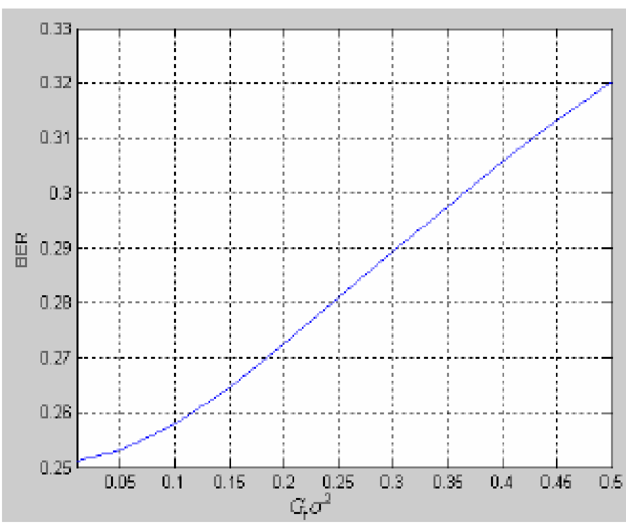

Fig. 4. BER as a function of the transmitter gain multiplied by σ^2

The BER expressed in Equation (11) has been plotted in Figure 4. This figure shows that the system performance is highly dependent on the amplitude. The BER increase when the vibration amplitude increases. As the vibration increases the signal will be much more noisy and original signal would be difficult to retrieve. Higher BER means there will be poor communication between two satellites which eventually result in pointing errors. So we have to reduce the vibration in order to improve the pointing errors so the BER will decrease and we can retrieve the original signal at the minimum error level.

V. INTRODUCTION OF FEED-FORWARD COMPENSATOR IN THE TRACKING SYSTEM

This chapter deals with the simulation of feed-forward compensator system (1) without compensator, (2) with compensator and (3) with PID controller. This work is an extension of [29]. First the idea of [29] has been implemented. Then the modified models have been proposed to further reduce the vibration. Lastly a practically realizable controller like PID controller has been proposed.

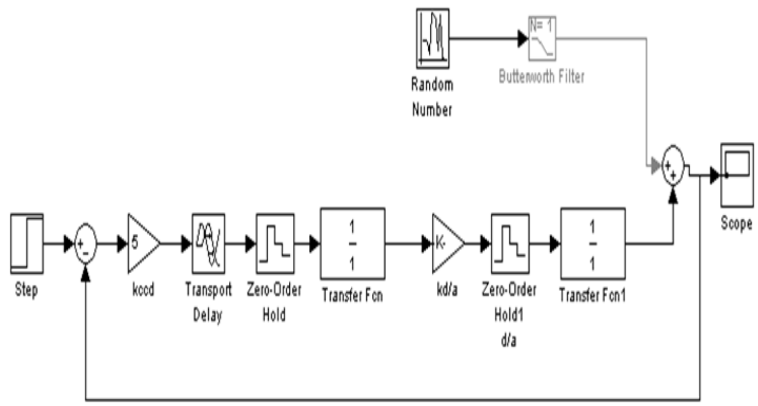

Fig. 5. Circuit diagram of Feed forward compensator without compensation

The simulation model for feed forward compensator without compensation is shown in Fig. 5. The algorithm of this system works as follows:

***Step 1**:* First of all we have given a signal by step block, which provides a step signal that is of analog type. The step block provides a step between two definable levels at a specified time. The step block outputs real signals of type double. In the simulations of this paper this step time was 1, the second and initial value was 0.

Step 2: Then the signal is transferred through a gain block which multiplies the input signal by a constant. The input and the gain can each be a scalar, vector or matrix. This supports fixed-point data types. If the input of the gain block is real and the gain is complex, the output is complex. In our simulation we have set the value of the gain to 5 and sample time is -1(for inherited).

Step 3: Then the amplified signal is passed through the transport delay block, which actually just delay the input signal by a given amount of time. It can also be used to simulate the time delay. The transport delay block accepts and outputs real signals of type double. In the block a time delay of 1 has been used.

***Step 4**:* Then the signal goes through the zero order hold, which implements a zero-order hold of one sample period. The block accepts one input and generates one output, both of which can be scalar or vector. This block actually converts the analog signal into discrete signal.

Step 5: This block is a transfer function block or in other words we can say this is a 1/(s+1) block. We have used this block as gain for three reasons, firstly this block deals with analog signal but after sample and hold block, the signal is converted to discrete signal which can't be detected by this block in initial state which is 1/(s+1) state. Secondly there is no zero in the output discrete signal to nullify with this 1/(s+1) block. Thirdly if we don't increase the value of the original signal it will be difficult for the system to differentiate between signal and noise or disturbance.

Step 6: **T**he signal then passes through gain block to amplify the signal. In the simulation we have set the value of the gain is 0.001 and sample time is -1(for inherited).

Step 7*:* The signal is passed through zero-order hold block which implements a zero-order hold of one sample period.

Step 8: Finally the signal is passed through transfer function block which is also used as gain.

Step 9: Then we have added a random number block through Butterworth filter block that is working as disturbance.

Step 10: Then the signal and added disturbance both are added by block and feed back to the input again, which is actually the compensation for the system occurs.

A. PID controller with compensation

We introduced PID controller into our simulation model. The PID controller has the transfer function:

$$G_c(s) = K_1 - K_2 / S + K_3 S \tag{12}$$

The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. To implement such a controller, three parameters must be determined for the given process: proportional gain, integral gain and derivative gain.

The integrator block outputs the integral of its input at the current time step. The following equation represents the output of the block y(t) as a function of its input u(t) and an initial condition y_0, where y and u are vector functions of the current simulation time t.

$$y(t) = \int_{t0}^{t} u(t)dt + y0 \tag{13}$$

Simulink can use a number of different numerical integration methods to compute the Integrator block's output, each with advantages in particular applications. To prevent the output from exceeding specifiable levels, we selected the 'Limit' output check box and enter the limits in the appropriate parameter fields. Hence the block works as an integrator. When the output reaches the limits, the integral action is turned off to prevent integral wind up. During the simulation, one can change the limits but you cannot change whether the output is limited. The total model that has been simulated is shown in the following Fig. 7.

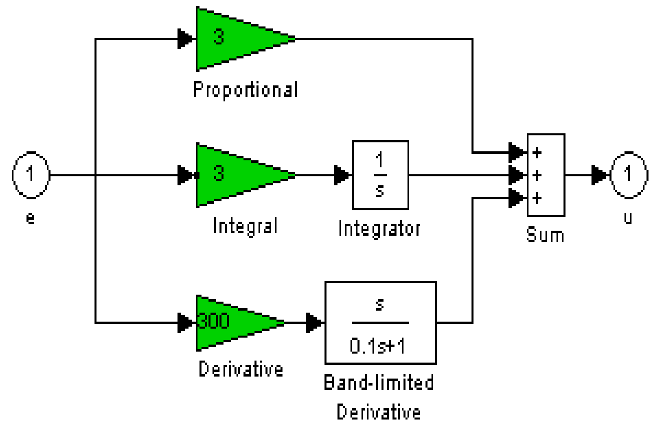

Fig. 6. Internal construction of PID block

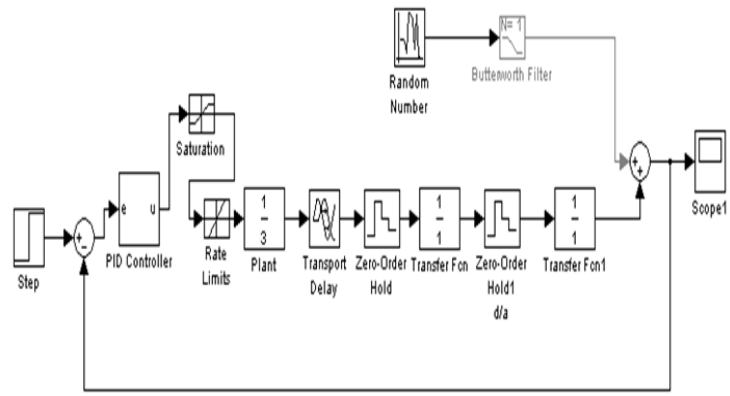

Fig. 7. Simulation diagram with PID controller

The Saturation block imposes upper and lower bounds on a signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound.

The simulation diagram of feed-forward compensator without compensation is shown in Fig. 7. The output of the simulation results is shown in Fig. 8. In this figure it is shown that that the peak of the vibration amplitude is 0.32. This kind of vibration definitely affects the transmission and reception between two satellites. This problem will cause high bit error rate (BER). Hence the feed-forward compensation without compensation is not a suitable choice in satellite communication. In order to overcome this problem we need to add some gain with receiver in order to reduce the vibration effects. This will decrease the value of the transfer function keeping the other gain values unchanged.

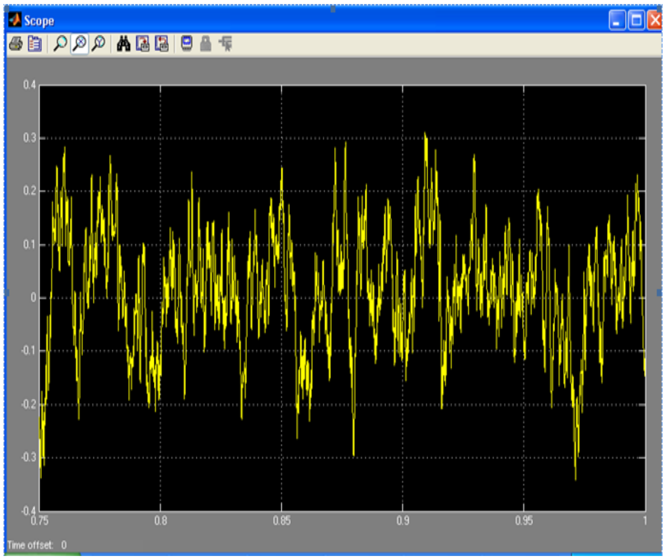

Fig. 8. Output of feed-forward compensator without compensation for TF=1, kccd=5 and kd/a=0.001.

B. Results with variable transfer function and fixed gain

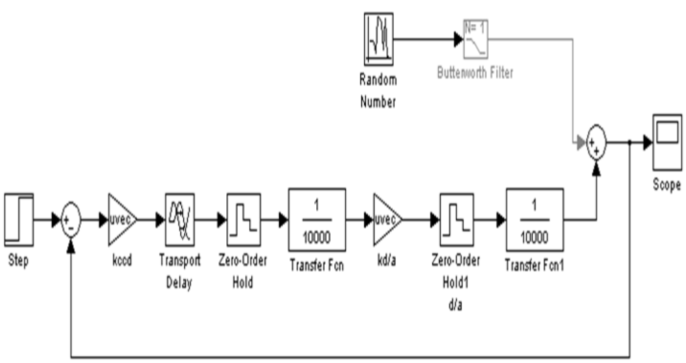

Fig. 9. Circuit diagram with variable transfer function and fixed gain

The simulation result is shown in Fig. 11. This figure shows that with variable transfer function and fixed gain there is not much impact with the large values of denominator of transfer function block. Rather than improvement the vibration increases. It means that the pointing error will definitely play a role and eventually BER will increase. So with the change in other gains, doesn't have an impact on the output of the receiver. From the figure it is depicted that a lot of noise involved in the signal, so it will be very difficult to retrieve the original signal. So only changes in other gains will not improve the signal we need to with transfer function and reduce the BER so that we can get a good signal.

C. Results with Variable transfer function and others fixed

Fig. 11 shows that the output with variable transfer function and fixed gain for T_F=1/1e-6, T_{F1}=1, k_{ccd}=1 and k_d/a=0.001. This figure shows that the error (or noise) is nearly 0 db with the change in denominator which is actually working as

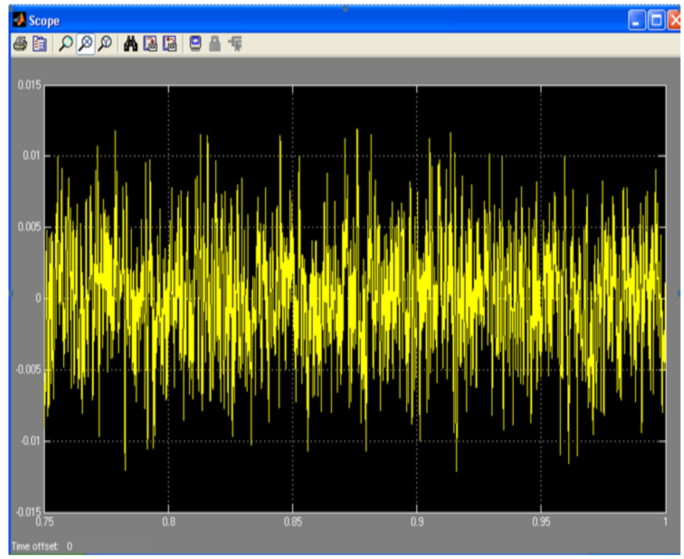

Fig. 10. Output with variable transfer function and fixed gain for TF=1/10000, TF1=1/10000, Kccd=1 and kd/a =0.001.

gain. This is the one of the major findings of this thesis and it clearly shows that noise has been almost been eliminated and hence the original signal can be retrieved easily. Since there is very low noise associates with this desired signal there will low BER.

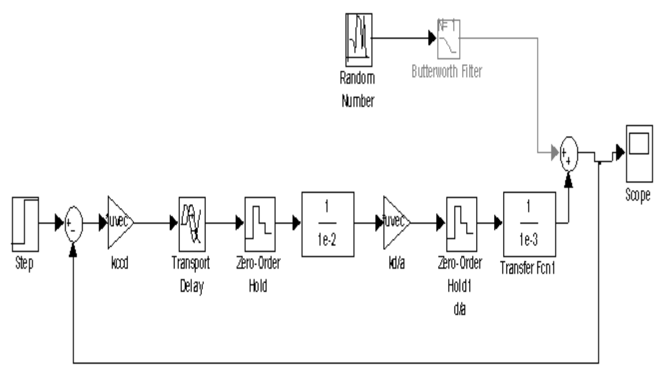

Fig. 11. Circuit diagram with variable transfer function and fixed gain

So the transmission and reception will be improved and as the vibration is decreased the receiver power will increase. Here the compensation is done with adding some gain with the receiver as for the vibration of the receiver power will eventually decreased. Adding gain means decrease the value of transfer function and while other gain values was held unchanged. So the change of values of transfer function does improve the signal quality and hence receiver output will also improve.

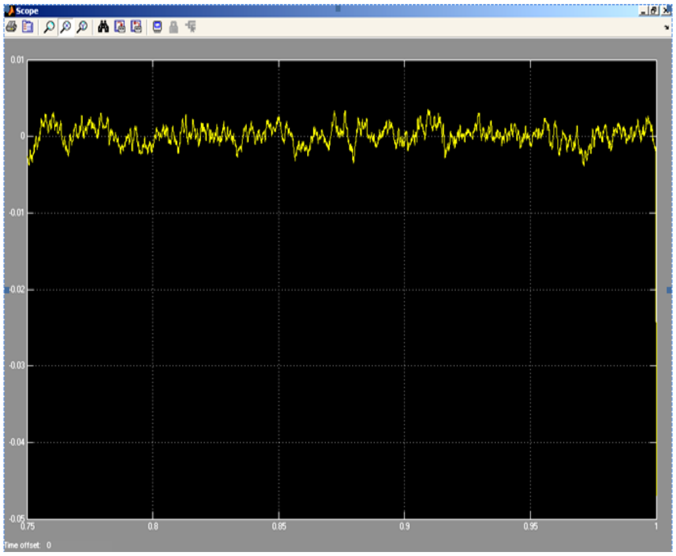

Fig. 12. The simulation output

D. Simulation with PID controller

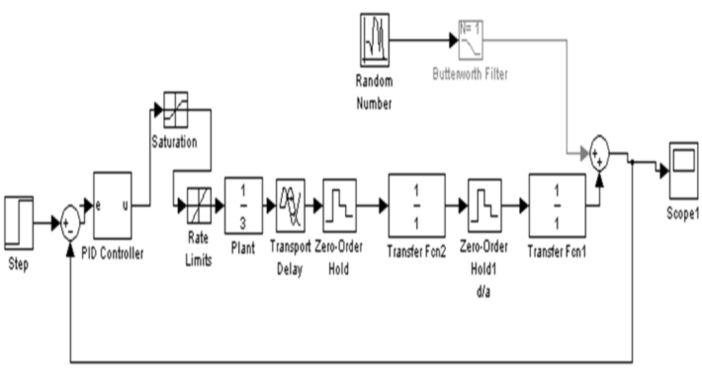

Fig. 13. Circuit diagram with variable proportional controller and other two gains fixed

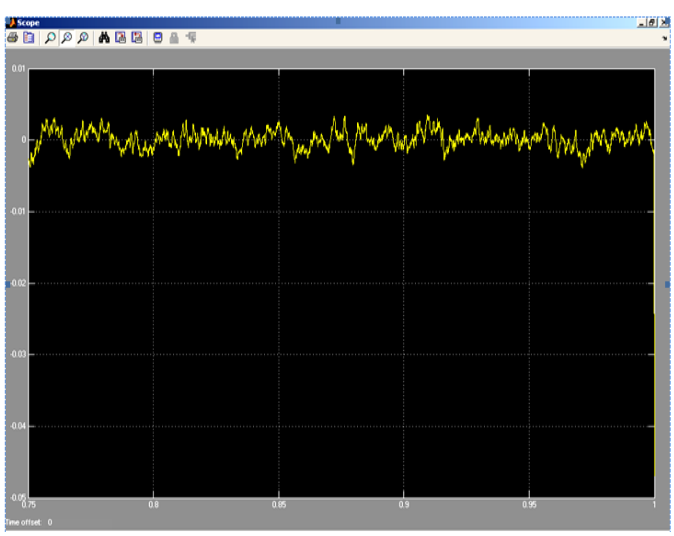

Fig. 14. Output with variable proportional controller and other two gains are fixed. (Here plant=0.33, TF2&TF1 =1, P =300, I=D=1)

The simulation diagram with the variable proportional controller and other two gains fixed are shown in Fig 15. The result of the simulation is shown in Fig. 15.

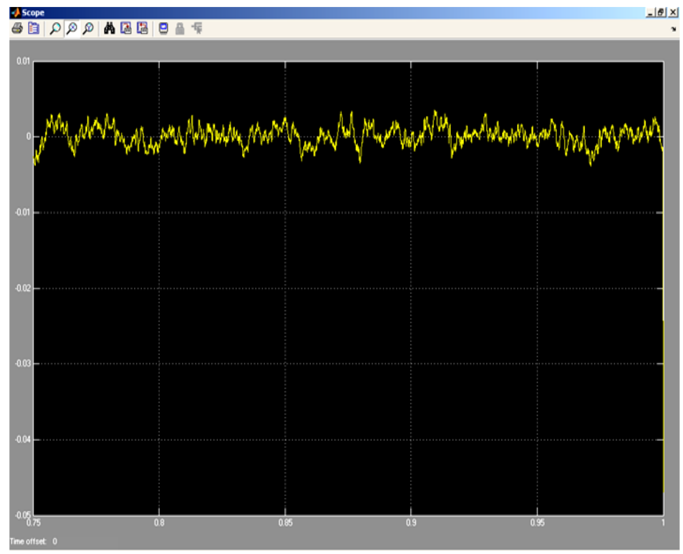

Fig. 15. Shows that the output with variable proportional controller and other two gains fixed minimized the noise.

Very low noise means that there is low pointing error. This low error results in the decreased value of BER. So the transmission and reception will be improved and as the vibration is decreased the receiver power will increase too. Here compensation is done with adding some gain with the receiver to compensate the vibration effects. Adding gain means decrease in the value of proportional block and while other two gain values was held unchanged. So the change of values of proportional block does improve the signal so as to get a good receiver output. Here the value of the transfer function was held constant and it is seen that the transfer function has no impact on the receiver output. The values of proportional block were changed but while other two blocks were constant and so as plant block. The BER of the with compensation and without compensation of PID controlled based feed forward system is shown in the following Fig. 16.

It is depicted in the figure that the BER remain constant at a fixed value in case of the compensated method. But the BER rate increases almost exponentially when compensation is not used.

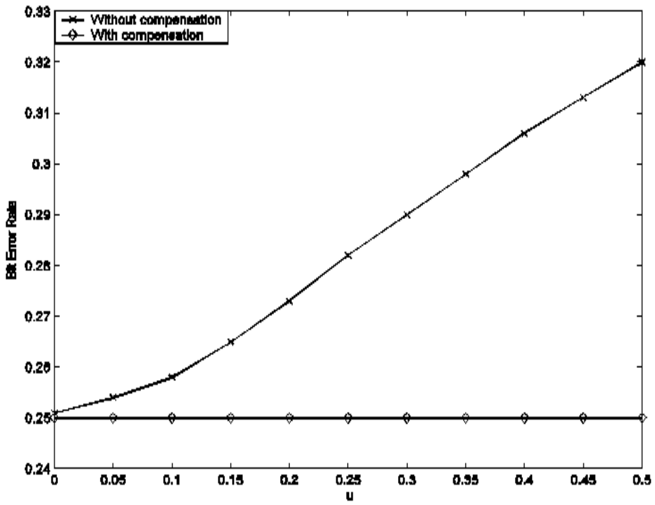

Fig. 16. The BER reduction is done by using with compensation and without compensation.

VI. CONCLUSION

The satellite vibration is major factor for high BER in satellite laser link. But we cannot reduce the vibration because it is beyond our control. The vibration obviously affects the received signal and the received signal is reduced at the receiver end. That is why a gain is added at the receiver to improve the signal. This gain actually increases the received signal power which is decreased due to vibration. Our work here is to damp the vibration and by damping the vibration is reduced. The ultimate effect is the reduction of BER. In this paper it has been shown that the BER can be significantly reduced if the vibration is compensated.

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