

# Method for Increasing Amplitude of Cluster Dither in RLG-based Small-size Inertial Measurement Unit

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## Summary:

The lock-in problem affecting ring laser gyroscopes (RLGs) is typically alleviated by applying a mechanical vibration to the RLG body using a dither. A cluster dither, which can excite three RLGs simultaneously, can facilitate the miniaturization of RLG-based inertial measurement units (IMUs). This study examines the mechanical parameters of an IMU that affect the amplitude of the cluster dither. For this purpose, a model with two linearly damped coupled linear oscillators was used, and the theoretical analysis results were experimentally validated.

**Keywords:** lock-in, ring laser gyroscope, cluster dither, inertial measurement unit

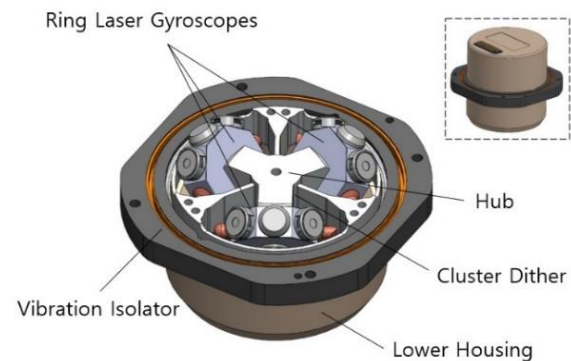
## Introduction

A dither is a device that alleviates the “lock-in” problem affecting ring laser gyroscopes (RLGs)—whereby the laser beams propagating in opposite directions become locked in phase—by applying mechanical vibration, such as rotational vibration, to the resonator. In a typical single-axis RLG, the rotation axis of a piezoelectrically driven dither is located on the RLG mount and coincides with the RLG’s sensing axis. However, smaller RLGs have inadequate space in the mount to accommodate the motor required for such dithers. Instead, if the dither can be kept outside the RLG, three RLG bodies can be simultaneously provided with a single-axis dither. Such a dither is called a cluster dither [1], and it facilitates miniaturization of RLG-based inertial measurement units (IMUs). However, unlike typical single-axis dithers, cluster dithers lack the amplitude required to solve the lock-in problem; this is because the rotation axis of a cluster dither does not coincide with the RLG’s sensing axis. The rotational vibration applied by the cluster dither to the RLG body decreases proportionally as the misalignment angle between the two axes increases. Moreover, the dither amplitude can be reduced by the vibration isolator, a component present in most IMUs, because the latter operates as a damper and thereby absorbs the rotational vibration produced by the cluster dither. An insufficient dither amplitude exacerbates the lock-in problem. To ensure sufficient dither amplitude, the preferred solution is to reduce the weight of the RLG. However, because the performance of an RLG is proportional to the reso-

nator length, reducing the weight of the RLG reduces its performance. In this study, the structure of the IMU was approximated using a model with two linearly damped coupled linear oscillators. The optimal mechanical design variables for improving the amplitude of the cluster dither were derived for this model, and the derived variables were validated through theoretical and experimental analysis.

## Two linearly damped coupled linear oscillators

Fig. 1 shows an RLG-based small IMU with a cluster dither. The dither is assembled in the lower housing connected to the vibration isolator, which is fixed to the body frame. Three RLGs are attached to the hub at 120° intervals. When the dither drive signal is applied, the dither produces rotational vibration, causing the RLGs to vibrate around its rotation axis. In this vibration system, the damping element of the vibration isolator attenuates the amplitude of the cluster dither.



*Fig. 1. RLG-based small-size inertial measurement unit with cluster dither*

The IMU, including the vibration isolator, cluster dither, and RLGs, can be approximated by a model with two linearly damped coupled linear oscillators, as shown in Fig. 2 [2].

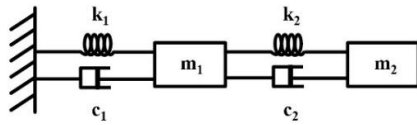


Fig. 2. Two linearly damped coupled linear oscillators

In the figure,  $k_1/k_2$  and  $c_1/c_2$  are the spring constant and damping constant of the vibration isolator/cluster dither, respectively;  $m_2$  represents the hub and RLGs, which experience rotational vibration due to the dither drive signal ( $F_d e^{i\omega t}$ ); and  $m_1$  denotes the mass excluding  $m_2$  in the IMU connected to the vibration isolator. In this approximate model, the rotation angle  $\theta_2$  of the cluster dither is expressed using Eq. (1):

$$\theta_2 = F_d \frac{I_1 I_2 \left( \frac{\omega_1^2 - \omega^2}{I_2} + \frac{\omega^2}{I_1} \right) + i\omega(\Gamma_1 + \Gamma_2)}{\left[ I_1 I_2 \left( -\omega^2 \left( \frac{\Gamma_1 \Gamma_2}{I_1 I_2} + \frac{l_2 \omega^2}{I_1} \right) \right) - i \left[ I_1 I_2 \left( \omega^3 \left( \frac{\Gamma_2}{I_1} + \frac{\Gamma_1}{I_2} \right) - \omega \left( \frac{\omega_1^2 \Gamma_2}{I_2} \right) \right) \right]} \right)}, \quad (1)$$

where  $\omega_1/\omega$  and  $\Gamma_1/\Gamma_2$  are the angular frequencies and damping constant of the vibration isolator/cluster dither, respectively, and  $I_1$  and  $I_2$  are the moments of inertia of the masses corresponding to  $m_1$  and  $m_2$ , respectively.

Eq. (1) shows that to increase the rotation angle of the cluster dither by modifying mechanical parameters, either the  $I_1/I_2$  ratio must be increased, or the cluster dither must be manufactured to have a low resonant frequency.  $I_1$  can be easily increased by increasing the diameter or housing weight of the IMU; however, this is not desirable for a small-size IMU. Conversely, reducing  $I_2$  would require the RLG to be miniaturized by reducing the resonator length, which would reduce the performance of the RLG. Therefore,  $I_1$  and  $I_2$  must be optimally designed considering the size and performance of the IMU.

### Analysis and test results

In this study, the  $I_1/I_2$  ratio and dither drive signal frequency were set as the design variables, and the gain of the cluster dither amplitude was evaluated. The  $I_1/I_2$  ratio was changed by adding a dummy mass to the housing, and two cluster dithers—one manufactured using stainless steel and the other using aluminum—were used to achieve different resonant frequencies (dither drive signal frequencies). To calculate the dither amplitude gain, modeling and simulation were conducted based on Eq. (1), and the output voltage of the piezoelectric material was experimentally measured. Figs. 3 and 4 present the simulation results and experimental measurements,

respectively, which are observed to be in agreement. The dither amplitude gain increased with the  $I_1/I_2$  ratio and was higher for the dither with the lower resonant frequency.

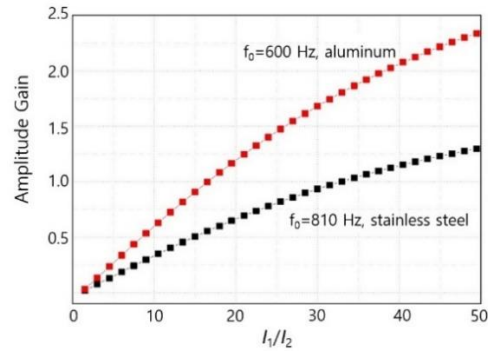


Fig. 3. Cluster dither amplitude gain determined via modeling and simulation

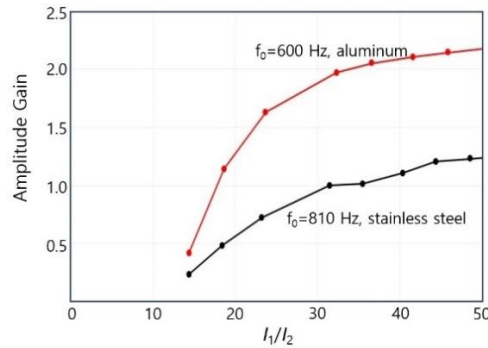


Fig. 4. Experimentally measured cluster dither amplitude gain

### Conclusion

This study aimed to improve the amplitude of cluster dithers in an RLG-based IMU. To achieve this, the IMU was approximated by a model with two linearly damped coupled linear oscillators, and the optimal design variables were derived. Among the mechanical parameters, these variables were determined to be the moment of inertia ratio ( $I_1/I_2$ ) and the dither drive frequency (resonant frequency). The correlation between the derived design variables and the cluster dither amplitude gain was verified through theoretical and experimental analysis. The findings confirmed that increasing the  $I_1/I_2$  ratio and lowering the dither drive frequency can increase the dither amplitude. Thus, the dither amplitude and drive frequency are important design variables for solving the lock-in problem affecting RLGs, and their optimal values must be determined considering the performance of the RLG.

### References

- [1] J. G. Hanse, Cluster Dither Apparatus, U.S. Patent 5173745, 1992.
- [2] Cline, Douglas. Variational principles in classical mechanics. University of Rochester River Campus Libraries, 2017.