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Dual Mode Closed–Loop Operation of a Vibratory Rate Gyro

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Abstract

This technical note presents simultaneous modal frequency tuning of two distinct Coriolis–coupled modes in a vibratory rate sensor and dual mode closed–loop operation. A degenerate condition is essential to maximize the sensor performance, however, only the fundamental Coriolis–coupled mode is often tuned and exploited to detect the rate of rotation experienced by the sensor while other Coriolis–coupled modes are ignored. By tuning two Coriolis–coupled modes at the same time, the second mode can be used to provide auxiliary rate data to enhance the overall sensor performance. To demonstrate the feasibility of dual mode operation, we have successfully tuned both n=2 and n=3 Coriolis–coupled modes of the Macro DRG within 100 mHz via mass tuning approach and implemented closed loops for both modes to detect the rate of rotation simultaneously.

I. Macro DRG

The Macro DRG is a large scale approximate model of Boeing's silicon disk resonator gyroscope (DRG). The sensor's vibrating structure is a 11.6 cm diameter 10–18 steel disk resonator that is composed of 16 thin concentric rings. The adjacent rings of the resonator are connected by "spokes" whose positions radially alternate by 22.5 degrees. Figure 1 illustrates the simplified schematic diagram of the Macro DRG. The resonator represented by a simple

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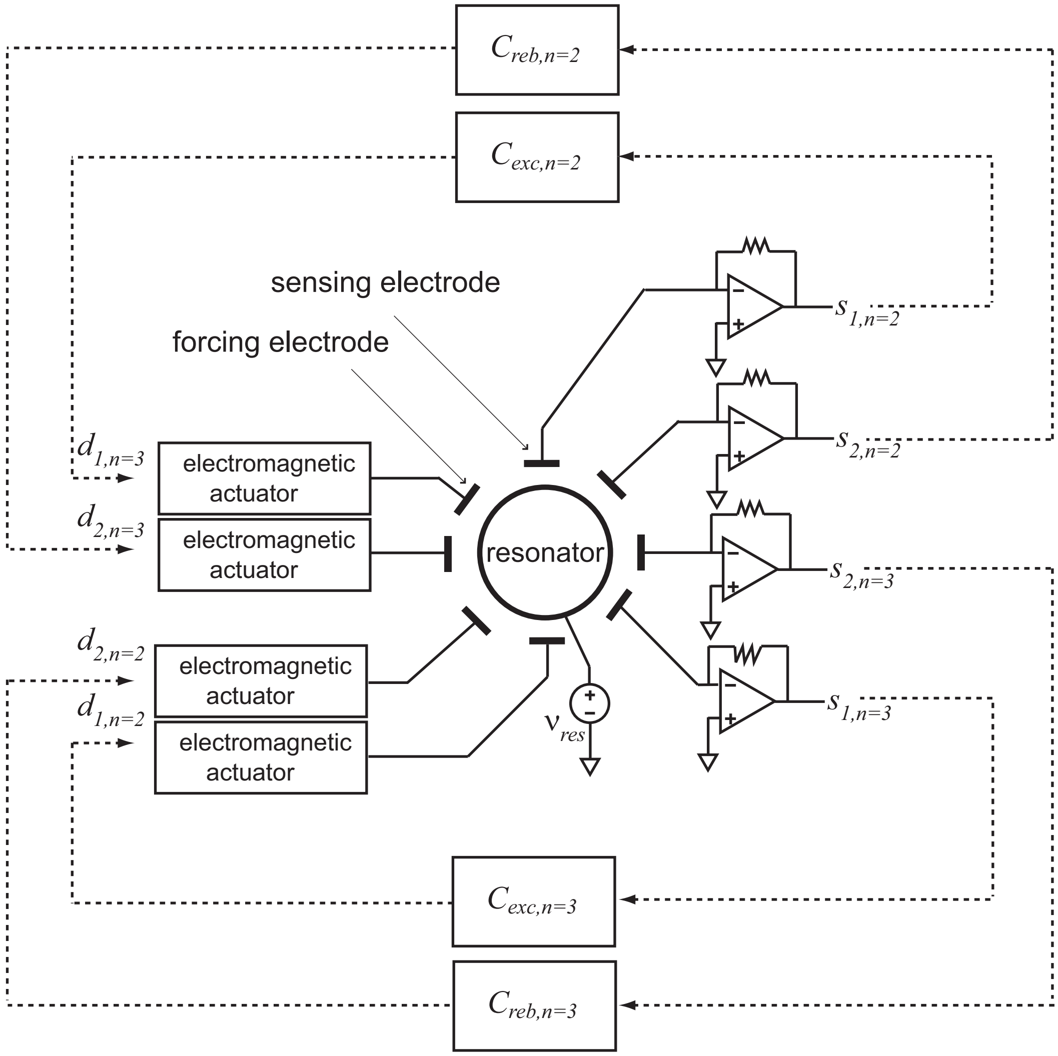

Fig. 1. Schematic diagram of the Macro DRG. Actuating and sensing signals are denoted as d and s, respectively and subscripts are used to identify the channel and the mode. For instance, $s_{1,n=2}$ represents the sense signal of the excitation loop for n=2 mode.

ring is biased at a constant potential and actuators and sensing pick–offs are distributed around the periphery of the resonator. The electromagnetic actuator excites the resonator's vibrating structure by providing a radial force on the resonator. The subsequent in–plane vibration of the resonator is measured by which the transresistance amplifier converts the charge on the sensing pick–off into a buffered output voltage proportional to the radial velocity of the resonator. For frequency tuning, small disc–shaped NdFeB magnets with a 1.6 mm diameter are added to the resonator to modify the sensor's mass so as to reduce the modal frequency split. More details

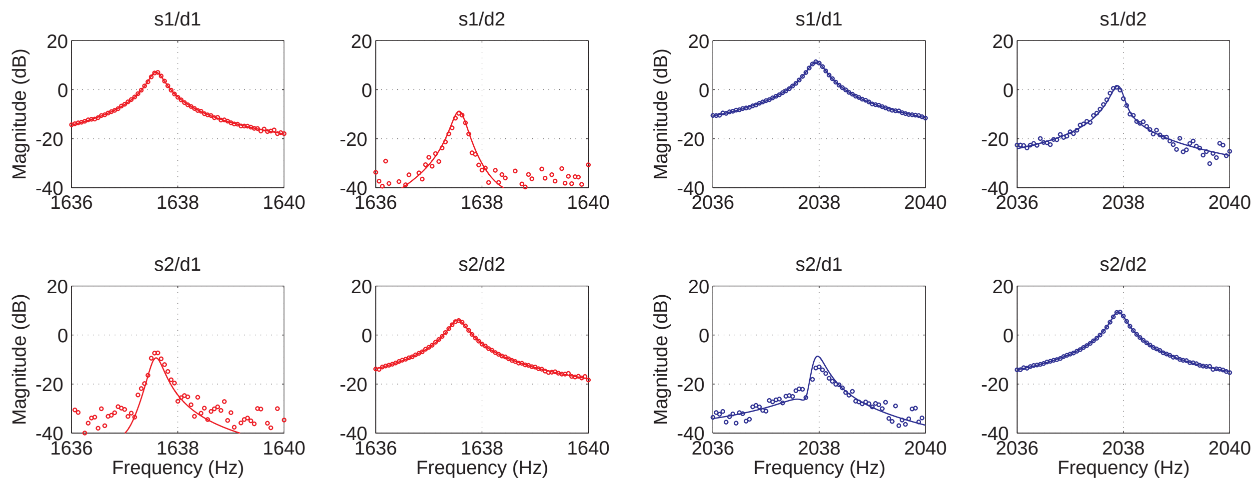

Fig. 2. Tuned open–loop transfer functions of n=2 mode (left, red) and n=3 mode (right, blue). Empirical frequency response data are individually plotted as circles and the frequency response of the identified model is plotted as a solid line.

on the Macro DRG including frequency tuning via mass matrix perturbation may be found in [1].

In order to facilitate the dual mode closed–loop operation in which two distinct Coriolis–coupled modes, e.g., n=2 and n=3 Coriolis–coupled modes, are simultaneously exploited to measure the rate of rotation, four pairs of sensor/actuator are placed around the periphery of the resonator. Two pairs are oriented at 45 degrees to each other for n=2 mode whose elliptical mode shapes are also separate by 45 degrees. The other two pairs are placed 30 degrees apart so as to provide orthogonal excitation and sensing for n=3 mode.

For each mode, two feedback control loops, labeled C_{exc} and C_{reb} in Figure 1, are implemented. The loop with C_{exc} is an excitation control loop that is present in all vibratory rate sensors to establish a constant sinusoidal response to provide a carrier signal onto which the angular rate is modulated. For the Macro DRG, an automatic gain control (AGC) loop is employed to maintain a stable amplitude while effectively tracking the modal frequency drift. The second loop with C_{reb} is a force–to–rebalance or simply rebalance loop in which the feedback signal regulates the Coriolis–force induced response to zero. The angular rate of rotation may be estimated by demodulating the feedback signal of the rebalance loop, d_2, with respect to the carrier signal, s_1. For more details of control architectures, the reader is referred to [2] and [3].

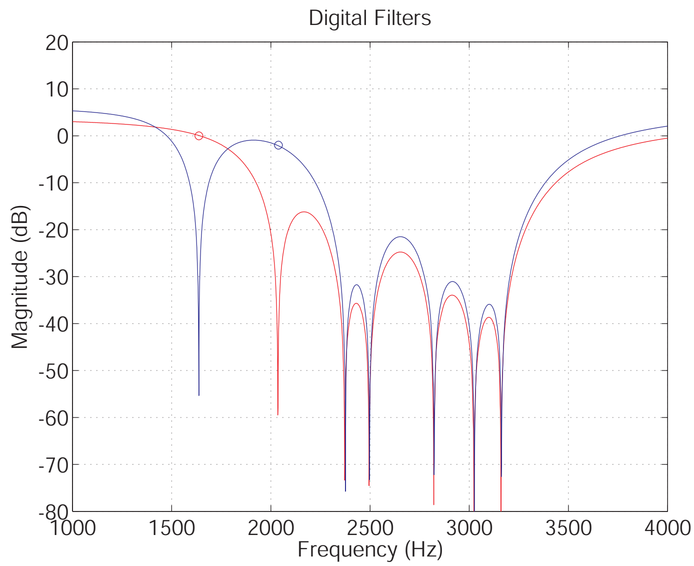

Fig. 3. Magnitude plots of digital filters for n=2 (red) and n=3 (blue) modes where the circle indicates the operating frequency of the loop.

II. Experimental Results

The Macro DRG in its native state displays a frequency split of 1.5 Hz and 1.8 Hz for n=2 and n=3 Coriolis–coupled modes, respectively. The mass tuning approach introduced in [1] permits the frequency tuning of n=2 and n=3 modes simultaneously by placing small magnets on the surface of the resonator. Two–input/two–ouput empirical frequency response magnitudes of n=2 and n=3 modes are plotted in Figure 2, which reveals that both modes are effectively tuned as well as decoupled. Analytical model fits to the data, indeed, indicate that both modes are tuned within 100 mHz.

Once the mode is tuned as well as decoupled, the excitation and force–to–rebalance controller designs can be carried out independently. Each loop contains analog filters whose pass–band only encompasses the mode of interest and digital filters to achieve the proper loop gain and phase. In addition, digital filters provide various notch frequencies so as to ensure the loop stability by attenuating other flexural modes as shown in Figure 3.

To demonstrate the successful implementation of dual mode closed–loop operation, closed–loop signals captured by the oscilloscope are shown in Figure 4 and the estimated rate (where the bias term is removed) by n=2 and n=3 modes when the Macro DRG is exposed to the external

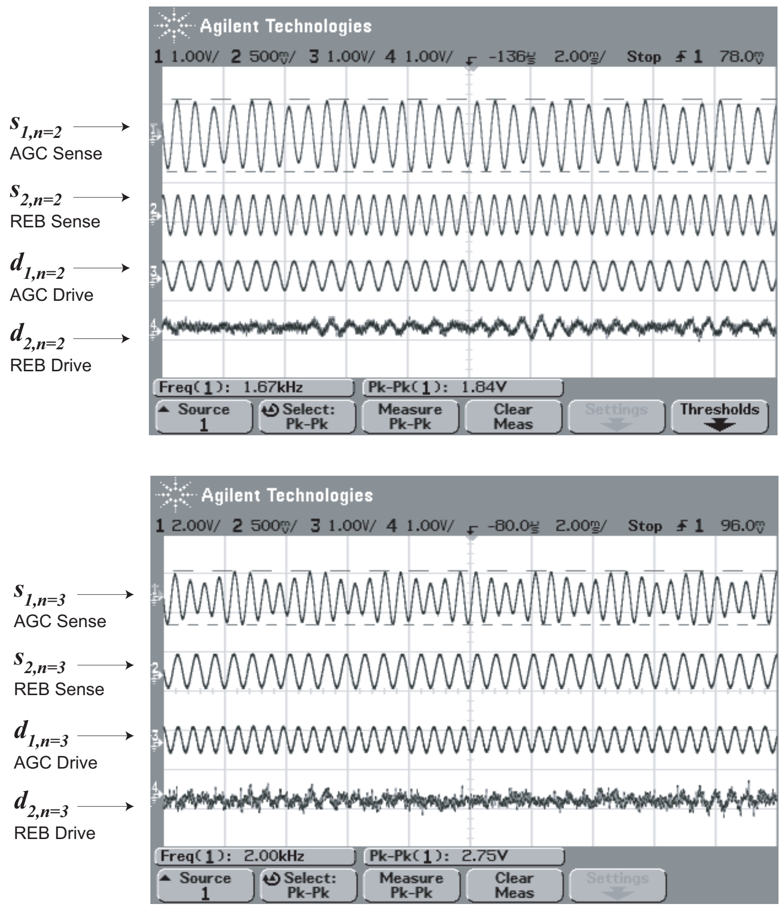

Fig. 4. Closed–loop signals of n=2 mode (top) and n=3 mode (bottom).

rate of rotation are plotted in Figure 5.

Rate bias stability is often quantified by plotting a Green chart that is a log–log plot of a standard deviation over a range of integration times. At short integration times, the quantization and electrical noise sources are dominant and the overall noise plot shows a negative slope. On the other hand, at longer sample times, long term drift processes such as temperature variations become more dominant resulting a positive slope. Figure 6 compares the rate bias stability of n=2 and n=3 modes from 4–hour long zero rate bias data. Higher green chart of n=3 mode can be attributed to a smaller Coriolis coupling strength but both modes achieve a minimum close to 20 deg/hr rate bias stability. In addition, by plotting the spectrum of the zero rate bias data as in Figure 7, the angle random walk (ARW) (that is associated with the low frequency white portion) of n=2 and n=3 modes are estimated as 0.62 deg/$\sqrt{\text{hr}}$ and 0.89 deg/$\sqrt{\text{hr}}$, respectively.

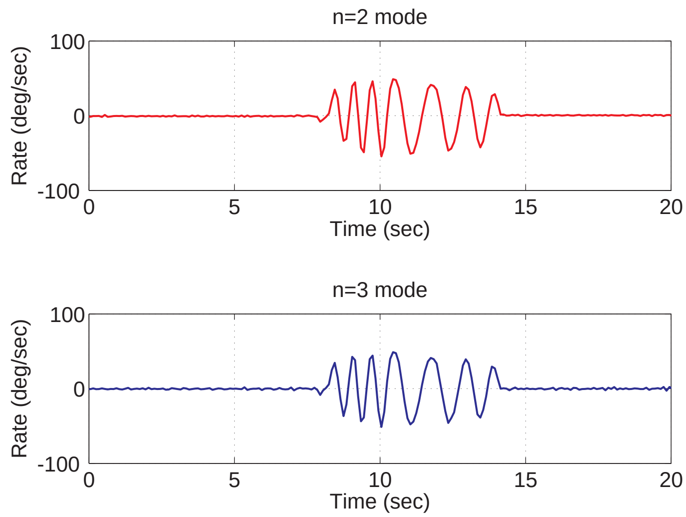

Fig. 5. Responses to external rate of n=2 mode (top, red) and n=3 mode (bottom, blue). Measured scale factors are 3.2 mV/deg/sec and 1.7 mV/deg/sec for n=2 and n=3 modes, respectively.

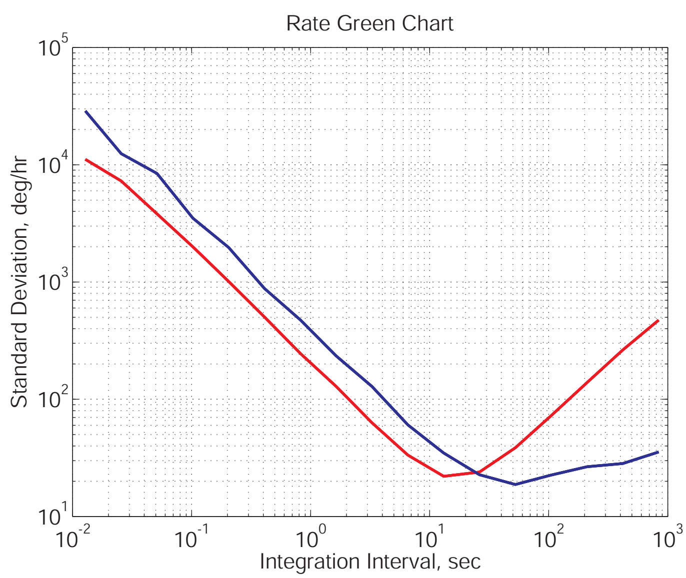

Fig. 6. Rate bias stability of n=2 mode (red) and n=3 mode (blue).

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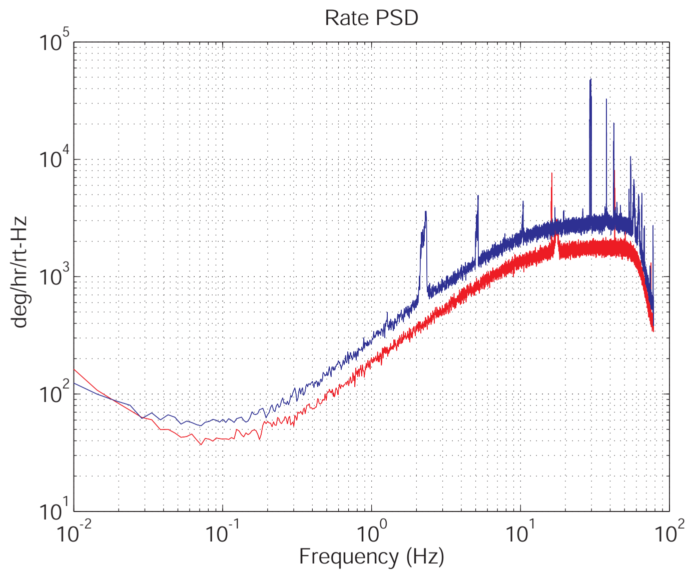

Fig. 7. Rate PSD of n=2 mode (red) and n=3 mode (blue).

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