OVERCOMING OF HIGH CENTRIFUGAL FORCES IN A 5 DOF MICRO AMB GYROSCOPE

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Keywords: navigation, magnetic levitation, gyroscope, H∞ control.

ABSTRACT

The need for motion sensing system is constantly growing for civil and mass applications, which require products that ally precision, low cost and compactness. The active magnetic bearing (AMB) technology because of its absence of friction between the rotor and the stator could be an interesting solution to reach the two first requirements. The miniaturization of the AMB system permits to satisfy the last one. Among other sensing devices, gyroscopes can benefit from the high spinning speeds of the rotor that AMB permit. These high speeds guarantee the high precision of the instrument. However, these high speeds have the inconvenience of destabilizing the rotor. Therefore, a good control of the rotor position is a key issue towards a precise gyroscope. On that purpose, this paper presents a two degrees of freedom H∞ controller based on the GS/T weighting scheme strategy and including an explicit integrative part. The simulations run with that controller show a great improvement in the quality of the angular velocity measurements compared to a classical two degrees of freedom H∞ controller as will be shown in this paper.

INTRODUCTION

The introduction of the active blocking system, better known as ABS, into cars revealed the growing need for inertial sensing. Among other data, that permit to apprehend the movements of a vehicle, the measurement of the vehicle angular velocity describes the rate of change of the vehicle attitude. The currently available gyroscopes are either very high precision instruments but very costly or cheaper products that lack precision to be used in vehicle navigation. Therefore, a real need for gyroscopes combining low cost and precision exists. Based on the same principles as classical mechanical gyroscopes [2] for the measurement of angular velocity, a gyroscope based on Active Magnetic Bearings has the advantage that the spun mass is levitated thus freeing it from any mechanical link to the base of the instrument what renders precise classical mechanical gyroscopes so expensive.

Although AMB are oftener used as motors [1], some previous research about AMB based gyroscopes have been done in the past among which [4] obtained promising results using an industrial AMB device. Our current research focuses on smaller devices that could be mounted on civil vehicles. One of the keys for mechanical gyroscopes to precisely measure angular velocity is the speed of the spun mass: the higher the speed, the more precise the angular velocity measurement. However, increasing the spin speed of the rotor means augmenting the centrifugal forces to which the rotor is subject. Hence, the controller that stabilizes the rotor within the stator must be able to be efficient over a large spectrum of centrifugal forces. This phenomenon associated with the uncertainties due to the inherent nonlinear behavior of magnetic bearings pleads in favor of the use of robust control. This paper will present a model of the gyroscope prototype on which a two degrees of freedom H∞ controller including an explicit integrative part has been tested.

PROTOTYPE DESIGN

In order to reach very high speeds, the rotor needs to be as short as possible [3]. In practice, this rotor must be tall enough so that electromagnets as well as position sensors can control its attitude and position. Figure 1 presents the prototype. As can be seen on Figure 1, the lateral positioning of the rotor is ensured by means of two stages of radial actuators. Each stage is made out of three electromagnets. This electromagnet arrangement inside the rotor has been chosen because of the size limitations that were imposed by the application.

PROTOTYPE MODEL

As its first bending mode is slightly over 11[kHz], the rotor is assumed to be rigid. The model therefore becomes:

$$M\ddot{X} = -G\dot{X} + m\vec{g} + \vec{T}_{gyro} + \overrightarrow{FT_{acc}} + \overrightarrow{FT_{u}} + \overrightarrow{FT_{AMB}} \quad (1)$$

In equation (1) the vector $X = [z, x, \theta y, y, \theta x]^T$ describes the position and the inclination of the rotor in the coordinate system bound to the stator of the gyroscope. The matrix G represents the gyroscopic effects due to the spin of the rotor, $\overrightarrow{T_{gyro}}$ and $\overrightarrow{FT_{acc}}$ the effect of the vehicle angular movements and acceleration on the rotor, $\overrightarrow{FT_u}$ the effect of the rotor unbalance.

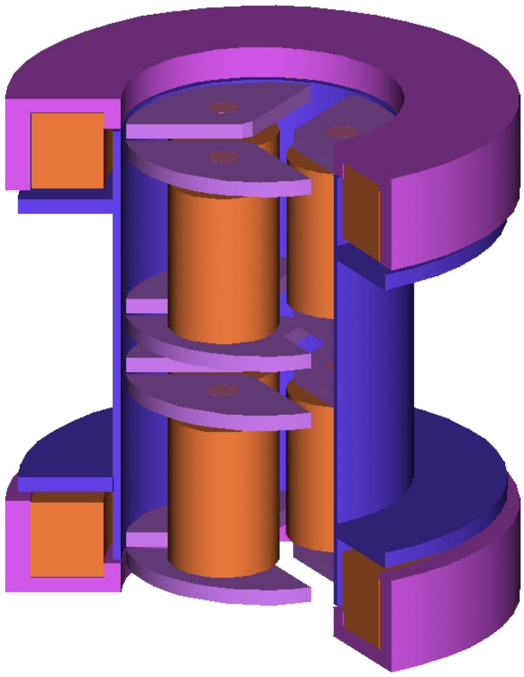

Figure 1: Cross section view of the prototype of the AMB gyroscope. The rotor is represented in blue, the coils in orange and the coil cores in pink.

Finally, $\overrightarrow{FT_{AMB}}$ represents the force and torque action of the electromagnets on the rotor. This action can be linearized as:

$$\overrightarrow{FT_{AMB}} = -K_x X + K_i I \qquad (2)$$

In equation (2), K_x represents the force displacement stiffness matrix of the system and K_i represents its force current stiffness matrix. As each level of radial bearings is made out of three electromagnets, the forces between the X and Y axes are strongly coupled. On the opposite, the Z forces are considered to act only along the Z axis. However the Z forces induce a moment about the X and Y axes that cannot be neglected and which is included in the expression $\overrightarrow{FT_{AMB}}$.
In order to have a more realistic model the current will be saturated between 0 and 500[mA].

CONTROLLER DESIGN

As previously written, a two degrees of freedom H∞ controller including an explicit integrative part will be tested on the prototype. This controller is synthesized based on the linear model of the plant and tested on a model based on the nonlinear expression of the force developed by the electromagnets. This protocol has been chosen to be as close to the reality as possible.

One DOF H∞ controller based on the GS/T strategy

From the different types of H∞ controllers that have been tested on the prototype, an H∞ controller based on the GS/T architecture [5] has been chosen. The advantage of this strategy over the S/KS/T weighting scheme is that it does not contain the inverse of the plant what leads to a slow response and may drive the system to instability because of the system uncertainty.

Two degrees of freedom H∞ controller

The H∞ controller found with the GS/T controller has the inconvenience that one cannot specify the perturbation rejection performance independently from the trajectory tracking one. To cope with that limitation the controller is extended with the help of a feed forward part to a two degrees of freedom H∞ controller. This controller is shown on Figure (2). On this figure, $K = \begin{bmatrix} K_f & K_b \end{bmatrix}$ stands for the controller (with K_f the feed forward part of the controller and K_b its feedback gain), G for the plant and the different W for the weights. The main interest of using a feed forward action is to anticipate the action of disturbances on the rotor. As the goal of the gyroscope is to sense the vehicle movements, the disturbances coming from the outside of the instrument base cannot be anticipated. Therefore, the only disturbances that can be compensated by the feed forward have an internal origin. Based on this observation, the unbalance effects will be considered as the internal disturbance which will be anticipated with the help of the feed forward controller. Thus, the weight W_d should be an approximation of the unbalance effects.

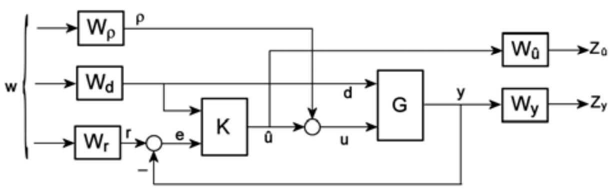

Figure 2: two degrees of freedom H∞ controller based on the GS/T weighting scheme

Including the explicit integrator to the H∞ controller

The main drawback of the two degrees of freedom controller is the static error showed during the simulations. The introduction of an explicit integrator to the two degrees of freedom (see Figure 3) permits in the case of a linear model to cancel this static error and in the case of the nonlinear model on which the controller is tested to reduce it. This should guarantee that the rotor stays within the domain of the small displacements around the point where the linear model has been derived. A second advantage brought by this explicit integrator is an increase in the disturbance rejection.

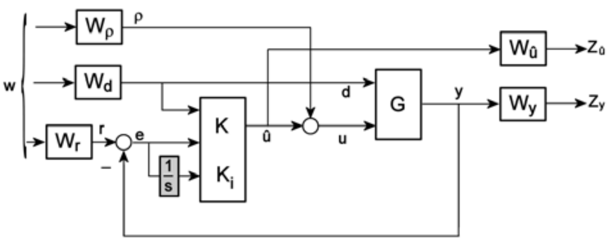

Figure 3: H∞ controller with an explicit integrator (in grey).

Finally, the transfer function of the closed loop system with the two degrees of freedom H∞ controller including the explicit integrator is:

$$T_{zw} = \begin{bmatrix} -W_{\hat{u}} T_u W_\rho & -W_{\hat{u}} S_u (K_b^* G_{yd} + K_f) W_d & W_{\hat{u}} S_u K_b^* W_r \\ W_y G_{yu} S_u W_\rho & W_y T_{yd} W_d & W_y T_e W_r \end{bmatrix} \quad (3)$$

With $K_b^* = K_b + K_i/s$, $S_e = \left(I + GK_b^*\right)^{-1}$, $T_e = S_e G K_b^*$, $T_{yd} = S_e G K_f$, $S_u = \left(I + K_b^* G\right)^{-1}$ and $T_u = S_u K_b^*$.

Choice of the weights

The synthesis of the H∞ controller is conditioned by the choice of the different weights which is explained in the following. During this explanation, only elements from equation (3) will be referred to.

In order to avoid a too important influence of the first and third elements of the first equation line on the plant, the weight W_u is chosen small and constant.

The weight W_y is chosen equal to 1 to have a better physical understanding about the choice of the weights W_r and W_ρ.

Due to the previous weight choices, the main action of W_r is on the third element of the second line of T_{zw}. Hence, W_r is used to shape T_e and thus permits to limit its bandwidth. On that purpose, W_r is designed as a high pass filter crossing the 0 dB line at 1[kHz]: the desired bandwidth of T_e.

The weight W_ρ shapes $G_{yu} S_u$ and is therefore chosen with a low order dynamics with a dichotomic approach.

As previously mentioned, the weight W_d is an approximation of the unbalance effects based on the measurement of the current spin speed of the rotor.

TEST RESULTS AND INTERPRETATIONS

Two series of tests have been run on the two previously mentioned H∞ controllers. First, the vehicle moves at different angular velocities and with different angular motion amplitudes in absence of any acceleration (the gravity is however included). Second, the same tests are run but the vehicle is subject to an acceleration of 1g. For both series of tests, the chosen quality criterion is the measurement mean error.

1. Measurements mean error without acceleration

The tests done on both controllers present two types of results. First, the measurement error of the controller including an integrative part is twice as big as the one measured by the other controller (see Figure 4). However, the results show that the error made by the integrative controller only depends on the angular velocity of the vehicle about that particular axis what is not the case for the non integrative controller. Moreover, the angular velocity measured by the integrative controller is proportional to the angular velocity imposed to the vehicle. Therefore a proper calibration of the gyroscope containing the integrative controller can overcome the measurement error. On the opposite, the non integrative controller will be harder to calibrate.

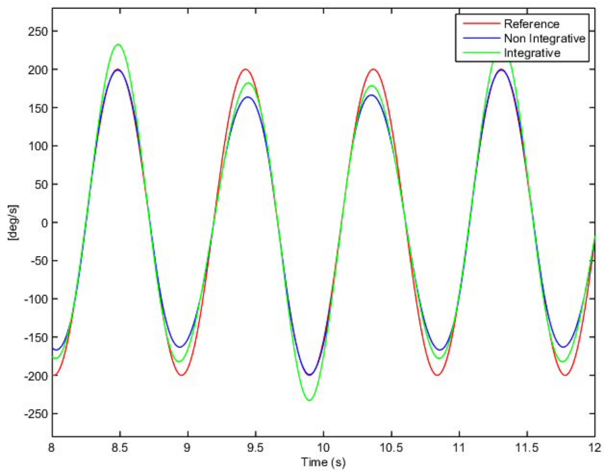

Figure 4: angular velocity measurement [°/s] about the vehicle Y-axis. The reference angular velocity is drawn in red, the non integrative measurement in blue and the integrative one in green.

Second, Figure 4 shows that the measurements done by both controllers are subject to the influence of the nonlinear cosine that comes from the change of coordinates between the inertial coordinate system and the coordinate system bound to the vehicle. Often, this effect is neglected which is only true in the case of small turns of the vehicle. In order to develop a navigation instrument that can be mounted on a large range of vehicles this cosine effect cannot be neglected. Hence, the drift due to the integration of the angular velocity must be as small as possible so that the gyroscope can correct this cosine effect.

2. Measurements mean error with a 1g acceleration

In presence of a 1g acceleration of the vehicle, what is a more realistic test for a gyroscope mounted on a vehicle, the non integrative controller cuts the peaks of the measures (see Figure 5). This is not the case of the integrative controller. The reason for the different behaviors among the two controllers is the ability of the integrator part to properly track the trajectory even in presence of external disturbances.

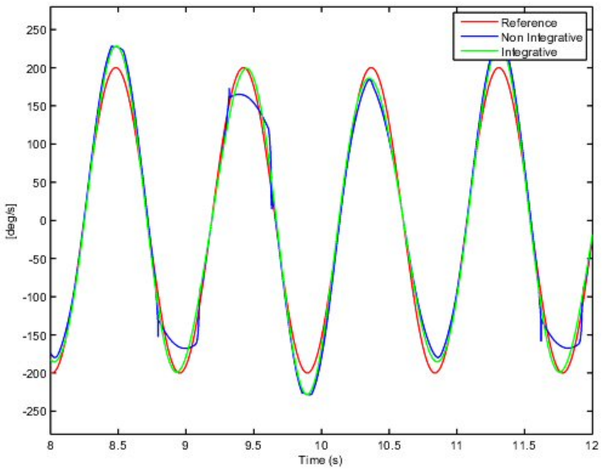

Figure 5: angular velocity [°/s] measurement about the vehicle Y-axis. The reference angular velocity is drawn in red, the non integrative measurement in blue and the integrative one in green.

CONCLUSION

A miniaturized gyroscope prototype based on the active magnetic bearing technology has been introduced. To counteract the effect of unbalance effects two H∞ controllers based on the GS/T weighting scheme strategy have been tested. Both controllers were 2 DOF H∞ controllers; an explicit integrative action has been introduced to one of these controllers. Two series of tests have shown that the introduction of the integrative part results in a clear improvement in the quality of the measurement. As a matter of fact, the integrative controller permits a good trajectory tracking even in presence of external disturbances such as an acceleration of the vehicle. A second advantage brought by the integrative part is the easiness of the gyroscope calibration because, first, of the independence between the axes of measurement and, second, of the measurement mean error which is proportional to the vehicle angular velocity. The advantages brought by the integrative action added to the two degrees of freedom H∞ controller makes its use within the gyroscope prototype a tremendous improvement for the quality and stability of the angular velocity measurement.

ACKNOWLEDGEMENTS

This research was supported by the company JTEKT Corp. in associtation with the Ecole Polytechnique Fédérale de Lausanne.

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