Miniaturized Gyroscope with Bearingless Configuration

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Abstract: One of the current topics in magnetic bearings technology is the exploration of their potential in the field of micro machines. Up to now in literature there are very few examples of realization and most of them are just experimental systems but it seems that further investigations can be performed.

In this paper the evaluation of the performance of micro magnetic bearings in an application dealing with the navigation of planes and cars is reported. The realization of a miniaturized gyroscopic sensor based on active magnetic bearings (AMBs) is described from the mechanical to the control design.

The mechanical and the actuation systems are analyzed along with the realization of the model and of two different control design strategies: a H_∞ and a decentralized MultiSISO control (a classical Proportional Derivative (PD) on each axis). For both the proposed approaches the modelling and the control design phases are discussed.

The H_∞ strategy has been evaluated to perform a robust control and consists in a Plant Non-Inverting GS/T Weighting scheme with an explicit integral action and an anti wind-up action.

In the case of decentralized strategy, the model of the system containing the transformation from the center mass coordinates to the actuators coordinates is exposed along with the tuning of the proportional and derivative actions.

The numerical and experimental results obtained on the prototype with the two control strategies are compared to evaluate their behaviour in this application.

Finally, the principle used to make the rotor spinning is exposed and the rotation results are discussed.

Keywords: Magnetic Bearings, Self Motor, Robust Control, Rotordynamics, Gyroscopes

INTRODUCTION

The growth of the Global Positioning System (GPS) has shown how important vehicle navigation becomes in our everyday life. The position of the vehicle is detected by satellites and sent back to the vehicle driver so that instantaneous trajectory of the vehicle can be adjusted in order for the vehicle to reach its destination. More generally, navigation consists in a set of constraints on the dynamics of a vehicle. These constraints can be, for example, its trajectory (travel between two geographical locations for the GPS) and its attitude regarding the ground (all four wheels of a car must stick on the road). This requires sensors to inform the driver (human being or computer) about the current dynamical state of the vehicle. Thus the driver can adapt his action in order to stick to predefined constraints. Two ways of navigation sensing exist: sensing the vehicle dynamics from its outside or from its inside. The two families can coexist according to the circumstances. Outside navigation sensors are for example the GPS, radars and light reflectors. The second sensor family (inside) is better known as inertial sensors [1]. For example, the magnetic compass belongs to the latter family. Inertial navigation (named after inertial sensors) uses gyroscopes and accelerometers to tell the driver about the vehicle current state of motion. With the help of this information, the driver can plan the vehicle trajectory. Inertial navigation has the main advantage of being self sufficient, i.e. the vehicle does not need to communicate with an external source of information. This advantage has firstly been used by the military for vehicles (submarines among others) that, in war circumstances, must stay invisible for the enemy. Twenty years ago, the inertial sensor price started to diminish because of a change of technology towards the electronics. By breaking this prosaic bottleneck, the inertial sensors were admitted into civil applications. Beside the price, two criteria for a large scale commercialization of inertial sensors are little or no maintenance needs and precision. Indeed, depending on the application, short term or long term precision is required [1]. Mechanical gyroscopes are more accurate for short term measurements whereas optical gyroscopes behave better. Therefore, an overlap of the two domains of use is desirable. In the case of mechanical gyroscopes, the angular velocity of the vehicle is measured by means of a mass spun about its inertia axis. One main limit of mechanical gyroscopes is the link between the spun mass and the base of the instrument. As a matter of fact, the ball bearings will induce friction responsible for measurement errors and tribology issues (a limit for the maintenance criterion) which can even lead to failure. Moreover, limitations in the instrument sensitivity will occur due to the contact between the mass and the base. This observation led to the idea of levitating, by means of electrostatic or magnetic forces, the spun mass to prevent it from any contact with the base. Hence, this solution could extend the domain of use of mechanical gyroscopes towards short term use.

The aim of this paper is to investigate the use of active magnetic bearings in a miniaturized application to exploit the possibility to use them as sensors and actuators at the same time. In principle, this solution can be characterized by several advantages: higher precision of the measurement, possibility of the use of the actuator as a sensor being the electrical behaviour or the coil strictly connected to required measurement of the angular velocities, just to indicate the main ones. The full magnetic levitation of the rotor can be achieved with the use of magnetic bearings [2,3] which have been already implemented in various applications, such as high precision accelerometers or high rotational speed motors with very low vibrations, which were otherwise limited by the friction due to conventional mechanical bearings.

The main originality and goal of the proposed system is the adaptation of the magnetic levitation to a high precision, two degree of freedom gyroscope. It must be noted that the developed gyroscope can only measure the roll and tilt angular velocities, hence its name of two dof gyroscope. One key component to reach high precision in the measurement is the levitation control accuracy, which is correlated to the desired gyroscope bandwidth and sensitivity. This accuracy depends, among others, on the ability of the controller to compensate for uncertainties of the gyroscope model and for external disturbances. For that purpose, two different controllers have been developed during this study: a robust two-degree-of-freedom H_∞ controller including an explicit integrator and a decentralized Multi-SISO control with eight different PD actions. A very challenging requirement is that the whole electromechanical system including rotor, stator, motor, sensors and actuators must fit within a 40 mm side cube. For that purpose the possibility of the integration of the bearing and motor action on the same coils has been evaluated. This kind of structure is called self bearing motor [3,4] and allows to reduce the number of actuators even if it presents some drawbacks related to the control that becomes complex due to the combined actions.

The paper starts with the description of the actuation and sensing system of the setup. The models realized for the design of the H_∞ and decentralized controls are presented along with the results obtained numerically and experimentally. The final part is devoted to the discussion of the principle used to put the cylinder in rotation and to the analysis of the main advantages and drawbacks of the adopted solution and to the possible alternative bearingless strategies.

DESCRIPTION OF THE SETUP

The prototype of the gyroscope is a 40[mm] side cube (Fig. 1.a)containing a cylinder rotor (Fig. 1.b) provided with two disks (Fig. 1.c.4) allowing to have a significant gyroscopic inertia. The cylinder is suspended in axial direction by means of two actuators (the lower one is reported in Fig. 1.c.2, the higher is similar) and in radial direction by means of six actuators arranged on two different radial layers (Figg. 1.c.2, 1.c.3, 1.c.4) to provide the torque allowing to control the pitch and roll angles of the rotor.
The main mechanical and electrical parameters are listed in Table 1.

TABLE 1: Main parameters of the rotor and of the actuators.

ROTOR			
Mass	0.014		kg
Transversal moment of inertia	2.0e-6		kg·m^2
Polar moment of inertia	1.8e-6		kg·m^2
ACTUATORS			
	AXIAL	RADIAL	
Number of turns	270	290	-
Airgap Section	1.04e-04	1.5e-5	m^2
Airgap	200e-6	200e-6	m

Fig. 1.d represents the magnetic field map induced by activating one winding of the upper layer. This FEM simulation shows that almost all the magnetic flux closes through the rotor. Fig. 1.d.2 shows that the two disks of the cylinder have also the function of closing the axial magnetic flux. One can conclude that the field generated by one radial actuator does not affect neither the other radial actuators nor the axial actuators. This prototype should not present main issues due to the coupling between the electromagnetic fields generated by the different actuators.
The radial actuators have three main tasks: a) keeping the rotor polar axis parallel to the gyroscope stator main axis (attitude control); b) keeping the rotor center of gravity at the geometric center of the stator (position control); c) rotating the rotor around its main axis (due to the bearingless configuration of the system).
The radial actuators are placed inside the cylinder to gain more space outside the rotor for the sensing system and to guarantee a larger sensitivity of the rotor attitude measurement through a distance between the sensors and the gravity center of the rotor. Furthermore the

precision of measurement is increased if the rotor is larger because the gyroscopic effects are more significant.
The axial actuators have to suspend the cylinder and position the center of gravity of the rotor along the stator Z-axis: one actuator on each side of the rotor is sufficient to maintain its center of mass at a precise Z position.

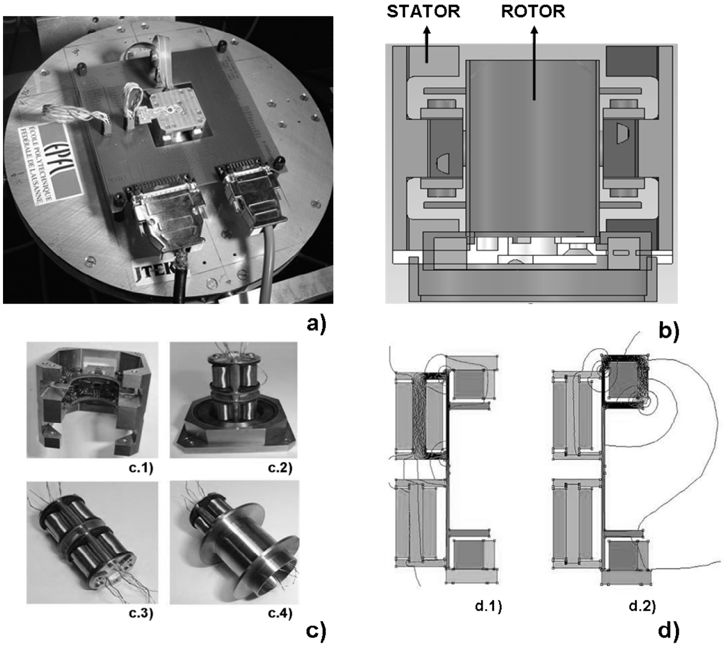

Figure 1: Setup: a) Overall view of the prototype assembly. b) Section view of the cube (actuators and sensors are not reported). c) Details of the setup: c.1) Internal view. c.2) Axial lower coil and radial coils c.3), c.4) Radial coils. d) Simulation of the field produced by one radial actuator of the upper set of the radial stage on the rotor (d.1) and by the upper axial actuator on the rotor (d.2) for a current of 0.1 [A].

The information of the rotor position is obtained by means of nine light reflection sensors OSRAM SFH9201 (six for the radial position and three for the axial) as shown in Fig. 2.

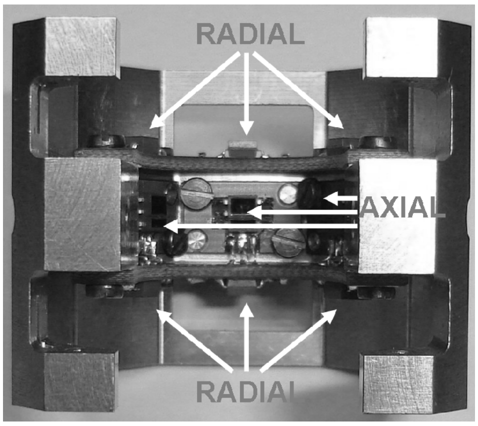

Figure 2: Position of axial and radial displacement sensors.

The current control is performed by means of linear operational amplifiers at high current (OPA544T Burr Brown), one for each coil, being high the required precision and very low the power involved in the system. The feedback and monitoring system realized on a xPC Target system, which allows to convert directly the designed control laws from the Simulink Model to the real time application. The signals coming from the sensors and the commands of the controls are converted by means of an (AD UEI – PD2-MF-16-500/16H) and a DA (UEI – PD2-AO – 8/16) card. Two boards, one for the conditioning of the sensors signals and the other used to regulate the current in the coils, allow to close the control loop.

MODELLING AND CONTROL DESIGN

Two different control strategies have been performed on the prototype in order to obtain the axial and the radial levitation: an H_∞ control law (robust approach) and a decentralized solution with a Proportional - Derivative (PD) action on each axis (simplified approach).

H_∞ Control. The first strategy used to control the axial and radial behaviour of the rotor is a robust approach realized by synthesizing a H_∞ law. This is a state-feedback controller including a model state observer. This approach allows to take into account uncertainties of the model parameters, unmodeled dynamics or hidden nonlinearities of the plant.

The model has been realized by considering the mechanical structure, the actuation system, the gyroscopic and unbalance effects, the coupling due to the gyroscopic effects and to the six electromagnets configuration.

The linear state space model of the plant can be formulated in the center of mass coordinates, i.e. its three displacements and two attitude angles of the rotor. However, the formulation of the problem is not intuitive because of the combination of positions and angles. Therefore, a classical method [10] is to express the previously mentioned model in the coordinates of the actuators. The positions of the rotor center mass and its attitude is converted in five data: the axial displacement, the X and Y coordinates measured by the upper and lower sensors.

Even if this reformulation cannot improve the control of the plant [11], however, it allows to get an easier understanding of the rotor behaviour and hence of the weighting parameters that must be tuned to improve the H_∞ controller. As a matter of fact, the singular values of the plant transfer function only explain the behaviour of positions regarding the frequency and not a mix of positions and torques.

The rotor has been modelled as a mass, the actuation system has been divided in radial and axial action. The combination of the actions of the coils on the rotor has been expressed in terms of forces and torques, considering that the force exerted by each coil can be estimated as:

$$F = \frac{\mu_0 N^2 A i^2}{(x - x_0)^2}. \tag{1}$$

where μ_0 is the magnetic permeability of the vacuum, N is the number of the turns, A is the cross sectional area of the magnetic circuit, i is the current flowing in the coil, x is the displacement of the rotor and x_0 is the nominal airgap, equal to 200 μm.

The gyroscopic effects appear when the rotor angular momentum is derived. Therefore its rotation must be well defined. The rotor is affected by four referential rotations and by its spin speed Ω_Z . Two referential rotations of the type φ_x and φ_y affect the stator (respectively the rotor) about the fix frame (respectively the stator). As the only available sensors permitting to describe the complete gyroscopic movement of the rotor are bound to the stator, the angular moment of the rotor is derived in the stator frame and the gyroscopic effect is computed.
The adopted solution of control is exposed referring to the basic scheme contained in Fig. 3 where ω represents the exogenous inputs, z the regulated outputs, u the command signals, y the controller inputs and T_{ZW} the transfer function from w to z .

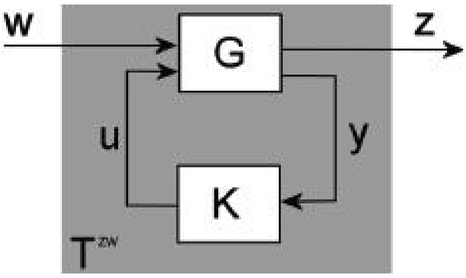

Figure 3: Basic scheme for the H_∞ control design

This system includes the controller K and the plant P which is called the augmented plant. P includes the general plant G as well as the weights W_W and W_Z designed in order to assign the closed loop performance of the system. In general, the computation of a standard form H_∞ controller can be reduced first to a problem of stabilization of the closed loop system and of perturbation rejection, and second to a minimization problem. As the maximum value between the energies of the output $z(t)$ and input $w(t)$ signals are represented by the H_∞ norm, its minimization is required to optimize both the perturbation rejection and the trajectory tracking.
In most cases, a H_∞ synthesis, that is directly computed from the model, i.e. without the use of any weight, does not enable to reach satisfactory performances in trajectory tracking, perturbation rejection and in robustness with respect to model uncertainties. Therefore, the user imposes, with the help of the calibrators (i.e. the weights), the desired shape of the singular values of the different transfer functions, such as the sensitivity, the complementary sensitivity, the transmission of the perturbations on the outputs.
The chosen weighting scheme is a Plant Non-Inverting GS/T [9], based on the use of weights at the system input, is a very well suited strategy for ill-conditioned plants. To avoid the need of inverting the plant model in the controller, the idea is to include the plant itself inside the weighting of the sensitivity function. On that purpose, the reference signal r is weighted instead of the error signal e . Thus, the closed loop transfer function of T_{ZW} becomes:

$$T_{zw} = \begin{bmatrix} -W_u T_u W_\rho & W_u S_u K W_r \\ W_y G S_u W_\rho & W_y T_e W_r \end{bmatrix}. \qquad (2)$$

The weight W_u can be chosen small and constant. Hence, this choice will lead to a small first line of T_{ZW} which will, therefore, barely influence the norm of T_{ZW}. Eq. 2 shows that the weighting scheme T_{ZW} contains the plant G in the term $W_y G S_u W_\rho$ which ensures the controller not to include the inverse of the plant. In order to have a physical feeling about the choice of the weights W_r and W_ρ , W_y , is fixed to 1 (it allows to have less degrees of freedom in the control design). Therefore the second line of T_{ZW} becomes $[GS_u W_\rho T_e W_r]$. Hence, the complementary sensitivity function T_e is shaped by W_r and GS_u by W_ρ. $GS_u W_\rho = S_e G\ W_\rho$ and therefore W_ρ shapes the term $S_e G$. Thus, W_ρ must reflect only that part of the sensitivity S_e which is not covered by G. Theoretically, we should choose $W_y = (S_e G)^{-1}$ but only the envelope of the plant singular values is to be taken into account to prevent the controller from including G^{-1}.

The weight W_r is used to shape the complementary sensitivity function T_e and thus permits to limit its bandwidth. Therefore W_r is designed as high pass filter crossing the 0[dB] line at the desired bandwidth that is in this case at 1[kHz]. The sensitivity function is shaped by the function GW_ρ. A low order dynamics weight W_ρ has been found using a dichotomic approach combined with the linear model of the plant. The perturbation rejection and the trajectory tracking are performed separately by realizing a two steps controller.

The introduction of the integral action leads to the possibility of a saturation of the actuators. This problem is solved by using an anti wind-up action realized with a back calculation in a series configuration.

Decentralized MultiSISO control. The second control method performed on the prototype consists in designing eight different controllers, one for each sensor/actuator couple.

The SISO controllers have been designed by means of the plant model of Fig.4 developed in the Matlab Simulink environment. The rotor is modelled as a 6 dof rigid body. The action of each actuator has been linearized about its nominal airgap and bias current.

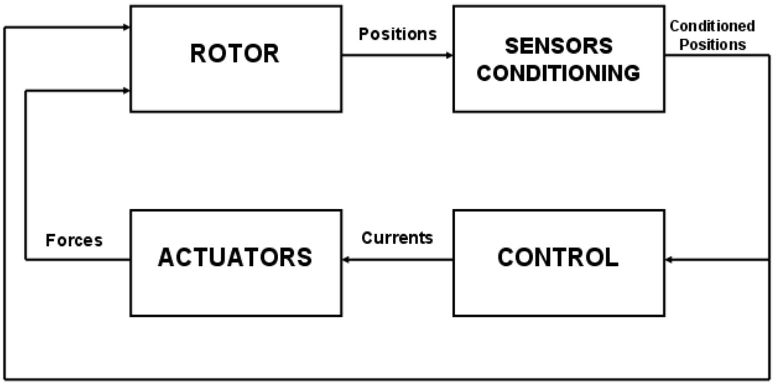

Figure 4: Basic scheme of the decentralized MultiSISO control

The eight forces are expressed in the coordinates of the actuators. This means that the positions of the rotor center of mass and its attitude are converted in five positions: the axial

(z) position of the center of mass, the X and Y coordinates of the rotor in the two planes defined by the upper and lower radial actuators. A further geometrical transformation is used to express the forces in the coordinates of the center of mass, what means that this model was based on the three positions of the center of mass plus the attitude of the rotor. The accelerations and then the velocities and the positions are computed in the latter reference, then they are transformed back in the actuators reference frame (6 radial positions and 2 axial positions) and then they are fed back in the controller block.
Fig. 5 shows more in detail the geometric transformations. Each position is filtered with a PD control and a current command is provided to the actuators board. The chosen control law is a PD performed on each axis, different dynamics are adopted for the axial and radial controls. The proportional and the derivative parts have been computed to satisfy the requirements of stability. The integral part has not been introduced in the control because of the configuration of the radial actuation system with three coils at 120 degrees. This kind of actuation leads the three coil to counteract one against the others to obtain the levitation. If an integrative part is present in the control and the electrical and mechanical centring is not perfect, the error is never zero and the integral action is always working, with the related risk of saturation and bad behaviour of the control.

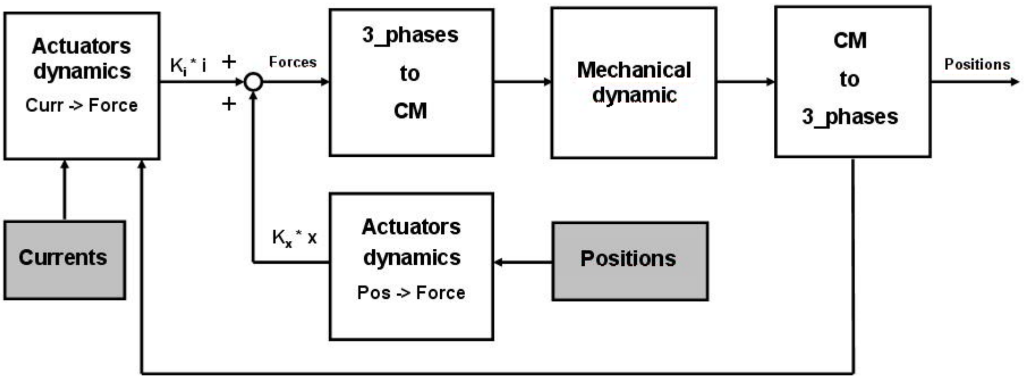

Figure 5: Model of the plant and of actuators dynamics. Axial and radial positions come from sensor box and actuator board respectively. The force is computed by means of the linearized equation $F = K_{ii}+K_{xx}$. Geometric transformation are used to change the references from actuators system to XY system and viceversa. The grey blocks are the variables coming from control block and sensor block.

EXPERIMENTAL VALIDATION

Both the proposed controls have been tested numerically and experimentally. Fig. 6 reports the results obtained with the decentralized control. The ones obtained with the robust control are very similar and so they are not reported.

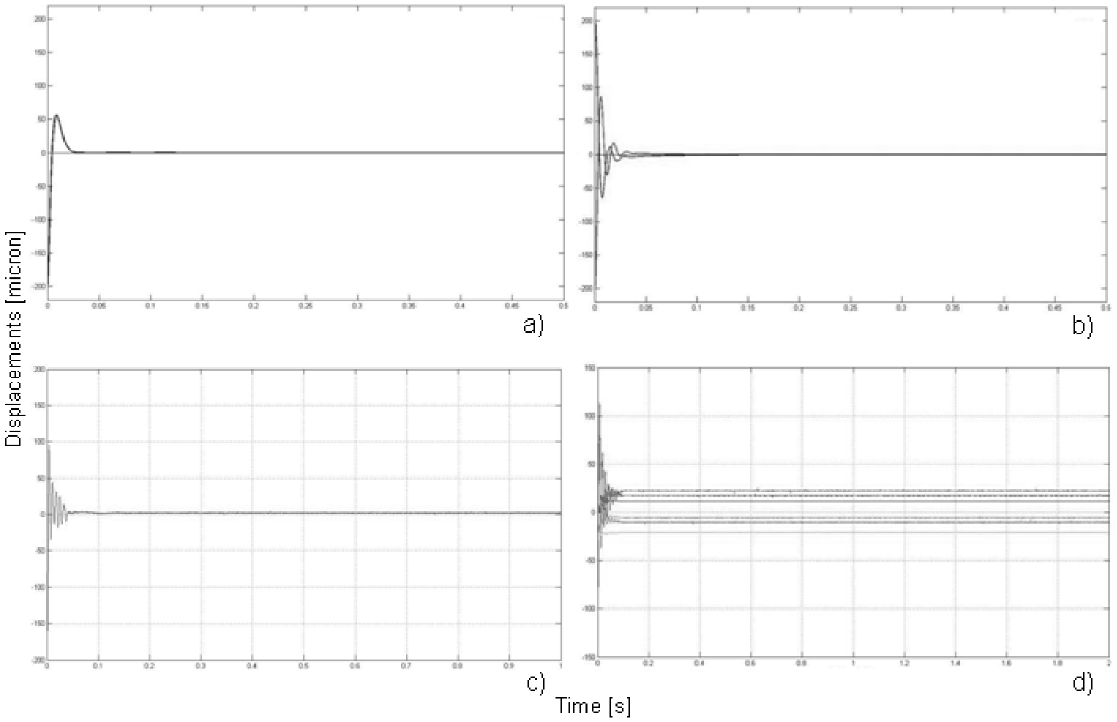

Figure 6: Numerical and experimental results: a) Numerical – Axial. b) Numerical – Radial. c) Experimental – Axial. d) Experimental - Radial

These tests have been realized in two configurations: a) only the axial control is on, b) the axial and radial controls are both on. It can be noted that the experimental results are similar to the ones obtained in simulation, hence the models are validated. Furthermore the effectiveness of the control actions is proved since the cylinder reaches the central point of rotation in less than 0.1 s. Fig. 6.d it shows that the measurement of position on the six radial directions (three on the upper stage and three on the lower one) does not stabilize at zero level but it presents a stationary error. This is due to the absence of the integral action on the radial control and to the unavoidable tolerances in the construction of the mechanical, electromechanical and sensors subsystems.

ROTATION OF THE CYLINDER

The developed prototype includes a motor function in order to spin the rotor around its axis. This function is realized exploiting the same radial actuators for the control and for the motor action. This choice has been compelled by the very small dimensions allowed for the complete system, that made very hard to integrate in the same envelope a dedicated motor. The bearingless configuration exploits the induction motor principle. This kind of motors permits to reach high rotation speed [5], which is an advantage for the precision of the gyroscope. In this type of motors, eddy currents are induced onto a conductive rotor. In our case, these eddy currents will be induced by a rotating magnetic field in the stator.

These eddy currents in the rotor generate a magnetic field whose frequency depends on the rotating speed of the rotor. The rotating magnetic fields at the rotor and at the stator interact and the difference between their frequencies will create the necessary torque to drive the rotor. This type of motor is also called asynchronous because it cannot reach, without any external drive, the same speed as the stator magnetic field one.

The rotation reference is provided to the radial actuators by superimposing on control currents the rotation currents consisting in a sinusoidal signal with a 120° phase shift between the coilsas reported in Eq.(3):

$$\begin{aligned} i_1 &= I\sin(\varpi_r t) \\ i_2 &= I\sin(\varpi_r t + \frac{2}{3}\pi) \\ i_2 &= I\sin(\varpi_r t + \frac{4}{3}\pi). \end{aligned} \qquad (3)$$

where i_i are the rotation currents, I and ω_r are the amplitude and the frequency of the signal.

As experimental validation, the cylinder has been put in rotation with this principle. The management of the superimposition of the control and motor action on radial actuators resulted to be very difficult in both the control strategies tested on the prototype. Further development of the research will be the study of other bearingless solutions able to optimize the spinning of the cylinder.

CONCLUSIONS

The paper investigates the possibility of using AMBs as micro-actuators for a miniaturized two dof gyroscope. Two different control strategies have been implemented to reach the full levitation of the rotor: a robust approach H_∞ and a decentralized strategy with eight PD actions.

The correctness of both the approaches was tested numerically and validated experimentally. The performance obtained with the two solutions are comparable in terms of time of response. Due to the small size of the structure and to the small airgaps, the correctness of the model is fundamental in the case of H_∞ approach. On the opposite, the MultiSISO solution showed a more straight approach and an easier possibility to tune the control parameters.

The spinning of the rotor has been achieved by using a bearingless configuration with the superimposition of the control and motor currents on the same actuators. The principle resulted to be correct but different strategies to put the cylinder in rotation will be tested for further research aiming to optimize the behaviour of the cylinder during the spinning.

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