A digital vibrating magnetic gyrometer
using a control motor DSP TMS320F243

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Introduction

This paper presents the design and realization of an all digital processing system to control a vibrating magnetic gyrometer (**VMG**). This low cost angular speed sensor has been developed by the company ISNAV [1] with an analog control electronic which is subject to the limitations of analog systems (temperature drift, noise, bias). A digital control and signal processing system has been developed in order to increase the accuracy and the range of measurement. This system is implemented on a Digital Signal Processor TMS320F243 dedicated to motor control. This DSP is perfectly suited to this application, because it includes ADCs and PWM peripherals.
In this paper, we first describe the principles of the angular speed sensor, then we present the different functions to be realized by the electronic system and at last the implementation on the DSP.

Principles of the gyrometer

The vibrating magnetic gyrometer [2] measures the angular speed of the rotating body on which it is fixed. It is made of a metallic cylinder containing a magnetic excitation system with 8 arms bearing coils. Four of these are used to excite the cylinder, the 4 remaining arms are used for the speed measurement, see figure 1.

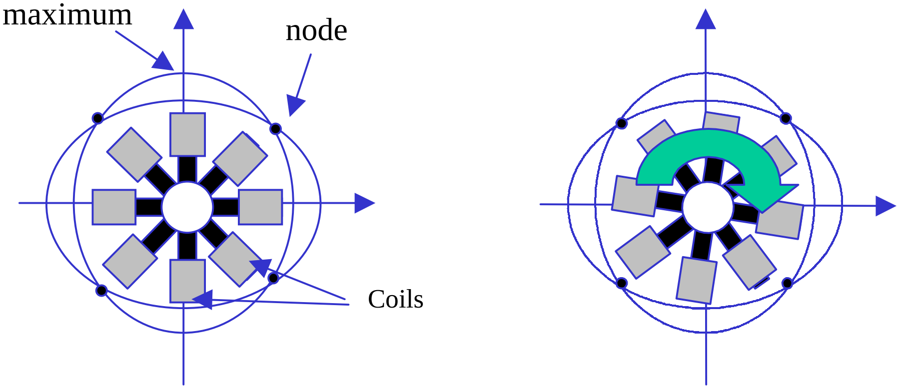

Fig. 1 : Principle of the gyrometer

When the cylinder is excited at its resonance frequency, maxima of vibration appear in front of the excitation coils. When the angular speed of the body is null, the amplitude of the vibration at the nodes is also null. For a given angular speed of the object, the angular speed of those nodes will be a fraction of the angular speed of the body because of the Coriolis effects, a signal will appear at the nodes due to Coriolis effects. Thus a signal will appear at the measurement coils. There is a relation of proportionality between the amplitude of vibration measured at the nodes and the angular speed of the rotating object.
It is necessary to excite the gyrometer at its resonance frequency. And since this frequency changes with temperature, a PLL must be used to track it.
A feedback control on the measurement is also implemented in order to improve the bandwidth of the measurement. This feedback leads to maintain the node in front of the measurement coils, so the magnitude of the feedback is proportional to the angular speed of the body.
The feedback is applied on the same coil where the signal (either maximum or measurement) is taken, using a time multiplexing pattern.
A polarization on the magnetic circuit is introduced in order to linearize the angular speed measurement. This bias is introduced thanks to eight coils that are on the same magnetic arms than the excitation and measurement coils.

Principle of the electronic processing

The electronic processing, either analog or digital, associated to the **VMG** sensor, requires several functions: detection, processing and multiplexing as shown on the figure 2.
The system includes 2 main parts:

- A loop for the excitation of the GVM which is based on a PLL [4],
- A loop for the measurement which include an in phase and quadrature demodulation and remodulation.

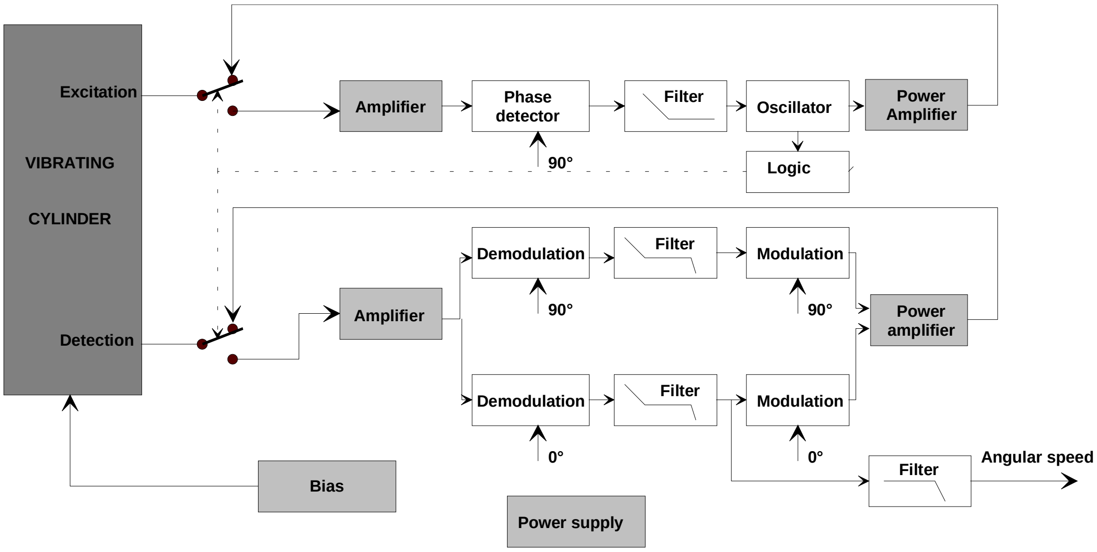

Fig 2 : Principle of the electronic processing

Excitation loop : The excitation loop is a PLL associated with the excitation coils. It is used to excite the cylinder at its resonance frequency and to track this frequency which varies with the temperature. The measure of the resonance frequency and the excitation are time multiplexed.

Measurement loop: The demodulation part of this loop is a synchronous detection. The in phase component is low-pass filtered and gives the angular speed information. This component is then remodulated to maintain the nodes of the vibration closed to the measurement coils. The quadrature component comes from physical and tooling imperfections of the vibrating cylinder, it is remodulated and fed back in order to null it. The measure and negative feedback are also time-multiplexed for this loop.

Principle of the digital electronic

The switching, pre and power amplification are the only analog parts of the system (in light gray on figure 2). All the remaining functions (excitation and measurement loop, in white on the same figure) are digitally implemented thanks to a Digital Signal Processor (**DSP**).

Excitation circuit: The function of the excitation circuit is first to determine the resonance frequency of the cylinder and then to track it at the power up of the system, the **DSP** has to estimate the resonance frequency, *fr*. This is done by a sweeping method in open loop. The starting guess f_0 is chosen depending on the temperature, the peak to peak voltage coming from the excitation coils is measured and compare to a threshold. If it is above the loop is closed and the PLL locks to the exact value, otherwise a new guess f_{i+1} is done. The successive frequency guess f_{i+1} are chosen alternatively on both sides of the initial guess, see figure 3.

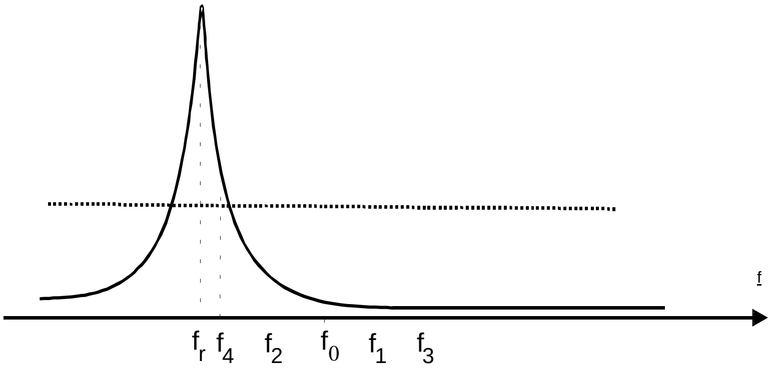

Fig 3 : Resonance frequency estimation

Once an approximate resonance frequency has been estimated by the above algorithm, the loop is closed and then the exact resonance frequency is found by the PLL. The main blocks of this function is shown on figure 2, they are: the phase detector (**PD**), the loop filter (**LF**) and the Numerically Controlled Oscillator (**NCO**) [3].

The phase detection function is simply realized by a multiplication followed by a low pass filtering to remove the double frequency component introduced by this kind of phase detector. This phase detector have then a gain $K_d = 0.5$.

When the PLL is started after the coarse estimate of the resonance frequency, its input can be seen as a frequency step thus, to reach the exact resonance frequency we need to introduce a pure integrator in the loop filter as it is shown on figure 2. Its transfer function is then, in analog formulation $(1+\tau_1 p)/\tau_2 p$, where τ_2 is the time constant corresponding to the *0dB* gain of the **LF** and τ_1 is the time constant which defines the corner frequency of this filter. The lead phase component in this filter is required to guarantee the loop stability.

The last sub function of the **PLL** is the **NCO** which is implemented by means of a phase integrator followed by a Look Up Table (**LUT**) in which a period of a sampled cosine is stored as shown on figure 4.

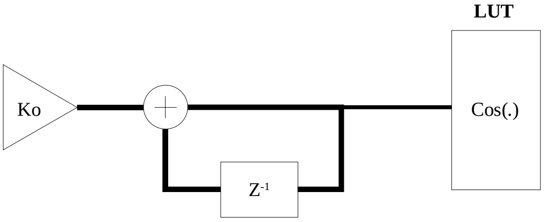

Fig 4: Principle of the **NCO**

In the figure above we can identify graphically two data-path width. The data path width of the integrator determines the frequency resolution of the **NCO**. This resolution is given by the formula $F_e/2^b$, where F_e stands for the sampling frequency and b is the data-path width. The second data-path width is directly connected to the length of the **LUT**, so there will be a lost of precision between the frequency integrator and the phase which addresses the **LUT**. This will give rise to some distortion on the output waveform. In our case this lost of precision is managed through rounding.

We have chosen a sample frequency that can be considered great enough regarding to the equivalent noise bandwidth of the **PLL**, so all the loop parameters are computed from the **PLL** analog model and then we apply a bilinear transform to obtain the digital counterpart of the loop.

Measurement circuit: As it has been said the measurement circuit relies on synchronous detection principles. That is why we talk of demodulation instead of phase detection. The basic blocks for this loop are mostly the same than in the excitation loop except that instead of having its own **NCO**, this loop uses the in phase and quadrature outputs of the excitation loop **NCO** for demodulation and modulation purposes. The parameters are then computed in a similar manner. The angular speed is estimated by low pass filtering the demodulated in phase component, and the measurement bandwidth is determined by the gain of this loop.

Principle of the implementation on a DSP

The digital control requires the acquisition of 2 input analog signals and the generation of 2 analog control signals. These output control signals drive currents in magnetic coils, also for efficiency reasons it is interesting to use **PWM** signals. We also need to get the temperature to have the initial resonant frequency guess. An analog output is needed to provide the angular speed, this can be done by the use of a **PWM** output followed by a low pass filtering. Finally we need digital **IO** to control the time multiplexing pattern used to interface the vibrating cylinder and to drive the bias of the excitation and measurement coils.

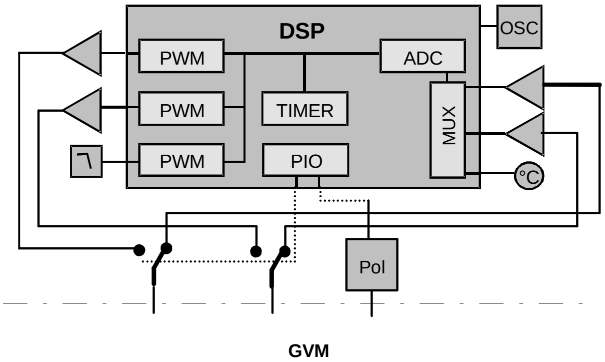

Fig 5 : Digital system

The peripherals needed to drive the gyrometer can be summarized as follow:

- 3 Analog to Digital converters,
- 3 PWM outputs,
- 2 Timers, one for the sampling frequency and the other for the PWM outputs.
- 2 IO ports
- Analog front end to the magnetic circuit that drive the vibrating cylinder.
- Such a system is shown on figure 5. Digital motor control **DSP** embeds all the necessary peripherals for our application. We have then chosen the 16 bits fixed point TMS320F243 [5]. This **DSP** offers enough internal memory and power computation (20 Mips) for this application.

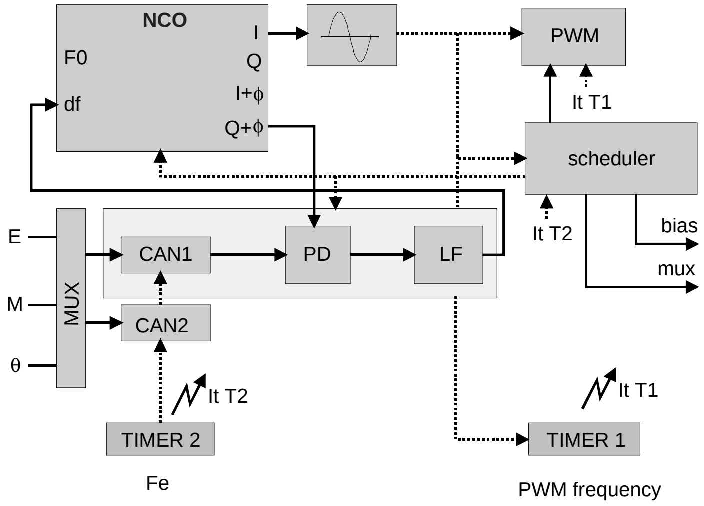

Fig 6 : Software architecture

The software architecture of the excitation loop is shown on figure 6. On this figure dashed line indicates control flow and straight line stands for data flow. The time base is given by the timer 2 that is used to generate the sampling frequency. This time base drive the two main control block of the application: the zero crossing detection of the output of the **NCO** which is necessary to drive the **PWM** output in phase with the resonance frequency of the vibrating cylinder. The scheduler manages the overall application depending on zero crossing detection and timer 2 interrupt. Because all **PWM** outputs are synchronized on the same timer (e.g. timer 1) and its phase is driven by zero crossing detection, there will be a problem with the measurement loop if we need the quadrature component. If we consider only the in phase component in the measurement circuit (see figure 2), the output of the remodulation process will be in phase with the output of the **NCO** which drives the vibrating cylinder, so the both **PWM** carrier will have the same phase. In this case the hardware architecture provided by this **DSP** meets the requirements. But if we want to introduce the correction on the quadrature component, which is needed the remove the error on the angular speed introduced by the imperfections of the vibrating cylinder, the output of the measurement loop will be no more in phase with the output of the **NCO.** Then we would need to lock the phase of the measurement loop **PWM** depending on the balance of the amplitude of the in phase and quadrature components. To achieve this goal we would need two **PWM** controllers, each one with its own timer. Unfortunately, this hardware is not provided in any **DSP**. To include the correction on the quadrature component we have finally use two external **DA** converters instead of internal **PWM** outputs.

Finally we have to say that the overall computation burden involved by the complete application requires approximately 75% of the available time between two samples.

Conclusions

A **DSP** such as control motor **DSP** with embedded peripherals is useful for this kind of application, it allow to embed all the necessary software and hardware functions in a single device except in our case for the **DA** converter in addition to an appropriate analog front end. The **DA** converter can be added with low hardware complexity thanks to the TMS320F243 **SPI** interface. This leads to a dramatic gain in the size of the electronic board compared to the analog one.

Another major advantage of the digital electronic over the analog one, is that it does not suffer of temperature drift, noise and offset.

The choice of a programmable digital electronic could allow to introduce new functions which cannot be implemented in another way : self calibration, auto-ranging … Finally, the embedded **CAN** interface allows to provide a field bus interface to this angular speed sensor.

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