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DC-SERVO MOTOR VELOCITIES CALCULATION BY MEMS ACCELERATORS

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Abstract **— This paper presented a novel study to calculate DC motor velocities based tilt sensing measurement. Four MEMS accelerators are used to assure the measurement task. A test bench is used to validate the experimental results which prove the effectiveness of the proposed method.**

Keywords — DC-motor, MEMS capacitive accelerator, ADXL**203*****, velocities***

I. Introduction

Nowadays, a growing interest has been accorded to the using of Micro-electro-mechanical system technology (MEMS). MEMS integrate, on only one silicon substrate, sensors, actuators, mechanical elements and electronics.

MEMS sensors are very little, robust and simple to use. Due to these characteristics this type of sensors has been utilized in several applications like electrical vehicles [1][2], navigation system [3][4], military [5], medicine [6]. Recently MEMS technology has been widely investigated in wireless communication to improve the electrical machine control [7].

The accelerometer presents one of the most common used MEMS sensors. Indeed, it represents a dynamic sensor which is able to accurately measure a wide range of sensing. The MEMS accelerators are also capable to measure the acceleration in one, two, or three axes.

According to MST NEWS of February 2007, the total market for accelerometers is probable to attained 630 dollar million, and according to the same source the MEMS accelerometer average price of all applications decrease.

These devices have been implemented in many commercial applications, such as automobile air bags [8], games (wii). They are typically used in inertial measurement (position and velocity) ,to detect inclination of an object in 2 or 3 dimensions [9] or also to study the vibration impact [10]. Three major principal to construct MEMS accelerometers sensors are found in manufacturer which are capacitive, thermal and piezoelectric one. A comparative study between the different types of operation has been carried in [11].

The capacitive based MEMS accelerometers devices have been increasingly employed because they offer more resolution and more sensitivity compared to similar piezoelectric accelerometers [11].

Due to its electrical and mechanical conditioning many technical problems caused to the devices are not understood and solved because it differs from an application to others. So, new testing methodologies need to be proposed. In this paper commercial MEMS-based capacitive accelerometers from Analog Devices ADXL203 are tested. A new method of velocities calculation is presented. The present work is organized as follow: Firstly, the modelization of MEMS sensors will be presented. Then analytical description of method will be detailed. After that, different steps of velocities calculation will be well presented. Then, an off line calculation will be achieved. Finally, a conclusion and perspective works are also given.

II. MEMS capacitive accelerators

A. *The principal of operation*

The principle of operation of MEMS accelerometer is based on the displacement of a small mass integrated into a silicon surface of the integrated circuit and which is suspended by small beams (fig.1). According to Newton's second law of motion ($F=m.a$). The acceleration applied to the device, caused a force which displace the mass.

The support beams proceed as a spring, and the fluid acts as a damper, consequential of a second order physical system. This is the origin of non-uniform frequency response and limited operational bandwidth of accelerometers.

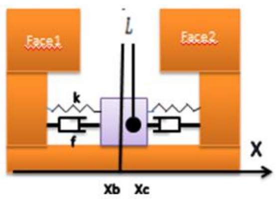

Fig.1. Mechanical model of the capacitive sensor

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B. *Characteristics of MEMS Accelerator*

One of the reasons of using of sensors from MEMS technologies is related to their accuracy compared to the performance allowed by the discrete sensor. The ADXL203 integrates two axis accelerators amplificatory demodulator and a filter. The sensor output depends on its position relative to the earth gravity. Indeed, the gravity is used as its stimulus.
The choices of the accelerator depend on numbers of factors which depend on the application. The most important one are the number of axis, the resolution, the range, the bandwidth and the power.

III. Analytical Study

In this part we are interested in the analytical parts developing which allow the velocity determination.
Firstly, some proposal must be done. The sensor is represented by m which defined its mass and it is placed at the position M of disc (O,r)

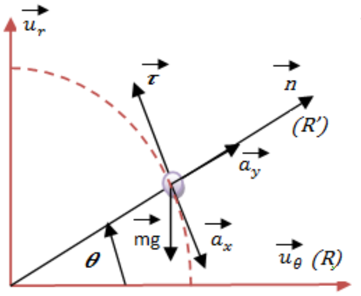


Fig.2. Mechanical model of the capacitive sensor

Note ***Ω*** the disc rotation speed and R' represents the rotating frame which is fixed to the disc though its center and R is a stationary frame.

The entrainment speed of the mass *m* is calculated as follow:

$$\vec{V_e} = \vec{V}_{O/R'} + \vec{\Omega}_{R'/R} \wedge \vec{OM} \quad (1)$$

$$\vec{V_a} = \vec{V_r} + \vec{V_e} \quad (2)$$

$$\vec{V}_{M/R} = \vec{V}_{M/R'} + \vec{V_e} \quad (3)$$

In the present case *O* and *M* belongs *R'* so

$\vec{V}_{O/R'} = 0$ and $\vec{V}_{M/R'} = 0$

The absolute speed will be as follow

$$\vec{V_a} = \vec{V_e} = \vec{V}_{M/R} = r\Omega\vec{\tau} \quad (4)$$

The absolute acceleration is written as follow

$$\vec{a_a} = \vec{a_r} + \vec{a_e} + \vec{a_c} \quad (5)$$

In the present state

$$\vec{a_r} = \vec{a_c} = 0 \quad (6)$$

$$\vec{a_a} = r\frac{d\Omega}{dt}\tau - r\Omega^2 n \quad (7)$$

Relating to the second Newton's low a resulting force is applied to the moving part of MEMS accelerator which can be decomposed on x-y axis as follow

$$\begin{cases} F_x = -mg\cos\theta - mr\dfrac{d\Omega}{dt} \\ F_y = mg\sin\theta - mr\Omega^2 \end{cases} \quad (8)$$

In order to oppose to the mass movement, the ADXL203 delivered acceleration on the 2 axis

$$\begin{cases} a_x = g\cos\theta + r\dfrac{d\Omega}{dt} \\ a_y = -g\sin\theta + r\Omega^2 \end{cases} \quad (9)$$

These forces presented the output of the first accelerator. Indeed, the output of the other one varied with the sense of rotation. In the case of variable speed a method consisted on the using of two accelerators in opposition in order to minimize the effect of gravities and to calculate the velocities values by integration.

$$\begin{cases} a_\tau = \dfrac{a_{x1} + a_{x2}}{2} = r\dfrac{d\Omega}{dt} \\ a_n = \dfrac{a_{y1} + a_{y2}}{2} = r\Omega^2 \end{cases} \quad (10)$$

The tangential acceleration held to the determination of the instantaneous image of the torque and can be used also to calculate the velocity value by integration. However, this method is not valuable in the case of constant velocities where $\frac{d\Omega}{dt} = 0$ that's why we will propose a novel study based on the tilt sensing determination. For this four accelerators are used.
In the case of constant velocities, the equation (9) will be as follow

$$\begin{cases} a_{x1} = g\cos\theta \\ a_{y1} = -g\sin\theta + r\Omega^2 \end{cases} \quad (11)$$

The output of the second accelerator

$$\begin{cases} a_{x2} = g\cos(\theta + \frac{\Pi}{2}) = g\sin(\theta) \\ a_{y2} = -g\sin(\theta + \frac{\Pi}{2}) + r\Omega^2 = g\cos(\theta) + r\Omega^2 \end{cases} \quad (12)$$

The angle deviation and the velocity are calculated as follow

$$\theta = \tan^{-1}\left(\frac{a_{x2}}{a_{x1}}\right) \quad (13)$$

Where θ is in radians

$$\Omega=\frac{d\theta}{dt} \quad . \tag{14}$$

In order to have more accurate results four accelerators are placed in the same disc as shown in fig.4.

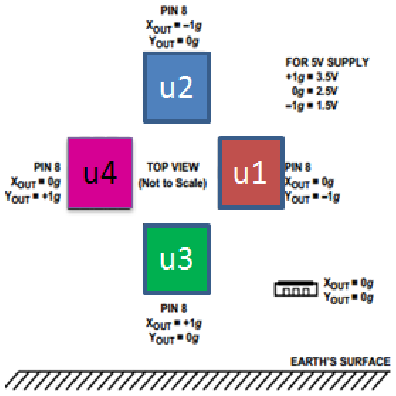
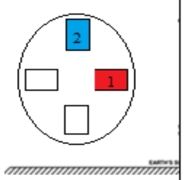
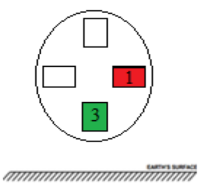
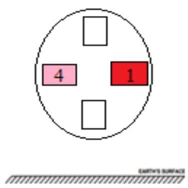


Fig.3. Accelerometers dispositions

The different cases of velocity calculation are treated in this table.

TABLE I. VELOCITIES CALCULATION METHOD

Constant velocity		Variable velocity
$\frac{d\Omega}{dt}=0$		$\frac{d\Omega}{dt}\neq 0$
Clockwise	Counterclockwise	
		
$\frac{a_{x2}}{a_{x1}}=\tan\theta$ $\Omega=\frac{d\theta}{dt}$	$\frac{a_{x3}}{a_{x1}}=\tan\theta$ $\Omega=\frac{d\theta}{dt}$	$a_{\tau}=\frac{a_{x1}-a_{x4}}{2}=r\frac{d\Omega}{dt}$ $\Omega=\int\frac{a_{\tau}}{r}.dt$

IV. SIMULATION RESULTS

Simulation study has been effectuated with Matlab in order to know how the different sensors behaviors in one period of measurement by taking into account only their angle deviation in the measure of velocities in clockwise and counter-clock.

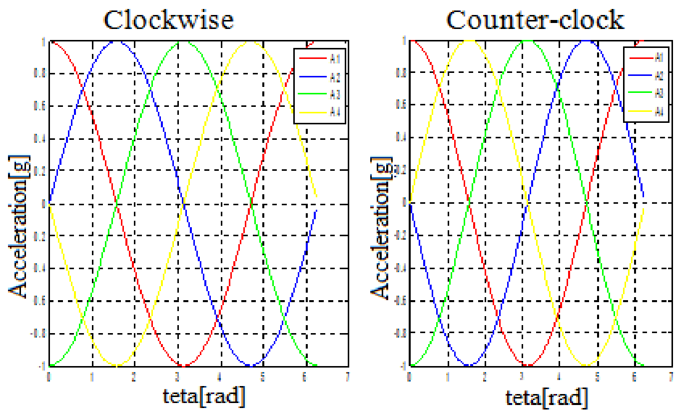


Fig.4. Sensors outputs evolution

These figures illustrate the different outputs of sensors relative to the angle of rotation in the two senses of rotation. Only the x-axis of the four accelerators is presented. It's clear from these figure that that the acceleration detected by the x-axis is proportional to the cosines of the angle of inclination for A_{cc1} and A_{cc4}. However, due to the orthogonality of the sensors the output of A_{cc2} and A_{cc3} are proportional to the sin of angle inclination. Then, using the relation (13) the velocity is calculated.

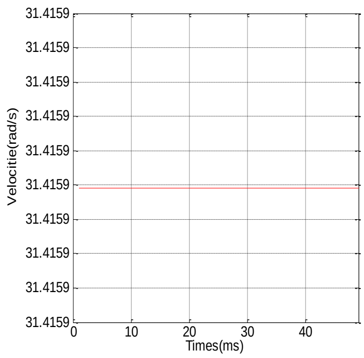


Fig5. Velocity calculation

As it's shown in the present figure the velocity calculation has been achieved. However, in reel cases stochastic errors decrease the performance of MEMS accelerators. Therefore, before accessing to velocities measurement it's important to evaluate these sensors and extract noises by using filter.

V. STEPS OF VELOCITIES CALCULAVTION

The calculation of DC-motor velocity can be resumed by this flowchart (Fig.6). Firstly a signal acquisition must be carrying out then localization of sensors, calibration and filtering should be done. After that real sensor deviation is calculated. Finally, velocity measurement is achieved.

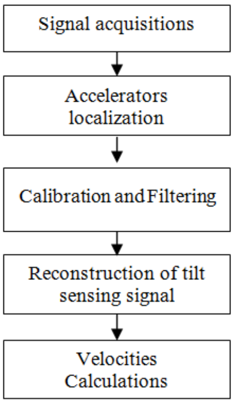


Fig.6. Flow chart of velocities calculation

VI. DATA COLLECTION AND EXPRIMENTAL TEST BENCH

A. *Exprimental study*

The test bench shown in Fig.7 consists on a DC servo motor feed by an autotransformer. An oscilloscope is used visualize and to store the different experimental acquisitions. Four accelerators are installed in an experimental model. Indeed, the accelerators are mounted in opposition as shown in the figure as follow.

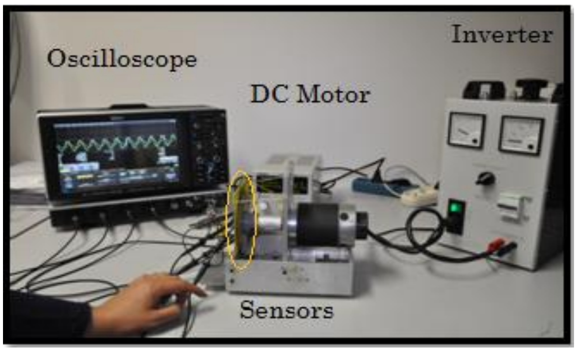


Fig.7. Bench of the test

The output of the accelerators from MEMS technology depends on the angle measurement referred to the vertical position. Moving the sensor generate a changing of its outputs. From the present figure is well noted that the increasing of motor velocity affected the output of the accelerator and the signal stabilities. Many acquisitions have been done by using this experimental test bench and with different values of velocities. The accelerator is mounted in such way it rotates with the motor shaft.

B. *Accelerators localization*

Indeed, our choice is accorded to two axis accelerator because it's ability to detect the incline angle comparing to single axis one. Depending on the orientation of the system it is capable to measure full 360°. However a single axis accelerometer is capable to measure only 180° and it can't define the direction of rotation in the case of electrical machine. The present figure illustrates the different combination of signs associated with x/y axis acceleration.

It's clear from it that the accelerators outputs allow to identify its placement (Quadrants I, II, III or IV) in order to identify the rotation sense and to choose which ones can be used to have more accurate results.

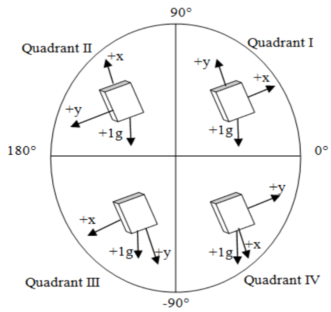


Fig.8. Sign of Acceleration for Quadrant Detection

Indeed, the accelerators from MEMS technologies are characterize by its stochastic and determinist errors which affected the measure results. The using of four accelerators allows more precise results in the case of constant and variable speed also. Indeed, when the sensibility of one sensor decrease the measure is taken from the other one respectively.

C. *Filtering and Evaluation of sensors signal*

Experimental measurement are always corrupted by different types of errors sources like scale factor, sensor noises, bias variation. By deriving or integrating these measurements errors will be accumulated, leading to a drift in the velocity output. Due to its simplicity and efficacy, Allan Variance is the most used method to evaluate these type of sensors [11]. Then a low pass filter is used to remove noise from accelerometer measurement.

D. *Calibration and offset calculation*

It's well noted that the bias and the offset has an important effect on the signal output. Indeed, if the errors dues the offset and sensitivity are combined, the total errors become large and out limit. In order to reduce this type of errors the offset and sensitivity must be calibrated.

Many methods have been used in the literature in order to minimise their effects [12]. In this paper, a simple calibration method is utilised. It consisted on placing a two points for each axis. While the axis is placed into a +1g and -1g the measurement output are expressed as follow

$$A_{+1g}[g] = A_{OFF} + (1g \times Gain) \quad (15)$$

$$A_{1g}[g] = A_{OFF} - (1g \times Gain) \quad (16)$$

These two points are used to calculate the offset and the gain

$$Gain = 0.5 \times \left(\frac{A_{+1g} - A_{1g}}{1g}\right) \quad (17)$$

$$A_{OFF} = 0.5 \times (A_{+1g} + A_{1g}) \quad (18)$$

The results of gain and offset calculation are illustrate in this table

TABLE II. GAIN AND OFFSET CALCULATION

Offset [g]	Gain [V/g]
2.46	0.98

Then the value of accelerator output is calculated as follow

$$A_{Actuel} = \frac{A_{OUT} - A_{OFF}}{Gain} \quad (19)$$

E. Reconstitution of tilt sensing signal

As it's mentioned before the calculation of tilt angle is effected by using a gravity vector and its projection on the axes of accelerometer. However the gravity represents a DC acceleration and any forces that result an additional dc acceleration distort the output signal. The rotation of device presents a source of Dc acceleration which induce a centripetal acceleration of the sensors. In order to attenuate these perturbations an off line tilt measurement angle is achieved by using the dispositive describe in part V.

F. Velocities calculations

The velocities calculation presented the last steps. Relating to (14) the angle velocity represents the derivative of tilt measurement. Then, linear velocity is calculated according this expression

$$V = R \times \alpha \quad (20)$$

Where R represent the radius of the disc

Many tests have been achieved. Indeed, by increasing the voltage of motor the speed is also increased. These tests are achieved by the same dispositive and allow having suitable results comparing to those found using tachymeter. The evolution of velocity is presented in the next figure.

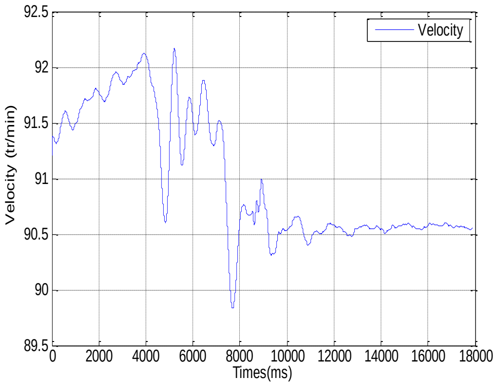


Fig.9. Velocities evolution

As it mentioned in fig.9 the value of velocity is varies between 90tr/min and 92tr/min. This result is compared to reference one which is approximately 91tr/min. Then the calculation of error is effectuated and the result is illustrated in the next part.

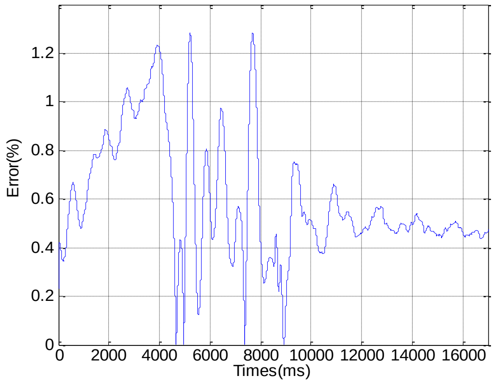


Fig.10. Error evolution

It's clear from the Fig.10 which represents the error evolution in percent. That this latter is little and don't exceeded 1.3% which highlight the effectiveness of the proposed method. MEMS accelerators can be used to calculated DC velocities and also torque. This technology is increasingly used due to their benefits.

In this paper only results for an off line constant speed calculation are explored. However, it is interesting to note that it possible to explore the on line calculation in order to control the motor especially in the case of synchronous or asynchronous one.

VII. CONCLUSION

This paper presents a novel study of instantaneous velocities based on MEMS accelerators sensors. A using of an adapted filter as wiener filter, or Kalman filter will allow having more accurate results. This embedded sensor can be used in multiple industrial applications like wireless control of electrical machines, inertial system. An off line experiments carried on a DC-servo motor proves the efficacy of this method.

NOMENCLATURE

V_a: absolute speed of M/R;
V_e: entrainment speed;
V_r: relative speed of M/R';
a_a: absolute acceleration of M/R;
a_e: entrainment acceleration
a_r: relative acceleration of M/R;
a_c: Corolis acceleration
g: gravities

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