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CONTROLLING THE OSCILLATIONS OF A SWINGING BELL BY USING THE DRIVING INDUCTION MOTOR AS A SENSOR

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Abstract – Swinging bells deliver the best sound quality when the swinging angle is kept to a specific value proper to each system. The aim of our paper is to propose an original method for controlling this swinging angle without any external sensor, by using the driving motor (actually a three-phase induction machine) as a sensor when it is not active as a motor. In the sensor mode, we control the maximum speed of the bell, which is related to the swinging angle by a time-invariant mechanical coefficient specific to each bell system. The main advantage of the proposed solution is that the speed information is practically insensitive to the motor parameters variations. This solution, well adapted to the problem of concern, establishes a close interrelation between the motoring, sensoring and regulating aspects.

The pertinence of our solution is deduced from theoretical developments and confirmed both by simulations and experimental observations on a real swinging bell system.

Keywords : smart sensor, smart actuator, bell control

1. INTRODUCTION

Sound of bells is an important attribute of numerous cities in the world, both for religious and recreative purposes. Swinging bells, at the opposite of carillon bells which are motionless, are ringing when they are animated by an oscillating movement around their rotation axis with such an amplitude that the clapper inside the bell strikes the wall (two times per cycle). For a given bell, the amplitude of this oscillating movement (swinging angle) must be accurately set to a specific value in order to obtain the best sound quality.

Most of swinging bells are today driven by a fractional horsepower three phase induction motor through a chain and cog-wheels system (figure 1). A static switch is used for shortly connecting the motor to the mains two times per cycle in order to give impulses to the bell which maintain the swinging angle at the wanted value. Generally, an optical position encoder located on the motor axis is used for the data input of a proper electronic control unit keeping the bell movement to a preset swinging angle.

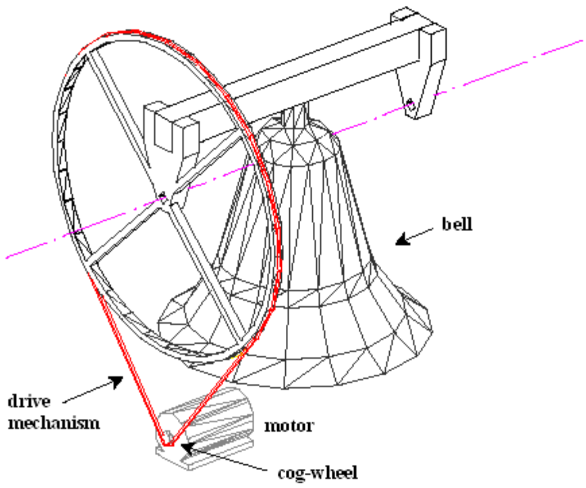

Fig. 1. Swinging bell system

The aim of this paper is to propose an original method for controlling the swinging angle of the bell without any additional position sensor, by using the motor as a sensor when its motor action is suspended. This solution is attractive namely when the purpose is to add a regulator to an in-place swinging system, where room is lacking for installing the classical encoder.

2. BELL MOTION ANALYSIS

The study of the swinging bell motion is performed by neglecting the presence of the clapper as its mass is negligible when compared to the mass of the bell.

The motion of the bell can be assimilated to a movement of rotation in the plane perpendicular to its rotation axis so that we can use as generalized position coordinate, the angle θ the bell makes with respect to its equilibrium position (figure 2).

If C_m is the external torque applied to the shaft supporting the bell (i.e. the torque produced by the driving system), the equation of the bell motion is ruled by the following equation :

$$C_m = J\ddot{\theta} + \nu\dot{\theta} + MgD\sin\theta \qquad (1)$$

where

J is the inertia of the bell and related moving parts referred to the rotation axis

$\nu\dot{\theta}$ is the friction torque assimilated to a viscous torque (< : viscosity coefficient)

M is the mass of the bell (including other moving parts)

D is the distance between the bell centre of mass and the rotation axis

g is the gravity acceleration.

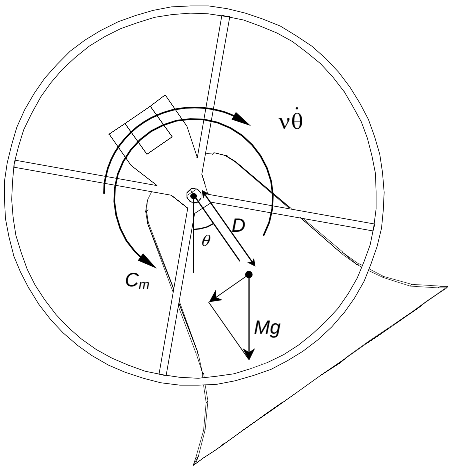

Fig. 2. Parameters associated to the bell motion

For computing the duration T (period) of the bell oscillation cycle and the bell maximum angular speed $\dot{\theta}_{max}$ (which is reached for θ = 0) in function of the amplitude θ_M of its oscillation, one may consider that the driving torque exactly compensates the friction torque so that the bell motion equation can be assimilated to :

$$J\ddot{\theta} + MgD\sin\theta = 0 \qquad (2)$$

Defining

$$\alpha = \frac{MgD}{J}$$

which is a time-invariant mechanical parameter specific to each bell system, one gets:

$$\dot{\theta}_{max} = 2\sqrt{\alpha}\,\sin(\frac{\theta_M}{2}) \qquad (3)$$

$$T = \frac{4}{\sqrt{\alpha}}\int_0^{\pi/2} \frac{d\varphi}{\sqrt{1-(\sin(\frac{\theta_M}{2})\sin\varphi)^2}}$$

$$\text{with} \quad \sin(\varphi) = \frac{\sin(\theta/2)}{\sin(\theta_M/2)} \qquad (4)$$

These results were verified on an experimental test bench, the swinging bell of which was a 350 kg model. The drive motor and its controller were used for imposing oscillations of constant amplitude θ_M, varying from about 0,35 radians to 1,3 radians. These amplitudes and the corresponding maximum speeds were recorded.

From the graph shown in figure 3 giving $\dot{\theta}_{max}$ in function of $2\sin(\theta_M/2)$, the linearity of this function as it appears from (3) is confirmed. The value of the parameter α of the bell was estimated using (3), by least-square fitting on a straight line. This yields in our case

$$\sqrt{\alpha} = 2.76\ s^{-1}$$

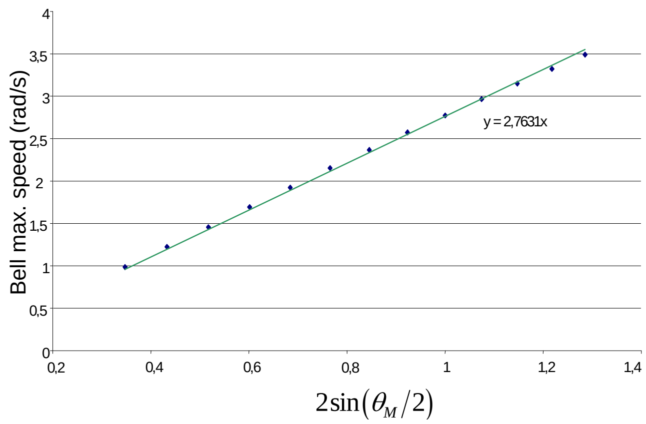

Fig. 3. Bell maximum speed $\dot{\theta}_{max}$ versus $2\sin(\theta_M/2)$

This value of α was used for computing, using (4), the period T of the bell oscillation cycle and to compare the results with the measured values (figure 4). The good agreement between the measurements and the theoretical curve confirms the validity of the approximation made by assuming that the driving torque exactly compensates the friction torque.

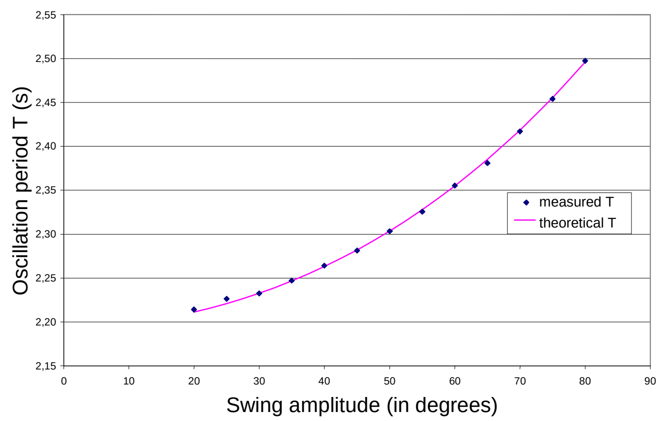

Fig. 4. Period of the oscillation cycle in function of the swing amplitude θ_M

Now that we have two parameters ($\dot{\theta}_{max}$ and T) related to the quantity θ_M of interest, the best choice will be selected from a sensitivity study. From equations (3) and (4), the sensitivities S_V of the maximum speed $\dot{\theta}_{max}$, and S_T of the oscillation period T, to the amplitude θ_M of the oscillation were computed. It is worthwhile to note that these quantities are independent of ∀. In figure 5, these sensitivities are expressed in relative value, f.i. :

$$S_V = (d\,\dot{\theta}_{max} / \dot{\theta}_{max})/ (d2_M/2_M)$$

It is clearly apparent that the maximum speed is much more sensitive to the swing amplitude than the oscillation period. Therefore, the maximum speed $\dot{\theta}_{max}$ was selected for the determination trough (3) of the swing amplitude $\theta_{M,}$ as it will gives more accurate results.

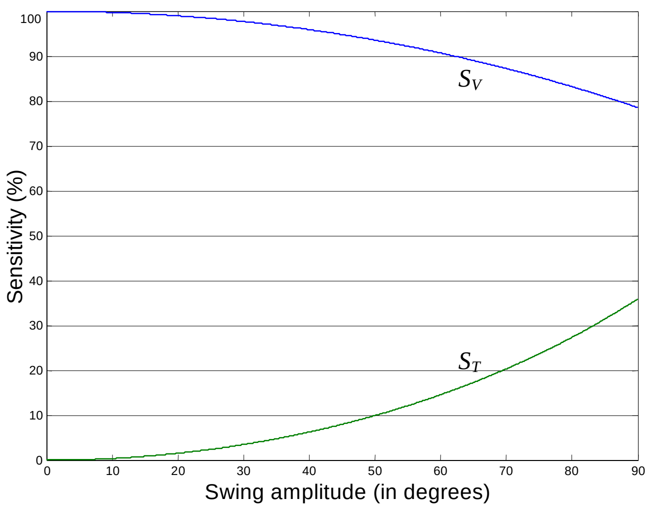

Fig. 5. Sensitivity of the maximum speed (S_V) and of the oscillation period (S_T) to the swing amplitude θ_M

3. USING THE DRIVING MOTOR AS A SPEED SENSOR

3.1. *Choice of the measurement strategy*

Figure 6 shows how to use a three-phase induction motor as a speed sensor:

- two statoric phases are series connected and used as excitation winding
- the third phase is used as detection winding.

The phases used as excitation winding are fed by an AC voltage source with a low amplitude in order that the machine in its sensor mode develops a negligible torque. The voltage induced in the detection winding gives the speed information since its amplitude and phase depend on the motor speed, as we will see hereafter.

Straightforward but somewhat tedious computation based on the motor equations in the stator αβ reference frame [1] allow to compute the amplitude of the voltage induced in the measurement winding in function of the

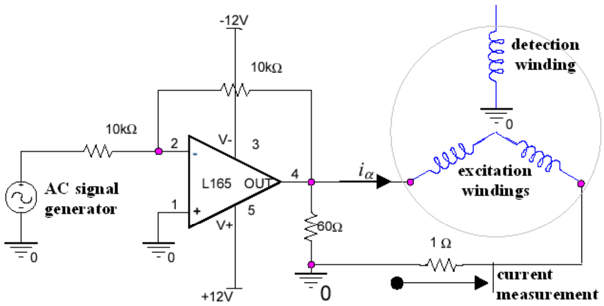

Fig. 6. Driving the induction motor in its sensor configuration

motor parameters, the rotor speed and the amplitude and frequency of the voltage applied to the excitation winding. The upper part of figure 7 shows that for a given excitation voltage, the relation between the induced voltage amplitude and the speed is highly non linear and strongly dependent on the machine rotor resistance (even for its peak value). As the starting of the bell motion can bring an important thermal rise of the rotor bars and thus a large variation of the rotor resistance, a direct measurement of the speed based on the voltage amplitude in the measurement winding was discarded.

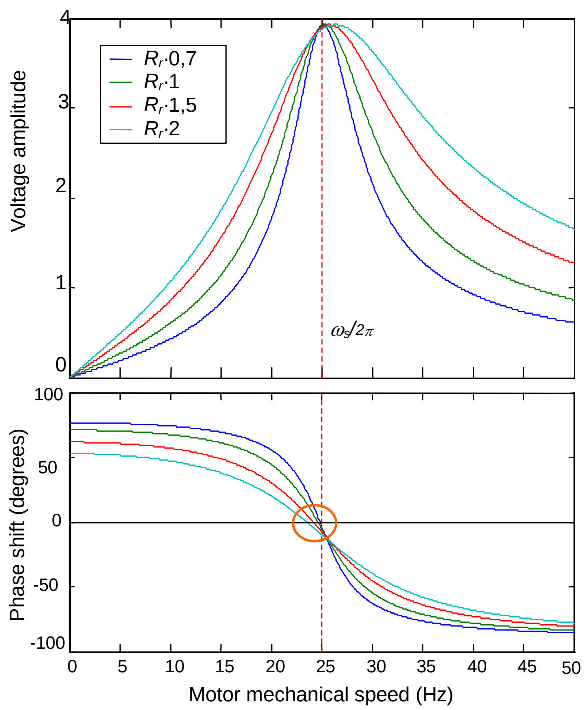

Fig. 7. Detected signal in the measurement winding in function of the speed, for various values of the rotor resistance (25 Hz oscillator frequency)

Upper : voltage amplitude

Lower : phase shift between the detected voltage and the current in the excitation winding

Computations also show that the phase shift between the voltage induced in the measurement winding and the current flowing into the excitation winding changes very quickly from a positive value to a negative one near the synchronous speed, the zero crossing point occurring at an angular speed ω_{m0} equal to (lower part of figure 7):

$$\omega_{m0} = \frac{1}{p}\sqrt{\omega_s^2 - (\frac{1}{\tau_r})^2}$$

where

ω_s is the motor electrical synchronous speed, equal to the angular frequency of the voltage applied to the excitation winding

τ_r is the rotor time constant L_r/R_r

p is the number of pole pairs.

Provided that $\omega_s\tau_r$>>1, the speed ω_{m0} (multiplied by p) is almost equal to the electrical synchronous speed, which is independent of the motor parameters. Therefore, for values of the excitation angular frequency which are high enough, is it possible to detect if the motor is driven at a speed which is below or above a given value ω_M, by feeding, with the help of the oscillator (figure 6), the excitation winding with a voltage having an angular frequency equal to $p\omega_M$ and by measuring the sign of phase shift between the current in the excitation winding and the voltage in the detection winding.

3.2. Experimental validation of the method

For validating this speed measurement method, use was made of the test bench shown in figure 8. It comprises two identical motors, with their shaft geared on the same chain. The main one (the driving motor) is equipped with a position optical incremental encoder and fed by an electronics which controls the bell swinging motion. The auxiliary one (called "sensing motor") is used as a speed sensor according to the measurement method described in the preceding paragraph.

The following measurement process was used :

- the frequency of the oscillator feeding the sensing motor is fixed at a given value
- a swinging motion is imposed to the bell with the help of the driving motor and its control electronics, and the amplitude of oscillations is increased until the minimum phase shift (with sign) between the voltage induced in the detection winding of the sensing motor and the current in its excitation winding goes periodically to zero without sign change: this means that the maximum motor electrical speed reaches periodically a value which is equal to the feeding frequency fixed by the oscillator, supposing that the phase shift is exactly zero at the synchronous speed .
- the maximum value of the motor electrical speed, determined by the control electronics on the basis of the signal generated by the position incremental encoder, is also measured at this moment (this speed is expressed in revolution per second i.e. in Hz). We recall that this maximum speed is proportional to the searched quantity $\dot{\theta}_{max.}$ with a coefficient of proportionality which is fixed by the diameter of the wheels of the drive system and by the motor number of pole pairs.

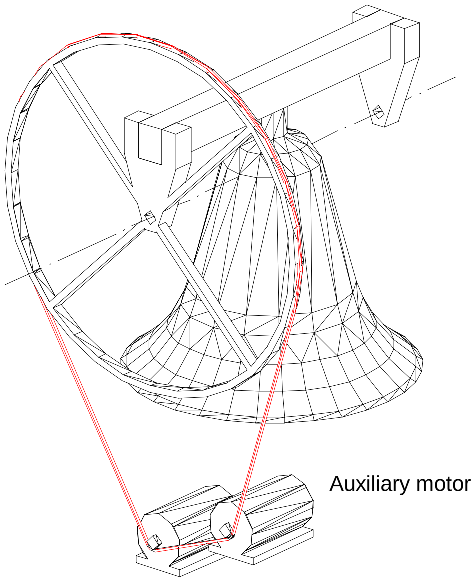

Fig. 8. Test bench with auxiliary motor used as a sensor

By repeating this process for various frequencies of the oscillator, the graph of figure 9 was obtained. The straight line plotted in broken line indicates the value of the speed corresponding to the electrical synchronous speed fixed by the oscillator frequency and the small squares the measured values delivered by the control electronics. The graph shows that, excepted for the highest frequency values (corresponding to the highest motion amplitudes), the measured frequency is very close to its theoretical value, which validates the selected measurement process.

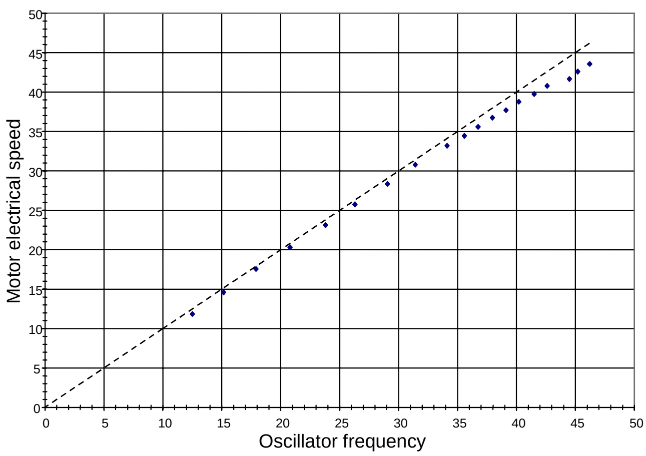

Fig. 9. Validation of the measurement process

The discrepancy between the two corresponding frequencies at high frequency is probably mainly due to imprecision in the measurement process implemented in the control electronics which is based on a numerical derivation of the position given by the optical encoder located on the motor shaft.

4. CONTROL STRATEGY

Equation (3) is used for computing the bell maximum speed corresponding to the wanted swinging angle, supposing that the parameter ∀ is known. From this speed, the corresponding maximum electrical speed of the motor is, as already set, computed by multiplying the bell maximum speed by the ratio between the diameters of the wheels of the drive system (see figure 1) and by the number of pole pairs of the motor. This speed expressed in revolution per second gives the frequency of the oscillator used for feeding the motor in the sensor mode (see figure 6).

In order to be able to use the motor in the sensor mode when the bell speed reaches its maximum value (at 2 = 0), we choose to push the bell by connecting the motor to the mains through a static switch just after the bell has reached one of its maximum positions 2_M, exactly as a child drives a swing.

Just before its connection to the mains, the motor is used as speed sensor. As the motor speed and hence the amplitude of the voltage induced in the detection winding goes to zero when the bell reaches its maximum position, we determine the starting instant of the motoring periods by measuring the voltage induced in the detection winding : the motor is connected to the mains when the amplitude of the measured voltage goes beyond a given threshold while increasing (figure 10).

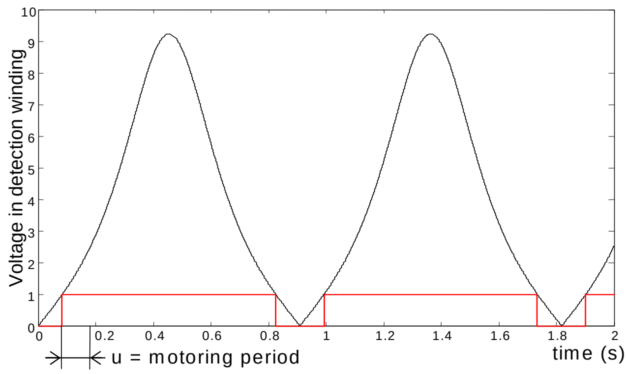

Fig. 10. Determination of the starting points of motoring periods

The maximum duration of the motoring period is limited to a value which is always smaller than one quarter of the oscillation cycle so that the motor reverses to its sensor mode of operation before the bell reaches its maximum speed.

During each oscillation cycle, the minimum value reached by the phase shift between the voltage induced in the measurement winding and the current in the excitation winding gives an estimation of the difference between the wanted maximum speed of the bell and its real value. It can be used as input error signal for a discrete PI controller the output of which gives the duration of the next motoring period.

A MATLAB-SIMULINK simulation program was developed for simulating this control strategy. Figure 11 shows the response of the bell to two steps in the maximum speed reference values at 0 s and 60 s, and to an increase of the friction torque at t = 200s. The good performance of the control is clearly apparent and validates the concept.

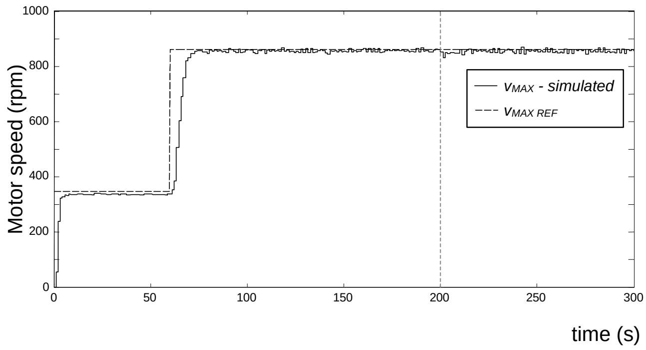

Fig. 11. Response to steps in the maximum speed reference values

5. CONCLUSION

In this paper, we analysed a method for controlling the amplitude of the oscillations of a swinging bell, using its driving induction machine both as a motor and as a sensor. The main advantage of the method we propose, relies on the fact that in the sensor mode, the maximum speed detection (related to the swinging angle) is almost insensitive to the variations of the motor parameters. Beyond the fact that this solution is well adapted to the problem of concern, we claim we discovered a new way to use the induction machine as a rotational speed sensor.

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