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# Instrument Comparison for Integrated Tuning and Diagnostics in High Performance Automated Systems

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**Abstract:** A comparison is discussed among different measuring methods to be used in control and tuning procedures for controllers and for actuating components of high performance automated systems. The system is based on a brushless servomotor and high speed programmable controller. Preliminary indications of the electrical and mechanical behavior of the system, provided by a simple model have been used to get information about the ability to perform the tuning and the monitoring of the system behavior. Measurement systems already present in the system, like encoder and transducers of feeding currents of the electric motor and other high performance added sensors, like accelerometers and fiber optic displacement sensors have been compared for this purpose. In particular, the possibility of using fiber optic displacement sensors has been analyzed, taking into account the improvement of system capability with respect to fault detection and the possibility of performing effective auto-tuning of controller parameters, also in cases of high electrical disturbances. Sensors behavior has been evaluated also taking into account the possibility of using not standard data processing techniques, like wavelet transforms. Experimental results show that interesting information for both a correct and automatic tuning of mechanical parameters and fault diagnostics can be obtained.

**Key words:** Diagnostics, signal processing, manufacturing control systems, measurement, positioning control system

## INTRODUCTION

The aim of contemporaneously assuring quality control of products and processes, productivity increase and cost reduction requires that a continuous improvement of production process is considered and pursued.

If automated production applications are taken into account which are very important in many industrial fields (textile, mechanical, food industries, ...), requirements are more and more increasing with reference to the speed of operation and accuracy of positioning of single handling arms and manipulators which allow to realize the operations the automated sequence is based on. This aspect is of particular interest in "real time", high performance automated systems where many operations have to be precisely synchronized and accuracy of positioning has to be guaranteed even though quick operation sequences have to be realized 1.

Accuracy of positioning of handling systems and vibration control and reduction require that both control procedures and measurement of process parameters are improved in order to satisfy increasing demand of manufacturing quality (Kai *et al*., 2018). This need is felt not only in the field of the manufacturing industry but also in other areas such as, for example, the field of the calibration of sensors in particular of accelerometers D'Emilia *et al*., 2015a, b).

Automated identification of system characteristics is often requested with the aim of optimizing control parameters settings in particular when mechanical characteristics of the components of production chain could be changed (Alicim and Shirinzadehm, 2005; Hauptmann, 2006; Yiu *et al*., 2003; Yin *et al*., 2017).

A further element to be taken into account with reference to measurement aspects on the whole is the possibility of setting a redundant measurement system for fault prevention and identification (Yiu *et al*., 2003; Betta and Pietrosanto, 2000; Ferrari *et al*., 2004; D'Emilia *et al*., 2015).

Many aspects have to be investigated in order to improve or set the above performances: quantity to be measured, sensors and measurement systems for motion control and monitoring, measurement data processing techniques, motion control procedures, especially in cases when traditional control strategies and quantities which are used for motion control are no more completely satisfactory.

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The capability of "auto-tuning" and/or "autodiagnosis" by means of already existing sensors or by means of other sensors added for this specific requirement, appears, on the other hand, interesting only if these additional functions can be integrated in an efficient and economical way with reference to the cost of added devices and to the acquisition and processing techniques of measured data.

These techniques must, in fact, be thoughts in order to research inside "real time" systems and the satisfaction of this requirement is not always easy in high performances controllers for automatic applications that require specific programming languages.

In this study, the possibility is evaluated of setting procedures that, using the indications of existing angular or current sensors are able to both tune on line the controller parameter and to diagnose faults by an integrated approach. In particular, the possibility of reducing vibrations and then, improving control will be analyzed.

High resolution fiber optic displacement sensors and accelerometers, mounted for this specific application will be used to both validate measurements and to evaluate by inter-comparison the possibilities offered by redundancy of sensors.

Particular attention will be devoted to the identification of the best parameter to be monitored in order to individuate the phenomena of interest also by the use of a theoretical model, even though preliminary and simplified.

In order to get experimentally validated data, a real test configuration will be examined with reference to a multi-axis automated production station to be used in a packaging application for food products: the system researches according to a real time operating system, allowing high velocity operation sequence.

The possibility of using not traditional data processing techniques, like wavelet transform (Chow and Hai, 2004; Lv and Du, 2004; Widodo and Yang, 2008; Su *et al*., 2011) will be also analyzed.

**The model:** A simple preliminary model of devices and phenomena of interest has been carried out in order to obtain information about parameters and sensors that could be more effective in the setting of auto-diagnosis and auto-tuning procedures.

As a preliminary situation, the possibility of sensors to individuate correct setting of some controller menu parameters and consequently, the system capability of accurately maintaining a set position during a production steps sequence without excessive vibration has been examined.

The automatic system that has been considered is a rotational one. Tuning the value of some parameters of the controller and in particular data concerning the inertial moment, J-load of elements to be automatically driven is a very important preliminary operation as for accuracy of displacements and vibrations of the servomotor shaft; furthermore, in many real applications accurate evaluation of correct inertial load is difficult to carry on by a theoretical way. The J-load parameter is defined according to:

$$J_{Load} = J_{Last} + J_{Gear}\left(\frac{GearOut}{GearIn}\right)^2 \quad (1)$$

Where:

$J_{Gear}$ = The moment of inertia of the Gear (on the motor shaft)

GearOut = Teeth on the Gearbox input on the motor side

GearIn = Teeth on the Gearbox output on the machine side

$J_{Last}$ = The moment of inertia of parts on the motor shaft

A procedure for auto-tuning, that means controller tuning on the basis of sensor indications, appears very interesting from an operating point of view, especially in case of multi-axis systems with respect to existing off-line procedures (Demirtas, 2011).

Nevertheless, mechanical or transmission faults are generally connected to the occurring of vibrations, so that, the sensor capability of correctly supplying vibration data for fault diagnosis will be analysed for diagnosing aspects (Singh and Al-Kazzaz, 2009; Al-Badour *et al*., 2011).

In order to get preliminary theoretical information about these aspects, a general electro-mechanical model of the motor has been developed for a generic electric motor 15, schematized as in Fig. 1 and has been specified for servomotors ELAU SM 070 16, the permanent field synchronous machine used for test.

An electric motor is splitted into an electrical part, controlled by equations of electrical circuits and into a mechanical one, acting according to mechanics equations, connected by a torque one.

The mechanical part of a motor can be described in a simplified manner by this relationship (Canini and Fantuzzi, 2001):

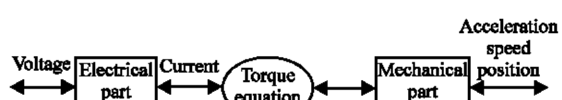


Fig. 1: Flow diagram of a generic electric motor

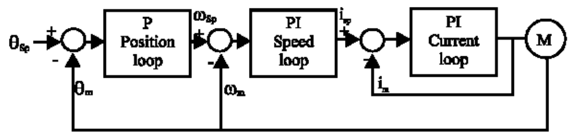


Fig. 2: Scheme of the motor position control

$$c_m(t) = F\omega(t) + J\frac{d\omega}{dt} + c_r \tag{2}$$

Where:
- $\omega$ = The angular speed of the electric motor
- F = The viscous Friction coefficient
- J = The inertia of the motor and of the load applied to the axis
- $c_r$ = An external resistant torque. In this case $c_r$ is considered constant

The torque equation represents the relation between the current i(t) that flows in motor windings and the torque supplied by the motor $c_m(t)$ and it has been considered linear:

$$c_m(t) = K \times i(t) \tag{3}$$

K is a constant, depending on the specific motor used and on the motor settings. In the applications of industrial automation, there is obviously a system for the position control that drives the electrical part.

The control scheme for a typical position controller can be represented by a sequence of P an PI loops: a position loop, a speed loop and a current loop (Canini and Fantuzzi, 2001) as can also be seen in the "SM-Motor", operating manual.

The control system of the motor is schematized by a sequence of a Proportional control (P) for the position, a Proportional-Integral control (PI) for the speed control and another loop PI for the current control (Fig. 2).

The model describing the dynamics of the positioning of the motor axis in a particular angular position $\theta_{sp}$ can be obtained by comparing the output of the P-PI-PI control system that is a command of current and the torque supplied from the motor divided by the constant K:

$$K_p''\left(K_p'\left(K_p\left(\theta_{sp}-\theta_m\right)-\omega_m\right)+K_i'\left(\int_0^t K_p\left(\theta_{sp}-\theta_m\right)d\tau-\int_0^t \omega_m d\tau\right)-i_m\right)$$
$$+K_i''\int_0^t\left(K_p'\left(K_p\left(\theta_{sp}-\theta_m\right)-\omega_m\right)+K_i'\left(\int_0^t K_p\left(\theta_{sp}-\theta_m\right)d\tau-\int_0^t \omega_m d\tau\right)-i_m\right)$$
$$d\tau = \frac{F}{K}\omega_m + \frac{J}{K}\frac{d\omega_m}{dt} + \frac{c_r}{K} \tag{4}$$

Where:
- $\theta_m$ = Measured angular position
- $\theta_{sp}$ = Set point of the angular position
- $\omega_m$ = Measured angular spee
- $i_m$ = Measured current
- $K_p$ = Proportional gain of the position loop
- $K_p'$ = Proportional gain of the speed loop
- $K_i'$ = Integral gain of the speed loop
- $K_p'$ = Proportional gain of the current loop
- $K_i'$ = Integral gain of the current loop

If $i_m$ is replaced by the following:

$$\frac{F}{K}\omega_m \frac{J}{K}\frac{d\omega_m}{dt} + \frac{c_r}{k} \tag{5}$$

and twice both members are derived, it could be obtained:

$$\begin{aligned}&J(1+K'_i)\frac{d^4\theta_m}{dt^4} + (KK''_p K'_p + K''_i F + K''_i J + F)\frac{d^3\theta_m}{dt^3} + \\ &(KK''_i K'_p + KK'_i + KK''_p K'_p K_p + K''_i F)\frac{d^2\theta_m}{dt^2} + \\ &(KK'_i K_p + KK''_i K'_p) + KK''_i K'_i)\frac{d\theta_m}{dt} + \\ &KK''_i K'_i K_p \theta_m = KK''_i K_i K_p \theta_{sp}\end{aligned} \tag{6}$$

Where:
- J = $8.00\times10^{-6}$ kg×m$^2$
- $K_i'$ = $6\times10^{-8}$ (SA)
- $K_p''$ = $1.00\times10^{5}$
- $K_p'$ = $1.5\times10^{-11}$ (SA)
- K = $4.90\times10^{-3}$ (N•mA)
- $K_i''$ = $1.00\times10^{-1}$
- F = $1.00\times10^{-8}$
- $K_p$ = $5\times10^{8}$ S$^{-1}$ Eq. 6 becomes

This is a fourth order linear differential equation in the variable $\theta_m$ that can have sinusoidal solutions if the roots of the corresponding characteristic equation are complex and conjugate.

If parameter values corresponding to the P and PI settings and physical, geometrical and mechanical data of the tested motor are inserted in Eq. 6 as in the following:

$$\begin{aligned}&8.10^{-6}\frac{d^4\theta_m}{dt^4} + 8.18.10^{-7}\frac{d^3\theta_m}{dt^3} + 6.08\times\frac{d^2\theta_m}{dt^2} + \\ &1.47.10^{-1}\frac{d\theta_m}{dt} + 1.47.10^{-2}\,\theta_m = 0\end{aligned} \tag{7}$$

It is to be pointed out that the model is a schematic representation of the system behavior on the whole nevertheless, according to the variation of the settings a very low vibration frequency is found in the range less than 1 Hz and a higher frequency in the order of 100 Hz. This indication suggests the opportunity of using displacement sensors for monitoring of the low frequency if this is important from a tuning and a diagnosing point of view.

## MATERIALS AND METHODS

In order to check the model, experimental activity has been carried out in a test bench based on the above mentioned little servomotor, driven and controlled by a high performance real time control system for industrial applications which is shown in the picture of Fig. 3.

Different measurement signals can be used in order to monitor the behavior of the servomotor axis which are all described in the diagram of Fig. 4, together with their measurement chain. In particular, high accuracy angular encoder and servomotor control current signals were monitored for different operating conditions which are already used for normal axis positioning and control, being integrated into the automatic system. Two more transducers were added for this study and installed to detect the vibrations of servomotor axis at rest when the final position of the cycle is achieved. The former sensor is a fiber optic displacement transducer, based on a Y shape and a random distribution of transmitting and receiving fibers for high sensitivity purposes.

(a) (b)

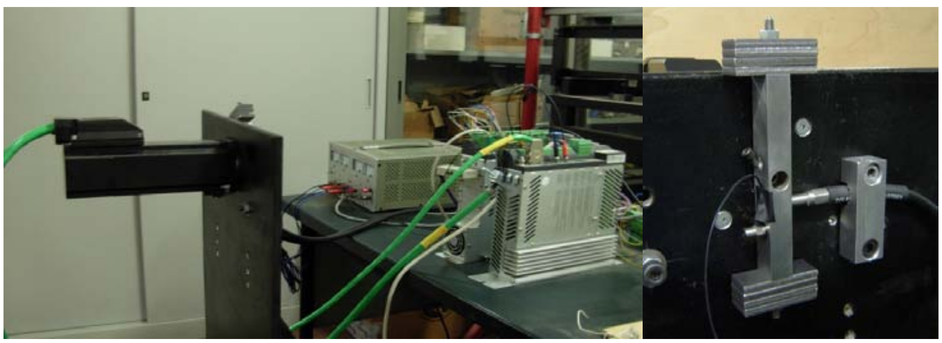

Fig. 3: a) Servomotor and control system used in the test bench and b) Detail of the mechanical component applied on the servomotor axis: the accelerometer and the fiber optic sensor are shown, used to monitor the axis vibrations

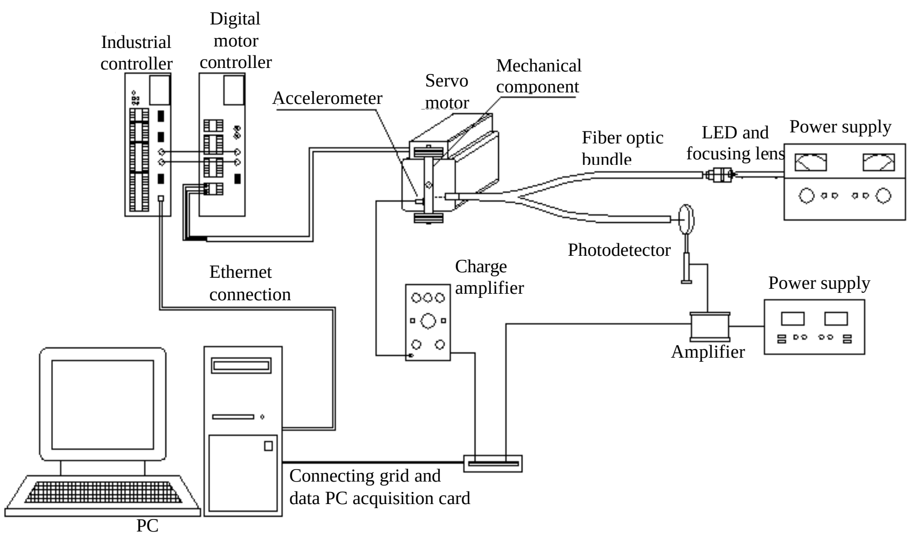


Fig. 4: Scheme of the whole test bench and data acquisition system. Four measurement signals were detected which are used for comparison, deriving from internal high resolution angular encoder and servomotor current sensor and from external sensors: a piezoelectric accelerometer and a fiber optic displacement transducer based on a Y bundle

This transducer was previously calibrated with reference to a static and a dynamic behavior. The second external transducer to be used for monitoring and fault detection purposes was a high accuracy piezoelectric accelerometer. An accelerometer was chosen as a comparison transducer with respect to the displacement one due to the different behavior with respect to the frequency content of the vibrations to be detected and monitored for the correct setting of parameters of the system controller. It is obvious that higher frequency phenomena could be better detected by an accelerometer than by a displacement transducer.

Different operating conditions have been experimentally simulated by changing the mechanical inertial load that has been connected to the axis of the servomotor. The studied inertial loads was in the range 1 to 100 times greater with respect to the internal angular inertial moment of the servomotor. For both auto-tuning and auto-diagnosing data have been processed also by means of wavelet transform which are useful in time positioning vibration effects due to both fault occurrence and incorrect setting of the induction motor.

## RESULTS AND DISCUSSION

The servomotor behavior has been tested with different inertial loads in order to evaluate the indications of the sensors with variable operating conditions. In all these conditions a setting of this parameter of controller could be found, corresponding to the spontaneous arising of vibration and noise usually, the working J-load parameter should be set less than this limit value. As an example with reference to a specific configuration with a fixed inertial load, time diagrams of signals of different sensors to measure vibration of the axis are compared in Fig. 5.

The setting of the J-load of the controller is less than limit value and vibration of servomotor axis occurs only in case of a remarkable external trigger action. In Fig. 6, the outputs of the same sensors are displayed when J-load limit has been passed. Spontaneous low frequency vibration and noise occur, compared to the previous situation.

It is to be pointed out that encoder and fiber optic sensor signals clearly show the occurrence of vibrations. In accelerometer and current for servomotor driving outputs this phenomenon is less evident. Exceeding the limit of J-load parameter setting makes the occurrence of strong low frequency vibrations that are well measured by angular (encoder) or displacement (fiber optic) sensors.

Quantitative comparison of the sensor capability to indicate the occurrence of vibrations due to the incorrect setting of J-load is shown in Fig. 7 and 8.

The lower frequency component is particularly evident in the fourier transform of the encoder and the displacement sensor signals (Fig. 7), instead it is much less evident in the other (Fig. 8).

If the value of the peak of the spectra corresponding to the lowest frequency for fiber optic sensor and encoder is considered as a function of the J-load, the trend in Fig. 9 can be obtained.

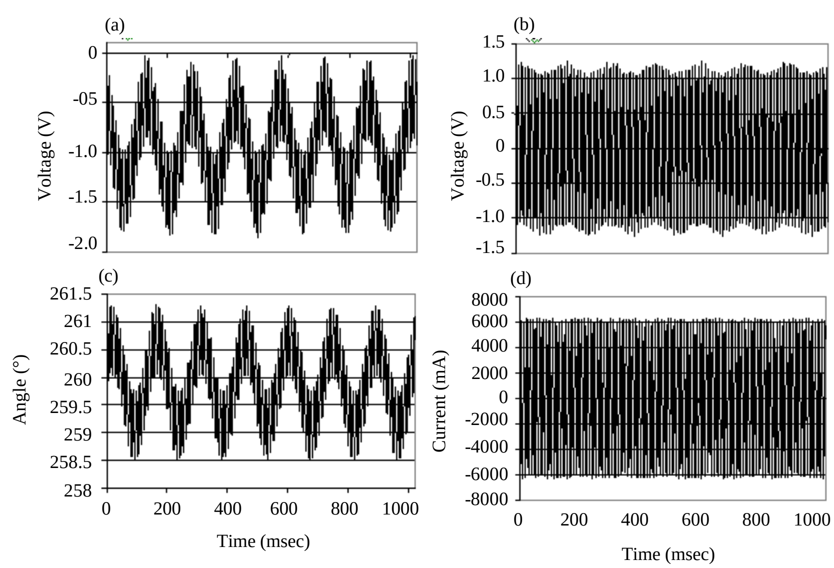


Fig. 5: Time diagram of different sensors, for J-load set in the controller menu less than the limit value of J-load: a) Optical sensor; b) Accelerometer; c) Angular encoder and d) Current signal

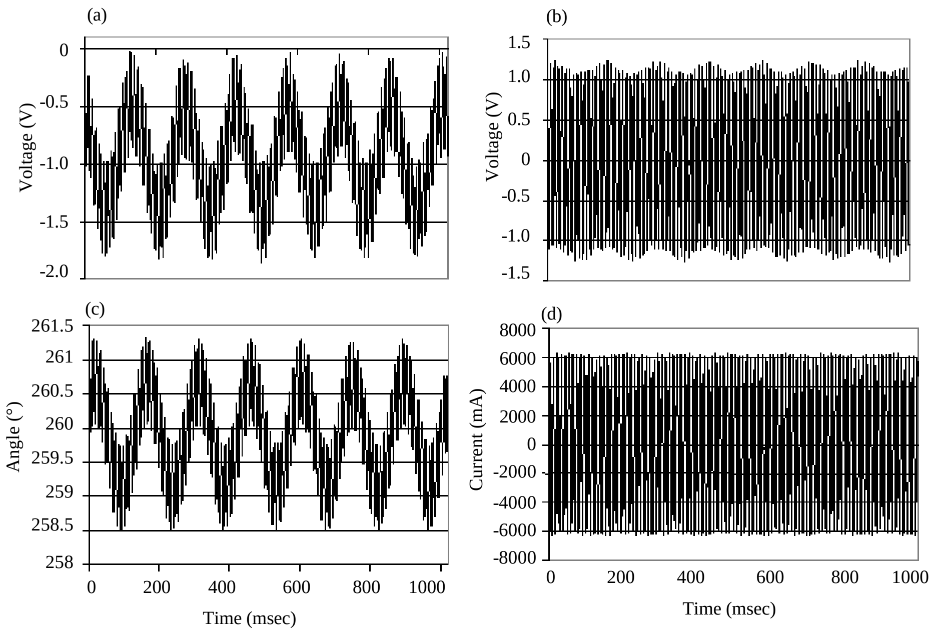


Fig. 6: Time diagram of different sensors, for J-load set in the controller menu higher than the limit value of J-load: a) Optical sensor; b) Accelerometer; c) Angular encoder and d) Current signal

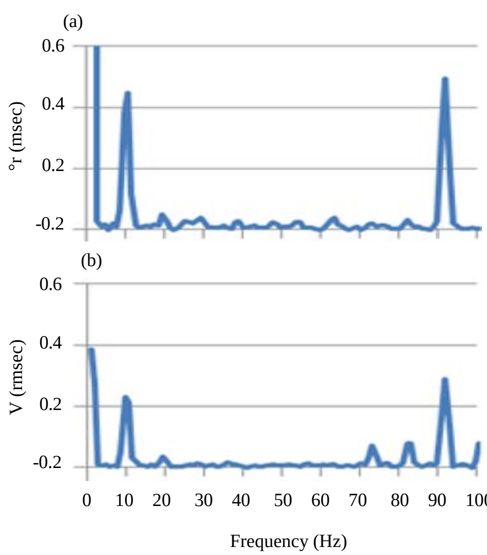


Fig. 7: Fourier transform of: a) Encoder and b) Optical sensor signals when J-load is set to 15 kgcm$^2$

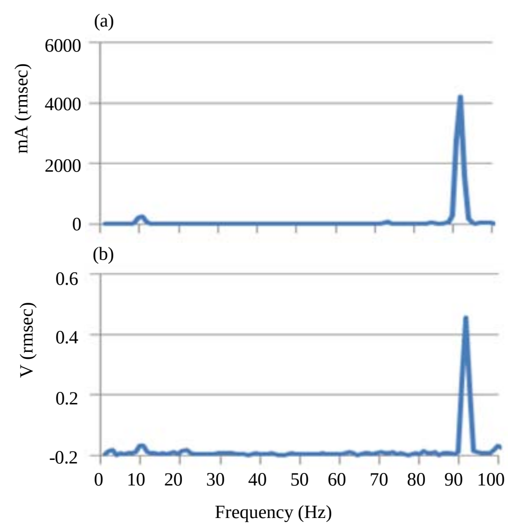


Fig. 8: Fourier transform of a) Current and b) Accelerometer signals when J-load is set to 15 kgcm$^2$

The signal of all the used sensors has also been processed by the Morlet continuous wavelet (Fig. 10). If this method is used, the amplitude of the 3-dimensional graph of the wavelet transform in correspondence to the scale value corresponding to the low-frequency component is proportional to the amplitude of vibrations at the considered frequency (Fig. 11).

The effectiveness of this analysis appears particularly interesting with reference to diagnostic purposes in cases when the temporal identification and location of phenomena during the operating sequence of the process is significant.

The behavior of the vibration amplitude in the Morlet wavelet as a function of the J-load is shown in Fig. 12 these results are very similar to that obtained by the Fourier transform (Fig. 9).

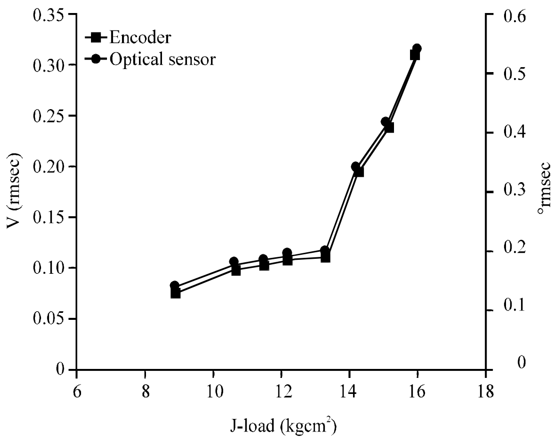


Fig. 9: Peaks amplitudes of the fourier transforms of the optical sensor and the encoder signals, corresponding to the low frequency vibration component as a function of the J-load settings

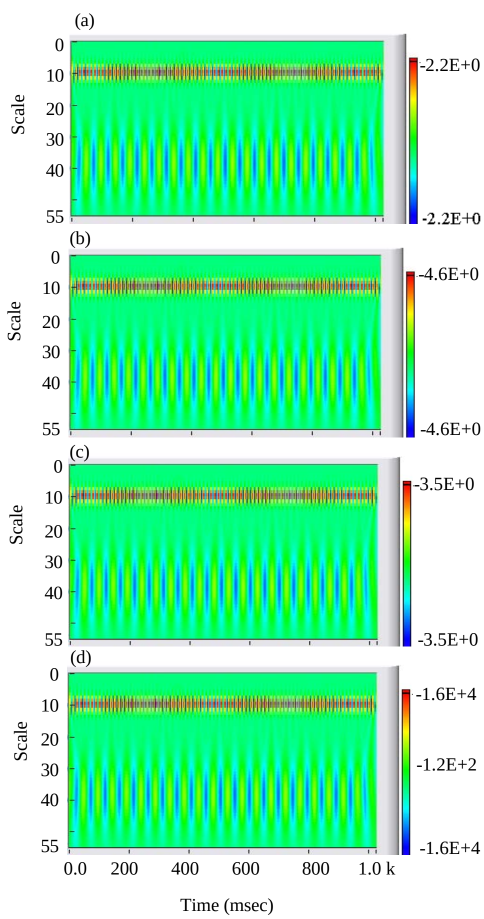


Fig. 10: Morlet continuous wavelet data processing: a) Scalogram 1: Optical sensor; b) Scalogram 2: Accelerometer; c) Scalogram 3: Angular encoder and d) Scalogram 4: Signal of current

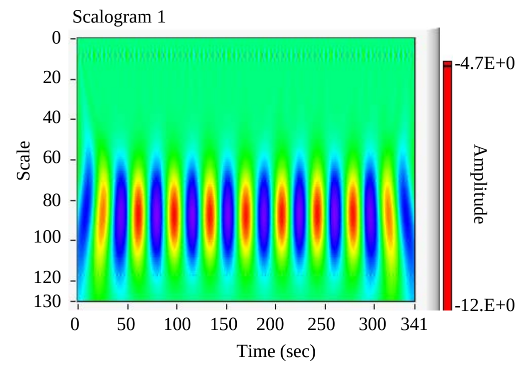


Fig. 11: Morlet continuous wavelet of optical sensor data in case of J-load limit trespassing

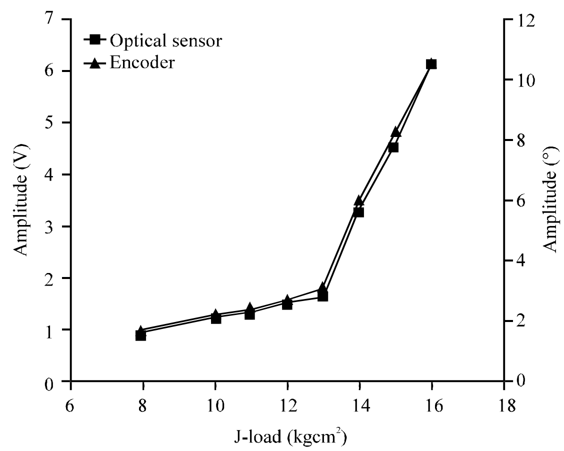


Fig. 12: Amplitudes of the wavelet transform of the optical sensor and the encoder signals, corresponding to the low frequency vibration component as a function of the J-load settings

Both FFT frequency analysis (Fig. 9) and wavelet transform processing (Fig. 11 and 12) show that, when the trespassing of the right J-load limit occurs, the amplitude of low frequency vibration suddenly increases. Vibration components having a frequency in the order of 100 Hz can be identified in all cases of both regular and irregular working with similar amplitude.

When the J-load is changed the peak frequency of low frequency vibration is changed too in Fig. 13 the effect of varying the set J-load in the controller menu is shown. In particular, the vibration low frequency value decreases when the set J-load is increased. A linear relationship could be detected.

It is to be pointed out that displacement and angular sensors show this effect much more clearly with respect to the other sensors also due to the range of frequency which is of interest for auto-tuning purposes or for diagnosing of low frequency vibrations due to fault in control procedures.

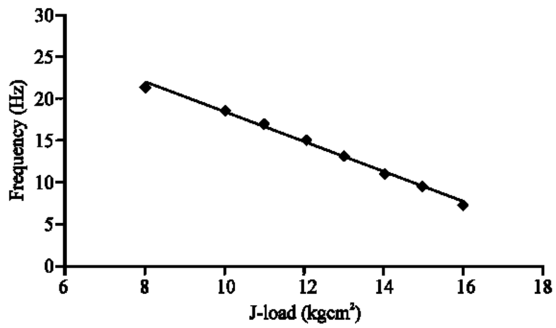


Fig. 13: Frequency value behaviour of the low frequency vibration when the J-load setting is increased

Finally, the ability of both encoder and fiber optic displacement sensor of identifying similar phenomena as for frequency content, appears to be very promising also with the aim of implementing simple fault diagnosis procedures based on sensor redundancy, obtained by means of simple and economic fiber optic sensors to be added for these specific purposes to transducers already installed for control of positioning.

## CONCLUSION

A comparison has been discussed in this study among different measuring methods to be used in control and tuning procedures for controllers and for actuating components of high performance automated systems to be "real time" managed in situations of industrial interest. In particular, the performances have been studied of sensors which are already present in the automated system (angular encoders and current sensors) and of sensors added for validation and redundancy purposes (fiber optic displacement sensor and piezoelectric accelerometer).

According to the indications of a simplified model of the system, low frequency content of vibration proved to be useful to automatically indicate the trespassing of the right limit of the J-load setting. By analyzing the angular encoder signal, it has been possible to accurately detect the J-load limit setting in order to avoid incorrect working of the automated system and this has been confirmed by the indications of the high performance fiber optic displacement sensor. The results of different data processing techniques have also been compared and wavelet transform indications were validated, showing that this data processing technique, able to identify the time occurrence of problems could be useful not only for diagnostic but also for automatic tuning purposes.

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