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FRACTIONAL ORDER FOURIER SPECTRA IN ROBOTIC MANIPULATORS WITH VIBRATIONS

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Abstract: This paper presents a fractional system perspective in the study of signals captured during impacts and vibrations of mechanical manipulators. In order to acquire and study the signals an experimental setup was developed. The system acquires data from the sensors, in real time, and, in a second phase, processes it through an analysis package. The experimental study provides useful information that can assist in the design of a control system to be used in eliminating or reducing the effect of vibrations. *Copyright © 2006 IFAC*

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1. INTRODUCTION

The advent of lightweight arm manipulators, mainly in the aerospace industry, where weight is an important issue, leads to the problem of intense vibrations. On the other hand, robots interacting with the environment often generate impacts that propagate through the mechanical structure and produce also vibrations.

This paper presents a fractional system perspective in the study of the robotic signals captured during an impact phase of the manipulator. In order to analyze these phenomena an acquisition system was developed. The manipulator motion produces vibrations, either from the structural modes or from end-effector impacts. The instrumentation system acquires signals from multiple sensors that capture the axis positions, mass accelerations, forces and moments and electrical currents in the motors. Afterwards, the Analysis Package, running off-line, reads the data recorded by the acquisition system and examines it.

Bearing these ideas in mind, this paper is organized as follows. Section 2 addresses the motivation for this work. Section 3 describes the robotic system enhanced with the instrumentation setup. Section 4 presents the experimental results. Finally, section 5 draws the main conclusions and points out future work.

2. MOTIVATION

Singer and Seering (1988) mention several techniques for reducing vibrations and its implementation either at the robot manufacturing stage or at the operational stage. Briefly, the techniques can be enumerate as: (i) conventional compensation, (ii) structural damping or passive vibration absorption, (iii) control based on the direct measurement of the absolute position of the gripper, (iv) control schemes using the direct measurement of the modal response, (v) control driving, actively, energy out of the vibration modes, (vi) use a micromanipulator at the endpoint of the larger manipulator and (vii) adjustment of the manipulator command inputs so that vibrations are eliminated.

The work presented here is a step towards the implementation of the sixth technique. In recent years the use of micro/macro robotic manipulators has been proposed for space applications and nuclear waste cleanup. Several authors have studied this technique (Yoshikawa, *et al*., 1993), namely (Magee and Book, 1995) and (Cannon, *et al*., 1996) that adopted the command filtering approach in order to position the micromanipulator. Also, (Cannon, *et al*., 1996) and (Lew, *et al*., 1995) used inertial damping techniques taking advantage of a micro manipulator located at the end of a flexible link.

The experiments used in this paper use a macro manipulator, with a low bandwidth, that is compensated through a much faster micromanipulator inserted at the robot endpoint. In this perspective, to control the macro/micro system in order to eliminate or reduce the effect of the vibration is fundamental to study the involved variables.

Bearing these ideas in mind, a study of the robotic signals, in a fractional system perspective, is presented. In fact, the study of feedback fractional order systems has been receiving considerable attention (Machado, 1997; Machado, 2003) due to the facts that many physical systems are well characterized by fractional-order models (Podlubny, 2002). With the success in the synthesis of real noninteger differentiator and the emergence of new electrical circuit element called “fractance” (Bohannan, 2000; Bohannan, 2002), fractional-order controllers (Oustaloup, *et al.* 1997), including fractional-order PID controllers (Barbosa, *et al.* 2004), have been designed and applied to control a variety of dynamical processes, including integer-order and fractional-order systems. Therefore the study presented here can assist in the design of the control system to be used.

3. EXPERIMENTAL PLATFORM

The developed experimental platform has two main parts: the hardware and the software components. In the following sub-sections these components are briefly described (Lima, 2005).

3.1 The Hardware Components

The hardware architecture is shown in Fig. 1. Essentially it is made up of a robot manipulator, a Personal Computer (PC) and an interface electronic system. The interface box is inserted between the robot arm and the robot controller, in order to acquire the internal robot signals; nevertheless, the interface captures also external signals, such as those arising from accelerometers and force/torque sensors, and controls the external micro-arm. The modules are made up of electronic cards specifically designed for this work. The function of the modules is to adapt the signals and isolate galvanically the robot’s electronic equipment from the rest of the hardware required by the experiments.

The force/torque sensor is the 67M25A model (JR3 Inc), comprising the sensor and a Digital Signal Processing PCI card, and is mounted on the robot’s wrist. Two aluminum pancakes were built to mechanically adapt the sensor to the flexible beam, on one side, and to the robot arm, on the other side. The digital signals from the sensor run through a cable along the length of the arm, and go into a JR3 PCI receiver card inside the PC which processes the data at 8 kHz per axis. The card has built in filtering, but raw force signals were adopted in the following experiments.

Two general purpose analog 1-axis piezoelectric accelerometers are used. Both are the same type, Model FA 208-15 with a range of ±5 g from FGP Instrumentation. The body of the accelerometer sensors is mounted electrically isolated from the manipulator robot in order to prevent ground loops of electrical currents. Actually, without the accelerometers’ isolation the signal presents a high level of noise that corrupts the main signal. One accelerometer is attached at the free-end of the flexible beam to measure its oscillations. The second accelerometer is attached on the clamped end of the flexible beam. Both accelerometer signals are processed through an A/D converter.

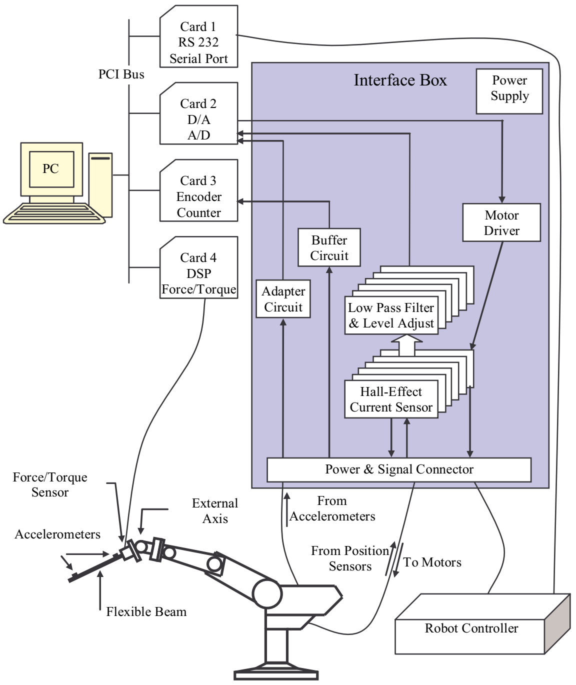

Fig. 1. Block diagram of hardware architecture.

The robot used is an anthropomorphic type with five degrees of freedom (dof), model Scorbot ERVII from Eshed Robotec. To measure the electrical current supplied to each motor a Hall-effect sensor is inserted to avoid interfere with robot electronics. A circuit board was developed to handle the signal from the sensor up to the A/D converter. The power supplied to the motors is based on a pulse width modulation (PWM) driver with a frequency of 20 kHz. The motors rotate according with the DC component of electrical current and, in order to measure it, a low-pass filter was implemented for each measurement channel. Thus, a first function of the interface circuit is to filter the high frequency components of the signal and a second function is to galvanically isolate the electrical circuit from the robot electronics.

The robot system and the external axis servomotor have position sensing by means of optical incremental encoders. Those position signals are also captured by the data acquisition system presented here. In order to isolate the robot feedback circuit from the PC card, for each encoder it is inserted a buffer (in the interface box) before connecting the signals to the corresponding high speed counter (in Card 3). This PC card is a high-speed counter/timer, PCI-6602 model from National Instruments and was programmed to read the signals from the encoders.

The transmitting and receiving of data between the computer and robot is carried out through a serial port RS 232C.

3.2 The Software Components

The Software runs in a Pentium 4, 3.0 GHz PC. The software architecture is shown in Fig. 2.

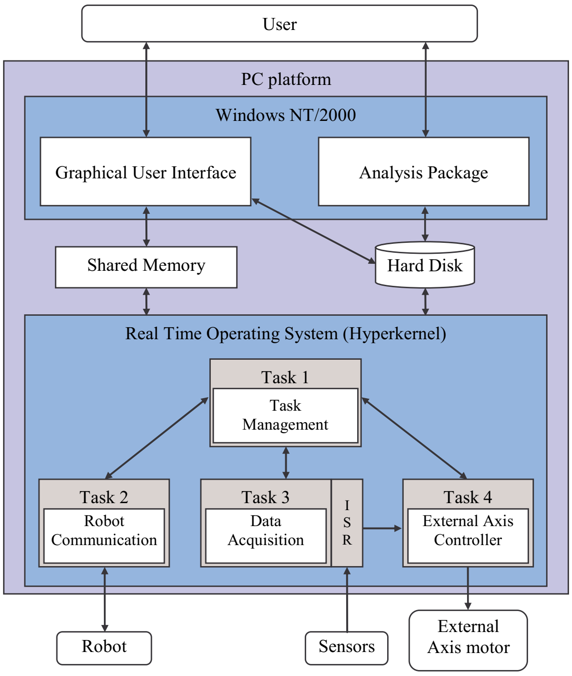

Fig. 2. Block diagram of software architecture.

The software package developed, from the user's point of view, consists of two applications. One, the acquisition application, is a program made up of two parts: The Graphical User Interface module and the real time module. The other application is an Analysis Package program that analyses the data obtained and recorded by the acquisition application. The real time software, running in the Hyperkernel, was developed in C based on a standard Windows NT/2000 development tool (MS Visual Studio) and the robot controller software was implemented in the ACL proprietary language. The Windows NT/2000 Software is made up of the GUI module of the acquisition system and Analysis Package. The acquisition system software was developed in C++ with MS Visual Studio.

The Analysis Package, running off-line, reads the data recorded by the acquisition system and examines it. The Analysis Package allows several signal processing algorithms such as, Fourier transform, correlation, time synchronization, etc. With this software platform both the Hyperkernel and the Analysis Package tasks can be executed on the same PC.

4. EXPERIMENTAL RESULTS

In the experiment a steel rod flexible link is used. To test impacts, the link consists of a long, thin, round, flexible steel rod clamped to the end-effector of the manipulator. The robot motion is programmed in a way that the rod moves against a rigid surface. Fig. 3 depicts the robot with the flexible link and the impact surface. The physical properties of the flexible beam are shown in Table 1.

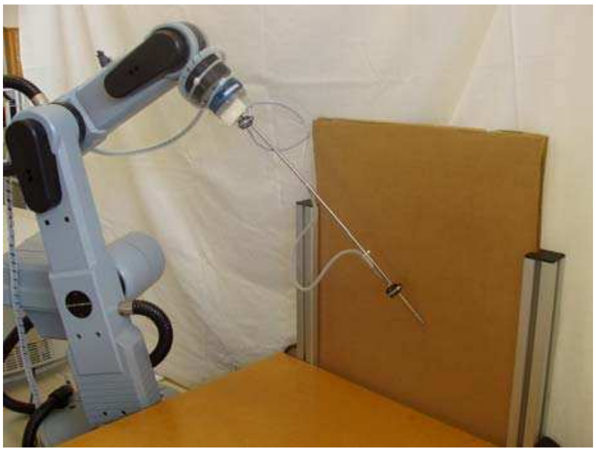

Fig. 3. Steel rod impact against a rigid surface

Table 1 – Physical Properties of the Flexible Beam

Characteristic	Steel Rod
Density [kg m^{-3}]	7.86×10^3
Elasticity Modulus [N m^{-2}]	200×10^9
Mass [kg]	0.107
Length [m]	0.475
Thickness/diameter [m]	5.75×10^{-3}

During the motion of the manipulator the clamped rod is moved by the robot against a rigid surface. An impact occurs and several signals are recorded with a sampling frequency of $f_s = 500$ Hz. The signals come from different sensors, such as accelerometers, force and torque sensor, position encoders and current sensors. The time evolution of the variables is shown in the figures 4–8 corresponding to: (i) the impact of the rod on a rigid surface and (ii) without impact.

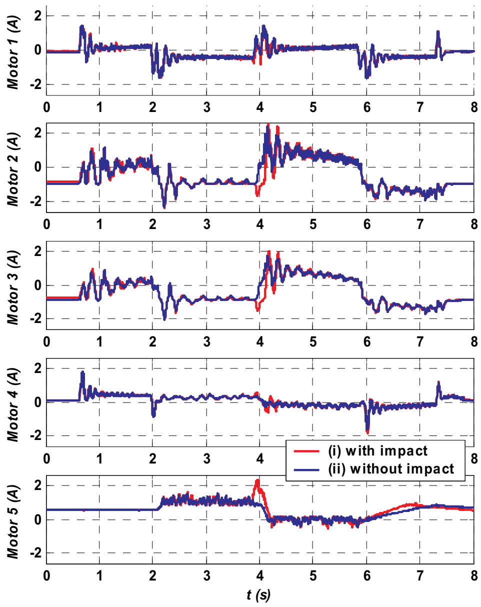

Fig. 4. Electrical currents of robot axis motors

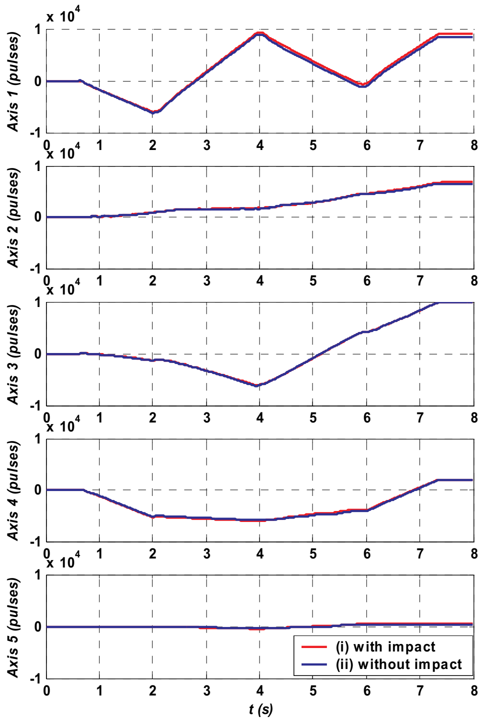

Fig. 5. Robot axis positions

These signals present clearly a strong variation at the instant of the impact, that occurs approximately for $t = 4$ sec. Consequently, the effect of the impact forces and moments, shown on figures 6 and 7, respectively, is reflected in the current required by the robot motors (Fig. 4).

Figure 8 shows the accelerations at the rod free-end (accelerometer 1), where the impact occurs, and at the rod clamped-end (accelerometer 2). The amplitudes of the accelerometers signals are higher near the rod impact side. The two signals are super imposed in Fig. 8. The first acceleration peak (accelerometer 1), due to the impact, corresponds to the rigid surface (i) while the second peak corresponds to the care of no impact (ii).

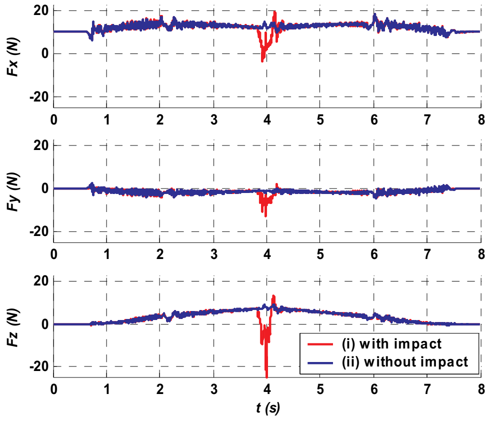

Fig. 6. Forces at the gripper sensor

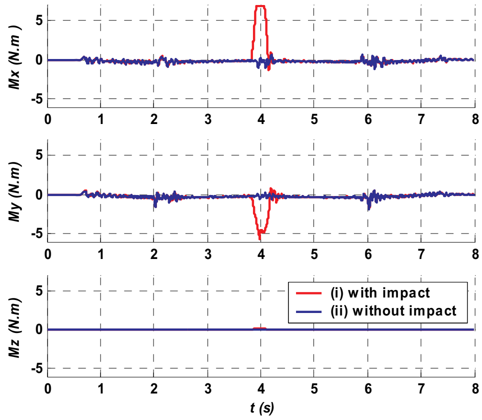

Fig. 7. Moments at the gripper sensor

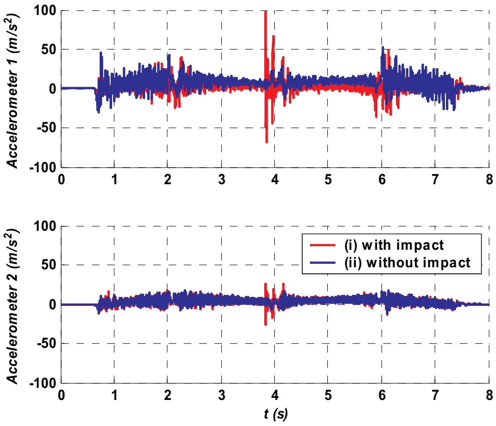

Fig. 8. Rod accelerations

Figure 9 shows the amplitude of the Fast Fourier Transform (FFT) of the axis 1 position signal. A trend line was calculated, and super imposed to the signal, with slope -0.99, that reveals, clearly, the integer order behaviour. The others position signals were studied, revealing also an integer behaviour, both under impact and no impact conditions.

Figure 10 shows the amplitude of the FFT of the electrical current for the axis 3 motor. The spectrum was also approximated by trend lines in a frequency range larger than a decade. These trend lines have slopes of -1.52 and -1.51 under impact (Fig 10, i-with impact) and without impact (Fig 10, ii-without impact) conditions, respectively. The lines present, clearly, fractional order behaviour in both cases.

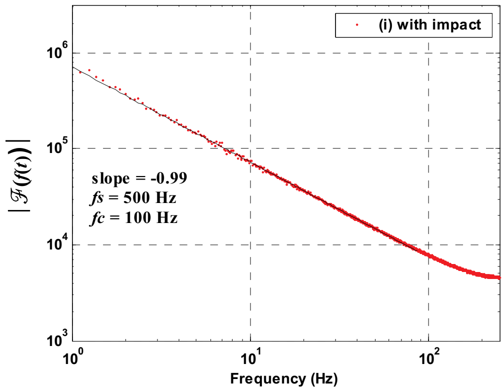

Fig. 9. Spectrum of the axis 1 position

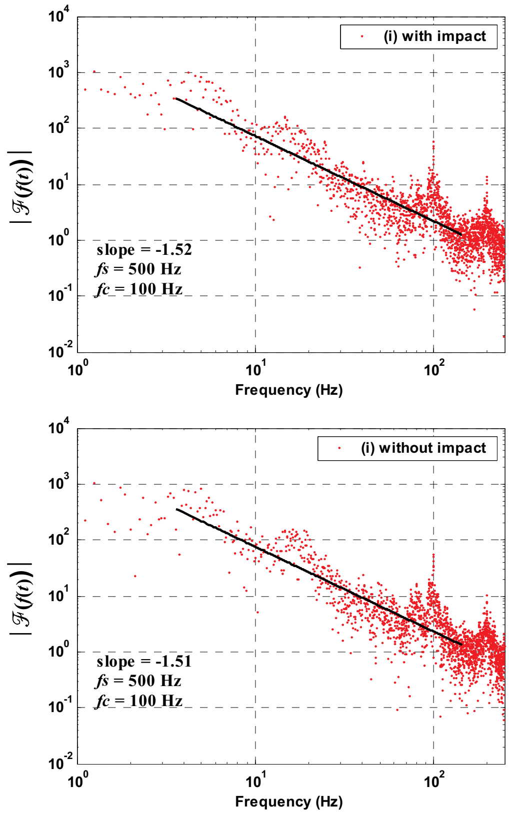

Fig. 10. Spectrum of the axis 3 motor current

Figure 11 depicts the amplitude of the FFT of the electrical current for the axis 4 motor. Here the trend lines present slopes that vary slightly (slope = -1.58 with impact and slope = -1.64 without impact) but, in both cases, continues to reveal a fractional order behaviour.

The others axis motor currents were studied, as well. Some of them for a limited frequency range present also fractional order behaviour while others have a complicated spectrum.

According to the robot manufacturer specifications the loop control of the robot has a cycle time of $t_c = 10$ ms. This fact is observed approximately at the fundamental ($f_c = 100$ Hz) and multiple harmonics in all spectra of motor currents (Fig. 10 and 11).

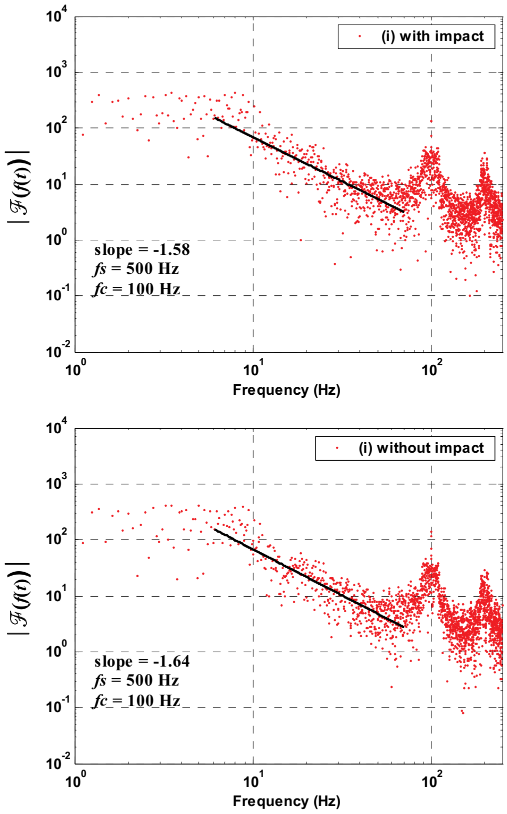

Fig. 11. Spectrum of the axis 4 motor current

Figure 12 shows the spectrum of the F_z force as an example.

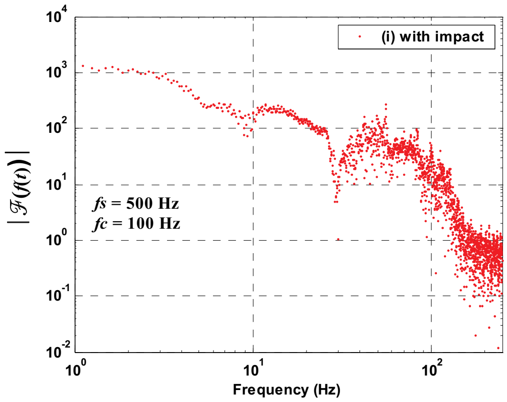

Fig. 12. F_z force spectrum with impact

This spectrum is not so well defined in a large frequency range. From this point of view all force/moments spectra present identical behaviour. Therefore, it is difficult to define accurately the behaviour of signals in terms of integer or fractional system.

Finally, Fig. 13 depicts the spectrum of the signal captured from the accelerometer 1 located at the rod free-end of the beam.

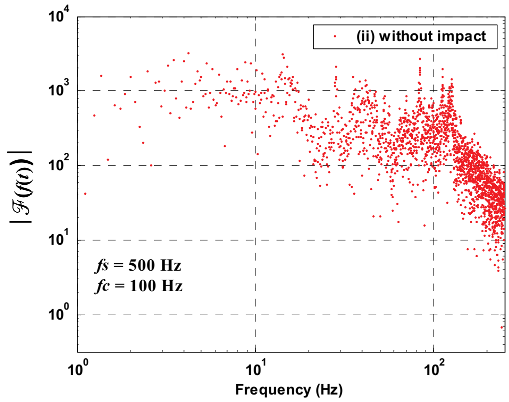

Fig. 13. Acceleration spectrum of the rod free-end without impact

Like the spectrum from the other accelerometer, this spectrum is spread and complicated. Therefore is difficult to define accurately the slope of the signal and consequently its behaviour in terms of integer or fractional system.

5. CONCLUSIONS

In this paper an experimental study was conducted to investigate several robot signals, in a fractional system perspective. This study provides useful information that can assist in the design of a control system to be used in eliminating or reducing the effect of vibrations.

The next stage of development of the software and hardware apparatus is to reduce the vibrations and its effect upon the robot structure. In this line of thought, is under development a micromanipulator, with a higher frequency response than the main manipulator, mounted at the end-effector and actively counter-acting the undesirable dynamics.

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