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CONTROL OF ALTERNATE MOTION MACHINE WITH HIGH INERTIA FORCES

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ABSTRACT - This paper describes the implementation and the validation of a digital controller driving a four-bar mechanism with high alternate motion masses. The control uses a mixed explorative and predictive technique based on off-line model of weight, inertia and friction. Particular care has been devoted to adjust an hybrid (analog-digital) system for the feedback signal acquiring. The control proved to satisfactorly be used to obtain electrical cams up to 250 rpm average speed with sharp acceleration diagrams. The responsiveness of the control permitted to appreciate advantages of motion law harmonic content reduction.

Keywords: Motion control, digital controller, feedforward, flywheel, harmonic content.

NOMENCLATURE

α: crank angle
ω: shaft speed
J: moment of inertia
K: speed splice constant
T_f: friction torque
T_i: inertia torque
t: time

INTRODUCTION

Classical devices like four-bar mechanisms are widely used in industrial applications for converting uniform rotary motion to alternate motion. In presence of high masses, oscillating motion of parts like rockers usually makes difficult obtaining an accurate and stable control with standard P-I-D techniques.

From a general point of view, in motion control the major sources of uncertainties are friction, inertia and external disturbance [1]. General purpose control equipment for advanced automation are required to yield high productivity and, at the same time, to fulfil increasingly stringent accuracy requirements. A universal solution has been proposed by [2] as a combinatin of friction compensation, a disturbance observer, a position feedback controller and a feedforward controller; in such an approach, inertia identification is obtained from the generic disturbance observer.

Also [3] proposed a four-parts control system consisting in velocity feedback control, inertia torque feedforward control, disturbance observer and inertia identification part in which the disturbance observer is used for the inertia identification as well as for disturbance compensation. A possible alternative has been proposed by [1] consisting in an adaptive robust control (ARC) instead od the disturbance observer (DOB) capable of better tracking performance and transient in presence of discontinuous disturbance.

These techniques, not available on commercial controller yet, are aimed at supply general solutions, apt to scenarios in which inertia force values are not a priori known, like in the case of a robot picking pieces of different dimension, or moving in a not controlled environment.

The purpose of this work, instead, is describing the situation, much more common in industrial practise, of an automated machine that performs a repetitive task and that is built up with low cost control hardware.

The implementation result has been used for experimentations on low harmonic content motion laws, showing a satisfactorly aptness to realize the required velocity curve.

THE TEST MACHINE

Tests have been executed with a four bar mechanism. This classical mechanism is widely used in industrial applications for converting uniform rotary motion to alternate motion. When the cranck is set in uniform motion, the supports are stressed mainly because of the inertia forces generated by the oscillating motion of the rocker.

Instead, in this work, the possibility of a non-uniform input rotation is considered in order both to obtain a particular rocker motion and to reduce the dynamic stress on the ground links. Special care has been paid in avoiding clearances in joints, where special precharged ball-bearing joints have been adopted in order to limit noise and unpredictable effects on measurements. In such four-bar mechanism, the crank acts also as a flywheel, and it is connected to the servomotor. The radius of the crank and the length of the truss can be changed, in order to investigate different settings.

The whole machine is grounded on a special anti-vibration support that allows a proper mechanical insulation.

The system is driven by an asynchronous motor with vectorial control Lenze DSVARS 056-22 provided with supply module 9212-E. The axis module 9222-E allows to set the speed or the torque by means of an analog voltage input (10 V). The system is not equipped with an axis control module, that is substituted with the controller running in the PC.

Is important to observe the absence of a reduction gear at the servomotor output shaft. Directly coupling servomotor and crank eliminates a possible source of backlashes but obliges to have a pass-band greater of that one would be required with such a transmission device.

The control system is built up by a personal computer with Linux operating system (kernel 2.4.19) equipped with an I/O board Sensoray 626 that reads the servomotor encoder and generates the output signal.

REAL TIME IMPLEMENTATION

In order to optimize the high computing power of modern personal computers, generally operating systems associate at each process a priority so that maximizing the overall system speed. Resources optimization of course implicates a more varying execution time for a single process and the possible violation of priority order.

In industrial contexts this approach does not result adequate. Using personal computers in applications with extremely severe timing constraints, like high pass-band controls, needs that at least a few processes do have execution time repeatability not endangered by searching the best system average performance. *Real time* operating systems are born from this requirement. Their meaning does not refer to speed higher or lower than general purposes ones, but to system determinism, by which tasks are executed exactly when expected.

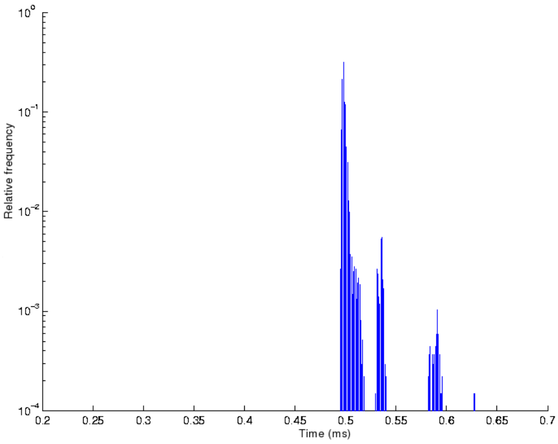

Figure 1: Execution periods relative frequency (with *nanosleep*).

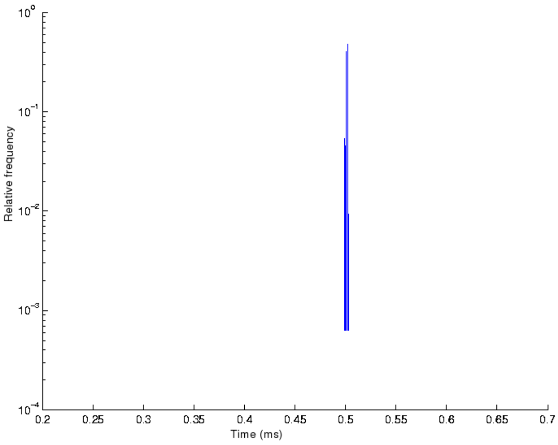

Figure 2: Execution periods relative frequency (with polling).

There are hard and soft real time implementations: firsts are those based on a specifically redesigned kernel, while others are obtained using traditional operating systems that allow to effectively manage static priorities and scheduling policies.

Seeing that Sensoray board driver is not available for real time operating systems, an adequate soft real time implementation has been arranged.

In particular, this is based on increasing process static priority, saving data in ram rather than in the hard disk and replacing the *nanosleep* function for sampling time computing with continuous polling the system clock until elapsed time reaches a value, multiple of the sampling period, causing a control frame execution.

Obtained results are close to an hard real time system ones, with the only drawback that, in such a solution, the process never returns control to the system scheduler and hence all the other tasks are indefinitely suspended.

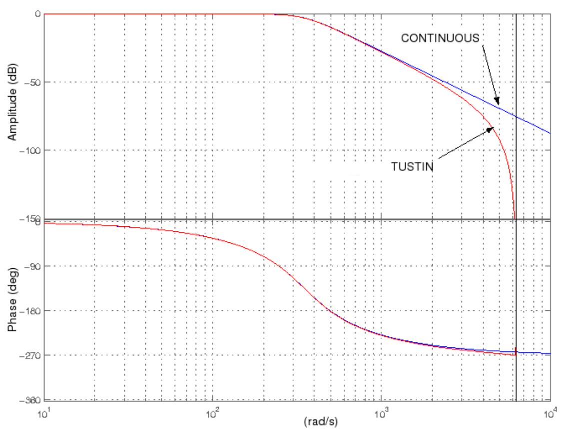

Figure 3: Bode diagram of Tustin discretization.

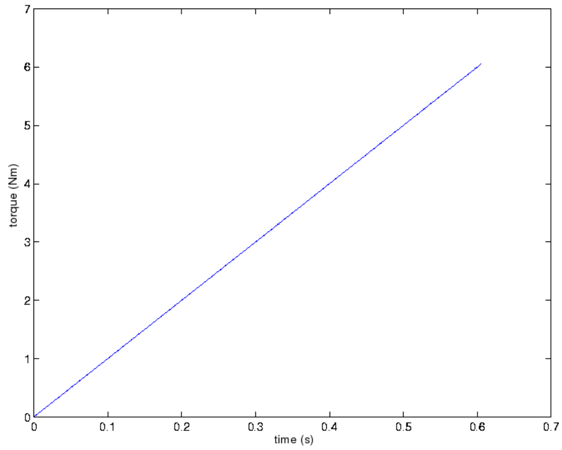

Figure 5: Applied torque for inertia measurement.

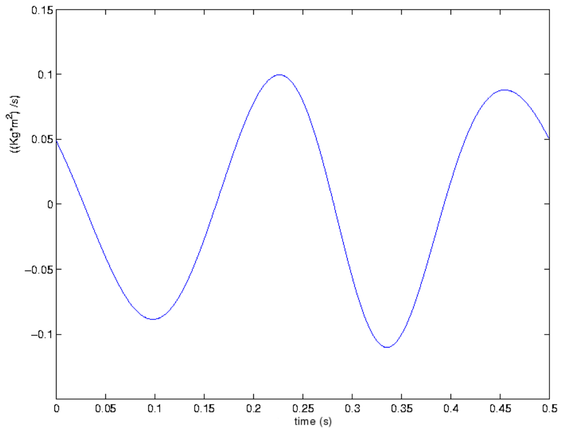

Figure 4: Moment of inertia (360 degrees).

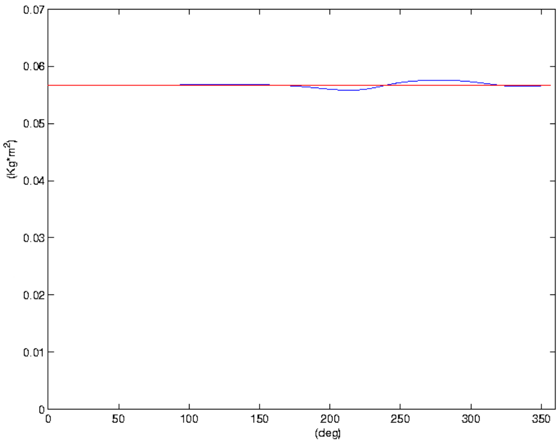

Figure 6: Verify that J_0 is constant.

Execution times result less than $200\mu s$, using a Pentium III at $500MHz$, so control frequency has been set at the precautionary value of $2KHz$: figures 1 and 2 show that, passing from using *nanosleep* function to polling the system clock execution time repeteability improves dramatically.

ENCODER READING

As often happens in commercial devices, the Lenze drive makes available the following signals for closing the control loop:

- analog voltage output
- synchronous simulated encoder
- asynchronous simulated encoder

The first, also after being properly filtered, mantains low frequency noise components. Synchronous reading the simulated encoder signal is subject to a considerable discretization error and requires a suitable filtering. Asynchronous handling of this imput implies harmful interactions with timing management described in the paragraph above.

The optimum solution, set up after several tests, consists in using an hybrid system combining the analog signal input at low speed and the simulated encoder synchronous reading at greater speed. Such a system includes adapting control loop constant values, on varying shaft speed.

Encoder signal is filtered by means of a 4^{th} order Butterworth filter and then discretized with a bilinear transformation (Tustin's method). Corresponding Bode diagrams are shown in figure 3.

PC-BASED CONTROL

The machine control has been performed by means of a software that combines a P-I regulator with a feed forward control that takes in account weight, inertia and friction.

Rather than the classical solution with a double speed loop, where the Lenze drive acts as inner P loop and the PC supplies the outer P-I loop, a better

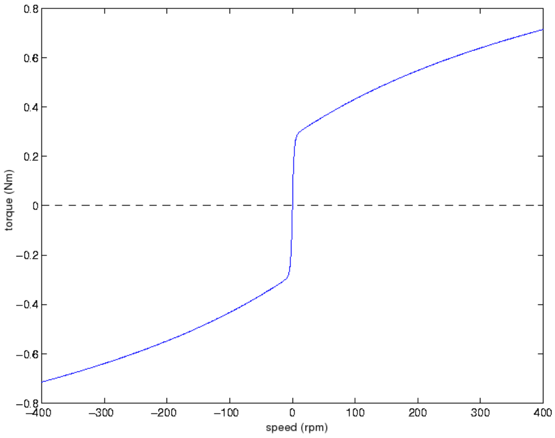

Figure 7: Calculated friction torque.

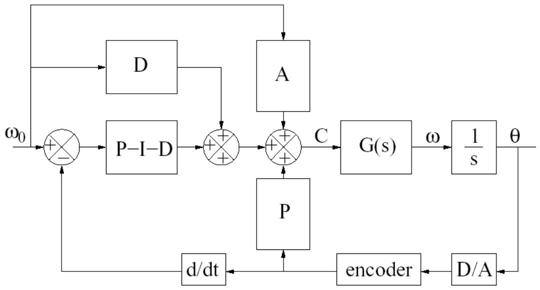

Figure 8: Control system diagram.

solution has been reached simply using the torque setpoint input port of the drive.

As the inner loop disappears, the PC software can be commanded in terms of precalculated torque. In other words, the software contains a dynamic model of the machine and calculates the torque value necessary to follow a given motion law, compensating for the foreseeable dynamic effects.

In this way, the P-I-D regulator is freed from the heaviest part of the work and can more easily give a control both stable and responsive.

In order to implement feedforward control the mechanism dynamic has been modelled with the aim of calculating torque values needed for counterbalancing:

- weight torque
- inertia torque
- friction torque

The machine model has been designed with Visual Nastran 4D software.

The center of mass of the system made up by the connecting-rod and the rocker is neither located on the rotation axis nor on a vertical plane containing the axis itself, so a moment caused by weight forces is transmitted to the shaft.

This disturbance is calculated by a simulation without friction and with low, constant speed, measuring the torque yielded by the motor in these conditions; founded precision points have been approximated by an 8^{th} degree polynomial. In this case, approximating a tabular function with an high degree polynomial does not exhibits drawbacks because is not necessary to extrapolate values outside the intepolation domain. Weight compensating can be easily experimentally tested: manually moving the mechanism with only motor weight torque counterbalancing, the four bar mechanism seems to be in absence of gravity.

Modelling inertia forces is more complex, because this quantity depends not only on crank angle but also on instantaneous velocity and acceleration:

$$T_i(t) = \frac{1}{2}\dot{J}(t)\omega(t) + J(t)\dot{\omega}(t) \tag{1}$$

hence, by a simulation with constant shaft speed ($\dot{\omega} = 0$), it gives:

$$\dot{J}(t) = 2\frac{T_i(t)}{\omega_0} \tag{2}$$

that, numerically integrated, results:

$$J(t) = J_0 - \Delta J(t) \tag{3}$$

The diagram of $\Delta J(t)$ is shown in figure 4; this graph has been expressed in function of cranck angle and approximated with CFT (Continuous Fourier Transform):

$$J(\alpha) = a_1 sin(b_1 x + c_1) + \cdots + a_4 sin(b_4 x + c_4) \tag{4}$$

being a, b and c constants.

Finally J_0 has been extracted from:

$$J_0 = \frac{T_i(t) + \frac{1}{2}\frac{d\Delta J}{dt}\omega t}{\omega} + \Delta J \tag{5}$$

applying the torque curve shown in figure 5 and verifying that the resulting J_0 value is actually constant. Figure 6 points out that the error does not exceed 1.5%.

Friction torque does not change quickly on varying the shaft speed; taking it in account allows to limit errors in steady state conditions, when the feedback is purely proportional.

In order to measure it, specific tests have been executed. Starting with a fixed shaft speed, motor torque has been zeroed: then, recording the shaft speed during the deceleration, and considering that:

- the weight torque average work is zero;
- the moment of inertia is considered constant, equal to the mean value $\bar{J}$;

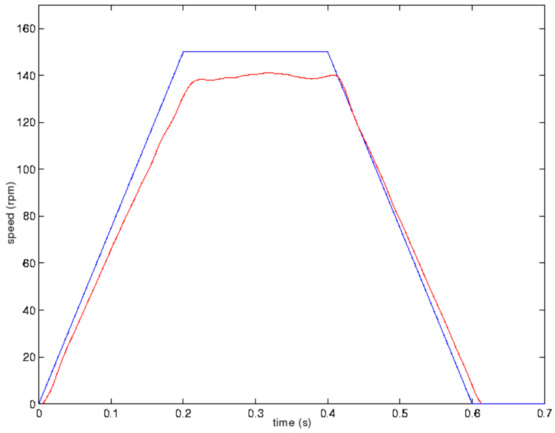

Figure 9: Open loop control: constant acceleration law.

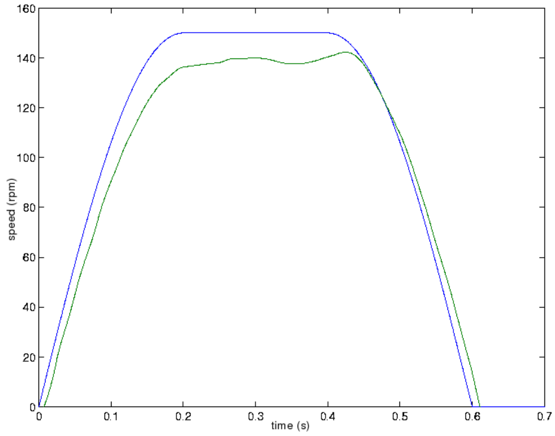

Figure 10: Open loop control: sinusoidal acceleration.

resulting:

$$T_f(t) = J\frac{-\Delta\omega}{\Delta t} \tag{6}$$

Using a polynomial interpolation of the speed, on obtaining an expression that, differentiated and substituted in 6, allows to calculate the friction torque curve.

In order to avoid discontinuities at reversing motion, functions have been joined with an exponential curve, obtaining:

$$T_f = \begin{cases} -(ae^{b|x|} + ce^{d|x|})(1 - e^{-\frac{|x|}{K}}) & \text{if } x < 0 \\ (ae^{b|x|} + ce^{d|x|})(1 - e^{-\frac{|x|}{K}}) & \text{if } x \geq 0 \end{cases}$$

its graph is shown in figure 7.

The overall diagram of the control is illustrated in figure 8.

RESULTS

Figure 9 and 10 show the effect of the predictive part of the control using two classical motion law. The corresponding torque set point is illustrated in figure 11. The explorative part of the control is a classical P-I loop: figure 12 highlights how the proportional constant K influences the system behaviour.

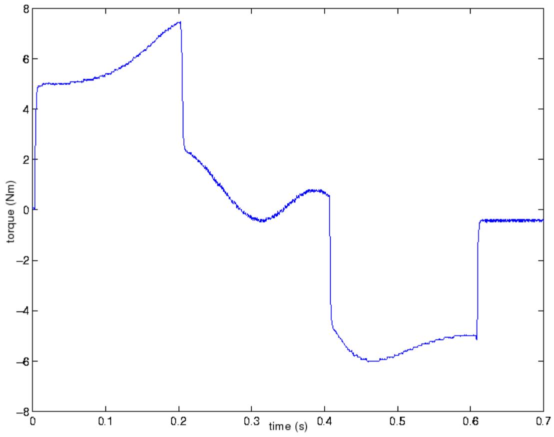

Figure 11: Open loop control: torque setpoint for fig. 9 law.

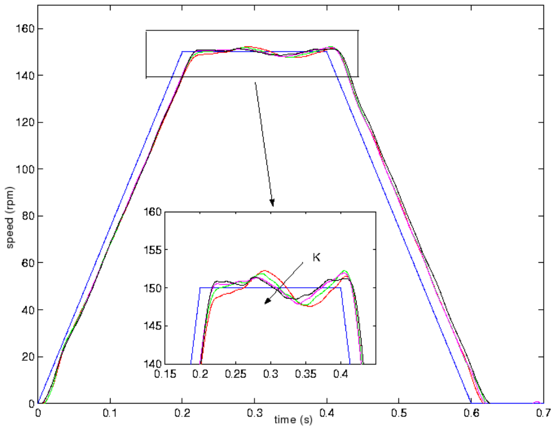

Figure 12: Control result for various proportional constant values.

The overall performance of the system can be evaluated by figure 13 that shows that the crank shaft satisfactorily follows a given setpoint for different speed curves.

The law of motion has been created with CamOMiLe language [4] that implements a kind of *Building Block Approach* [5].

The comparison of figures 14 and 15 allows to focus the difference between the torque setpoint loop adopted and a similar implementation but using the speed setpoint input of the Lenze driver. The last one is less regular and the motor appears to be less capable to follow high acceleration laws.

The system has been used for validating reduced harmonic content laws of motion [6] and proved to work properly [7] until 250 rpm speed.

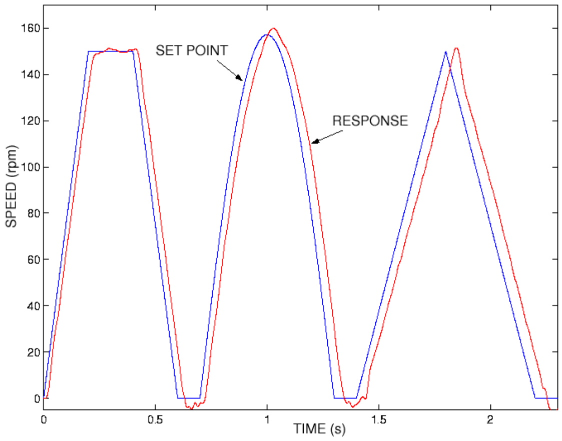

Figure 13: Control results: setpoint vs measured speed.

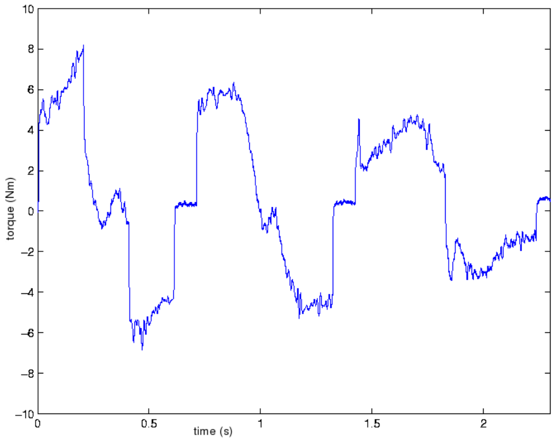

Figure 14: Yielded torque (torque setpoint).

CONCLUSIONS

Has been implemented a digital controller driving a four-bar mechanism with high alternate motion masses. The control uses a mixed explorative and predictive technique based on off-line model of weight, inertia and friction.

Particular care has been devoted to adjust an hybrid (analog-digital) system for the feedback signal acquiring.

The control proved to satisfactory be used to obtain electrical cams up to $250\ rpm$ average speed with sharp acceleration diagrams.

The responsiveness of the control permitted to run some test session devoted to verify advantages of motion law harmonic content reduction.

Using an obsolete Pentium III personal computer and an inexpensive, widely available asynchronous vectorial motor, ensures the achieved results can be considered significant for a wide range of industrial applications.

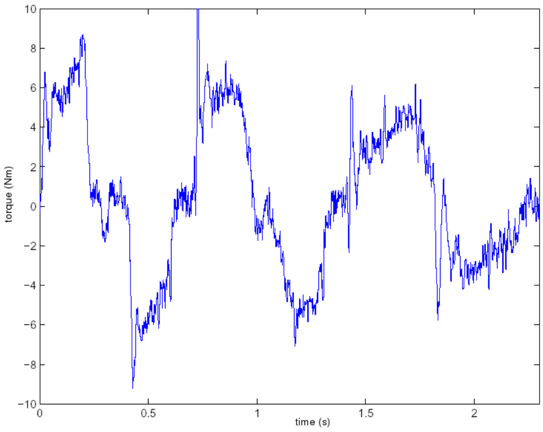

Figure 15: Yielded torque (speed setpoint).

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