On the vibration control of a flexible metallic beam handled by an industrial robot within an ARX-based synthetic environment

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Abstract. This study addresses the problem of vibration control of a flexible metallic beam which is transferred by an industrial robot. The control is designed in a special Matlab/Simulink synthetic environment that is founded on AutoRegressive with eXogenous (ARX) stochastic modelling of the robot-beam system through exclusively experimental data. Based on this, a simple closed-loop control system consisting of a feedforward typical Proportional-Integral (PI) controller and a feedback that enables the minimization of the induced force at the wrist of the robot is developed for beam vibration control. The data-based modelling of the robot-beam system allows for the precise design of the control system in offline mode, without interrupting normal production conditions, and achieves excellent performance in real time application.

Keywords: industrial robot, flexible beam, vibration control, PI controller, ARX modelling, system identification, force sensor

1 Introduction

A common, undesirebale, characteristic in the manipulation of flexible metallic beams by industrial robots is the caused vibrations at their free-end. In a production line this fact leads to longer cycle time and thus higher production cost, less precision in tasks like assembly and/or sliding of objects into slots as well as to reduced safety. The handling of such type of flexible objects is highly challenging and a proper control system should be capable of attenuating the stimulated vibrations at the free-end of a variety of beams very fast and without human intervention.

Chen and Zheng optimize robot's end-effector trajectory through open-loop vibration control of flexible beams with the use of a passive mechanism that is incorporated into the robot gripper [1]. This technique employs physics-based mathematical representations of the beam and the desired robot's end-effector trajectory. A fuzzy-based controller that eliminates the residual, undesirable, vibration at the free-end of a beam through active damping, is presented in [2]. Alternatively, the suppression of the residual vibration of a deformable linear object (DLO) which is presented in [3], is achieved through a force/torque sensor based method and a template matching technique. This is based on the period of the vibration that is determined through the embedded force sensor at the robot wrist while the DLO's stiffness is considered as known. On the other hand there are also techniques which are based on extra vision sensors on the robot for treating the problem [4]. Similar vibration control techniques are also employed for crane anti-sway problems [9]. Yet, for most techniques, the need for detailed physics-based models representing the flexible object and its interaction with the robot, the significant time period with the robot out of the production line for the design and tune-up of the control system and the set-up of additional, costly, equipment on the robot constitute important practical difficulties in their real time application.

This study aims at the development of a *synthetic environment* in which the problem of vibration control of a flexible beam that is transferred by a robot manipulator is effectively tackled overcoming the above difficulties. The cornerstone of this environment is the *A*utoRegressive with eXogenous (ARX) *stochastic modelling* of the robot-beam system dynamics based on actual measurements that can be acquired even under *normal production conditions*. Based on the obtained ARX model, a closed-loop vibration control system consisting of a typical feedforward Proportional Integral (PI) controller and a feedback that enables the minimization of the induced force at the robot wrist is designed and automatically tuned through an *offline* procedure within a synthetic (simulation) environment of high precision. This procedure is suitable for various types of robots and flexible objects avoiding the use of more involved physics-based models that necessitate intensive tuning based on actual measurements as well as it *minimizes* the robot idle time and the production line interruptions.

2 Problem Statement: the industrial robot, the beam and the experiments

The fast minimization of the vibrations caused at the free-end of a flexible metallic beam due to its rapid transfer by an industrial robot constitutes the general problem that is presently investigated (also see Fig. 1). This leads to the beam's availability without delay and with precision with respect to its position for the next step of a production process, as for instance, the beam's sliding in a slot.

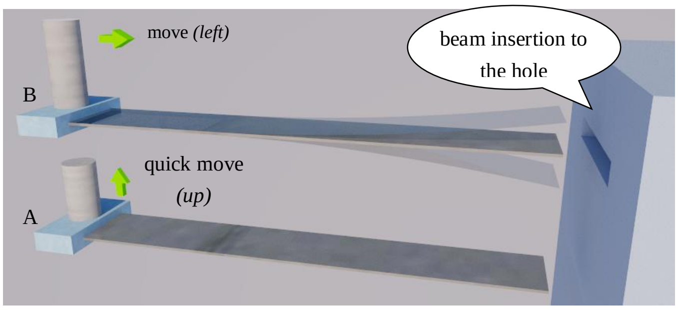

Fig. 1. Schematic representation of the investigated problem.

In this study, an Adept Cobra s800 manipulator with 4 DoF (Fig. 2) equipped with a force sensor (ATI Industrial Automation, Gamma 65/5, resolution 0.05 N, baud rate 38400 bps or 150 Hz) which is mounted on the wrist of the robot, is used. The manipulated structure is a solid aluminum beam with dimensions 1000mm×50mm×3mm (L×W×T), which is clamped to the robot gripper at the one end, while a lightweight accelerometer (PCB ICP 352C22) is mounted at the free-end for the monitoring of the vibration acceleration. It is noted that under normal operation only the force signal is used for the ARX modelling of the robot-beam system and the control design (see section 3), while the acceleration measurement is solely used for the estimation of an ARX model representing the beam in various simulations for the controller's performance assessment (see section 4).

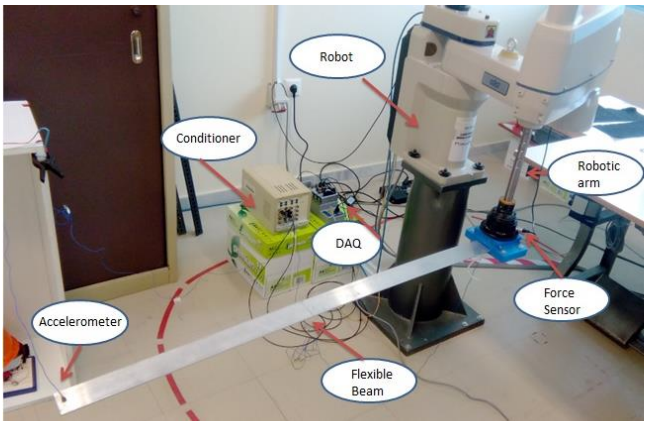

Fig. 2. The robot-beam system, the data acquisition (DAQ) unit with the signal conditioner and the accelerometer.

Multiple experiments have been initially performed with the robot-beam system in order to study its dynamics as well as to confirm experimental repeatability of the certain investigated robot action. Yet, the signals of a single experiment are used with the robot end-effector to execute a rapid vertical movement between point A and point B of short duration (~0.3 s) with maximum speed and acceleration inducing thus impulse-type excitation to the beam. More specifically, a signal of 3003 samples length (~20 s) is acquired with a sampling frequency of 150 Hz via the force sensor of the robot. The measured acceleration response signal at the free-end of the beam is driven through a signal conditioner (PCB F482A20) into the data acquisition (DAQ) system (National Instruments 9234 module) with a sample frequency of 1651.6 Hz. All signals are normalized via sample mean subtraction and division by its sample standard deviation while the acceleration measurement is additionally filtered via a digital Chebyshev Type II filter (6th order, cut-off frequency = 75Hz) and resampled at 150Hz.

3 ARX-based synthetic environment

The synthetic environment consists of: (i) The development of an ARX model representing the *robot-beam system dynamics* within the closed-loop control system and, (ii) the *offline* design of a typical PI controller.

3.1 ARX based modelling of the robot-beam system

The stochastic modelling of the robot-beam system dynamics is achieved by using the given, trapezoidal-type, velocity to the robot arm and the force measured at the wrist of the robot as the input-output signals in an AutoRegressive with eXogenous (ARX) input modelling procedure. Thus, a single-excitation single-response data-based ARX transfer function of the following form is obtained [5, pp. 81-82]:

$$y[t] + \sum_{i=1}^{\mathrm{na}} a_i y[t-i] = \sum_{\mathrm{i=0}}^{\mathrm{nb}} \mathrm{b_i} x[\mathrm{t-i}] + e[t], \qquad e[t] \sim \text{ iid } N(0, \sigma_e^2) \tag{1}$$

with t = 1, …, N designating the normalized discrete time, x[t], y[t] the force and acceleration response signals, respectively, na, nb the corresponding AR and X model orders, a_i, b_i the i-th AR and X parameters, e[t] the model residual (one-step-ahead prediction error) that is a white Gaussian zero-mean with variance σ_e^2 sequence and iid stands for independent identically distributed. The estimation of an ARX(na,nb) model involves parameter and structure estimation. The estimation of the parameter vector $\theta = [a_1\ a_2\ ...\ a_{na} \mid b_0\ b_1\ ...\ b_{nb}]^T$ is obtained based on a Least Squares (LS) estimator [5, pp. 203-207]. Model structure estimation, referring to the determination of the AR and X orders, is achieved by fitting increasingly higher order models to the signals until no further improvement is observed. Improvement may be judged via the combination of typical model order selection criteria, such as the Bayesian Information Criterion (BIC) and the RSS/SSS (Residual Sum of Squares / Signal Sum of Squares) criterion [5, pp. 498-514]. Final model acceptance is based on formal verification of the model residual uncorrelatedness (whiteness) hypothesis [5, pp. 512-513].

Using the backshift operator $\mathcal{B}$ ($\mathcal{B}^i x[t] = x[t-i]$) the main expression of the discrete ARX model may be written in a transfer function form as:

$$A[\mathcal{B}]y[t] = B[\mathcal{B}]x[t] + e[t] \Rightarrow y[t] = \frac{B[\mathcal{B}]}{A[\mathcal{B}]} x[t] + \frac{1}{A[\mathcal{B}]} e[t] \tag{2}$$

with $A[\mathcal{B}] = 1 + \sum_{i=1}^{na} a_i \mathcal{B}^i$ and $B[\mathcal{B}] = \sum_{i=0}^{nb} b_i \mathcal{B}^i$.

The identification of an ARX model for the robot-beam system representation is based on the measured velocity (trapezoidal-type) - force signals of N = 3003 samples length (~20 s) and parameter estimation is based on Ordinary Least Squares with QR implementation [5, pp. 318-320]. Fig. 3 depicts the BIC and the RSS/SSS criteria for ARX models of increasing orders (n = na = nb) in the range of 2 up to 50 which reach a plateau for the model $\mathcal{M}1$: ARX(33,33).

ARX(33,33) model validation is achieved by testing the model residual uncorrelatedness (whiteness) through a standard procedure with the normalized autocorrelation function mostly lying within the 99% confidence intervals (risk level of 1%) as shown in Fig. 4(a) indicating white residuals. In addition, the model one-step-ahead prediction of the force at the robot wrist is excellent as it is shown in Fig. 4(b) for a signal segment of ~0.9 s (not used for model estimation). Thus, the ARX(33,33) model is used in the following for representing the robot-beam dynamics in the closed-loop control system of the synthetic environment.

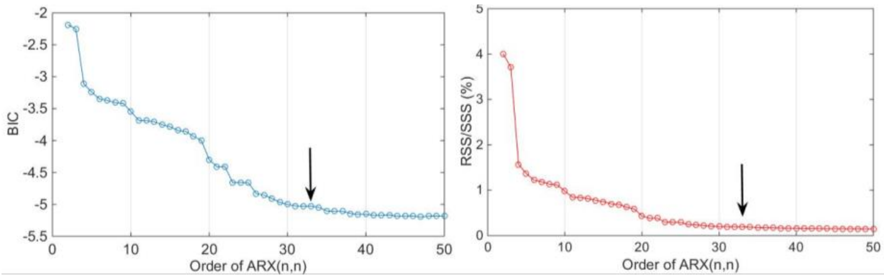

Fig. 3. BIC and RSS/SSS criteria for increasing model orders ($n = na = nb$).

3.2 PI - based vibration control

Fig. 5 depicts the Proportional-Integral (PI) - based closed-loop control system that is designed for the attenuation of the vibration acceleration response at the free end of the beam based on the minimization of the oscillatory force at the robot wrist. The controller design is achieved through the *offline* procedure that is described below where the $\mathcal{M}_1$ model represents the actual robot-beam system. Thus, a position control command (e.g. move from point A to point B; see Fig. 1) - carried out by the robot internal controller - is given to the robot-beam system and the force at the robot wrist is compared through the feedback with the reference zero value. The discrete PI controller is of the Backward Euler form [6]:

$$G(z) = K_P + K_I \frac{T_S\, z}{z-1} \tag{3}$$

where K_p, K_I are the corresponding gains of the Proportional and Integral parts of the controller, z designates z-transform and T_s (= 1/150 s) is the sampling period.

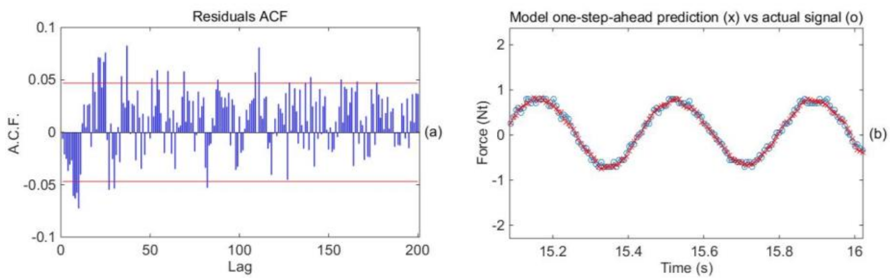

Fig. 4. ARX (33,33) model validation: a) residual autocorrelation (blue bars) and confidence intervals (red solid lines; risk level of 1%); b) force one-step-ahead predictions.

The controller receives the error signal and supplies the system with the necessary velocity that leads to the attenuation of the vibration acceleration at the beam's free-end. It is noted that although more advanced controllers were investigated a typical PI was found adequate for the fast minimization of the force preserving reasonable overshoot as shown in the next section (see Figs. 8, 9). Once the controller tune-up procedure has been completed based on the typical Matlab/Simulink PID Controller block dialog [7], its real time application may be accomplished. Before this, its further assessment under various system operating conditions may be performed (see section 4).

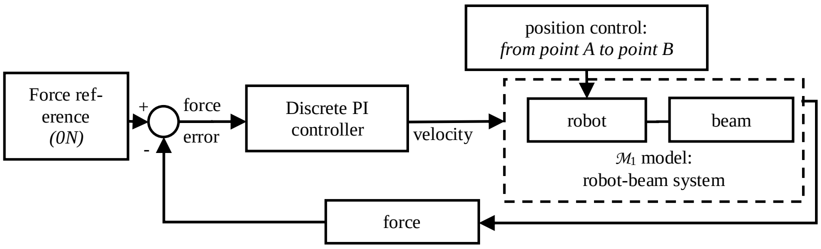

Fig. 5. Block diagram of the synthetic environment.

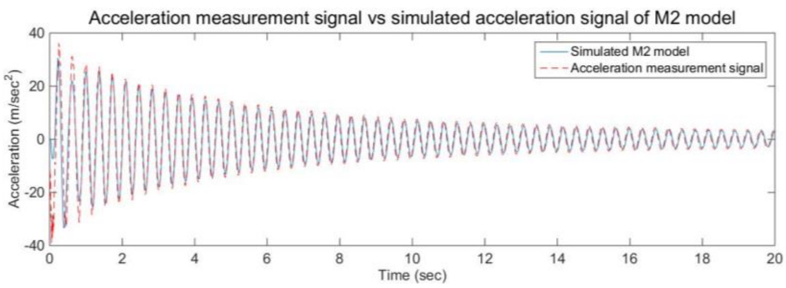

Fig. 6. Actual acceleration response signal at the free-end of the beam and its ARX(4,4) model based simulation.

4 Vibration control simulation and experimental results

An additional ARX model representing the beam dynamics is obtained based on the procedure that is described in subsection 3.1. The measured force at the robot wrist is now used as the input (beam excitation) to the model while the acceleration response at the free-end of the beam as the output. Thus, an $\mathcal{M}_2$: ARX(4,4) model is obtained and it is used only for the simulation of the beam vibration acceleration response. Such type of models may be used instead of approximated physics-based models for any type of flexible object achieving thus more realistic simulations. Fig. 6 depicts the measured acceleration response at the free-end of the beam and the simulated by the ARX(4,4) model. The excellent agreement is evident verifying the accurate representation of the beam's dynamics through the obtained model.

Based on this, the tuning of the PI controller within the synthetic environment (left part of Fig. 7) is initially activated. Once the PI controller gains have been obtained, the synthetic environment is connected with model $\mathcal{M}_2$ and the beam vibration acceleration response at its free-end is simulated for 20 seconds with and without the incorporation of the PI-based control system. Fig. 8 depicts simulation and experimental[1] results for the vertical acceleration at the free-end of the beam where the effect of the control system is evident as in less than 4 seconds the induced acceleration becomes almost zero. The agreement between experimental and simulated results is remarkable and confirms the precise design of the control system within the synthetic environment.

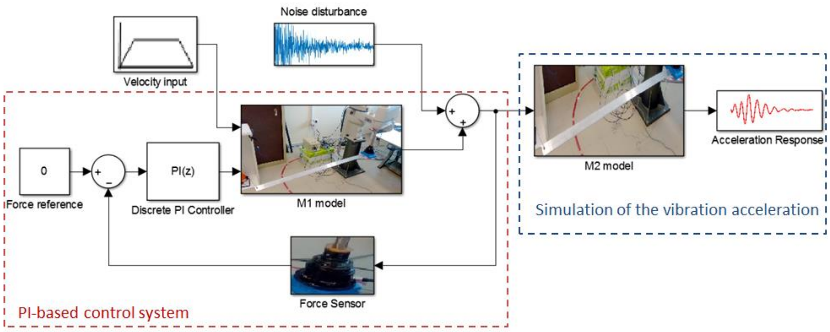

Fig. 7. Schematic representation of the simulation procedure.

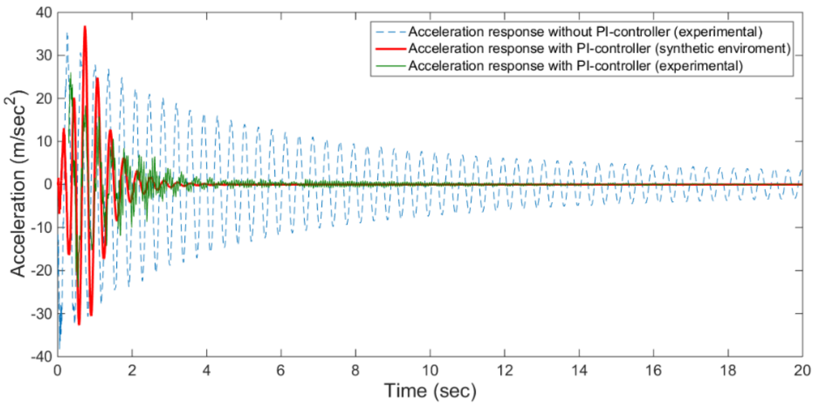

Fig. 8. Acceleration response at the free-end of the beam with and without the PI-based control system based on simulation and experimental results.

Two additional simulations are performed with the control system activated while noise-corrupted force measurements are transferred by the feedback. The force signal is significantly corrupted by non-stationary uncorrelated noise at 10% and 20% noise-to-signal (N/S) local levels, in the standard deviation sense [8]. Fig. 9 depicts the acceleration response at the beam's free-end with the force signal contaminated by measurement noise as well as without noise. As it is obvious the control system's performance is slightly affected by the added noise and suppress rapidly the vibration acceleration

[1] https://youtu.be/QBJ-nUtPhys (vibration of the beam without control)
https://youtu.be/fAVysBIFMYM (PI-based vibration control of the beam)

although the PI controller is not re-tuned for the cases of added noise, indicating thus its robustness even under noisy industrial conditions.

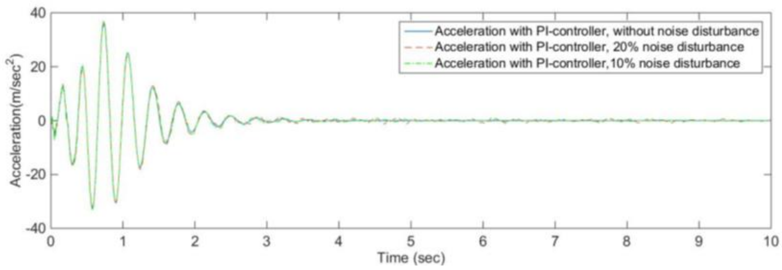

Fig. 9. PI-based vibration control of the acceleration response at the free end of the beam.

5 Conclusions

The problem of vibration control of a flexible metallic beam, rapidly transferred by an industrial robot, was tackled in a novel Matlab/Simulink synthetic environment. This was based on ARX stochastic modelling of the robot-beam system dynamics and a closed-loop control system with a typical PI controller. All procedures were performed offline with even a single experiment with the actual robot-beam system being adequate for the design of the control system minimizing thus the interruptions to the robot normal production activity. The obtained results through simulations and experiments with the robot-beam system demonstrated that the vibration acceleration at the free-end of the beam was attenuated very fast through the control of the induced force at the robot wrist in all considered cases. Furthermore, the excellent agreement between the simulation and experimental results indicated the precise design of the control system within the synthetic environment.

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