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Research article

A generic method for servo tuning based on dynamic modeling and task description

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A B S T R A C T

In robotics or machining, task quality is strongly linked to servo tuning. Indeed, geometrical and dynamic behavior of the mechanical structure could be degraded when a coarse tuning is achieved. Several P/PI or PID tuning methods can be used but generally uncorrelated with industrial context or mechanical considerations. In this paper, we propose a generic tuning method based on dynamic modeling of the mechanical structure and model parameters experimental identification. Therefore, the proposed tuning is adapted to the real dynamic behavior of the mechanical structure under task load while being sufficiently simple to be implemented in an industrial context. The method is illustrated on a vertical axis.

1. Introduction

Control of industrial systems is a well-known and active field of research works. Thus, PID controller gain tuning has been already treated many times by the automatic control community [1–6]. Many methods for gain tuning are employed from time domain tuning to frequency domain analysis, dealing with stability, robustness and digital control effects. However, in industrial context, systems are mainly tuned by empiric methods based on the experts skills without any modeling or computation. Thus, improvements are still expected [7]. Furthermore, there is an important gap between academic theoretical approaches and industrial needs increases.

For this work, the main applications are machine-tool or robotics feed drive based on P/PI position control. Thus, the classical tasks requires geometrical accuracy (steady state) and dynamic accuracy (tracking error) under high loads sollicitations. The global performances are thus linked to the mechanical behavior of the machine structure and servo tuning loaded with task sollicitations. On the one hand, automatic control works are based on high level control theory such as genetic algorithms [8,9], fuzzy control [10], robust control theory with classical models (first or second order with delay) [5,11,12]. These methods requires a high level of skills in modeling and computation. The theoretical concepts are often tested on dedicated controller in ideal conditions. Therefore, the versatility and adaptability to an industrial context could be questionable. On the other hand, mechanics community works on modeling and identification in order to simulate tasks or to plan trajectory generally without controller architecture considerations [13–15]. Last but not least, Electrical engineering works deal with actuators and drive tuning without task load considerations [16,17]. Thus, the task quality realized by a control system can be improved by a tuning method which takes into account control scheme, mechanical behavior of system structure and task load for a given technology of actuators. For example, in Ref. [6], the tuning is obtained with simple considerations. The PID tuning aims an over-damped second order with time delay system behavior. The rules used for PID tuning computation are applied to general systems with approximations and empirical considerations. However, the work focuses on general application and the tuning performances criteria are not adapted to machining or robotic tasks.

Our approach is to propose a tuning methodology based on mechanical modeling and model parameter identification coupled with simple theoretical tuning dealing with task quality. The aim is to develop a tuning method which takes into account the mechanical structure behavior under task load and the technological structure of the actual servo-drives to guarantee a task quality and a short implementation time. Moreover, our method should be simple to implement in an industrial context without controller modifications.

This article is organized as follows: a first part deals with the proposed tuning thus presenting method. A second part presents the experimental validation on a vertical axis.

2. Proposed tuning method

The proposed tuning method is based on dynamic modeling of a

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mechanical axis and control schemes analysis. The tuning aim is to control the time response characteristics with regards to the task specificity. Thus, dynamic parameters are identified to perform a tuning adapted to the real mechanical behavior of the axis during the task realization. This section presents the mechanical modeling of a classical axis, the proposal of speed and position loop tuning of an industrial control scheme and finally the dynamic parameters identification method.

2.1. Modeling

Dynamic modeling of a single servo-axis is well-known. The actuator torque is linked to the axis motion by the following equation:

$$\Gamma = J\ddot{q} + F_v\dot{q} + F_s\operatorname{sign}(\dot{q}) + Q \tag{1}$$

where:

- Γ is the actuator torque
- J is the mechanical structure system inertia expressed along the actuator axis
- F_v is the viscous frictions parameter
- F_s is the dry frictions parameter
- Q is the torque generated along the actuator axis by part system weight

Inertia parameter and weight could generally be estimated with CAD. Friction parameters are estimated with a theoretical approach or simply neglected.

2.2. Servo control scheme

The control scheme of an industrial servo-axis is based on a P/PI loop with linear speed and acceleration feed-forward, and gravity and dry frictions compensation (see Fig. 1).

Hence, the controller tuning parameters are:

- K_p: the position loop proportional gain
- K_v: the speed loop proportional gain
- K_i or τ_i: the speed loop integral gain or time constant
- *FFv*: the speed feed-forward gain
- *FFa*: the acceleration feed-forward gain

The classical empirical tuning method consists in:

1. Setting the inertia parameter to the calculated theoretical value
2. Speed loop manual tuning in time or frequency domain in speed control mode with unloaded axis
3. Gravity compensation tuning with theoretical value
4. Position loop manual tuning with unloaded axis
5. Speed and acceleration feed-forward activation (no dedicated tuning)
6. Filter cut-off frequency tuning in case of vibrations or audible noise
7. Manual tuning of dry frictions compensation if needed
8. A validation test with loaded axis and tuning refining if needed

This tuning method imposes many tests and is thus quite long to achieve. For example, for a machine tool, the tuning of one axis locks the machine and the technical staff during one day in general.

The proposed tuning method is based on the axis dynamic model and aimed time response characteristics such as settling time, maximal tracking error or damping ratio. The tuning set-up should be faster and more sustainable than manual tuning. Moreover, it should require an easier implementation than high-level theoretical tuning based on signal and robust control theory coupled with modification of the control schemes.

2.2.1. Speed loop tuning

Referring to Eq. (1) and assuming that dry frictions and gravity are well compensated (or have no influence on the end-effector behavior), the transfer function of the axis ($H(s)$ in Fig. 1) can be expressed as:

$$H(s) = \frac{1}{Js + f} \tag{2}$$

A simple pole compensation is thus applied for the speed loop tuning:

$$K_v = \frac{3J}{tr_5} \tag{3}$$

$$\tau_i = \frac{J}{F_v} \tag{4}$$

$$K_i = \frac{K_v}{\tau_i} \tag{5}$$

$$= \frac{3F_v}{tr_5} \tag{6}$$

where tr_5 is the tuned five percent settling time of the speed loop which should be fixed with regards to the axis dynamic performance and mechanical frequency behavior.

Therefore, the speed loop function transfer can be expressed as:

$$H_v s = \frac{1}{\frac{tr_5}{3}s + 1} \tag{7}$$

2.2.2. Position loop tuning

Hence, the position loop function transfer can be expressed as a simple second order function:

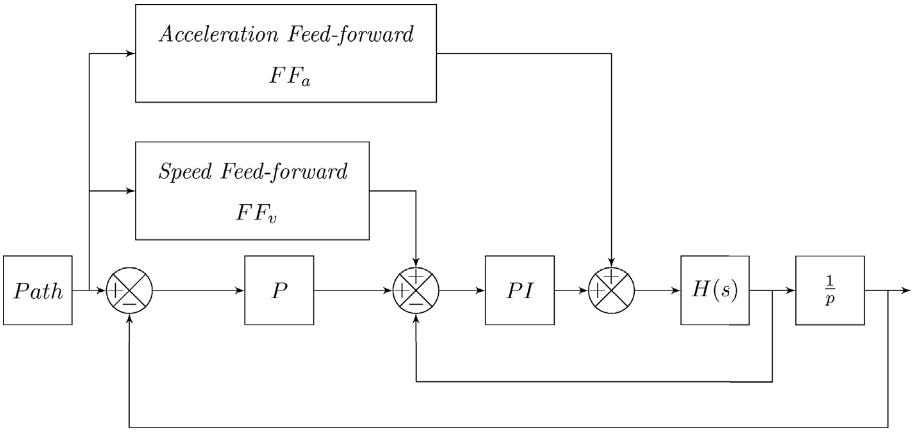

Fig. 1. Control scheme of an industrial servo-axis [15,18].