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Hardware-in-the-Loop Experiments in Presence of Delay

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Abstract

A widely used tool of engineering research and development is the hardware-in-the-loop (HIL) experiment. Instead of building the full prototype of a developed machine, only its most critical parts are constructed physically, while the rest of the machine is emulated by means of actuators, sensors, and digital control in between. If the mathematical model of the rest of the machine is available, the control unit provides a realistic environment for the physically constructed test part. The control, however, introduces digital effects into this system which is originally continuous. From dynamical view-point, the most relevant digital effects are the appearances of delay and zero-order-hold (ZOH). The paper compares the nonlinear dynamics of the real system and the one constructed by means of the HIL experiment. The two systems are compared from stability and nonlinear vibrations view-point in case of a brake system where stick-slip phenomenon occurs. The limitations of HIL experiments are identified by means of Hopf bifurcation calculations, numerical simulations and dynamic measurements carried out on the corresponding experimental test rig.

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1. Introduction

There is a set of historical dynamical problems in engineering that causes permanent difficulties in the design of certain machines, machine parts. One common feature of these systems is that the desired steady-state behavior of the machine may become unstable at certain speed ranges. The most critical cases are when the loss of stability is dynamic, namely, vibrations occur at the limit of stability. In mathematical terms, these are called Hopf bifurcations. What makes this kind of loss of stability even worse is the presence of subcritical Hopf bifurcation, that is, when unstable oscillations appear close to the the otherwise stable equilibria. In these cases, the system may perform large amplitude oscillations for some finite perturbations of the stable equilibria, which makes the system behaviour quite unpredictable.

The above described critical dynamic behavior appears typically in systems with time delay. Machine tool vibrations[1], wheel shimmy[3], robotic position control[4] or even traffic dynamics[5] belong to this set of problems. It is a rule of thumb that increasing delay tends to destabilize the steady-state dynamics. It can be also observed, that in most of the cases, the bifurcations are also destabilized in the sense that subcritical Hopf bifurcations occur at the

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stability limits. Further bifurcations lead to the birth of further unstable periodic motions (in mathematical terms, limit cycles), even unstable quasi-periodic motions (tori) appear, and in this jungle of unstable motions, chaos can often be observed. It is an obvious choice to use hardware-in-the-loop (HIL) experiments during the development of these systems.

2. HIL tests in engineering development

HIL tests [7] (also called real-time substructuring [8]) are widely used in the engineering research and development in order to reduce the costs of the development. There are two basic scenarios for this. The developed critical part of the machine is constructed physically, but instead of fitting it to the machine and going to field tests, they are installed between sensors and actuators, and the signals of the sensors are fed back to the actuators via a controller that emulates the behavior of the rest of the machine. In these cases, the rest of the machine must have a reliable and validated mathematical model loaded into the controller. Another possibility is that the developed critical part having a still approximate mathematical model is substituted by a control loop and the rest of the machine is there physically. This case may also be software-in-the-loop (SIL), which is useful to test and find the best models of the part under development, or to optimize its characteristics, and so on. Both approaches have the same basic idea from mechanical view-point.

3. Stick-slip performance in a HIL test

Due to the infinite dimensional nature of time-delay systems, the investigation of the above mentioned mechanical engineering problems is difficult either theoretically or experimentally by means of HIL tests. This is the reason why a classical non-delayed dynamic problem, the stick-slip phenomenon [9] was selected to study the nonlinear dynamic behavior of the systems when the digital effects existing in the control loop of the HIL tests are considered to be relevant. While the stick-slip phenomenon has well studied low (even single) degree-of-freedom (DoF) models, it presents a dynamic loss of stability below a critical speed, and the corresponding Hopf bifurcation is subcritical in the presence of mixed viscous and dry friction between the contact surfaces sliding on each other.

The goal of this paper is to collect information about the deviations of the dynamic behavior of the HIL test and the real stick-slip phenomenon. The relevant digital effects are the time delay and the zero order hold (ZOH) that are introduced by the sampling effect of the digital controller. The more complex the model of the emulated machine part is, the more time needed for the controller to do the necessary calculations and to command the actuators, that is, the larger the time delay is. Even if this delay is in the range of milliseconds only, the stability limits and the corresponding bifurcations may change even qualitatively, which is an essential issue when the HIL test is designed and the necessary sensors, controller and actuators are selected.

The stick-slip phenomenon can be described by a 1 DoF damped oscillator subjected to the so-called Stribeck force:

$$\ddot{x}(t) + 2\zeta\omega_{\mathrm{n}}\dot{x}(t) + \omega_{\mathrm{n}}^2 x(t) = F_{\mathrm{Str}}(\dot{x}(t_j - \tau))/m\,, \quad t \in [t_j, t_j + \tau), \quad t_j = j\tau, \quad j = 1, 2, \ldots\,. \tag{1}$$

$$F_{\mathrm{Str}}(\dot{x}) = \left(C + (C_0 - C)\mathrm{e}^{-c_{\mathrm{v}}|v_0 - \dot{x}|}\right)\mathrm{sgn}(v_0 - \dot{x}) + b_{\mathrm{Str}}(v_0 - \dot{x})\,, \tag{2}$$

where the HIL test can run with sampling time τ. The compiled experimental setup is presented in Fig. 1, where the control part emulated the Stribeck force.

4. Discrete nonlinear map

To analyse the bifurcation structure due to digital effects, we neglect the damping coefficient b of the physical system. This also allows us to derive compact analytical formulae. Notice that the equation of motion (1) is a linear differential equation with a constant inhomogeneity for every interval $t \in [t_j, t_j + \tau)$. Solving this equation for any interval, and writing the state of the system at time $t_j + \tau$ as the function of the state at t, the system can be transformed to a nonlinear discrete map of the variable $\mathbf{x}_j = \left[x_j,\ \dot{x}_j,\ \Delta F_{\mathrm{Str},j-1}\right]$, where the third coordinate is a normalized actuator