Control and Cybernetics

vol. **30** (2001) No. 3

Book review:

Lyapunov-Based Control of Mechanical Systems

by

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Roughly speaking, in control theory one can distinguish two main classes of problems and considerations. The first covers theoretical problems while the second pertains to applied problems. The book reviewed belongs to the second class. Both discrete and rather simple distributed parameter systems are investigated in it. The book has one basic feature: the authors consequently apply Lyapunov-type stability analysis to all the problems considered.

The book consists of a comprehensive Introduction, seven chapters and four appendices.

In Introduction (Chapter 1) the contents of the book is outlined.

The second chapter is concerned with the control of one-degree of freedom systems in the presence of friction. Two mechanical systems are studied. The first of them is of the following form (the reduced-order friction model)

$$M\ddot{q} + B\dot{q} + [F_c + F_s \exp(-F_\tau \dot{q}^2)\,\mathrm{sat}(\dot{q}) = \tau] \tag{1}$$

where $q(t), \dot{q}(t), \ddot{q}(t) \in R$ represent the position, velocity, and acceleration, respectively; M denotes the constant inertia of the system; B denotes the constant viscous friction coefficient; F_c denotes the Coulomb friction-related constant; F_s denotes the static friction-related constant; F_τ is a positive constant corresponding to the Stribeck effect; and $\tau(t) \in R$ is the control input. The saturation function $\mathrm{sat}(\dot{q})$ is properly defined and may be discontinuous.

The control objective is to achieve position/velocity tracking or regulation despite the uncertainty of the parameters. The position and velocity tracking error signals are defined as follows:

$$e(t) = q_d(t) - q(t), \;\; \dot{e}(t) = \dot{q}_d(t) - \dot{q}(t), \tag{2}$$

where $q_d(t)$ is the desired position trajectory. The filtered tracking error is defined by

$$r(t) = \dot{e}(t) + \alpha e(t), \tag{3}$$

where α is a positive control gain. The authors discuss several possible condesired state is achieved as $t \to \infty$. The second system studied is a full-order friction model of the form

$$M\ddot{q} + B\dot{q} + T_L(q, \dot{q}) + \chi(\dot{q})z + f(\dot{q}) = \tau \tag{4}$$

Here the auxiliary functions $\chi(\dot{q})$ and $f(\dot{q})$ are properly defined, and $z(t)$ denotes the unmeasurable internal friction state. Partial-state feedback, position-tracking controllers for system (4) are presented along the lines, in mathematical sense, similar to the model (1). The experimental setup used to implement the controllers, the same for both systems, was briefly described and the results were presented in the form of figures, for depiciting, instance, position tracking errors and parameters estimates.

The third chapter constitutes an extension to the n degrees-of-freedom, rigid mechanical system. More precisely, considerations are focussed on the full-state feedback (i.e., position and velocity are available for feedback) control problem for such a general, nonlinear system with parametric uncertainty. The system studied is called MIMO (multiple-input, multiple-output) and has the following form

$$M(q)\ddot{q} + V_m(q, \dot{q})\dot{q} + G(q) + F_d\dot{q} = \tau$$

where $q(t), \dot{q}(t), \ddot{q}(t) \in R^n$ and have the well-known meaning; $M(q) \in R^{n\times n}$ represents the system's interia matrix, $V_m(q, \dot{q}) \in R^{n\times n}$ represents the centripetal-Coriolis matrix; $G(q) \in R^n$ denotes the gravity effects; $F_d \in R^{n\times n}$ is the constant, diagonal, positive-definite, viscous friction coefficient matrix; and $\tau(t) \in R^n$ stands for the control input vector.

Both standard and desired trajectory-based adaptive controls were investigated, as usual by introducing the appropriate Lyapunov functions. Stability is achieved as time tends to infinity. Also, the modular adaptive control design of the one degree of freedom system was extended to MIMO mechanical systems. The calculations and experiments were performed for a two-link, direct-drive, planar robot. It was shown that the least squares controller constitutes an advantage over the GR controller; the latter is simply a filtered tracking error-based, gradient update law.

The position tracking controllers presented in the previous chapter required full-state feedback (FSFB). In other words, the control implementation required the measurement of the position and velocity of the mechanical system. Chapter 4 addresses the problem of position tracking under the constraint of minimizing the sensor count, i.e. elimination of velocity measurements. Consequently, the authors investigate the means of constructing the velocity signal surrogates for use in closed-loop, position tracking control strategies, i.e., output feedback (OFB) controllers. Three solutions to the OFB tracking control problems are presented. The first result is a model-based observer-controller that guaranand the position tracking error. The second result is a linear filter-based adaptive controller that ensures semiglobal asymptotic position tracking while compensating for unknown system parameters. Finally, a nonlinear filter-based, adaptive control is developed that produces global asymptotic position tracking similarly as in the previous chapter. The illustrative examples concern the experimental implementation of the observer-controller on the two-link, rigid robot manipulator.

Chapter 5 opens the study of deformable systems. More precisely, the control of linear and nonlinear strings and cables is investigated. The dynamic model for the actuator-string system comprises the boundary control force.

Two types of control law are studied: (i) the model-based control law (an *exponentially* stabilising controller) which requires exact knowledge of some of the system parameters, (ii) the adaptive control law which compensates for constant parametric uncertainty while asymptotically stabilising the string displacement. An experimental setup is briefly described and experimental results were presented in the form of plots. These results pertain to both types of controllers. Similar control strategies were employed for a distributed cable model. In space structures, flexible link robots, helicopter rotor/blades, turbine blades, etc., the flexible elements can be modelled as a beam-like structure. Two such beam models are considered in Chapter 6.

The first model is the classical Euler–Bernoulli beam theory where the rotory inertia of the beam is neglected. The second model is more accurate; it is the Timoshenko beam model where both the rotary inertial energy and the deformation of the beam due to shear are taken into account. For both models only cartilevered beams have been investigated. For both beam types boundary control strategies were developed with actuator dynamics at the free end-point of the beams. Again, as previously, the model-based control law and the adaptive control law were elaborated. Possible extensions were suggested and the results of simulation were also provided.

In the last chapter three different engineering applications of fexible mechanical systems are given. The first application concerns a vibration control system that uses two actuators to regulate the displacement in an axially moving string. The remaining two applications pertain to flexible link robot arm and flexible rotor system. In all these three cases the procedure is similar: the authors develop model-based control laws and adaptive control laws. Also, experimental setups and results are presented. Similarly to the previous-sections, the proofs of controllability theorem are based on Lyapunov-type functions.

Three appendices useful in applications of Lyapunov-based methods, and control programs complete the book. Nevertheless, the book is not quite self-contained. For instance, the reader not familiar with LaSalle's invariance principle has to refer to an appropriate book. The list of references is not excessively comprehensive. On the other hand, though, each chapter is accompanied by the Notes where a brief literature overview is given. Among abundant literaclass of systems described by ODE and PDE. The book addresses to researchers and professionals in the areas of systems, controls and robotics. It successfully complements other available books on controllability and stabilization.

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M.S. de Queiroz, D.M. Dawson, S.P. Nagarkatt and F. Zhang: *Lyapunov-Based Control of Mechanical Systems*. Birkhäuser Verlag, Boston–Basel–Berlin, 236 pages, 2000. ISBN 0-8176-4086-X. Price: CHF 128.– (hardcover).