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Application of Model Reference Adaptive Control to Industrial Robot Impedance Control

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Abstract. The paper deals with the application of model reference adaptive control to robot impedance control, which is actually a technique of steering the end-effector on a prescribed path and satisfying a prescribed dynamic relationship between the force and the end-effector position. Due to unknown parameters of the environment (stiffness, exact position), a model reference algorithm is proposed which differs from classical algorithms in its method of excitation. The results of the proposed procedure are illustrated by implementation on the ASEA IRb 6 industrial robot.

Key words: industrial robots, robot impedance control, model reference adaptive control, constrained motion.

1. Introduction

Model reference adaptive control, an explicit adaptive technique, has been very attractive from the very beginning of adaptive control era. The basic idea of the method is to specify a reference model involving the desired performances of the basic loop consisting of a controlled process and a classical controller. Its main applications are in the field of the tracking control, where the plant output is supposed to track a reference trajectory. However, in industrial practice, such as robot control, problems are met which do not correspond to the classical applications of model reference adaptive control. The purpose of this paper is to describe one such application, the adaptive control of an industrial robot with the end-effector contacting the environment.

In the basic control loop represented by an *impedance controller*, the force is regulated by controlling the position and its dynamic relationship (mechanical impedance) with the contact force. The pioneering work on impedance control was published by Hogan in [4]. In this work a second-order mass-spring-damper system is used to specify the target dynamics; however, simpler models, such as pure stiffness or combination of dampening and stiffness, can also be used [1, 11]. In this manner the basic equation of the second-order dynamic relationship between the end-effector position X and the contact force F is given by:

$$F = \mathbf{M}(\ddot{X}_R - \ddot{X}) + \mathbf{B}(\dot{X}_R - \dot{X}) + \mathbf{K}(X_R - X), \quad (1)$$

where the diagonal matrices **M**, **B** and **K** contain the impedance parameters along Cartesian axes representing the desired inertia, damping and stiffness of the robot, respectively. The X_R is the steady state nominal equilibrium position of the end effector in the absence of any external forces. As X_R is software specified, it may, during the contact with the environment, reach positions beyond the reachable workspace or inside the environment.

On the other hand, industrial robots are in general position-controlled with independent joint controllers and kinematic software joining them into a single entity. The unavailability of an adequate robot model and, from the hardware point of view, control system with no access to direct motor current (torque) control, imply the usage of force feedback to modify the reference position commands. The resulting position-based impedance control scheme consists of an inner/outer feedback loop configuration. The inner loop represents the non-modified position robot controller, while the outer loop uses a force feedback signal to modify the inputs to the position servo and at the same time to satisfy the impedance dynamic equation.

Several studies analyzed the performance of position-based impedance controllers [2, 7]. Volpe and Khosla [10] have made a theoretical and experimental comparison of the explicit force and impedance control methods. They showed that an impedance controller has an algebraic structure similar to the proportional gain explicit force controller with feedforward. Furthermore, this correspondence becomes exact when the position feedback is constant, which occurs when the robot is contacting a stiff environment. As the industrial robot applications in most cases involve interactions with rigid objects, the introduction of a reference force signal into the impedance control scheme is possible. Thus, one of the major shortcomings of the impedance control – indirect specification of the desired contact force – can be overcome.

The paper is organized as follows: first the classical position-based impedance control is introduced in Section 2, where the necessity of adaptive control is also stressed. In Section 3 the adaptive controller is presented and the differential equation describing the basic loop of the adaptive system is rewritten in a form suitable for model reference adaptive control. This equation differs from the classical model reference approach in the fact that there is no reference signal present. The only excitation of the adaptive system is the initial condition due to zero force prior to impact. The implementation of the adaptive control system on the ASEA IRb 6 robot is presented in Section 4.

2. The Basic Loop – Position-based Impedance Control

Controlling the robot mechanical impedance by generating the reference position trajectory of the existing positional controller has been recognized as a practical approach to industrial robot impedance control. When applying the contact force, the reference position is to be chosen inside the environment and cannot be reached

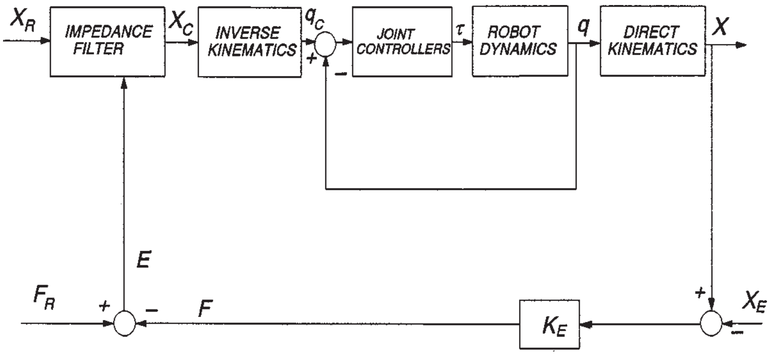

Figure 1. Position-based impedance controller.

by the robot because of the geometrical constraints. The positional controller responds to the resulting error in position with additional actuator current and exerts a force to the environment.

The class of position-based impedance controllers is usually focused on the most frequent robot contact applications, interactions with rigid objects. When the robot is contacting a stiff environment, the terms $\ddot{X}_R$ and $\dot{X}_R$ of the impedance Equation (1) become approximately zero and, thus, the impedance equation is reduced to

$$-F = \mathbf{M}\ddot{X} + \mathbf{B}\dot{X} + \mathbf{K}(X - X_R). \tag{2}$$

In this case the term $\mathbf{K}X_R$ acts simply as a scaled reference position and can be directly replaced by the reference force signal [10]. Moreover, following the idea of Seraji and Colbaugh [8], who were using the reference force input for specifying the desired contact force and the reference position input for improving the controller performance, the position-based impedance controller depicted in Figure 1 can be designed.

Signals X_R, X_C and X are vectors in Cartesian space and represent the reference, commanded and the actual position trajectories, while X_E belongs to the location of the environment and E is the error between the reference force F_R and the measured contact force F. The impedance filter is a linear second-order system with the transfer function (3) defining the dynamic relationship between the force error and the position:

$$E = F_R - F = \mathbf{M}\ddot{X}_C + \mathbf{B}\dot{X}_C + \mathbf{K}(X_C - X_R). \tag{3}$$

The parameters of the diagonal matrices $\mathbf{M}, \mathbf{B}$ and $\mathbf{K}$ define the desired robot inertia, damping and stiffness along the particular Cartesian axis.

In order to determine the behavior of the impedance controller when in contact, the environment is modelled by a linear spring with the stiffness K_E. The measured contact force can be then calculated as:

$$F = \mathbf{K}_E(X - X_E). \tag{4}$$

When deriving the control laws we assume that the robot is equipped with an ideal position control system ensuring the commanded position X_C to be reached with negligible dynamics ($X \approx X_C$). This assumption allows one to consider variables of the vectors X and F independently. The elements of vectors X and F are then denoted as scalars by the lower-case letters x and f. The force tracking error e is obtained from Figure 1 as:

$$e = f_R - f = f_R - k_E(x - x_E). \tag{5}$$

Assumption $x = x_C$ in Equation (3) together with Equation (5) yields the equation of the force error dynamics:

$$m\ddot{e} + b\dot{e} + (k + k_E)e = k(f_R + k_E x_E) - kk_E x_R. \tag{6}$$

It can be noted that the input signal x_R can be used to control the force error trajectory. In the steady-state, when x_R is constant, the Laplace transform of Equation (6) defines the steady-state force tracking error:

$$e_{ss} = \lim_{s\to 0} se(s) = \frac{k}{k + k_E}\big[(f_R + k_E x_E) - k_E x_R\big]. \tag{7}$$

The steady-state force tracking error will equal zero when the following reference position trajectory is chosen:

$$x_R = \frac{f_R}{k_E} + x_E. \tag{8}$$

Unfortunately, in practical applications the environmental parameters, stiffness k_E and location x_E, are almost never known precisely and may change considerably during the task. To improve the force tracking characteristics one should therefore employ an adaptive control approach.

3. The Model Reference Controller

In this section the adaptive control algorithm will be introduced in order to cope with the problems of unknown environmental parameters. The basic loop controller is given by:

$$x_R = f(t) + k_p(t)e + k_d(t)\dot{e}, \tag{9}$$

where $k_p(t)$ and $k_d(t)$ are proportional and derivative feedback gains acting on the force error $e(t)$ and the error rate $\dot{e}(t)$. Signal $f(t)$ is an auxiliary signal which compensates the steady-state error. All three adjustable parameters are generated by the model reference adaptive algorithm.

Next, the basic equation suitable for the application of the model reference controller will be derived. Substituting x_R in the equation of error dynamics (6) by Equation (9) yields the equation of the complete adjustable system in the frame of the model-reference adaptive control (MRAC):

$$\ddot{e} + \left(\frac{b + kk_E k_d(t)}{m}\right)\dot{e} + \left(\frac{k + k_E + kk_E k_p(t)}{m}\right)e = \frac{k(f_R + k_E x_E - k_E f(t))}{m}. \tag{10}$$

The parameters $f(t)$, $k_p(t)$ and $k_d(t)$ of the adjustable system are varied in order to minimize the difference between the actual force error $e(t)$ and the desired force error $e_m(t)$. The desired force error trajectory $e_m(t)$ is determined by the output of the reference model. The reference model is designed as a second-order linear system:

$$\ddot{e}_m + 2\zeta\omega\dot{e}_m + \omega^2 e_m = 0, \tag{11}$$

with the output representing a response to the initial conditions. The user-specified parameters ζ and ω determine the profile of the reference model output trajectory. When in initial contact with the environment, the value of the reference force falls to zero. The parameters ζ and ω represent the undamped natural frequency and the damping ratio, respectively.

The essential difference between the described approach and the classical approach lies in the existence of the reference signal. While in the classical model of reference control the reference signal excites the basic loop and the reference model, there is no such signal in the application described. The excitation of both subsystems of the adaptive control is the initial condition. It should be stressed that the reference signal is absent only in the reformulation of the problem, i.e. in the equation describing as a model reference control system, but not, however, in the control problem where the manipulator end-effector is supposed to follow a prescribed path while tracking a prescribed force.

The theory of the direct model reference adaptive control provides the adaptation laws for the variable system parameters (12)–(15). The adaptation ensures the tendency of the response of system (10) to approach to the response of the reference model (11). The adaptation laws are derived following the Lyapunov approach to the nonlinear system control [5].

$$f(t) = f(0) - a_1 \int_0^t q \,\mathrm{d}t - a_2 q, \tag{12}$$

$$k_p(t) = k_p(0) + b_1 \int_0^t qe \,\mathrm{d}t + b_2 qe, \tag{13}$$

$$k_d(t) = k_d(0) + c_1 \int_0^t q\dot{e} \,\mathrm{d}t + c_2 q\dot{e}, \tag{14}$$

$$q = w_p(e - e_m) + (\dot{e} - \dot{e}_m). \tag{15}$$

In the adaptation laws, the parameter w_p represents positive weighting factor, while the parameters a_i, b_i and c_i are small positive proportional and integral adaptation

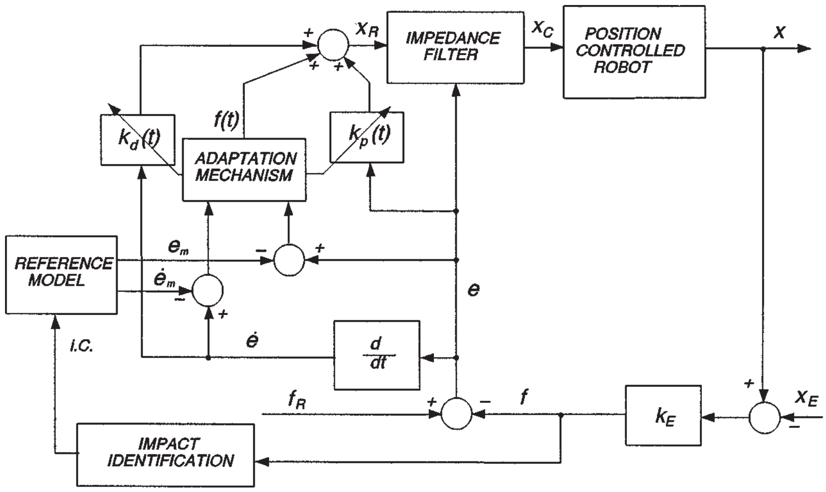

Figure 2. Adaptive impedance control scheme.

gains, and $f(0)$, $k_p(0)$, $k_d(0)$ represent adaptive parameter initial values. While the initial proportional and integral gains are selected to be zero, the initial value $f(0)$ defines the position trajectory of the robot's free-space motion. Thus, before the contact occurred, the trajectory x_R had the same value as the signal $f(0)$, while after the contact the parameter $f(0)$ holds the value assessed at the instant of contact.

Figure 2 depicts the control scheme of the impedance controller including the adaptive algorithm to generate the reference trajectory. The system adaptation is based on simple expressions (12)–(15) that can be computed on-line in real-time. The entire procedure for deriving the adaptation laws can be found in the appendix.

4. Implementation of the Model Reference Controller

The model reference adaptive impedance control algorithm was first tested by simulation in *Matlab-Simulink*™. The control scheme was realized on ideal position control of the robot, i.e. under ideal circumstances corresponding to the theory described in Section 3. Thereafter an identified model of the position control subsystem of the ASEA IRb 6 robot was introduced in order to test the robustness of the algorithm. The simulation results, presented extensively in [6], proved that the system is capable of tracking the desired contact force trajectory determined by the reference model output and of altering the robot arm dynamic characteristics in terms of the impedance parameters m, b and k.

Furthermore, the present adaptive impedance controller was implemented on a real industrial ASEA IRb 6 robot. The ASEA robot is a 5 DOF robot driven by DC motors and gear transmissions. As the original ASEA controller performs only position control in the joint coordinates, a 486/66 PC computer was added, providing

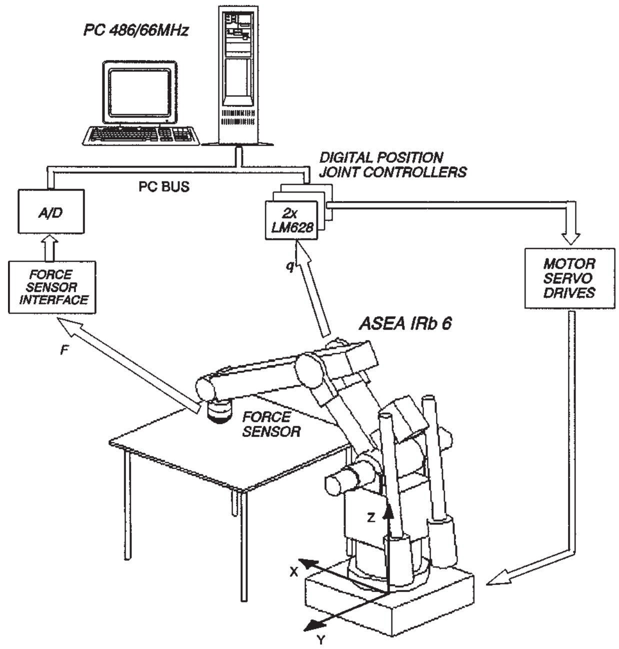

Figure 3. Force control system setup.

the computational platform for both the positional control algorithm in the world coordinates and the impedance control algorithm. Such controller enhancement would not be required for a modern industrial robot controller, enabling velocity control in Cartesian coordinates. Figure 3 shows the organizational scheme of the impedance controller with functional blocks representing the positional and force control loops.

The contact force is measured by the JR^3 four-axis force/torque wrist sensor mounted at the robot end point. Each of the sensor voltage outputs is digitized by the A/D converter and after filtering an estimate of the force error rate is obtained by digital differentiation. The impedance control algorithm calculates the commanded position trajectory defined in the Cartesian space on the basis of force feedback and by taking account of the adaptive algorithm. Using the inverse Jacobian matrix and the joints-to-motors transformations, the reference value is transformed into the motor velocities which are, at the end of the sample cycle, transmitted to the servo systems through D/A converters at a sample rate of 120 Hz.

The impedance control scheme of the industrial manipulator consists of three separated adaptive controllers described in the previous sections. Each controller independently performs the impedance control along a single axis of the Cartesian coordinate system. To test the effectiveness of the impedance controller, a simple task was chosen: the robot end-effector was first approaching the constraining surface (horizontal wooden table) along a straight line in the direction normal to the surface and after the impact compliant motion in the positive y direction was

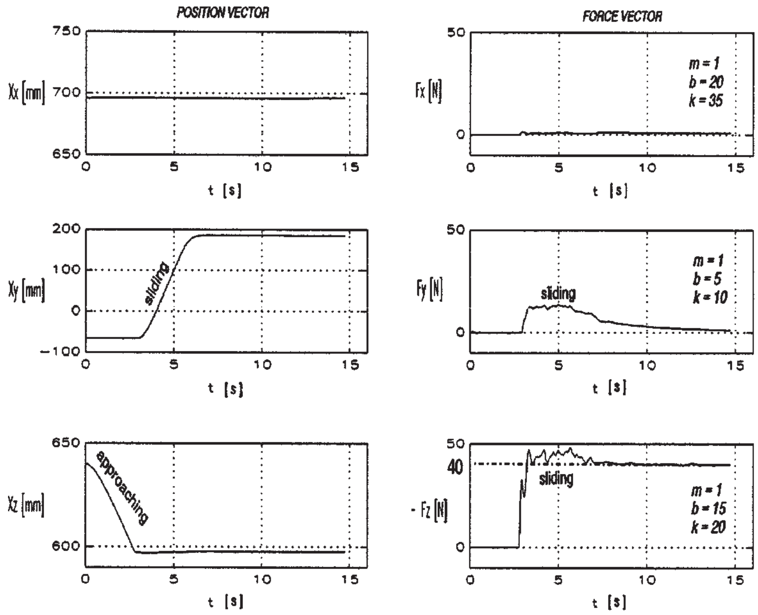

Figure 4. Position and force profiles during impact and sliding over horizontal surface.

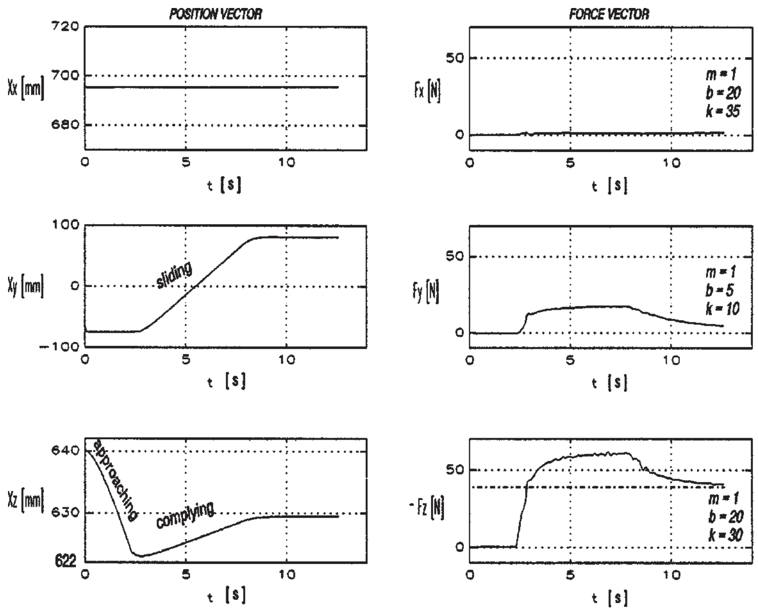

Figure 5. Position and force profiles during impact and sliding over inclined surface.

performed along the surface, while exerting a contact force of –40 N. Robot was approaching the surface with a velocity of 20 mm/s and was moving at 100 mm/s when sliding over the surface. The tests were performed by the following adjustments of the controller gains: $a_1 = 0.11$, $a_2 = 0.011$, $b_1 = 2\times 10^{-5}$, $b_2 = 5\times 10^{-5}$, $c_1 = 10^{-8}$, $c_2 = 10^{-8}$ and $w_p = 5$. The performance plots of the described algorithm are given in Figure 4. On the left side of the figure the actual robot positions along the particular axis are presented, while the right side describes the contact forces.

It can be noted that after impact a stable contact is achieved ensuring the desired contact force in the z direction. The presence of the force in the y direction can be also observed being the consequence of the Coulomb friction due to sliding.

Another example task presented in Figure 5 is aimed at showing the capability of the system to comply with an environment represented by an uneven surface. Figure 5 demonstrates the system performance when the robot with the same control parameters contacts and slides over the surface inclined at an angle of three degrees. The stable contact is again achieved with the constant force error during sliding over the surface. The impedance controller is a Type 1 system, as is apparent from the zero steady state error to the step input and the constant error to the ramp input.

5. Conclusions

The paper has presented the application of the model reference adaptive control to the impedance control of a robot end-effector contacting a rigid environment. The present control approach employs the original industrial manipulator position control system with no demands for controller hardware reconstruction. The added force control algorithm makes use of adaptive terms for the system adaptation to unknown environmental and robot dynamic parameters. The basic difference between the classical model reference control and the given algorithm is the method of adaptive system excitation. The reference signal used in classical MRAC is replaced by the nonzero initial condition of the system.

Laboratory simulation and experimental tests on the ASEA IRb 6 robot have shown that the system remains stable throughout all phases of the task, both constrained and unconstrained, regardless of the high environment stiffness. Furthermore, the robot is able to exert the desired forces at the end-effector and simultaneously achieve the desired end effector impedance characteristics.

Using the reference model in the control scheme has introduced a step toward impact control. Continuous and stable transition from the unconstrained into constrained motion and the possibility of preshaping the force trajectory are achieved. However, the problems of the brief impulsive collision force due to the end-effector inertia and the rigid surface still remain to be investigated. Further study is also needed to confirm the applicability of the impedance controller developed in the tasks, such as robot grinding or polishing.

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Appendix

This appendix derives the adaptation control laws in the frame of the Lyapunov based model reference adaptive control (MRAC) theory. Let us rewrite the equation of the adjustable system (10) in a more compact form:

$$\ddot{e} + \alpha_1 \dot{e} + \alpha_2 e = \beta_0, \tag{16}$$

and define the differences between particular parameters of the above equation and Equation (11):

$$\delta_{b_0} = \beta_0, \qquad \delta_{a_1} = \alpha_1 - 2\zeta\omega, \qquad \delta_{a_2} = \alpha_2 - \omega^2. \tag{17}$$

By subtracting Equations (16) and (11) we obtain:

$$(\ddot{e} - \ddot{e}_m) + \alpha_1 \dot{e} - 2\zeta\omega\dot{e}_m + \alpha_2 e - \omega^2 e_m = \beta_0, \tag{18}$$

which can be transformed by the definition of the error between the actual and desired force error ($\varepsilon = e - e_m$) into the form:

$$\ddot{\varepsilon} = -2\zeta\omega\dot{\varepsilon} - \omega^2\varepsilon - \delta_{a_1}\dot{e} - \delta_{a_2} e + \delta_{b_0}. \tag{19}$$

Let us now propose a scalar Lyapunov function V:

$$\begin{aligned} V \;=\; & \left(\omega^2 + 2w_p\zeta\omega - w_p^2\right)\varepsilon^2 + q^2 + \frac{1}{\gamma_0}\left[\delta_{b_0} + \gamma_0' q\right]^2 + \\ & + \frac{1}{\gamma_1}\left[-\delta_{a_1} + \gamma_1' q\dot{e}\right]^2 + \frac{1}{\gamma_2}\left[-\delta_{a_2} + \gamma_2' q e\right]^2, \end{aligned} \tag{20}$$

where q defines a linear combination of ε and $\dot{\varepsilon}$ ($q = w_p\varepsilon + \dot{\varepsilon}$), while the parameters γ_i and γ_i' are positive constants. The proposed Lyapunov function is positive definite when the parameter w_p is chosen to satisfy the inequality:

$$0 \leqslant w_p < 2\zeta\omega. \tag{21}$$

The time derivative of V, after applying (19) and after addition and substraction of terms $2\gamma_0'(q)^2$, $2\gamma_1'(q\dot{e})^2$, $2\gamma_2'(qe)^2$, takes the form of:

$$\begin{aligned} \dot{V} \;=\; & 2\dot{\varepsilon}^2(w_p - 2\zeta\omega) - 2w_p\omega^2\varepsilon^2 - 2\gamma_0' q^2 - 2\gamma_1'(q\dot{e})^2 - 2\gamma_2'(qe)^2 + \\ & + 2(\delta_{b_0} + \gamma_0' q)\left\{q + \frac{1}{\gamma_0}\left(\dot{\delta}_{b_0} + \gamma_0'\frac{\mathrm{d}}{\mathrm{d}t}(q)\right)\right\} + \\ & + 2(-\delta_{a_1} + \gamma_1' q\dot{e})\left\{q\dot{e} + \frac{1}{\gamma_1}\left(-\dot{\delta}_{a_1} + \gamma_1'\frac{\mathrm{d}}{\mathrm{d}t}(q\dot{e})\right)\right\} + \\ & + 2(-\delta_{a_2} + \gamma_2' qe)\left\{qe + \frac{1}{\gamma_2}\left(-\dot{\delta}_{a_2} + \gamma_2'\frac{\mathrm{d}}{\mathrm{d}t}(qe)\right)\right\}. \end{aligned} \tag{22}$$

Now, according to the Lyapunov theory, for the response error ε to vanish asymptotically, $\dot{V}$ must be negative-definite. For this purpose, we set the terms { } equal to zero, while the parameter w_p is chosen according to inequality (21). Integrating the resulting equations yields the adaptive controller terms:

$$f(t) = f(0) - \frac{\gamma_0' m}{k k_E} q - \frac{\gamma_0 m}{k k_E} \int_0^t q \, \mathrm{d}t, \tag{23}$$

$$k_p(t) = k_p(0) + \frac{\gamma_2' m}{k k_E} q e + \frac{\gamma_2 m}{k k_E} \int_0^t q e \, \mathrm{d}t, \tag{24}$$

$$k_d(t) = k_d(0) + \frac{\gamma_1' m}{k k_E} q \dot{e} + \frac{\gamma_1 m}{k k_E} \int_0^t q \dot{e} \, \mathrm{d}t, \tag{25}$$

which are apparently slightly extended terms of the adaptation laws (12)–(14).

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