ISSN 1068-798X, Russian Engineering Research, 2016, Vol. 36, No. 4, pp. 328–334. © Allerton Press, Inc., 2016.
Original Russian Text © Yu.V. Ilyukhin, Yu.V. Poduraev, 2015, published in STIN, 2015, No. 9, pp. 30–37.

Improving the Precision of Mechatronic Robot Drives

Yu. V. Ilyukhin and Yu. V. Poduraev

Stankin Moscow State Technical University, Moscow, Russia
e-mail: Ilyv_178@mail.ru; y.poduraev@stankin.ru

Abstract—A new structure is proposed for precision servo drives in industrial robots, and its properties are analyzed. The servo drive is a mechatronic device containing high-precision sensors, microcontrollers, and electrical and mechanical components. The theoretical results that underlie the design of a precision drive containing an elastic mechanical transmission with free play are outlined. Computer simulation indicates high precision of the drive and its suitability for use in industrial robots.

Keywords: industrial robots, servo drives, precision, mechatronics
DOI: 10.3103/S1068798X16040067

INTRODUCTION

Industrial robots may be used to automate laser and plasma treatment, assembly, and labeling and also to measure the coordinates of large complex components. In all those cases, high precision is required. As a rule, robots with an open kinematic chain are preferred, on account of their large region of activity, within which they may automatically position and orient the tool or measuring head.

The control of industrial robots is generally based on a kinematic model of its manipulator [1, 2]. The desired coordinates of the working component, specified in the robot's basic coordinate system, are converted to the corresponding generalized coordinates by solution of the inverse kinematic problem regarding the manipulator position. Obviously, if complex technological operations are to be successfully completed, the actual position of the robot's working component must precisely correspond to its desired position. If the actual position of the robot's working component diverges greatly from its desired position, the consequence will be defects in the final products.

Such displacement depends on the error of the drives and imprecision of the mathematical model of the manipulator used in the inverse kinematic problem. Given that the model of the manipulator may be corrected by parameter identification, we see that the errors in the drives are often the dominant factors affecting the precision of tool motion and the quality of the industrial operations.

Industrial robots may be based on drive modules with or without gear systems. Gearless mechatronic drives are of most interest in machine-tool design today [3]. By contrast, most robot drives include mechanical motion converters, because gear systems generally improve the mass, size, cost, and energy parameters of drive modules and the industrial robot as a whole. In addition, in robots with gearless drives, we observe considerable mutual influence of the degrees of mobility, with consequent impairment of precision and the stability of motion [4, 5].

Therefore, industrial robots mainly employ gear-based servo drives with closed control loops for the motor-shaft position [6, 7]. In that case, the mechanical transmission has an open chain (apart from the closed position-control loop). That simplifies the maintenance of stability in the servo drive and the industrial robot as a whole. However, the precision of motion of the working component or measuring instrument may be significantly reduced in that case on account of elastic deformation and free play in the mechanical transmissions.

For example, when using planetary and wave gears with kinematic errors of 3–6′, the corresponding positional error of the working component when it is moved away from the axis of manipulator rotation by 1 m may be 1.75 mm. Under the action of imbalance torques in the manipulator mechanism, the elastic pliability of the mechanical transmissions may lead to errors of 10 mm or more. Special precision gear systems also have a permissible limit of precision.

Analysis of the influence of the rigidity, kinematics, and damping of the mechanisms is important in the design not only of robots but of machine tools [8–10]. The importance of increasing the precision of robots whose drive modules include gear systems, which will always be characterized by elasticity and free play, cannot be overstated — especially when using progressive analytical programming of the robot, in which no provision is made for training.

Numerous studies have been devoted to the design and precision of servo systems with elastic mechanical transmissions (for example, [11, 12]). Researchers have expended considerable effort in improving the control of mechatronic drives [13–16] and creating computer control systems [17, 18].

Proposals to improve the properties of servo drives with elastic gear systems are usually based on particular corrections or compensations. In practice, this approach is ineffective on account of the presence of nonlinearity — an insensitivity zone — in gears with free play.

One approach to increasing the precision of tool motion in machine tools and robots is to compensate the influence of free play outside the position-control loop by correction of the specifications from the numerical control system [19–21]. In that case, however, the precision is not significantly increased, especially with frequent changes in direction of the object of control.

Another approach is to use drives with two jointly controlled motors, one of which produces a torque opposing the primary motor [7, 22]. That creates a closed force system and rules out the negative influence of gaps in the mechanical transmissions on the drive precision. Important conclusions regarding the design of servo drives in the control loop of elastic mechanical transmissions with free play may be found in [7]. Those conclusions provide the basis for the present analysis.

To reduce the influence of elastic deformation and free play in the mechanical transmission on the precision of the resulting motion, we may expand the information and measuring subsystem of the industrial robot and use a nontraditional position of the sensors in the primary feedback loop for the manipulator position: directly at the axis of manipulator rotation.

In principle, the servo drive directly controlling the manipulator position is able to overcome the negative influence of the external forces producing elastic displacement on account of the elasticity of the gear, and therefore the static and dynamic rigidity will be considerably increased. However, the nonlinear element (the insensitivity zone) in the position-control loop, in combination with the elasticity of the mechanical transmission, may produce self-oscillation in the servo drive, as shown in [7].

Without expansion of the equipment in the drive module, no changes in structure of the control system can prevent self-oscillation, as established in [7]. At the same time, drives with considerable self-oscillation amplitude do not ensure the required positional precision and undergo rapid wear and hence are unsuitable for precision industrial robots.

In the present work, we propose means of significantly increasing the precision of the tool or measuring-instrument position and motion over a specified trajectory, on the basis of mechatronics and the coordinated development of electromechanical, informational, and control components for a servo drive with a closed control loop for the manipulator position.

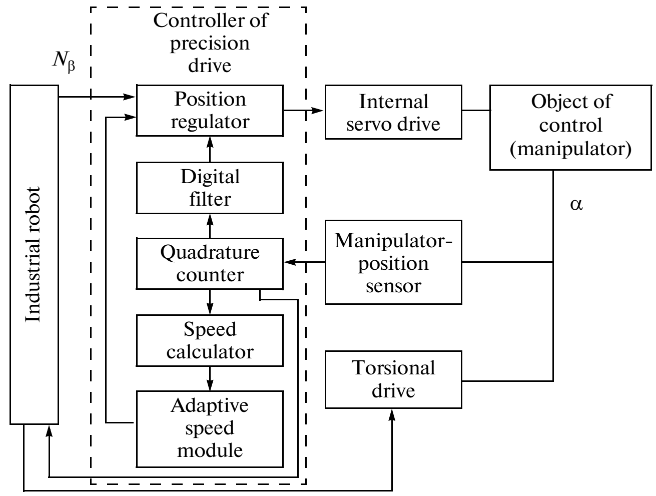

Fig. 1. Structure of a precision servo drive for industrial robots.

STRUCTURE OF PRECISION DRIVE

To improve the precision in positioning and motion of the robot's working component, we expand the composition of the servo drive (Fig. 1). It includes the precision drive controller, an internal gear-based servo drive, a torsional drive, and a high-precision position sensor. Thus, the precision servo drive contains two motors, while the control channel for the manipulator motion has an internal component in the form of a servo drive with a closed control loop for the position of the motor shaft; and an external component with special correction ensuring high dynamic rigidity and the absence of self-oscillation. The drive configuration with both dominant and subordinate position-control loops permits the development of the traditional robot drive on mechatronic principles so as to ensure high precision.

The shaft on which the high-precision sensor turns is rigidly connected to the shaft of the controllable manipulator drive. That permits direct measurement of the drive coordinate and its transmission to the control computer. In selecting this sensor, we must take into account that, as shown later, its error and resolution considerably determine the drive precision and the possible vibration. Hence, it is expedient to use a precision incremental encoder in combination with a quadrature counter.

The external precision drive controller is a key addition to the design in [7]. Digital control signal N_β, proportional to the desired angle β of manipulator rotation, is sent to the controller input from the robot's control unit. The quadrature counter in the controller processes the incremental-encoder signals regarding the actual position of the object of control and generates the corresponding code. That code is transmitted to the robot's control unit, where it is used to calculate the required drive correction. The external

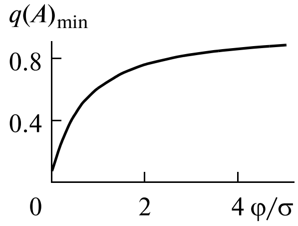

Fig. 2. ependence of $q(A)_{\min}$ on φ/σ.

high-precision drive controller includes a PI controller, a digital unit computing the manipulator speed; a digital low-frequency filter in the position-feedback loop; and an adaptive-correction module in the speed-feedback system.

Another key feature of the precision drive is that it contains a servo drive with a closed position-control loop for the motor shaft. This servo drive generates controllable forces transmitted through the gear system to the object of control. It plays a subordinate role, executing the commands of the external position regulator in the drive controller. This servo drive has the regular structure, with internal subordinate control loops for the speed and current.

Thus, the proposed servo drive uses two position sensors, one on the motor shaft and one on the manipulator axis. In all, there are four control loops in the manipulator's position-control channel. As a result, the precision drive is a second-order astatic system and therefore is characterized by high precision in both positioning and motion at constant speed.

The torsional drive actively controls the free play. It is necessary to prevent self-oscillation, with the appropriate selection of control algorithms. Its operation simply requires a control loop for the currents in the motor windings. At the same time, it is expedient to use a hybrid drive that has a closed speed-control loop for the motor shaft and operates with limits on the torque developed. That permits the use of mass-produced components for the robot's precision drive. That is the third distinguishing feature of this design.

THEORETICAL ASPECTS OF DRIVE DESIGN

Servo drives of the proposed structure are potentially able to ensure precision motion of the object of control. Since they have a closed position-control loop, there will be no static error due to the elasticity and free play of the mechanical transmission.

The mechanical subsystem consisting of the mechanical transmission (gear system) and the mechanical object of control (manipulator) has a significant influence on the servo drive's dynamic behavior. Therefore, in selecting the torque developed by the torsional drive and the parameters of the control algorithms in the precision drive controller, we must take account of the manipulator's moment of inertia and the free play and elastic properties of the mechanical transmission.

The mechanical subsystem is nonlinear, since its mathematical model includes an insensitivity zone. In analysis and synthesis of drives containing such nonlinearities, it is expedient to use harmonic linearization, which permits the replacement of the nonlinear element by its harmonic linearization coefficient $q(A)$. The servo drive has the worst properties at the minimum value $q(A)_{\min}$. The amplification factor of the servo-drive controllers, which affect its transmission band, must be determined for this case, since the margin of stability is less in this case than for other values of $q(A)$.

Thanks to the torsional drive, the vibration of the motor shaft and the manipulator shaft do not center on zero but on some angle due to the external torque M_{ex} and the rigidity C_{p} of the mechanical transmission. That introduces the constant component θ_0 of the twist angle θ for the elastic element equivalent to the gear system. As a result of harmonic linearization of the insensitivity zone, not only a variable component but also a constant component φ may be observed at its output when constant external torque acts on the object of control. There is a relation between $q(A)_{\min}$, M_{ex}, C_{p}, and half the free play σ of the mechanical transmission

$$q(A)_{\min} = f\{M_{\text{ex}}(C_p\sigma)^{-1}\},$$

where $M_{\text{ex}}(C_p\sigma)^{-1} = \varphi/\sigma$. This dependence, obtained by computer analysis, takes the form in Fig. 2.

With increase in M_{ex} and decrease in σ, the range of possible $q(A)$ values becomes narrower. Its minimum value $q(A)_{\min}$ increases with increase in φ/σ; the maximum value is one, as in the absence of free play. For example, when $M_{\text{ex}} = 45$ N m, $C_{\text{p}} = 250000$ N m/rad, and $\sigma = 1.4545 \times 10^{-4}$ rad, we find that $q(A)_{\min} \approx 0.65$. Therefore, by introducing an external torque and selecting a gear system with little free play, we may ensure that the properties of a mechanical transmission with free play are similar to those of an ideal transmission without free play. It is expedient to select M_{ex} so as to ensure the required acceleration of the manipulator. For example, with the maximum moment of inertia of the manipulator $J_{0.\max} = 20$ kg m^2 and the required angular acceleration 2.25 rad/s^2, we require $M_{\text{ex}} = 45$ N m. Then the rated moment of inertia of the motor in the internal servo drive must be twice M_{ex} at the exit from the gear system; in other words, it must be 90 N m.

Assuming that θ varies harmonically, we may write the linearized equation of the mechanical transmission in the form

$$M_{\text{gs}} = C_{\text{equ}}(1 + T_{\text{el}}p)(\alpha_{\text{mo}}i^{-1} - q),$$

where M_{gs}, α_{mo}, and q are the first harmonics of the torque at the gear system's output shaft with gear ratio i, the positional angle of the motor shaft, and the positional angle of the manipulator, respectively; C_{equ} is the equivalent rigidity of the gear system, reduced to its output shaft; T_{el} is the time constant of the elastic gear system; p is the differential operator. We know that

$$C_{equ} = C_p q(A)_{min}; \quad T_{el} = \chi_p / C_p,$$

where χ_p is the loss factor due to internal viscous friction in the equivalent elastic element of the mechanical transmission.

The mathematical model of the mechanical subsystem consisting of the elastic mechanical transmission with free play and the manipulator with moment of inertia J_0 is described by the transfer function

$$W_0(s) = (1 + T_{el}s)(\omega_0^{-2}s^2 + 2\xi_0\omega_0^{-1}s + 1)^{-1},$$

where s is a Laplacian variable; $\omega_0 = \sqrt{C_{equ}/J_0}$ is the eigenfrequency of the elastic subsystem; ξ_0 is the relative damping coefficient ($\xi_0 = 0.5T_{el}\omega_0$). Since ξ_0 is small, slightly damping vibrations may arise in the mechanical subsystem. That interferes with stability of the precision drive. The properties of the dynamic object consisting of the mechanical subsystem and the internal servo drive with a closed position-control loop for the motor shaft must be corrected. In the first approximation, given that the reaction of the mechanical subsystem to the internal-drive motor is weak, we may write the transfer function of this dynamic object in the form

$$W_2(s) = (1 + T_{el}s)(\omega_0^{-2}s^2 + 2\xi_0\omega_0^{-2}s + 1)^{-1} \times (T_2 s + 1)^{-1},$$

where T_2 is the time constant of the model of the internal servo drive with a closed position-control loop for the motor shaft.

Note that more precise motion of the industrial robot calls for correction formulas that increase the relative damping factor and thus suppress the resonance of the mechanical subsystem.

Research shows that the damping may be intensified by means of correcting speed feedback for the manipulator components at the inputs of the internal servo drives. Such correction permits the replacement of ξ_0 in the transfer function $W_2(s)$ by ξ_1, with values in the range 0.7–0.9. That permits increase in the cutoff speed ω_C of the open drive and hence reduction in the response time by using a PI controller with the following transfer function in the direct link of the external control loop

$$W_{od}(s) = k_{od}(T_{co}s + 1)(T_{co}s)^{-1},$$

where k_{od} and T_{co} are, respectively, the amplification factor and time constant ($T_{co} = \omega_C^{-1}$). At the same time, the transmission band of the closed servo drive in the position feedback loop for the manipulator may be expanded by means of a correction filter with the transfer function

$$W_{cf}(s) = (T_{co}s + 1)^{-1}.$$

The amplification factor k_{od} of the PI controller in the precision drive and the amplification factor k_I of its integral component are determined from the formulas

$$k_{od} = k_{psm} i k_{ps}^{-1}, \quad k_I = \omega_C,$$

where k_{ps} and k_{psm} are, respectively, the gains of the position sensors for the manipulator and the motor shaft according to their linearized characteristics [2]. To ensure drive stability, the cutoff speed ω_C must be no more than half of ω_0.

An important property of the proposed servo drive is evident if we consider the transfer function of the closed drive with respect to the error

$$\Phi_\delta(s) = s^2 \frac{(\omega_0\omega_C)^{-1}[s^2 T_2\omega_0^{-1} + s(\omega_0^{-1} + 2\xi_1 T_2) + 2\xi_1]}{s\omega_C^{-1}(\omega_0^{-2}s^2 + 2\xi_1\omega_0^{-1}s + 1)(T_2 s + 1) + T_{el}s + 1}.$$

Analysis shows that the servo drive with the proposed structure is a second-order astatic system in terms of the control signal. Therefore, it is characterized by high precision in both steady positioning and motion at constant speed.

DYNAMIC PROPERTIES OF PRECISION DRIVE

As an example, we investigate the dynamic properties of the proposed precision servo drive for a rotary manipulator drive in a robot with a closed kinematic system of PUMA type relative to the vertical axis [6]. This example is chosen because such drives lack a static torque. In other words, they operate in the most unfavorable condition, with high probability of intense self-oscillation. Therefore, in this example, the most significant benefits of the proposed precision servo drive will be apparent. We assume that the resultant drive error is the sum of two components: the error of the sensor for the primary feedback signal in terms of the manipulator position; and the error of the drive due to its structure, the parameters of its components, and the resolving power of the position sensors.

Computer simulation of the mechatronic servo drive is based on the assumptions in [2, 18]. In the mathematical model we assume the following parameter values. The moment of inertia of the manipulator is 20 kg m^2. We use a Harmonic Drive (Germany) HFUC-2A precision harmonic gear (type 50), with rigidity 250000 N m/rad and free play of 1′. That corresponds to manipulator rotation by 2.909×10^{-4} rad. Note that the calculated resonance frequency of the

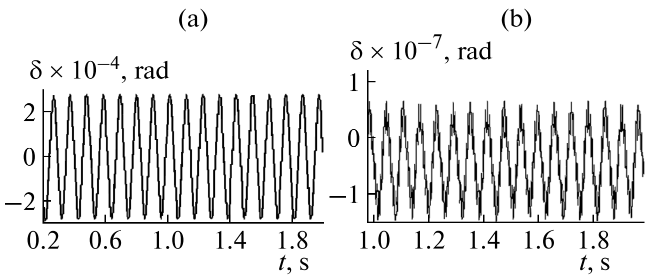

Fig. 3. Self-oscillation of the error δ for a manipulator drive system with no torsional drive (a) and with real feedback sensors and a torque of 45 N m from the torsional drive (b).

mechanical subsystem is 17.8 Hz. The parameter χ_p = 500 N m s/rad. The sensor in the primary feedback loop for the manipulator position is a precision incremental encoder of second-class precision (error ±1.5′) and sampling rate 3600000 per rotation (for example, a LIR-1170 sensor produced by SKB IS). Given the quadrupling of the pulses by the quadrature counter, a change of decimal one corresponding to the code at the counter output occurs in manipulator rotation by 4.3633×10^{-7} rad.

The controller parameters in the internal servo drive are selected in accordance with the rules for tuning a system of subordinate control loops, on the assumption that the frequency in the drive's mechanical converter is 20 kHz [2]. We use a sensor in the feedback loop for the motor shaft's position with a sampling rate of 5000 per rotation. For these parameter values, we obtain a cutoff speed of 105 rad/s for an internal servo drive with an open position-control loop.

The dynamic properties of the mechanical subsystem and the internal drive are corrected by introducing negative feedback with respect to the manipulator speed. This speed is calculated by the controller of the precision servo drive by means of data from the quadrature counter. The efficiency of correction may be improved by adaptive adjustment of the feedback coefficient, on the basis of the estimate of the manipulator's moment of inertia from the robot's control unit.

Computer simulation shows that, in a drive with a closed position-control loop for the manipulator, in the absence of a torsional drive, symmetric self-oscillation appears, with amplitude 2.9×10^{-4} rad and frequency 9.5 Hz (Fig. 3a). The amplitude is very large: it practically matches the free play in the gear system. This indicates that such drives are unsuitable for industrial robots. As follows from our assumptions, no control measures can eliminate such self-oscillation.

Two test modes are considered in the computer simulation of a precision servo drive with the structure in Fig. 1. In the first, a stepped control signal is supplied. The character of the process and the positioning error are monitored. In the second, manipulator motion over a smooth trajectory—for example, a circle—is simulated. The dynamic error of the rotary drive processing the harmonic control signal is monitored.

In the first case, there is no self-oscillation with ideal (continuous) position feedback sensors if the torque from the torsional drive is more than 10 N m. Constant displacement of the manipulator relative to its desired is not observed. The error of the manipulator drive in positioning mode after completion of the transient process (which lasts 0.1 s) tends to zero.

The computer model behaves somewhat differently when the actual resolving power of the feedback sensors is taken into account. Since the characteristic of the sensor with the quadrature counter is stepped [12] and it behaves as an ideal relay when the deviations are small, self-oscillation always appears in the system at the end of the transient process. However, its amplitude is considerably less than in the absence of the torsional drive. With a torque of 45 N m, the self-oscillation amplitude is about 1.1×10^{-7} rad (Fig. 3b). Slight displacement (constant mismatch) of about 4×10^{-8} rad is observed. The oscillation frequency is 16 Hz; that is close to the resonance frequency of the manipulator connected to an elastic gear system.

The self-oscillation amplitude in the precision servo drive is smaller than that in the system without the torsional drive by a factor of 2600. The resulting total error in the tool position relative to the workpiece is no more than 0.15 μm when the distance from the tool to the manipulator's axis of rotation is 1 m.

In addition, the self-oscillation is qualitatively very different from that observed in the absence of the torsional drive. Motion is such that the elastic elements of the mechanical subsystem are constantly pressed together. The constant component of the elastic deformation due to the torque generated by the torsional drive is 1.8×10^{-4} rad; that is more than 1600 times the amplitude of the manipulator vibrations. Consequently, there are never situations in which the manipulator and the motor shaft move independently of one another. That ensures controllability of the manipulator and high precision of the motion. The self-oscillation actually observed in a two-motor precision drive has little effect on the precision of manipulator positioning. In the first approximation, its influence may be ignored.

Simulation shows that, with decrease in the torque from the torsional drive, the self-oscillation amplitude increases, while its frequency declines. Therefore, to ensure high precision of the robot motion, it is expedient to increase the torque generated by the torsional drive. We propose a torque equal to the product of the maximum moment of inertia of the manipulator and its desired acceleration.

In analysis of the processing of a harmonic control signal by the drive, it is calculated as a function of the time t on the basis of the equation $\beta = A\sin\omega t$, where A and ω are, respectively, the amplitude and angular velocity of the signal. As an example, in Fig. 4a, we show the variation in drive error when $A = 1$ rad and $\omega = 0.2$ rad/s. In this case, evidently, the amplitude of the error is no more than 1.56×10^{-5} rad.

The drive is a second-order astatic system and therefore its speed error is zero. Simulation shows that, in processing a harmonic signal, the drive error in steady conditions is $\delta = -\delta_A \sin\omega t$,where the amplitude δ_A of the error is proportional to the second derivative of the control signal with respect to the time; the constant of proportionality is 3.91×10^{-4} s^2. This indicates that the drive precision may be significantly increased, with motion of the manipulator over the specified trajectory.

Further increase in precision of the servo drive is possible by introducing compensating feedback. We propose feedback with respect to the second time derivative of the control signal, with amplification factor k_{el}. If we assume that $k_{\mathrm{el}} = 2\xi_1(\omega_0\omega_C)^{-1}$, the transfer function of the closed drive with respect to the error takes the form

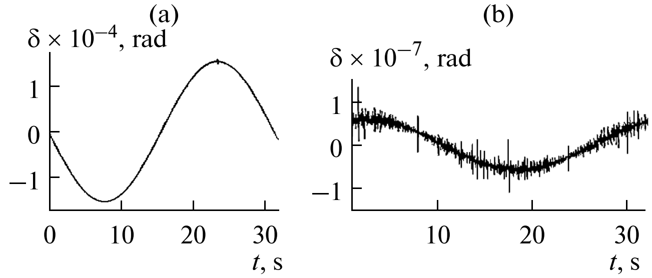

Fig. 4. Variation in the drive error δ when processing a harmonic control signal (a) and with compensating feedback (b).

$$\Phi_{\delta\mathrm{co}}(s) = s^3 \frac{(\omega_0\omega_C^2)^{-1}\{s(T_2\omega_0^{-1} - 2\xi_1 T_{\mathrm{el}}\omega_C^{-1}) + [\omega_0^{-1} + 2\xi_1(T_2 - T_{\mathrm{el}}) - 2\xi_1\omega_C^{-1}]\}}{s\omega_C^{-1}(\omega_0^{-2}s^2 + 2\xi_1\omega_0^{-1}s + 1)(T_2 s + 1) + T_{\mathrm{el}}s + 1}.$$

Hence, this drive is a third-order astatic system. Note that effective utilization of the benefits offered by compensating feedback entails that the robot's control unit must form the control signal on the basis of smooth functions, which are calculated from analytic formulas. It follows from the given transfer functions that the frequencies ω_0 and ω_C may expediently be increased in order to increase the precision in processing a fluctuating signal.

Computer simulation shows that the introduction of compensating feedback with respect to the second time derivative of the control signal, when $A = 1$ rad and $\omega = 0.2$ rad/s, results in drive error within the range $\pm 0.8 \times 10^{-7}$ rad (Fig. 4b).

In many cases of practical importance, this is sufficient not only for precision laser machining but also for contactless robotic measurements with continuous motion of the relative head relative to the object being measured. For example, when $A = 1$ rad and $\omega = 0.2$ rad/s, a measuring head at a distance of 1 m from the axis of manipulator rotation may move in steady conditions at speeds up to 200 mm/s with error due to drive imprecision no greater than 0.07 μm.

Given significant increase in drive precision, we may turn our attention to reducing other components of the error in manipulator positioning. The first priority might be improvement in the kinematic model of the industrial robot, which permits control of the robot on the basis of the inverse position-kinetics problem. To that end, the kinematic model of the manipulator must take account of reliable information regarding the deviation in component lengths and skewing of the axes in hinges and also regarding the elastic and thermal deformation of the manipulator components.

CONCLUSIONS

(1) For operations requiring high precision of manipulator motion and also for contact and contactless measurements of large complex objects, it is expedient to use industrial robots with a closed kinematic chain, which are characterized by a large working region and are based on two-motor precision servo drives with gear systems. This is especially important in the case of analytical programming of industrial robots.

(2) Industrial robots whose drive modules contain elastic mechanical transmissions with free play may be based on two-motor drives with torsional drives, including two position-control loops. These drives include algorithms for adaptation to change in the manipulator's moment of inertia and also compensating feedback with analytical formulation of the control signals.

(3) The proposed precision servo drive offers numerous benefits. It is characterized by high positioning precision, depending on the error and resolution of the sensor that directly measures the manipulator position; by acceptable response times; and by high precision of motion at constant speed, since it is a second-order astatic system with respect to the control

signal. Mass-produced components may be used in such precision drives.

(4) The operation of these servo drives in industrial robots will be most efficient if the cutoff speed of the open drive is increased. That may be accomplished by the introduction and adaptive adjustment of compensating feedback with respect to the manipulator speed so as to intensify the damping of vibrations in the mechanical subsystem.

(5) In industrial robots processing control signals that fluctuate over time, the precision of manipulator motion may be further increased by introducing compensating feedback with respect to the second time derivative of the control signal. The control unit of the industrial robot may be used for that purpose.

ACKNOWLEDGMENTS

Financial support was provided by the Ministry of Education and Science of the Russian Federation (program 2014/105, project 1678). The research was conducted on equipment at the Collective-Use Center, Stankin Moscow State Technical University, with additional financial support from the Ministry of Education and Science of the Russian Federation (contract 14.593.21.0004, December 4, 2014; project identifier RFMEFI59314X0004).

REFERENCES

1. Zenkevich, S.L. and Yushchenko, A.S., *Upravlenie robotami. Osnovy upravleniya manipulyatsionnymi robotami* (Robot Control: Principles of Control Robot Manipulations), Moscow: Mosk. Gos. Tekhn. Univ. im. N.E. Baumana, 2000.
2. Ilyukhin, Yu.V., *Computernoe upravlenie mekhatronnymi sistemami* (Automated Control of Mechatronic Systems), Moscow: Mosk. Gos. Tekhnol. Univ. Stankin, 2014.
3. Bushuev, V.V. and Ostretsov, A.G., Design of new generation gear milling machine based on mechatronic modules, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2013, vol. 26, no. 3.
4. Makarova, T.A. and Stebulyanin, M.M., Analysis of interrelationship of the motion of the mobility degree of three-tier robot with gearless drive, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2012, vol. 22, no. 3, pp. 145–150.
5. Makarova, T.A. and Stebulyanin, M.M., Robust algorithm of motion stabilization of three-tier robot with gearless drive, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2013, vol. 25, no. 2, pp. 74–79; pp. 77–82.
6. Ilyukhin, Yu.V. and Poduraev, Yu.V., *Proektirovanie system robotov. Linearizovannye sistemy* (Design of Operation Units of Robots. Linearized Systems), Moscow: MPI, 1989.
7. Bleiz, E.S., Zimin, A.V., Ivanov, E.S., et al., *Sledyashchie privody. Tom 1. Teoriya i proektirovanie sledyashchikh privodov* (Follower Actuators, Vol. 1: Theory and Design of Follower Actuators), Chemodanov, B.K., Ed., Moscow: Mosk. Gos. Tekhn. Univ. im. N.E. Baumana, 1999.
8. Kozochkin, M.P., Maslov, A.R., and Porvatov, A.N., Analysis of dynamic rigidity of a machine for micromilling, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2013, vol. 25, no. 2, pp. 12–16.
9. Bushuev, V.V. and Molodtsov, V.V., Role of the machine tool's kinematic structure in ensuring machining precision, *Russ. Eng. Res.,* 2010, vol. 30, no. 10, pp. 1053–1059.
10. Khomyakov, V.S., Damping in dynamic machine-tool calculations, *Russ. Eng. Res.,* 2010, vol. 30, no. 9, pp. 934–938.
11. Bortsov, Yu.A. and Sokolovskii, G.G., *Avtomatizirovannyi elektroprivod s uprugimi svyazyami* (Automated Electric Drives with Flexible Connections), St. Petersburg: Energoatomizdat, 1992.
12. Bortsov, Yu.A., Polyakhov, N.D., and Putov, V.V., *Elektromekhanicheskie sistemy s adaptivnymi i modal'nym upravleniem* (Electromechanical Systems with Adaptive and Models Control), Leningrad: Energoatomizdat, 1984.
13. Kuzovkin, V.A., Filatov, V.V., and Chumaeva, M.V., Nonlinear models of dynamic processes in impulse control systems of brushless DC motors, *J. Comp. Syst. Sci. Int.,* 2014, vol. 53, no. 3, pp. 420–429.
14. Andreev, A.G. and Stebulyanin, M.M., Formation of stator currents in the simulation of switched electric drives in robots, *Russ. Eng. Res.,* 2010, vol. 30, no. 10, pp. 1046–1052.
15. Lukinov, A.P. and Solov'ev, D.P., Table regulation of mechatronic drives based on asynchronous engines with vector control, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2014, vol. 31, no. 4.
16. Ilyukhin, Yu.V., Kharchenko, A.N., and Arfikyan, S.A., Mechatronic electropneumatic servo drives, *Russ. Eng. Res.,* 2010, vol. 30, no. 9, pp. 964–966.
17. Martinov, G.M. and Martinova, L.I., Creation of computer database for CNC to organization of specific control systems, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2014, vol. 28, no. 1, pp. 92–97.
18. Ilyukhin, Yu.V., Role of computer simulation in understanding of technical objects, *Vestn. Mosk. Gos. Tekhnol. Univ. Stankin,* 2012, vol. 23, no. 4, pp. 141–145.
19. Wescott, T., *Applied Control Theory for Embedded Systems,* Amsterdam: Elsevier, 2006.
20. Shen, X., Hu, J., Zhang, M., and Zhang, L., Experimental study on backlash compensation of CNC machine tool, *Adv. Mater. Res.,* 2012, vol. 580, pp. 419–422.
21. Feng, B., Mei, X.S., Guo, L., et al., Backlash compensation on CNC machine tool based on semi-closed loop control, *Adv. Mater. Res.,* 2011, vol. 346, pp. 644–649.
22. Robertz, S.G., Halt, L., Kelkar, S., Nilsson, K., Robertsson, A., Schar, D., and Schiffer, J., Precise robot motions using dual motor control, in *IEEE Int. Conf. on Robotics and Automation,* Anchorage, Alaska, 2010, pp. 5613–5620.

Translated by Bernard Gilbert