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(54) **Method and device for the active compensation of periodic disturbances during hot or cold rolling**

(57) In a method and a corresponding device for the active compensation of periodic disturbances of known frequency during hot or cold rolling, such as roll eccentricities, by means of a control system, with the aid of a linear dynamic controller (2) which comprises a model ($\bar{P}_u$) that describes one part of the dynamic behaviour of the controlled system (1), an output variable ($\bar{y}$) is determined from an input variable (u) on the basis of a reference variable (r), and a compensation signal (u_{LMS}) is generated on the basis of said output variable and a measured output variable (y) of the controlled system (1) and is impressed on the input variable (u) fed to the controlled system (1). As a result, the tracking control is decoupled from the disturbance control, and the controller according to the invention can therefore be inserted into existing control loops for the thickness of the rolling material and/or for the position of the rolls and/or for the rolling force and/or for the roll bending. The compensation signal is generated without prior identification of the eccentricity, which thus permits a more rapid correction of the disturbances.

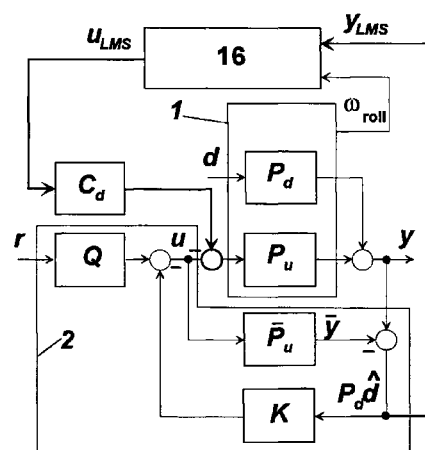


Fig. 4

Description

[0001] The invention relates to a method for the active compensation of periodic disturbances of known frequency during hot or cold rolling, such as roll eccentricities, by means of a control system, and to a corresponding device for carrying out such a method.

[0002] In order to achieve a satisfactory quality of the rolled product, such as strips, for example, in rolling mills on the basis of the existing eccentricities of the rolls, the roll eccentricities must be compensated. The causes for the occurrence of roll eccentricities are, for example, inexact roll grinding, non-circularities in the roll bearings, non-uniform thermal expansion of the rolls or defects in the barrel surface. This leads to periodic thickness fluctuations in the rolled strip which can sometimes be very considerable (up to 40 μm in hot-rolling mills). The thickness deviations of the strip caused by the eccentricities can be counted among the limiting factors in complying with the tolerances by stipulating ever narrower thickness tolerances (for example < 0.8%).

[0003] The active compensation of eccentricities is particularly in demand whenever the aim, when revamping old rolling mills whose mechanical equipment is not state of the art, is to achieve good strip qualities with new automation systems.

[0004] By contrast with passive methods, which merely prevent a gaining effect of the eccentricity by the external thickness control loop, with the active compensation methods an additional signal is generated in the force and/or position control loop of the rolls, the result being that the influence of the eccentricity is effectively suppressed.

[0005] For example, methods are known which determine the total axial displacement of the roll from the available measured signals, see F. Teoh, G. Goodwin, W. Edward and W.R. Davies, "An improved thickness controller for a rolling mill", Proc. 9th IFAC Congress, Budapest, 1984. These methods have the disadvantage that they require precise knowledge of the mill modulus and the plastic deformation coefficient, and that an exact material tracking is required.

[0006] Other methods eliminate the influence of eccentricities directly in the measurement signals, the eccentricity being identified in a first step, and this identified eccentricity being further processed in a further step in a compensation block (PI controller, filter, least squares methods), see EP-0 424 709-A2, for example. These methods have the disadvantage that they react slowly to eccentricities which occur, and can therefore be used only conditionally for short strips.

[0007] One object of the present invention consists in developing a method which overcomes the disadvantages set forth and can be inserted in a simple way into existing control loops for the thickness of the rolled material, the position of the rolls and the roll force, the aim being that the method should not influence the

existing control loop to a greater extent.

[0008] The invention is characterized in that with the aid of a linear dynamic controller which comprises a model that describes one part of the dynamic behaviour of the controlled system, an output variable is determined from an input variable on the basis of a reference variable, and in that a compensation signal is generated on the basis of said output variable and a measured output variable of the controlled system and is impressed on the input variable fed to the controlled system.

[0009] It is a novel feature of this invention that as a result, the tracking control is decoupled from the disturbance control, and the controller according to the invention can be inserted into existing control loops for the thickness of the rolled material and/or for the position of the rolls and/or for the rolling force and/or for the roll bending, because the set-point response is influenced only slightly thereby. The compensation signal is generated without prior identification of the eccentricity, which thus permits a more rapid correction of the disturbances.

[0010] One refinement of the invention consists in that in the frequency domain of the disturbances the model describes the dynamic behaviour of the undisturbed controlled system. If the model coincides with the actual undisturbed behaviour of the roll stand in the frequency domain of interest, the required decoupling is obtained.

[0011] A further refinement of the invention consists in that a compensation signal u_{LMS} is generated on the basis of the difference between calculated output variable and measured output variable and on the basis of at least one frequency of a disturbance. This represents a simple possibility of compensating disturbances, since only the frequency, but neither the amplitude nor the phase of the disturbance, nor the disturbance dynamics (= the disturbance transfer function) need to be known.

[0012] For this purpose, it can advantageously be provided that the angular velocity of a roll is measured for the purpose of determining the frequency of a disturbance. Use is thereby made of the fact that the frequencies of disturbances on the basis of eccentricities correspond to the frequencies of the roll rotation. It is also ensured thereby that the change in the frequencies of the disturbances is also taken into account when there is a change in the strip speed.

[0013] It is possible for the feature that the frequencies of other disturbances are determined with the aid of the geometrical data of the rolls from the measured angular velocity of a roll, to be used to determine the frequencies of the disturbance variables with adequate accuracy, even when the diameter of the rolls differ only to a slight extent.

[0014] It is also advantageous that in the case of a plurality of frequencies which occur, one compensation signal each is generated for each frequency, these compensation signals being superimposed to form one compensation signal. This has the advantage that a plu-

rality of disturbances, such as, for example, a plurality of eccentricities which differ in frequency from one another can be taken into account and compensated.

[0015] A further feature of the method can consist in that the compensation signal $u_{LMS,k}$ is formed for a specific frequency ω in accordance with the equation $u_{LMS,k} = U_{1,k} \sin(k\omega T_a) + U_{2,k} \cos(k\omega T_a)$ with the sampling time T_a and the sampling step k , the factors $U_{1,k}$ and $U_{2,k}$ being determined by a method which is suitable for solving a general quadratic optimization problem. This represents a particularly simple solution adapted to periodic problems. Consideration is given as methods of solution, for example, to online least squares methods, LMS (Least Mean Squares) methods or the Biermann algorithm.

[0016] One embodiment of the invention provides that the input variable corrected by the compensation signal is additionally subjected to non-linear control. Since the method according to the invention is based on a linear input-output-behaviour of the controlled system, the input-output-behaviour of the controlled system must, if appropriate, be exactly linearized by a non-linear control. This is the case, for example, when the servo current of the servo valve for the hydraulic cylinder of the mill stand is used as input variable for the controlled system.

[0017] The method can be designed such that the force in the hydraulic cylinder, or the roll force is used as output variable. These forces can be determined simply and with an accuracy which suffices for the method. The force in the hydraulic cylinder can be determined by measuring the pressure (in one chamber of the cylinder piston in a single-acting cylinder) or the pressures (in both chambers of the cylinder in a double-acting cylinder) in the hydraulic cylinder. The roll force can be determined in the stationary state from the force in the hydraulic cylinder, taking account of the weights of the rolls and any forces from the bending cylinders or by a dedicated measuring device. The eccentricities can be rapidly reduced in this way. By contrast with this, there is less advantage in using the strip exit thickness, since there is a relatively large distance between the roll gap and thickness measuring instrument, and the strip exit thickness is detected only with a time delay, the dead time not being constant but depending on the strip exit speed.

[0018] A further variant of the method can be configured such that use is made as output variable of a relevant signal of at least one bending or balancing cylinder, such as the force in the cylinder or a input signal for the cylinder. If the eccentricities to be suppressed are present in the measurement signals (force, pressures, input signal), by comparison with the force in the hydraulic cylinder or the rolling force this generally permits a reduction in the eccentricities which is larger in absolute terms, but slower.

[0019] Finally, it has proved to be particularly advantageous that in sequential time intervals use is

respectively made as output variable of the force in the hydraulic cylinder or the rolling force or a relevant signal of at least one bending or balancing cylinder, such as the force in the cylinder or a drive signal for the cylinder. It is thereby possible to make an optimum combination of the advantages of the two embodiments of the invention.

[0020] The variant method that a phase shift between the input signal and output signal of more than 90° is prevented serves the purpose of ensuring the mode of operation of the control system and of avoiding a gaining effect of the disturbances by the control system according to the invention.

[0021] It can be provided that for this purpose the compensation signal is subjected to a transfer function C_d which obeys the condition $|(C_d P_u)(j\omega) - 1| \approx 1$ in the domain of the frequencies of the disturbance, P_u being the transfer function of the controlled system without disturbance.

[0022] Moreover, with regard to the linear dynamic controller, the method can provide that the model is a mathematical model. This permits individual adaptation to the real behaviour of the mill stand by mathematically taking account of the corresponding effects which occur.

[0023] Another possibility consists in setting up the model on the basis of an identification method. In this case, the behaviour of the mill stand in the frequency band of interest can be determined from measured data such as input and output variables for the roll stand. This does not constitute a disadvantage, since this operation is performed only once to determine the model and need not be repeated continuously during the rolling process, as in the case of the identification of eccentricities.

[0024] The method can also be configured such that the control system according to the invention is integrated into the control loop for a bending or balancing cylinder.

[0025] The device for the active compensation of periodic disturbances of known frequency during hot or cold rolling, such as roll eccentricities, using a control unit, is characterized in that the control unit has a linear dynamic controller which comprises a model that describes one part of the dynamic behaviour of the controlled system and which determines an output variable from an input variable on the basis of a reference variable, and in that the controller is connected to a disturbance controller which generates a compensation signal from the difference between a measured output variable of the controlled system and the determined output variable, and in that the disturbance controller is connected to the input of the controlled system for the purpose of feeding the compensation signal to the input variable. The decoupling of the tracking control from the disturbance control is thereby achieved.

[0026] The possible design that a non-linear controller is additionally arranged at the input of the control-

led system serves the purpose of exactly linearizing the input-output-behaviour of the controlled system in the entire operating range.

[0027] The possible design that a device for determining the angular velocity of at least one roll is connected to the disturbance controller permits the generation of a compensation signal taking account of the frequency of the disturbance, which corresponds to the frequency of rotation of the roll.

[0028] The invention is explained in more detail with the aid of an exemplary refinement and of Figures 1 to 8.

Figure 1 shows a diagrammatic representation of the general configuration on which the control system according to the invention is based, with a linear dynamic controller.

Figure 2 shows a diagrammatic representation of the mill stand.

Figure 3 shows the position and force control loop.

Figure 4 shows a control system according to the invention with a disturbance controller.

Figure 5 shows the force characteristic and strip exit thickness characteristic, with and without control according to the invention and with the use of one compensation variable.

Figure 6 shows the force characteristic and strip exit thickness characteristic, with and without control according to the invention and with the use of two compensation variables.

Figure 7 shows the force characteristic and strip exit thickness characteristic, with and without control according to the invention and in the case of a step in the reference variable.

Figure 8 shows the corresponding characteristics of the position of the hydraulic cylinder and the servo valve in relation to Figure 7.

[0029] Illustrated in Figure 1 are the input variable u , which represents the manipulated variable or input variable acting on the system 1, and the disturbance variable d , which represents a harmonic disturbance of known frequency but unknown phase and amplitude. The input variable u is subjected to a transfer function P_u , and the disturbance variable d is subjected to a transfer function P_d , the result being the measured variable or the variable to be controlled or the output variable y . The transfer function P_u can be assumed as known in the frequency domain of interest from a mathematical model or from an identification method. Since it is generally not possible to determine exactly at which point in the system 1 the disturbance acts, it must be assumed in the case of the disturbance transfer function P_d that the latter is unknown, or can even change during the process. This is the case whenever the disturbance acts at a different point in the system. This is the case, for example, with a four-high roll stand when prior to a roll change only the work roll has a significant eccentric-

ity, and after the roll change only the backup roll has a significant eccentricity.

[0030] The general solution consists in using a linear dynamic controller 2 having two degrees of freedom $C = [C_r, C_y]$ in its most general form. It holds for a controller having one degree of freedom (P, PI, PD, PID controllers) that $C_r = C_y$. With the secondary condition that the disturbance transfer function P_d is not exactly known and the frequency of the disturbance changes, it is not possible to determine C with the aid of standard methods such that the effect of the disturbance variable d in the measurement signal y is effectively suppressed and immediately follows the desired reference signal r as effectively as possible.

[0031] Since the disturbance variable d is periodic, and its frequency is present as measured variable, the control can be effected by the control concept according to the invention as described below.

[0032] The design of a four-high stand is shown diagrammatically in Figure 2. The hydraulic piston 3 of the hydraulic cylinder 4 acts in accordance with the arrow on the axis of the upper backup roll 5. The backup rolls 5 engage with the work rolls 6. The variables named below are fed to the automation system 8, p_{h1} , p_{h2} and s_h denoting the pressures and the position of the hydraulic cylinder 4, x_{spool} denoting the position of the servo valve 7, ω_{roll} denoting the angular velocity of one of the rolls, in this case the upper work roll 6, and h_{ex} denoting the strip exit thickness of the strip 17. The servo current i_{servo} is prescribed for the servo valve 7 by the automation system 8.

[0033] The force acting on the hydraulic cylinder 4 is represented as F_h and is calculated from the measured pressures p_{h1} , p_{h2} of the two chambers of the hydraulic cylinder 4. The force F_h corresponds in the stationary state to the rolling force corrected for weights and possible forces of bending cylinders. The force thus measured is available with sufficient accuracy despite the occurrence of the effects of hysteresis and friction, and of quantization errors.

[0034] Represented in Figure 3 is the position or force control loop, which comprises an inner control loop for the servo valve with the servo controller 10, and an outer control loop with a non-linear controller 9 for compensating the non-linearity of the hydraulic cylinder, and a linear dynamic controller 2. The servo controller 10 prescribes the servo current i_{servo} , which acts on the system 15. The eccentricity force F_{ecc} reproduces the influence of the eccentricity on the system 15. The system 15 takes account of the operations 11 in conjunction with the servo valve, the operations 12 in conjunction with the hydraulic cylinder, the stand dynamics 13 and deformation processes 14. With the aid of p_{h1} , p_{h2} and s_h , the system 15 delivers as measurement results the pressures and the position of the hydraulic cylinder, which are fed to the non-linear controller 9. One of the two variables is fed to the linear dynamic controller 2 as output variable y . A possible fur-

ther output variable y (not represented) would be the pressure in a bending or balancing cylinder. The variable x_{spool} denotes the position of the servo valve, and ω_{roll} denotes the angular velocity of one of the rolls.

[0035] By comparison with classical control concepts, which take account only of the static non-linearity in the case of the non-linear controller 9, an exact linear input-output-behaviour can be generated using the methods of differential geometry (see, for example, A. Isidori, "Nonlinear Control Systems", Springer Verlag, 1989) or flatness-based control systems. With this assumption, that the system in Figure 3 from the input u to the output y (p_{h1} and p_{h2} , s_h , pressure in a bending or balancing cylinder) behaves linearly in the operating region (the one where eccentricities are to be expected), it is possible to describe the elements of non-linear controller 9 servo controller 10 and system 15 with the aid of the system 1 represented in Figure 1, the linear dynamic controller 2 again being considered in its most general form as a controller having two degrees of freedom $C = [C_r, C_y]$.

[0036] The linear dynamic controller 2 of Figure 3 can be represented as in Figure 4 for BIBO-stable transfer functions P_u (BIBO = bound input bound output) by factorizing all internally stabilizing controllers on a control loop (see, for example, M. Vidyasagar, "Control System Synthesis: A Factorization Approach", MIT-Press, 1987). In this case, $\bar{P}_u$ is a model of the transfer function P_u , it being possible to decouple the tracking control and disturbance control in the frequency domain of interest given agreement between $\bar{P}_u$ and P_u . This has the advantage that a possibly existing control loop, as represented in Figure 3, can be retained for the output variable y , all that need be done is to change the implementation. K and Q are controllers whose properties are calculated from the controllers used.

[0037] The suppression of the periodic disturbances d is performed with the aid of a control concept which is based on the projection theorem in Hilbert space (see, for example, D.G. Luenberger, "Optimization by Vector Space Methods", John Wiley & Sons, 1968). The application of the projection theorem leads to the disturbance controller 16 in Figure 4 with the input variables y_{LMS} and ω_{roll} and the output variable u_{LMS} .

[0038] The transfer function C_d is fixed in this case so as to fulfil the condition $|(C_d P_u)(j\omega) - 1| \approx 1$ with the imaginary unit j in the frequency domain where eccentricities can occur. The disturbance controller 16 comprises a reference generator which, at the instant kT_a , generates the signals $e_{1,k} = \sin(k\omega T_a)$ and $e_{2,k} = \cos(k\omega T_a)$ with the sampling time T_a , the sampling step k and the known eccentricity frequency ω , which is proportional via geometry factors, to the measured angular velocity ω_{roll} of the rolls. The output variable u_{LMS} at the instant kT_a , $u_{\text{LMS},k}$ follows via the relationship $u_{\text{LMS},k} = U_{1,k}e_{1,k} + U_{2,k}e_{2,k}$. According to the projection theorem, the variables $U_{1,k}$ and $U_{2,k}$ are the online solutions of a general quadratic optimiza-

tion problem which can be solved using methods known per se, such as, for example, using the recursive least squares method (L. Ljung, "System Identification: Theory for the User", Prentice Hall, 1987) or using an adaptive LMS = (Least Mean Squares) algorithm (M. Gevers and G. Li, "Parametrizations in Control, Estimation and Filtering Problems", Springer Verlag, 1993).

[0039] In the case of the adaptive LMS algorithm, the recursion rule for U_1 and U_2 is

$$\begin{bmatrix} U_{1,k+1} \\ U_{2,k+1} \end{bmatrix} = \begin{bmatrix} U_{1,k} \\ U_{2,k} \end{bmatrix} + \mu \begin{bmatrix} e_{1,k} \\ e_{2,k} \end{bmatrix} y_{\text{LMS},k}$$

with a suitably selected $\mu > 0$, but small enough in order to guarantee convergence.

[0040] According to Figure 4, the output variable y is compared to the corresponding values calculated by the model $\bar{P}_u$, the difference being fed to the controller K as $P_d \hat{d}$ and the disturbance controller 16 as y_{LMS} .

[0041] In the lower illustration, Figure 5 shows the strip exit thickness deviation (in metres) with eccentricity compensation according to the invention (thick line) and without it (thin line), as a function of time t , the force F_h of the hydraulic cylinder serving here as compensation variable. In the upper illustration, the deviation ΔF_h (in newtons) of the force F_h from the set point is represented as a function of time t , respectively with eccentricity compensation according to the invention (thick line) and without it (thin line).

[0042] In the case of the use of the force F_h of the hydraulic cylinder as relevant compensation variable, the eccentricity in the force F_h , certainly does vanish almost completely, and the residual eccentricity remaining in the strip exit thickness is now a function, on the one hand, of the friction forces and, on the other hand, of the ratio of plastic deformation coefficient to mill modulus and the roll weights. In the case indicated, there was a pronounced work roll eccentricity in conjunction with a strip having a low material stiffness coefficient.

[0043] If it is desired to achieve a further suppression of the residual eccentricity, depending on the stand design recourse must be made to other signals such as pressures in the bending cylinders. In Figure 6, the lower illustration shows the strip exit thickness deviation (in metres) with eccentricity compensation according to the invention (thick line) and without it (thin line), as a function of time t , use having been made as compensation variable of the force F_h of the hydraulic cylinder for the period from $t=0$ to t_1 , and of the pressure or the force in the bending cylinder for positive bending in the case of the full Mae West mill stand design for the period from t_1 onwards. The upper illustration once again shows the deviation ΔF_h (in Newtons) of the force F_h from the set-point, as a function of time t , respectively with eccentricity compensation according to the invention (thick line) and without it (thin line).

[0044] It is to be seen that, by comparison with Figure 5, it was possible for the strip exit thickness deviation to be further reduced. In the case of the use of the force F_h as compensation variable, the eccentricity defect in the strip exit thickness decreases rapidly, and a further, but slower reduction in the eccentricity defect can be achieved by the subsequent use of the pressure or the force in the bending cylinder as compensation variable.

[0045] In the lower illustration, Figure 7 shows the strip exit thickness deviation (in metres), with eccentricity compensation according to the invention (thick line) and without it (thin line), as a function of time t , and, here again, the force F_h of the hydraulic cylinder serving as compensation variable. In the upper illustration, the deviation ΔF_h (in newtons) of the force F_h from the set-point is represented as a function of time t , respectively with eccentricity compensation according to the invention (thick line) and without it (thin line).

[0046] In the upper illustration, Figure 8 shows the associated time characteristic of the position s_h of the hydraulic cylinder, and in the lower illustration the time characteristic of the position x_{spool} of the servo valve, respectively with eccentricity compensation according to the invention (thick line) and without it (thin line).

[0047] In the case both of a work roll and of a backup roll, there is a corresponding eccentricity here, the rolled strip having a relatively low material stiffness. After 1 second, there is a step in the reference variable by 100 micrometres in the position control loop for s_h , in order to cause the reduction in the strip exit thickness. It is to be seen that the reference step after 1 second is not impaired by the compensation according to the invention, and that the suppression of the eccentricity in the strip exit thickness is very good.

[0048] The invention is not limited to the application in four-high stands, but can be used for any type of roll stands in the case of cold-rolling or hot-rolling mills, plus also for two-high roll stands.

Claims

1. Method for the active compensation of periodic disturbances of known frequency during hot or cold rolling, such as roll eccentricities, by means of a control system, characterized in that with the aid of a linear dynamic controller (2) which comprises a model ($\bar{P}_U$) that describes one part of the dynamic behaviour of the controlled system (1), an output variable ($\bar{y}$) is determined from an input variable (u) on the basis of a reference variable (r), and in that a compensation signal (u_{LMS}) is generated on the basis of said output variable and a measured output variable (y) of the controlled system (1) and is impressed on the input variable (u) fed to the controlled system (1).
2. Method according to Claim 1, characterized in that

in the frequency domain of the disturbances (d) the model ($\bar{P}_U$) describes the dynamic behaviour of the undisturbed controlled system (P_U).

3. Method according to Claim 1 or 2, characterized in that a compensation signal (u_{LMS}) is generated on the basis of the difference (y_{LMS}) between calculated output variable ($\bar{y}$) and measured output variable (y) and on the basis of at least one frequency of a disturbance (d).
4. Method according to one of Claims 1 to 3, characterized in that the angular velocity (ω_{roll}) of a roll (5, 6) is measured for the purpose of determining the frequency of a disturbance (d).
5. Method according to Claim 4, characterized in that the frequencies of other disturbances (d) are determined with the aid of the geometrical data of the rolls (5, 6) from the measured angular velocity (ω_{roll}) of a roll (6).
6. Method according to one of Claims 1 to 5, characterized in that, in the case of a plurality of frequencies which occur, one compensation signal each is generated for each frequency, these compensation signals being superimposed to form one compensation signal (u_{LMS}).
7. Method according to one of Claims 1 to 6, characterized in that the compensation signal is formed for a specific frequency ω in accordance with the equation $u_{LMS,k} = U_{1,k} \sin(k\omega T_a) + U_{2,k} \cos(k\omega T_a)$ with the sampling time T_a and the sampling step k , the factors $U_{1,k}$ and $U_{2,k}$ being determined by a method which is suitable for solving a general quadratic optimization problem.
8. Method according to one of Claims 1 to 7, characterized in that the input variable (u) corrected by the compensation signal (u_{LMS}) is additionally subjected to non-linear control (9).
9. Device for the active compensation of periodic disturbances of known frequency during hot or cold rolling, such as roll eccentricities, using a control unit, characterized in that the control unit has a linear dynamic controller (2) which comprises a model ($\bar{P}_U$) that describes one part of the dynamic behaviour of the controlled system (1) and which determines an output variable ($\bar{y}$) from an input variable (u) on the basis of a reference variable (r), and in that the controller (2) is connected to a disturbance controller (16) which generates a compensation signal (u_{LMS}) from the difference between a measured output variable (y) of the controlled system (1) and the determined output variable ($\bar{y}$), and in that the disturbance controller (16) is connected to the

input of the controlled system (1) for the purpose of feeding the compensation signal (u_{LMS}) to the input variable (u).

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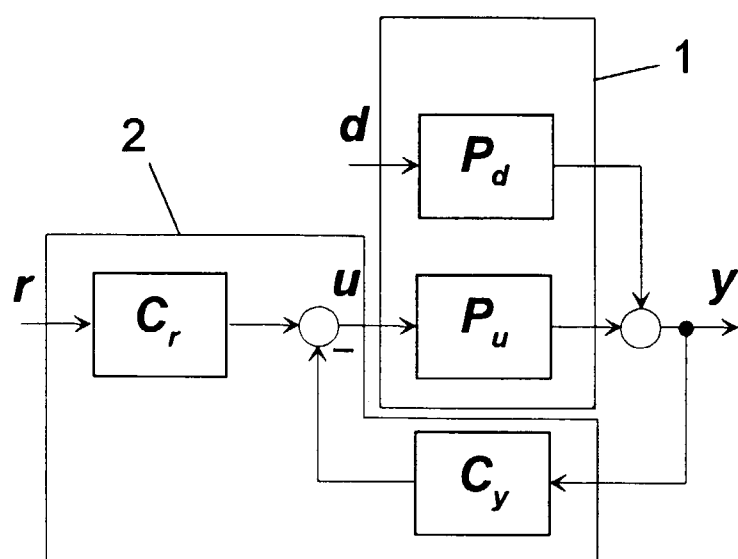


Fig. 1

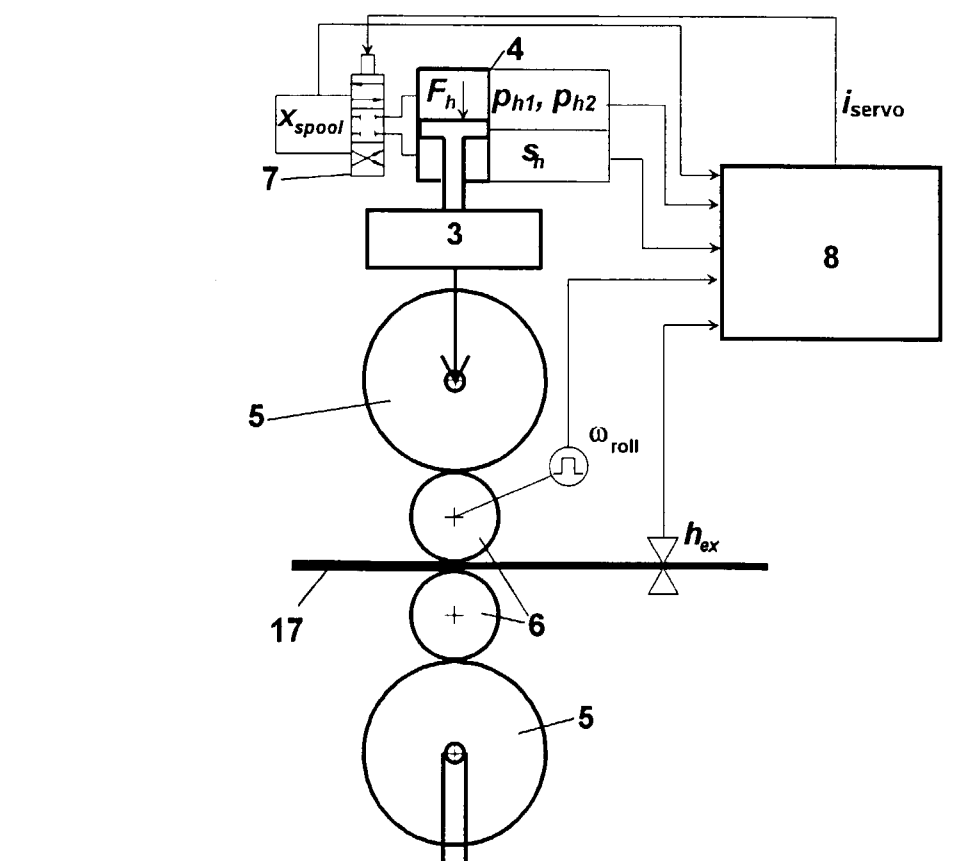


Fig. 2

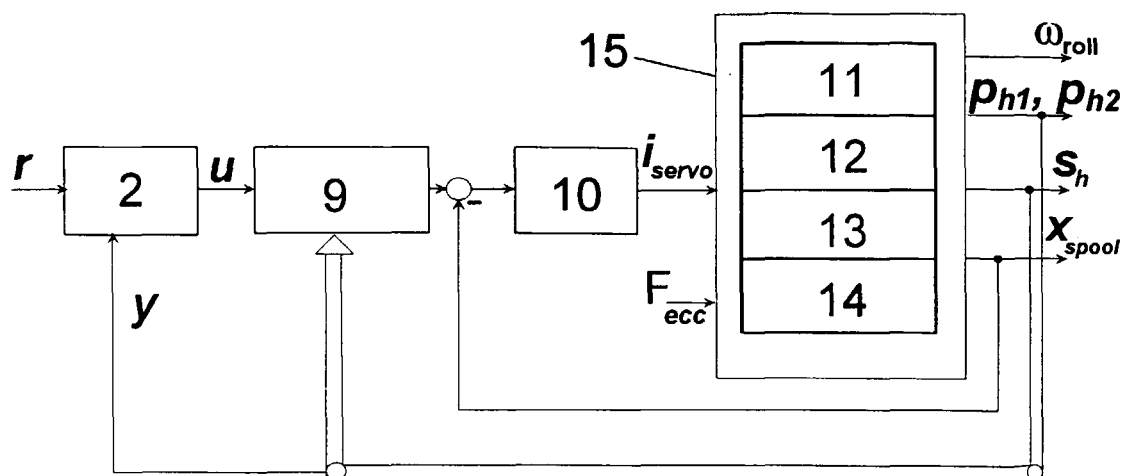


Fig. 3

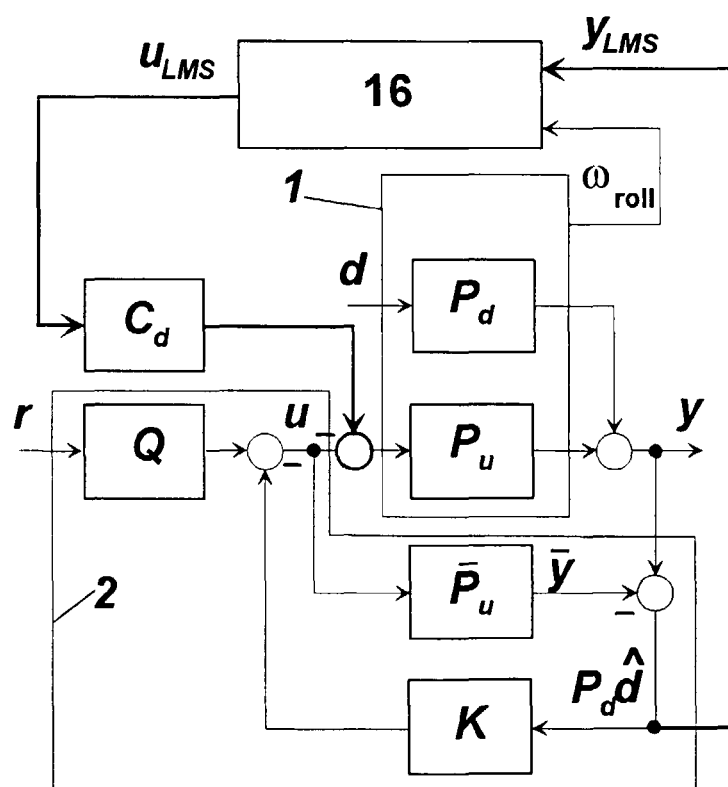


Fig. 4

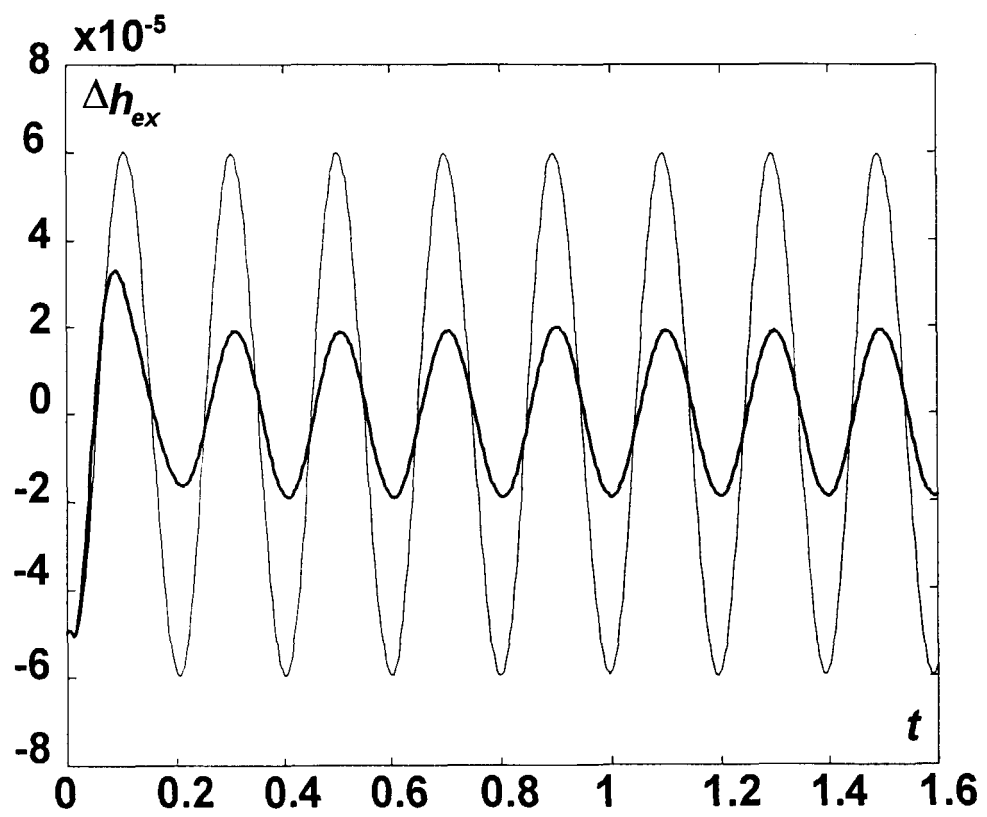
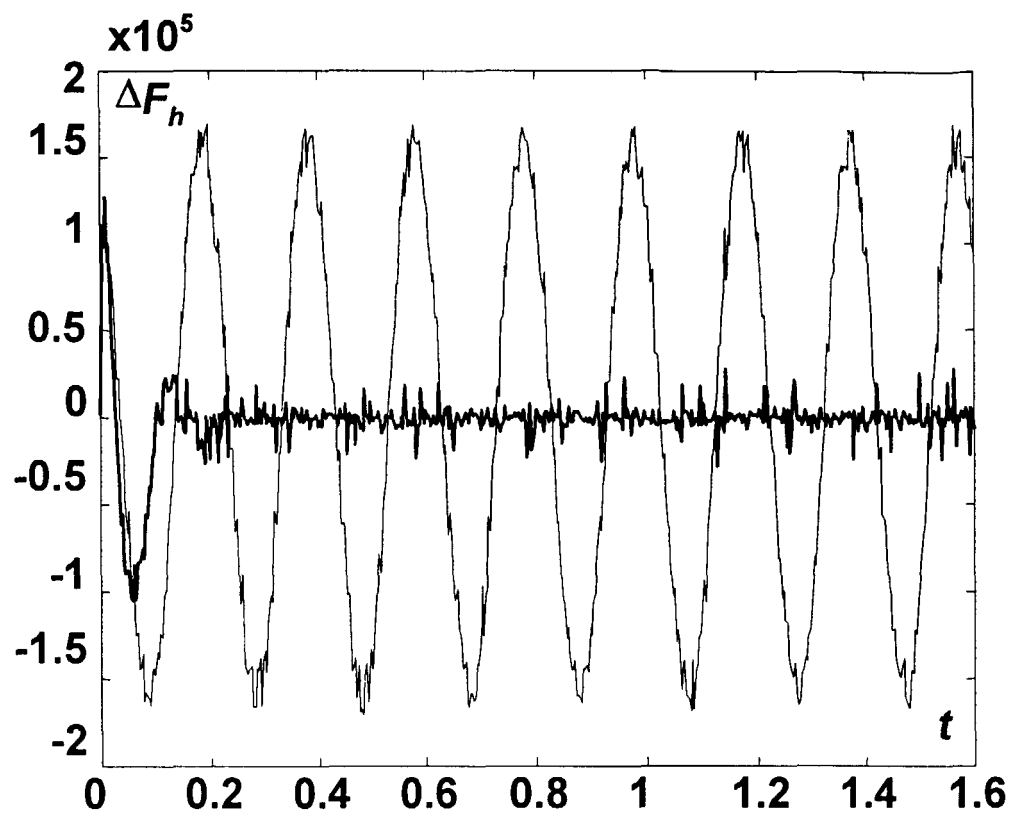


Fig. 5

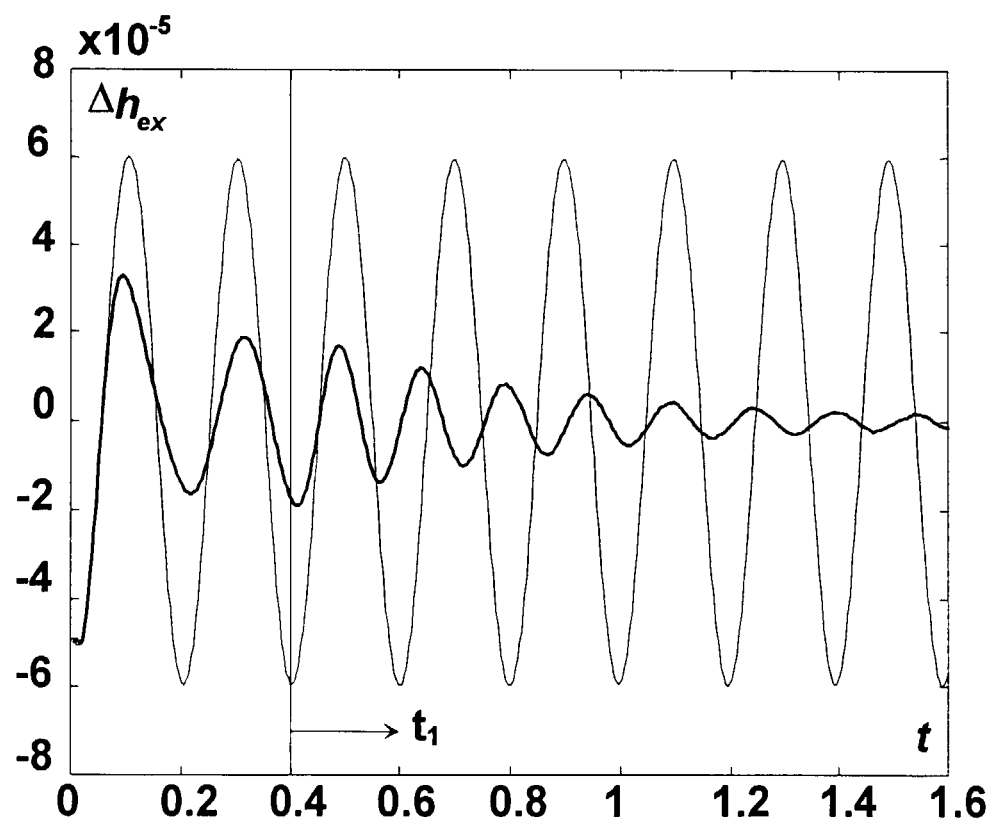
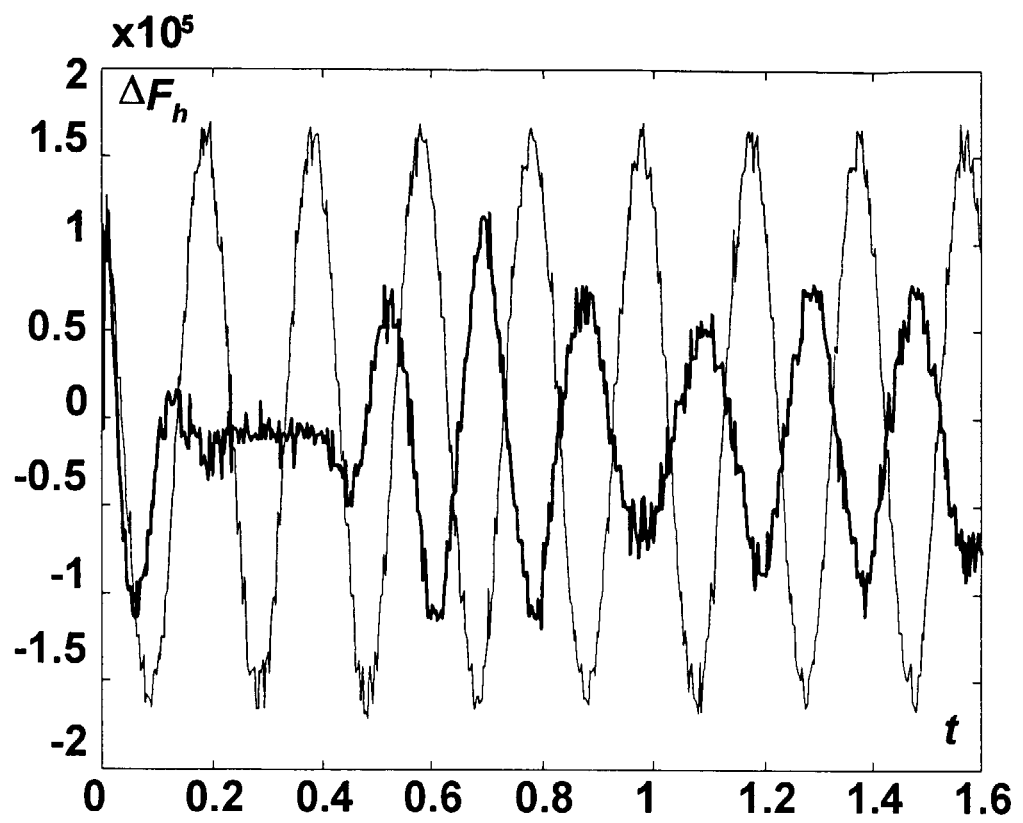


Fig. 6

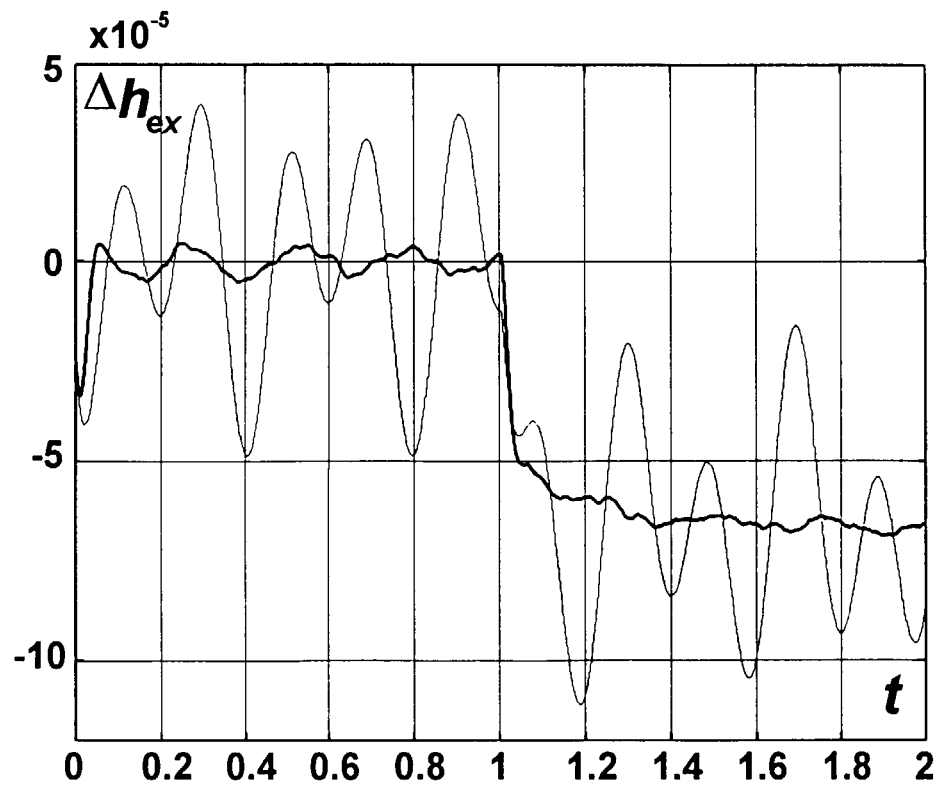
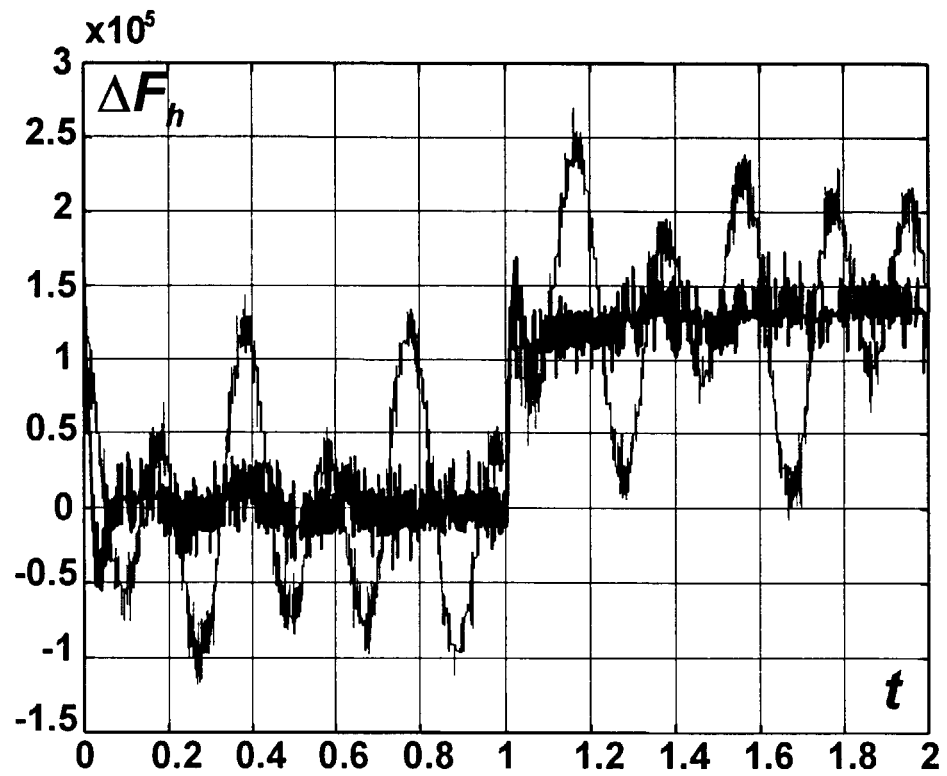


Fig. 7

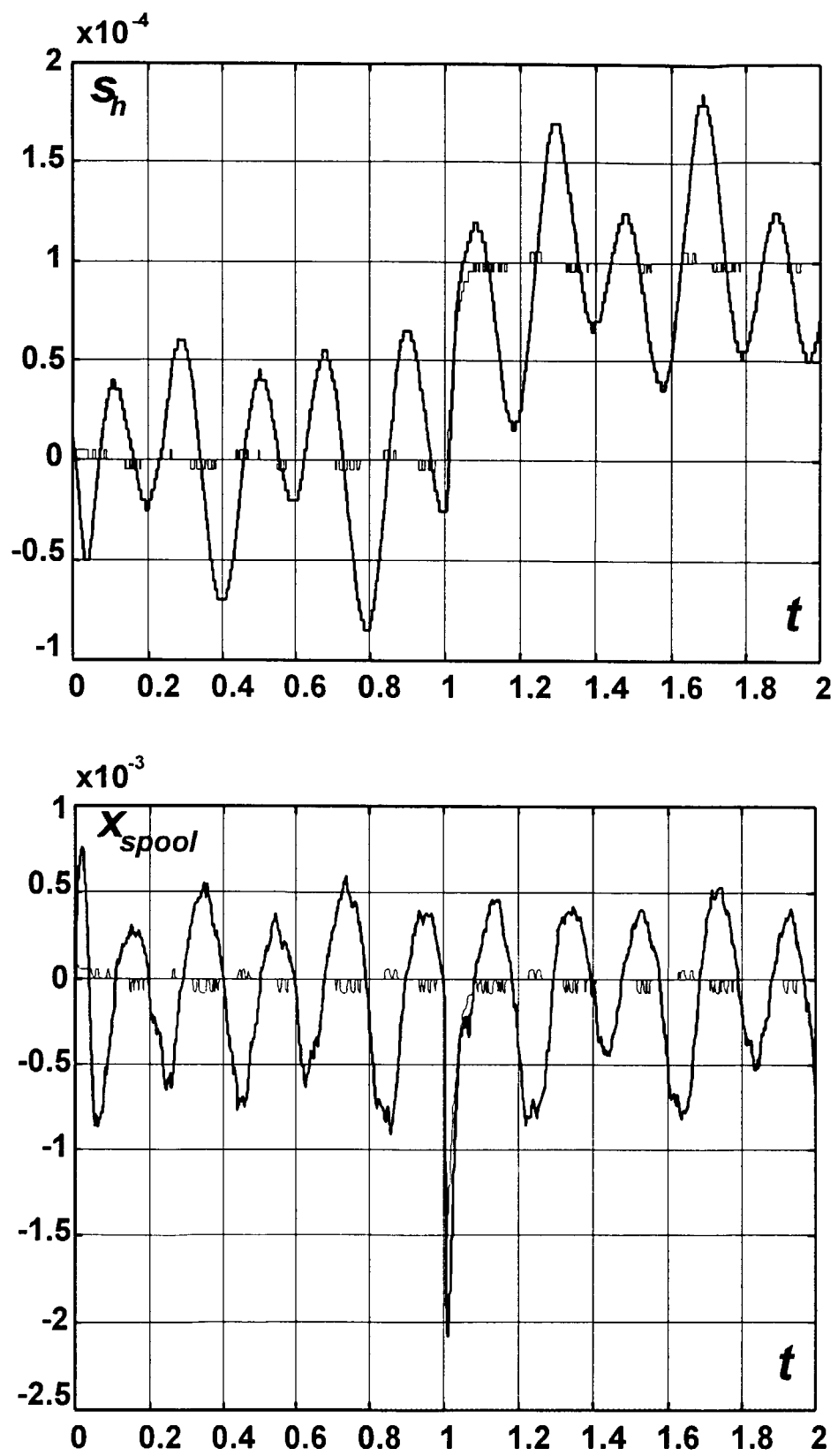


Fig. 8