INNOVATIVE ADAPTIVE CONTROL OF MATERIAL FATIGUE TEST MACHINES USING AN MCS CONTROLLER

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Abstract: The paper presents some issues related to the control of fatigue test machines based on *W(t)* parameter taking into account the simultaneous interaction of stress and strain. This parameter is defined as a product of these values. Such a research method represents a new approach in fatigue testing with an innovative control system. Because of the *W(t)* function characteristics, the system presents nonlinear behavior and there is a significant deterioration of the control quality and the controlled signal significantly differs from the reference signal waveform. This problem can be solved by introducing a nonlinear block into the feedback loop. Fatigue tests have been carried out for sinusoidal and randomized reference signal waveforms. These tests have proved that the controlled signal follows reference values with an appropriate control quality.

Key words: fatigue test machines, stress, non-linear control, adaptive control, Minimal Control Synthesis

1. INTRODUCTION

Application of high performance and endurance materials is nowadays one of fundamental tasks of the production engineering. But materials tend to fail after being exposed to a repetitive stress. Therefore materials fatigue testing is a very important research, because of safety and economical reasons in many industry branches. Fatigue tests are performed on fatigue test stands, using specially designed devices which expose material samples to different loadings. Control system of a fatigue machine should force stress and strain time sequence consistent with the preset user requirements. This task can be solved by generating an appropriate voltage signal applied to the input of hydraulic servo valve. An example of such a machine is presented in Fig. 1. This voltage control signal is generated by a controller operating in a closed-feedback loop. An extensive survey of control methods for these machines has been presented in (Pereira-Dias et al., 2013). Fatigue testing machine is a hydraulic servo system with an output feedback. The main control problems are the dynamics of the machine, nonlinearities and parameter variations (including variations of the material sample parameters) so there is a need of an adaptive control (Ann and Truong, 2009). This paper presents some issues related to control of these machines based on the $W(t)$ parameter taking into account the simultaneous interaction of stress and strain. This parameter is defined as a product of these values. Detailed description of this parameter can be found in (Macha et al., 2009). Direct determination of material fatigue characteristics is possible when the control system measures both stress and strain values. Then, the $W(t)$ parameter is compared with preset reference waveform. Research has been performed for both sinusoidal and random signal reference waveforms. Problems of combined torsion and bending fatigue have been discussed in (Rozumek and Marciniak, 2008; Rozumek et al., 2010).

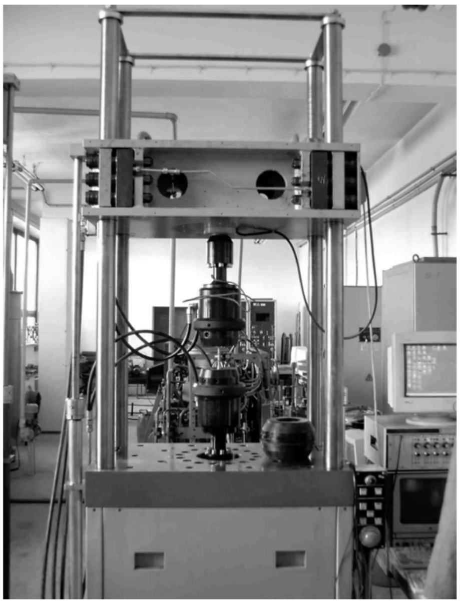

Fig. 1. An example of the hydraulic fatigue testing machine

2. AN EXAMPLE OF *W*(*t*) PARAMETER CONTROL

As an example of the *W(t)* parameter control there has been assumed a functional form, described in detail in (Łagoda et al., 1999; Łagoda, 2001b)**:**

$$W(t) = \tfrac{1}{4}\sigma(t)\varepsilon(t)\{\mathrm{sgn}[\sigma(t)] + \mathrm{sgn}[\varepsilon(t)]\} \quad (1)$$

where:

$\sigma(t)$ – stress (force),

$\varepsilon(t)$ – strain.

In order to determine the fatigue effort of the material, the sample should be exposed to a cyclic stress with preset waveform *W*(*t*) until there is an evidence of loss of mechanical properties. Standard automatic control system of the machine might look as shown in Fig. 2.

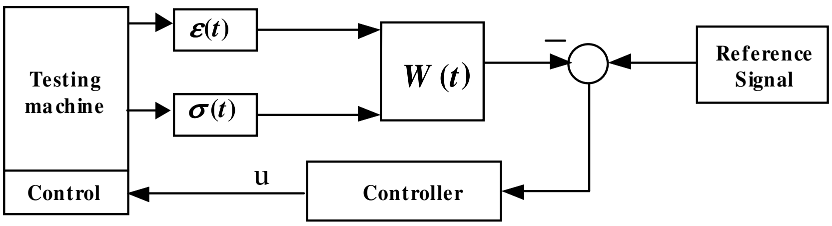

Fig. 2. An example of the hydraulic fatigue testing machine

Due to the nature of the *W*(*t*) the system becomes non-linear and there is a significant deterioration in the control quality and controlled signal is significantly deformed. An example system response to the typical sinusoidal signal has been presented in Fig. 3 (Łagoda, 2001a). Figure 3 shows courses of a cycle of stress, strain and the *W(t)* parameter for a sinusoidal course according to Eq. (1). On the right courses of the *W(t)* parameter taking into account the signs of both stress and strain. As it can be seen the shape of output signal differs from the reference signal (sinusoidal signal).

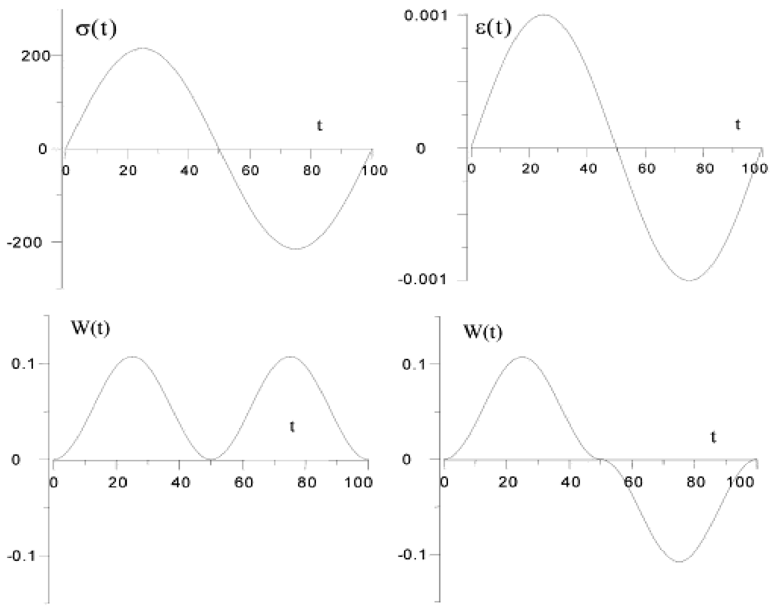

Fig. 3. Cycles of stress, strain and *W(t)* parameter

The solution to this problem can be achieved by introducing a non-linear block *S(u)* (Gluza and Kalinowski, 2009; Kalinowski et al., 2004) into the feedback loop. This block modifies the control signal as follows:

$$S(u) = \begin{cases} \sqrt{u} & for \;\; u \geq 0 \\ -\sqrt{|-u|} & for \;\; u < 0 \end{cases} \tag{2}$$

This is illustrated by a block diagram shown in Fig. 4.

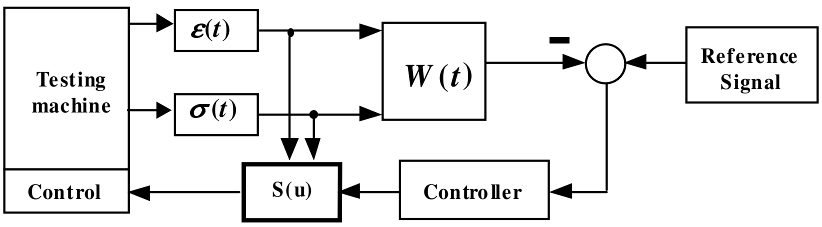

Fig. 4. An idea of the *W*(*t*) parameter control

In order to ensure the desired accuracy of the reference waveform tracking it is advisable to apply an adaptive control algorithm in the feedback loop. This is necessary because of (among others) time varying mechanical properties of the sample. The PID control – even precisely tuned (Kasprzyczak and Macha, 2007; Kasprzyczak and Macha, 2008) – is not enough because over time and increasing fatigue, the system parameters deviate from their initial values.

3. ALGORITHM OF MINIMAL CONTROL SYNTHESIS ADAPTIVE CONTROL

3.1. The basic version of the MCS algorithm

Properties of the Minimal Control Synthesis (MCS) algorithm are discussed in detail in (Stoten and Benchoubane, 1990a; Stoten and Benchoubane, 1990b; Stoten and Benchoubane, 1993). Figure 5 shows a block diagram of the control system with an adaptive MCS control.

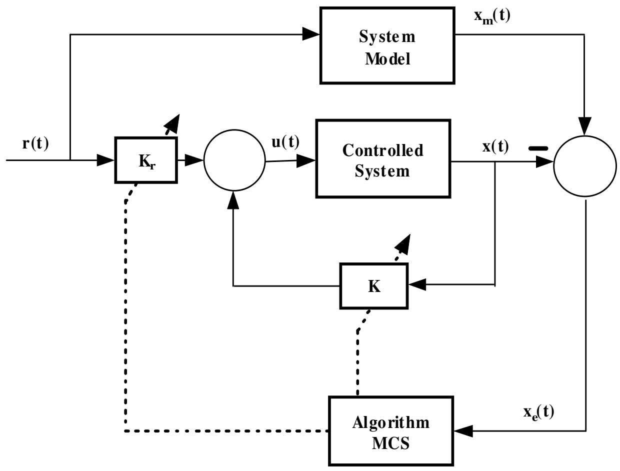

Fig. 5. Block diagram of a control system with MCS controller

Below there are described the key assumptions concerning the discussed algorithm. Control vector defined by the MCS algorithm can be described by the following equation:

$$u(t) = K(t)x(t) + K_r(t)r(t) \tag{3}$$

where:
K (vector) i K_r (scalar) are adaptive gains of the MCS algorithm,
x,(x_m) – state vector characterizing the state of the object (object model),
u – control signal vector,
r – reference values vector.
Time-varying (adaptive) MSC gains can be described as follows:

$$K(t) = \int_0^t \alpha e_y(\tau)x^T(\tau)d\tau + \beta e_y(t)x^T(t) \tag{4}$$

$$K_r(t) = \int_0^t \alpha e_y(\tau)r(\tau)d\tau + \beta e_y(t)r(t) \tag{5}$$

where:
scalar values α, β – weight parameters of MSC algorithm gains,
e_y – output error signal.

$$e_y(t) = C_e x_e(t) = C_e(x_m(t) - x(t)) \tag{6}$$

where:
x_e – state equation errors,
C_e – matrix coefficients obtained from the solution of the Lyapunov equation (Stoten and Benchoubane, 1990a).

3.2. A modified version of the MCS algorithm

In this control algorithm for higher order systems there are required higher-order derivatives (i.e. speed, acceleration) of the *x*(*t*) signal. But these signals are often unavailable for direct measuring, so there is a need to estimate their values in an indirect way. Due to the above-mentioned limitations, and the computational complexity, a modified (simplified) version of the present algorithm has been proposed. SMCS algorithm (Kalinowski et al., 2004) is shown in Fig. 6.

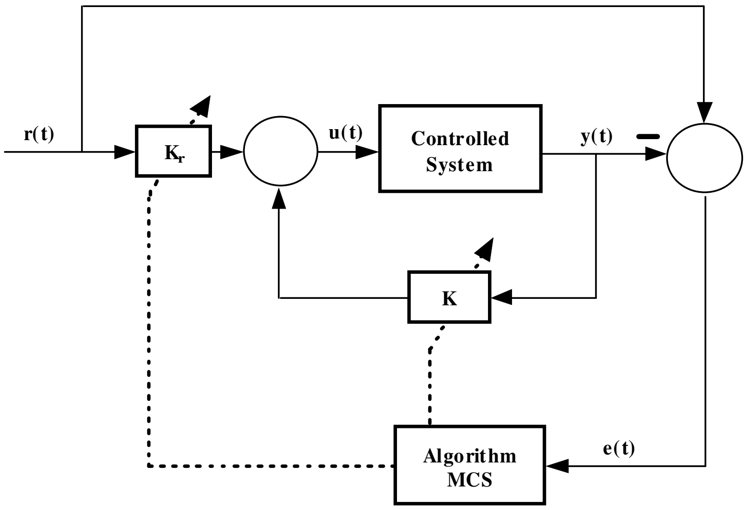

Fig. 6. Block diagram of a control system with SMCS controller

Gains K and K_r have been directly determined using controlled object output signal $y(t)$. Gain K is, in this case, a scalar, and only the algorithm parameters α, β have to be tuned. Then the SMCS gains can be described as follows:

$$K(t) = \int_0^t \alpha e(\tau) y(\tau) d\tau + \beta e(t) y(t) \tag{7}$$

$$K_r(t) = \int_0^t \alpha e(\tau) r(\tau) d\tau + \beta e(t) r(t) \tag{8}$$

Continuous SMCS control algorithm, can be approximated by an expression, in which continuous integration have been replaced by a discrete summation. Therefore the time-discrete incremental algorithm SMCS with sampling period T_p can be described by the following equations:

$$K(i) - K(i-1) = \beta[e(i)y(i) - e(i-1)y(i-1)] + \alpha T_p e(i)y(i) \tag{9}$$

$$K_r(i) - K_r(i-1) = \beta[e(i)r(i) - e(i-1)r(i-1)] + \alpha T_p e(i)r(i) \tag{10}$$

The α, β parameter values have been chosen empirically on the basis of simulation experiment using an identified dynamical model of the controlled object. There has been adopted an integral control quality assessment criterion as an Integral of Squared Error (ISE)

4. CONTROL OF FATIGUE TEST MACHINES WITH W(t) PARAMETER ON THE EXAMPLE OF SHM 250 MACHINE

Digital control system of the fatigue test machine SHM 250 enables control of the following parameters: stress, strain and $W_o(t)$ parameter. The essential feature of this system is the direct use of sensors and actuators installed on the machine. Therefore input signals to the system are amplified signals from a strain gauge bridge and the output signals are the signals from the DAC cards. In order to ensure the appropriate accuracy of the reference waveform tracking, it is necessary to control in closed feedback loop. In the dynamic loading process there exist some disturbances, that can cause the control performance to decrease, so there is a need to adaptive control (Ann and Truong, 2009). The control system must be able to work with classic controllers and - in the case of time varying mechanical properties of the sample – as an adaptive system. Below, there are presented examples of waveforms of output signals of the controlled object. The waveforms have been recorded during the fatigue tests performed on the machine SHM-250. The signal values shown in the graphs are represented in volts. The following notation has been applied to the drawings: W – controlled value of the $W(t)$

parameter, W_{ref} – reference value of the $W(t)$ parameter. Figure 7 and Fig. 8 show excerpts of the control program reports in the control system with a SMCS controller - when the reference signal is a sinusoidal signal.

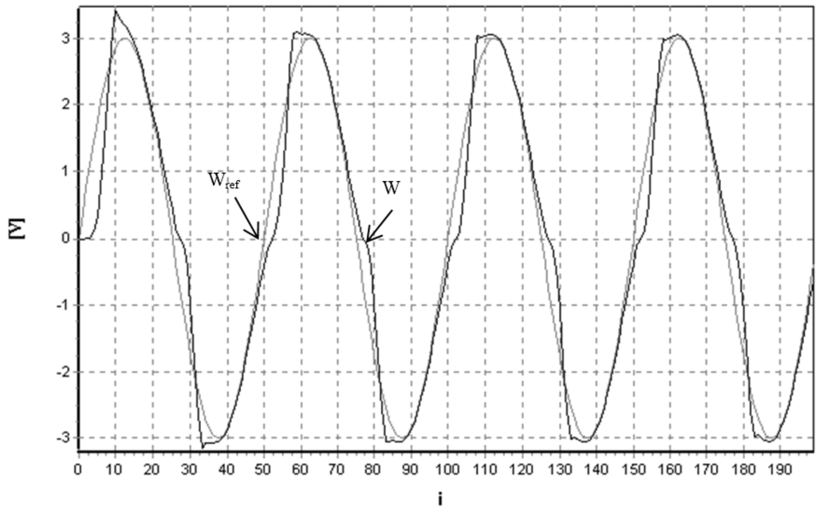

Fig. 7. Sinusoidal signal with SMCS controller

Figure 7 shows the initial waveforms of the controlled and reference signals. Figure 8 shows the waveforms of these signals recorded after twenty cycles. By a comparison of the waveforms from Fig.7 and Fig.8 it can be seen that the adaptive algorithm operates correctly. As shown in Fig. 8 controlled signal tracks the reference signal waveform with high accuracy. The longer is the operating time, the better is the accuracy (controller parameters adjust to the machine and material sample parameters).
Figure 9 shows some excerpts of reports from the control program when the reference signal is a pseudo-random waveform obtained by adding up some sinusoidal signals. It can be seen that the controlled signal waveform follows a preset reference signal waveform with good control quality.

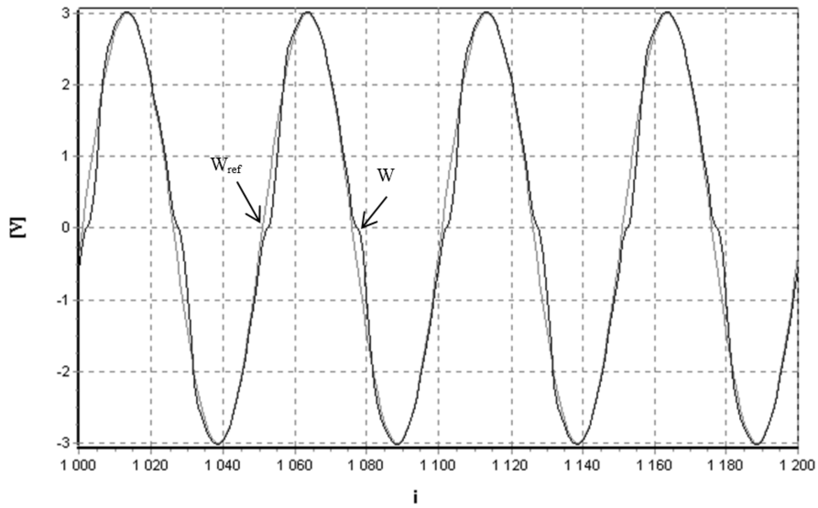

Fig. 8. Sinusoidal signal with SMCS controller (after a longer time)

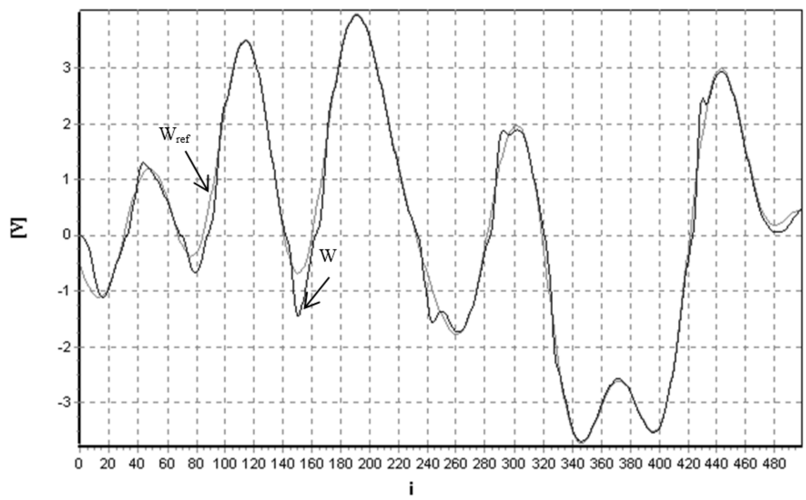

Fig. 9. Pseudo-random waveform with SMCS controller

5. CONCLUSIONS

The paper presents some issues related to the control system implementing a methodology of fatigue tests of structural materials using *W*(*t*) parameter, which is the product of stress and strain signals. Direct determination of the material fatigue characteristics is possible if the control system measures both stress and strain values, and then calculates the value of the *W*(*t*) parameter. In the conventional control system, because of the $W_\sigma(t)$ function nature, the system becomes non-linear and there is a deterioration of the control quality, and the controlled signal is considerably distorted. The solution to this problem is to introduce a non-linear block into the feedback. Structure of this nonlinear block is described by equation (2). To ensure the accuracy of the corresponding reference waveforms it is necessary to use control system with an adaptive controller. The proposed control system operates in an algorithm with adaptive SMCS control. Therefore control innovation is based on application – in the feedback loop – a nonlinear adaptive controller block. In order to verify the proposed control algorithm, a number of fatigue tests have been performed. Research covered a variety of signal types selected in the sinusoidal and random. As it can be seen from the examples, controlled signal closely follows the reference value, with the appropriate control quality. despite the complex shape and the wide frequency band.

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