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GENETIC ALGORITHM BASED METHOD OF ELIMINATION OF RESIDUAL OSCILLATION IN MECHATRONIC SYSTEMS

PETER HUBINSKÝ, LADISLAV JURIŠICA AND BRANISLAV VRANKA

The paper presents control signals generation methods, preventing the excitation of residual vibration in slightly damped oscillational systems. It is focused on the feedforward methods, as most of the vibrations in examined processes are induced by the control, while the influence of disturbances is mostly negligible. Application of these methods involves ensuring of the insensitivity to natural frequency change, which can be reached in classical approach only by considerable increase of transient response duration. Genetic algorithms can be effectively applied for the numerical optimization of developed shaper while maintaining the insensitivity to parameter change and short time delay.

Keywords: elimination of residual vibration, input signal shaping, genetic algorithm

AMS Subject Classification: 93C83

INTRODUCTION

Increasing demands on effectivity and quality of industrial production expand requirements on the dynamics and accuracy of positioning. These can be negatively affected by the vibration excitation in the flexible mechanic parts of positioning system structures and manipulators. Increasing the dynamics of drives by itself does not enhance the speed of technology or manipulation process, since the excitation of vibration in the driven mechanic structure is bringing considerable tracking errors. The oscillational character poses the main problem especially in the control of hanging transport systems and cranes. With the growing amplitude of swings, the possibility of collision with obstacles in the environment arises, which is a serious safety problem. In the robotic applications, excitation of vibration causes the prolongation of settling time in point-to-point movement and dynamic trajectory tracking errors in the continuous path control. Dynamic equations describing these oscillational processes are equivalent and allow us to apply presented method of control.

1. ANALYSIS OF THE SYSTEM

We will focus on cranes, typical representatives of the examined class of processes. Figure 1 shows a model of planar gantry crane. The payload of mass m is hanging on a cable of length L in a gravitational field of intensity g. Overhead trolley moves with acceleration a. The angle between the cable and its settled position is φ and the viscous friction coefficient is b.

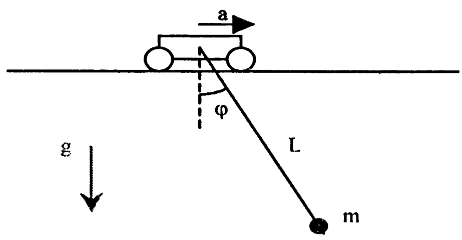

Fig. 1. Sketch of a gantry crane.

The control task is to position the payload of the crane without the excitation of sways. We expect that the positioning of the overhead trolley is satisfactorily assured by the standard feedback controller (e.g. PID or LQR), which suppresses the influence of outer disturbances, friction and backslash in the gears. We assume no feedback from the endpoint position of the driven structure (payload), since its measurement is usually difficult. The examined system is the driven mechanic structure itself. It can be shown [5, 10, 12], that amplitude of residual vibration of cable yaw (φ) is linear dependent on amplitude of residual vibration of its derivative (ω). In this paper we consider the acceleration of the overhead trolley (a) as the input variable and the angular velocity of yaw of the cable (ω) the controlled variable (simple system, sufficient to demonstrate effects of developed algorithms).

After the linearization the transfer function describing presented system can be expressed as follows:

$$F_{\frac{\omega}{a}}(s) = \frac{K\omega_0^2}{s^2 + 2b\omega_0 s + \omega_0^2} \cdot \frac{1}{s}, \quad \omega = \frac{\mathrm{d}\varphi}{\mathrm{d}t}, \tag{1}$$

where K is the amplification factor, b is the damping coefficient and ω_0 is the natural frequency of the system ($\omega_0 = \sqrt{g/L}$). Naturally damped systems with high damping don't account problems with oscillations and for $b > 0.707$ have even aperiodic character. Further in the paper we consider $b = 0$ (the influence of nonzero damping is described in the referred works [1, 2, 5, 7, 10, 12]). All oscillating systems with one mode of vibration can be described by similar transfer function.

The classical approach to the control design assumes the implementation of position (velocity or acceleration) feedback from the endpoint of driven structure – in our case it is the payload. However, the measurement realization is problematic, according to the cable deflection, stretch and deformation of trolley parts. The control structure we use implements a feedback loop only from the trolley position, ensuring the required trolley settled position is reached also with the friction influence and distortion compensation. Whole process is then a serial sequence of the closed loop trolley part and an open loop crane part. Dynamics of the trolley can be then described by a linear transfer function. The vibrational character of a crane is not suppressed. To suppress the sway excitation, application of feedforward control methods, consisting of specific control signal generation is necessary. In this case no complementary sensors are needed, but there is a significant influence of identification of mechanic part of the system, definition of possible parameters leakage and robust methods application.

2. FEEDFORWARD CONTROL

These methods are based on knowledge that the amplitude of residual vibration proportionally depends on control impulse spectral amplitude on natural frequency of the system [1, 2, 5, 6, 7, 10, 12]:

$$A = KS_M(\omega_0). \tag{2}$$

Necessary conversion of control signal consists in a proper change of input impulse shape, which ensures its spectrum has no frequency compounds near to ω_0. It is usually realized as filtration of the setpoint (since expected linear character of trolley control loop doesn't affect the presented vibration excitation suppression method [1, 5, 10]). Several methods can be used to assure this, providing different levels of quality. Actual solution is chosen depending on the controlled object characteristics, the level of quality requirements and the realization costs. The simplest way is a low-band filtration, but increasing demands on quality induces significant lengthening of transient responses. Solutions for the direct suppression of chosen spectrum intervals are algorithmically more difficult, but considerably more effective, while their main feature is a possibility to generate a control impulse completely eliminating the excitation of sways with relative short prolonging of the impulse duration. They provide also the advantage of easy redesign of algorithm for the elimination of several natural system modes and thereby also the reduction of parameter change sensitivity.

Time optimal impulse (enforcing the required change of position $1.5\,\Delta y_{z0}$, where Δy_{z0} is the amount of controlled variable change caused by the square impulse of saturated amplitude and length equal to the natural sway period) response of the system described by the transfer function (1), as well as the spectral density of this impulse are shown in Figure 2.

The first used control algorithm of feedforward shaping type was the posicast control suggested by O. Smith [8]. The basic operation was the division of the action force into two delayed signals. P. Meckl and W. Seering formed the method of offline input signal shaping based on versine functions [6]. P. Hubinský expanded this method using polynomial functions, assuming the torque saturation [1]. P. Hubinský and M. Závodský explored versine function based shapes with saturated sections [12]. Very effective method was developed by W. Singhose, W. Seering and N. Singer [7]; the control signal is convoluted with an exquisite sequence of Dirac impulses. If applied set of pulses accounts zero spectral density at the natural frequency of the

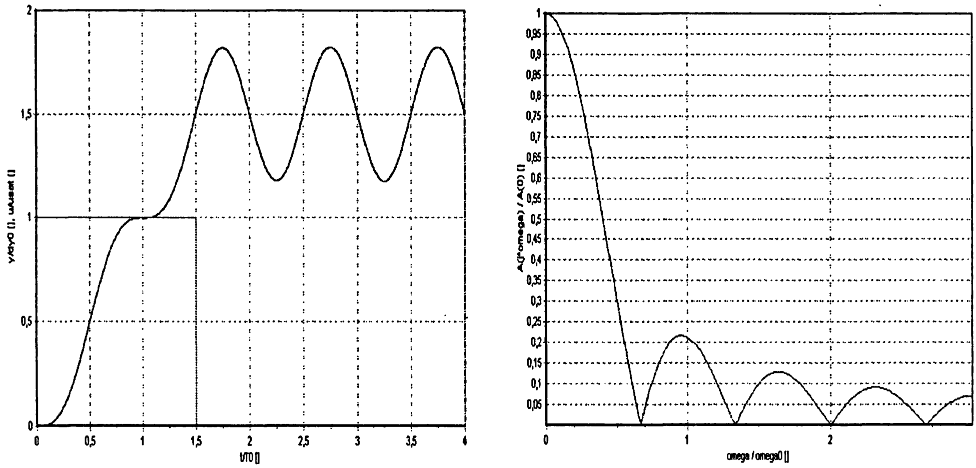

Fig. 2. Time optimal impulse response of the system (left) and spectral density of this impulse (right).

controlled system ω_0, the convolution with an arbitrary signal results again in a signal with zero spectral density at ω_0. I. Ivanov and P. Hubinský presented offline analytical optimization of polynomial shapes and their tests on a crane system [5]. P. Hubinský and L. Jurišica presented application of developed algorithms in robot and manipulator control [2]. B. Vranka applied genetic algorithm for optimization, tested basic shaping by application of neural networks and explored effectivity in 2-dimensional trajectory tracking in a space containing obstacles [10].

Considering a set of Dirac impulses, A_i are amplitudes and τ_i delays of impulses, the condition ensuring zero spectral amplitude at ω_0 and thus preventing residual sways energizing is:

$$\sum_i A_i e^{-j\omega_0 \tau_i} = 0. \tag{3}$$

The condition ensuring that the magnitude of the change will be preserved is:

$$\sum_i A_i = 1. \tag{4}$$

The simplest solution fulfilling the conditions (3) and (4) is a sequence of 2 impulses with amplitudes equal to 0,5 and relative time offset $T_0/2$ (T_0 is a period of natural sways of the system).

The vector representation of Dirac impulses allows us to understand the equation (3) as a condition of their zero vector sum and the equation (4) as a condition of their scalar sum to be equal to 1. Figure 3 shows the most usual simple sequences of impulses in a complex plane.

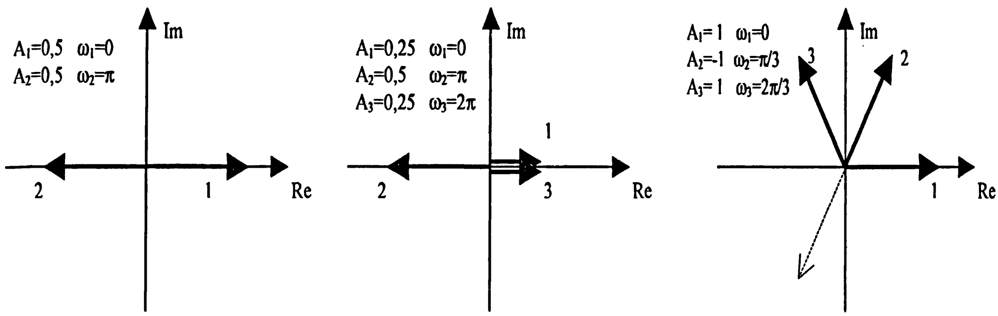

Fig. 3. Vector interpretation of the most usual simple series of Dirac impulses.

The control signal generation method using a set of Dirac impulses offers an inherent benefit in the possibility of easy on-line implementation. Modification of any control signal to suppress sway excitation consists in the generation of the sum of its time delayed amplitude modified continuances. The technical realization of the filter consists in saving the input values in a shift memory and summing of the multiples of values in selected positions in memory (Figure 4).

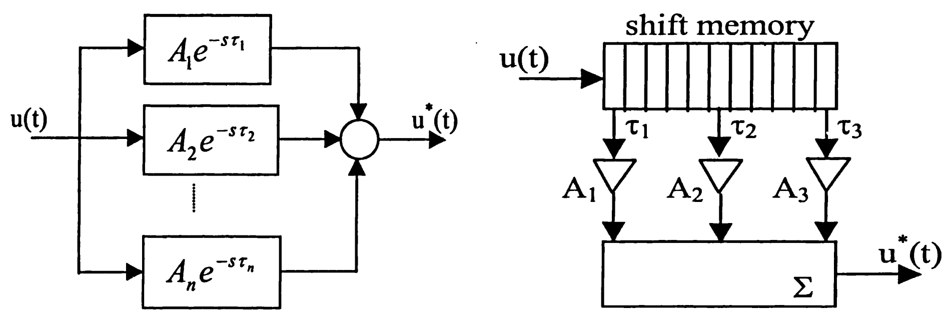

Fig. 4. Implementation of feedforward control using Dirac impulses, $u(t)$ is a time-optimal impulse designed for controlling the system not regarding its flexible character, $u^*(t)$ modified control impulse (left); technical realization (right).

Convolution fulfils the role of digital filter, its application ensures no sways are excited by the control signal. Figure 5 shows the modified control impulse (the simplest sequence of 2 pulses was used), response of the system and the spectral density of such an impulse. Comparing the profiles of spectral densities in Figure 2 and Figure 5 we can see the obvious effect of designed convolutionary filter.

While setting the parameters of the filter, we use the nominal value of natural frequency $\overline{\omega_0}$, gained in advance (off-line) by an identification method or analytically computed. The digital filter nullifies the amplitude of control impulse spectrum at this frequency. Changing the system parameters – thus the natural frequency (in

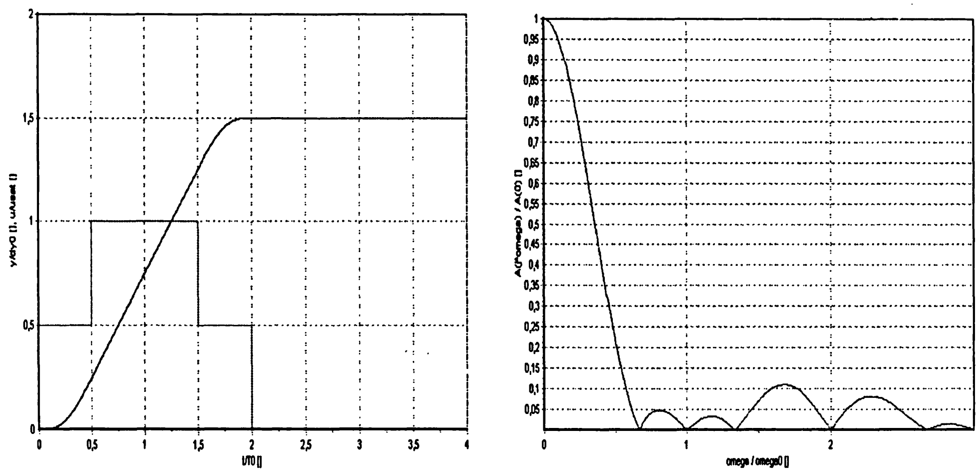

Fig. 5. Modified control impulse (use of the simplest sequence of 2 pulses) response of oscillating system (left) and spectrum density of used control impulse (right).

the case of the crane it is change of the cable length L) results in the loss of effectivity, while already in the nearest neighborhood of $\overline{\omega_0}$ the spectral density of impulse is rapidly growing. Even a relatively small variation causes sway excitation again. Solution of this robustness problem consists in the use of specific sequences of impulses, nullifying the spectrum density of the signal (or at least definably reducing the spectrum amplitude under an acceptable border) in the chosen frequency interval. To create those parameter change less sensitive sets of Dirac impulses we can use the following feature: if there is a sequence of Dirac impulses nullifying the spectral amplitude at ω_1 and another sequence nullifying the spectral amplitude at ω_2, the convolution of these 2 sequences creates a new set of Dirac impulses, nullifying the spectral amplitude at both frequencies ω_1 and ω_2. The repeated convolution between the acquired sequence and another elementary one can nullify the spectral amplitude at the optional amount of selected frequencies.

The most often used methods are nullifying the spectral density at two frequencies near to the nominal natural frequency (so-called ZV shaper) or nullifying the spectral density and its first time derivative at the nominal natural frequency of the system (so-called ZVD shaper) – which is an equivalent to twice shaper application at the same frequency. Figure 6 shows the control signal modifications using ZV and ZVD shaper, corresponding responses of the system, spectral densities of the modified signal and their details in the neighborhood of the nominal natural frequency.

Application of the method presented above can almost completely suppress the frequency compounds of the signal of higher than selected boundary frequency [7]. On the other hand, the described technique of parameter change insensitivity outcomes in an exponential increase of the amount of impulses (depending on the number of nullification points) and especially in increase of the filter delay time.

If the resultant sequence of Dirac impulses is gained via the convolution of ele-

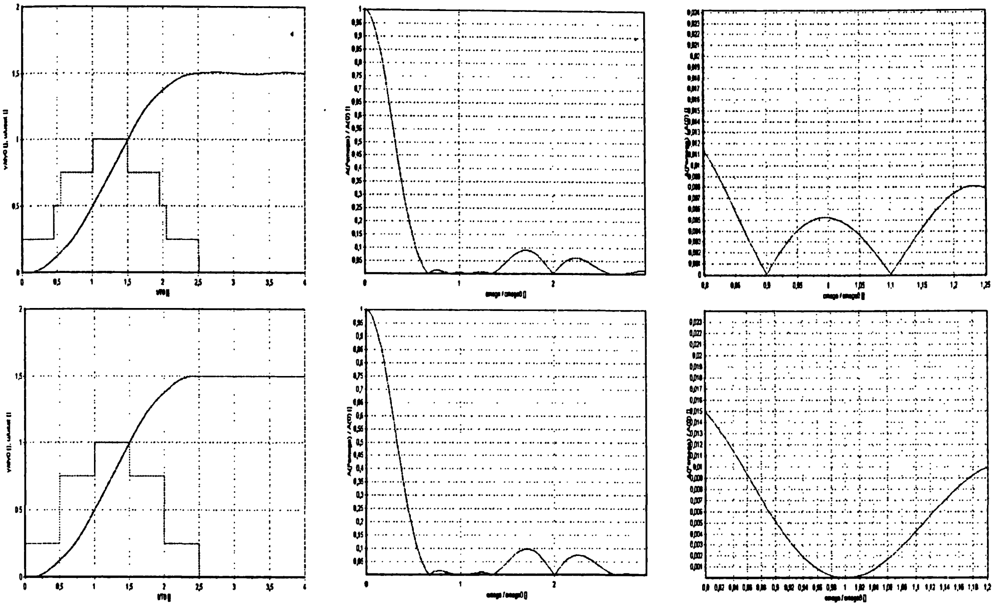

Fig. 6. Modified control impulse response of oscillating system (left), spectrum density of used control impulse (middle) and detail of spectrum near the nominal natural frequency (right). ZV shaper nullifying the spectrum density at $0.9\,\omega_0$ and $1.1\,\omega_0$ (top), ZVD shaper nullifies the spectrum density and its first time derivation at ω_0 (bottom).

mentary sets of two impulses, the amount of impulses N depends on the quantity of spectral nullification frequencies n:

$$N = 2^n \tag{5}$$

and the time delay of the filter is:

$$T = \sum_{i=1}^{n} \tau_{2,i}. \tag{6}$$

Increasing the amount of impulses doesn't affect control system complexity much, however the growth of filter delay time may be a problem. Inserting a big time delay into the system decreases the overall system dynamics and it can negatively affect especially systems with several degrees of freedom, while tracking required space trajectories (can lead to the failure of the safe path generation) [3]. Increasing the algorithm insensitivity to the change of natural frequency of the system without large prolongation of the delay time also extends possible area of its application.

3. GENETIC ALGORITHM OPTIMIZATION OF DIRAC IMPULSE SEQUENCE

Unacceptable growth of the amount of impulses and the delay time of the filter necessitates searching for an alternative design method of amplitudes and phases of Dirac impulses. Sequences, ensuring the maintenance of required step size, suppression of the natural frequency sways by nullification of input signal spectral density at the natural frequency have to satisfy the equations (7), (8) and (9), derived from (3) and (4) (eventually to provide natural frequency change insensitivity by nullification of spectral amplitude continuance derivative also equations (10) and (11)):

$$\sum_i A_i = 1 \tag{7}$$

$$\sum_i A_i \cos(\omega_v \tau_i) = 0 \tag{8}$$

$$\sum_i A_i \sin(\omega_v \tau_i) = 0 \tag{9}$$

$$\sum_i A_i \tau_i \cos(\omega_v \tau_i) = 0 \tag{10}$$

$$\sum_i A_i \tau_i \sin(\omega_v \tau_i) = 0. \tag{11}$$

If the particular equation redemption rate is scored by a penalty coefficient and thereby a criterial function is formed, generally we search for an extreme of function of several variables. To decrease the complexity of the optimization task, we set the amplitude of the first impulse to 1 and its time delay to 0. Then we adjust only the relative amplitudes and delays of remaining impulses. Fulfillment of the equation (7) we provide after the optimization process by dividing impulse amplitudes by their sum. During the optimization, the following criterial function is minimized:

$$F_{\text{crit}} = \sqrt{\left(\sum_i A_i \cos(\omega_v \tau_i)\right)^2 + \left(\sum_i A_i \sin(\omega_v \tau_i)\right)^2} + k_1 \sum_i \tau_i + k_2 \sum_i A_i \tau_i, \tag{12}$$

where k_1 and k_2 are the weight constants of time delay influence. If $k_1 > 0$, shorter solutions are preferred; if $k_2 > 0$, solutions where significant action force is done at short delays and only small action forces are done at higher delays are preferred.

Considering the shape of penalty functions containing terms with goniometric functions we can guess that they have a lot of local extremes (examples are shown in Figure 7). In this case, application of analytic methods cannot find the global optimum. Multidimensional optimization of criterial function with a lot of local extremes is a typical objective in genetic algorithm application. The method is based on the parallel stochastic scan of variable space. According to the numerical character of the method, it is clear that the obtained solution is only an approximation. The choice of the terminating condition can set the required precision. If the amount of generations limit is low, the solution can also stall in the local extreme. As we evaluate and minimize a broad criterial function, we can append additional demands here (e. g. preferring shorts delay solutions), it also allows us to look for solutions minimizing the spectral amplitude (alternatively its continuance derivation) for fewer impulses, than it is analytically needed to completely fulfill the conditions (3) and (4). According to 2^n impulses in the classical convolutionary multiplication, or $2n+1$ impulses in the pole compensation method (in a Z operator space), we can significantly reduce the quantity of impulses. Requirement of spectrum amplitude minimization in the selected interval can be applied in the genetic algorithm too.

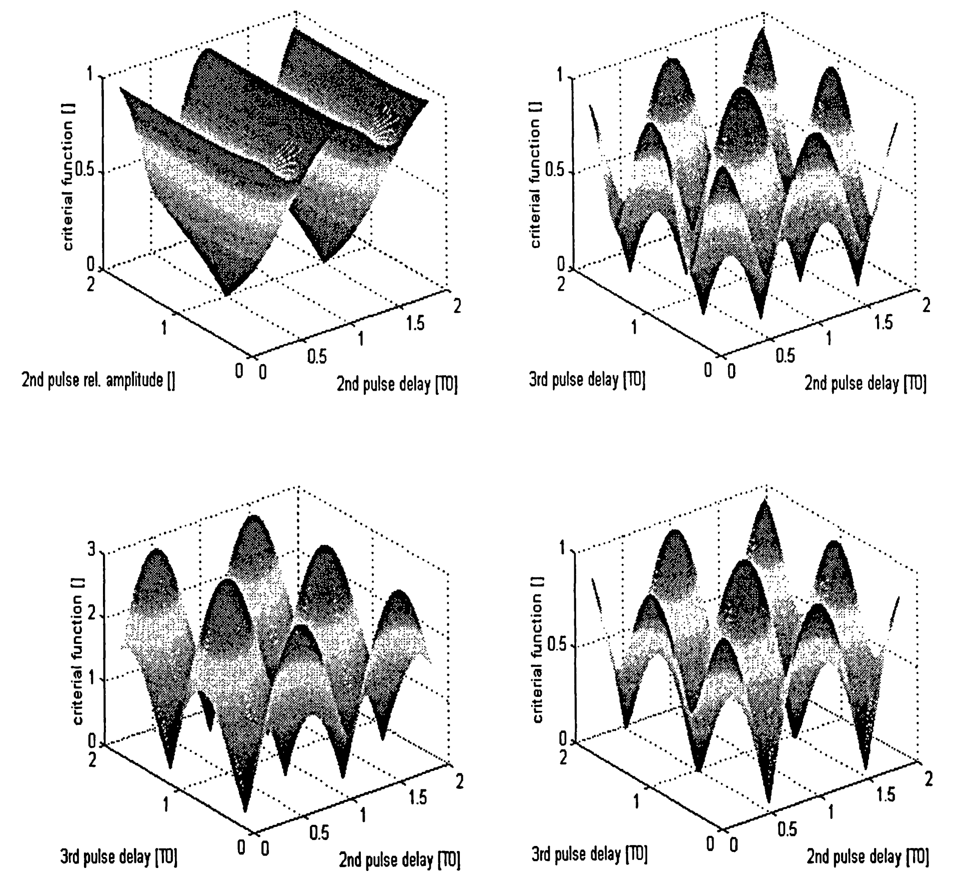

Fig. 7. Shapes of criterial functions;
a) 2 impulse sequence, optimized: 2nd pulse relative amplitude and time delay
b) 3 impulse sequence ($A_{1r}=1$ $A_{2r}=1$ $A_{3r}=1$), optimized: 2nd and 3rd pulse time delay
c) 3 impulse sequence ($A_{1r}=1$ $A_{2r}=-1$ $A_{3r}=1$), optimized: 2nd and 3rd pulse time delay
d) 3 impulse sequence ($A_{1r}=1$ $A_{2r}=2$ $A_{3r}=1$), optimized: 2nd and 3rd pulse time delay.

Another possibility is in forming the criterial function by using the time domain characteristics of signal continuances (mean square error, area of aberrance, settlement time). In comparison to the frequency domain characteristics, where the criterial function was analytically expressed (9), penalty is determined using the time continuance signals obtained by a simulation or an experiment. According to the large amount of required criterial function results in the genetic algorithm, performing simulation computing for all these points would lead into very lengthy optimization process (performing so many experiments is even nearly not possible). Exact value of criteria can be estimated by neural network, approximating selected criterial function. This approach is currently under development.

We have applied the described algorithm considering several requirement levels and for several quantities of optimized set of Dirac impulses (Figure 8). As a representative example we present the sequence of 5 Dirac impulses. The quantity of pulses and also the time delay of the filter are similar to those of ZV and ZVD shaper, while the insensitivity to the natural frequency changes is much better.

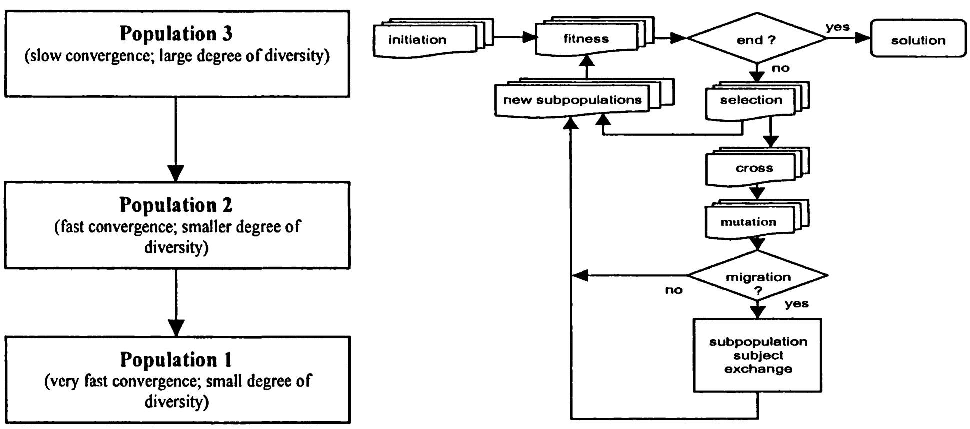

Fig. 8. Best individuals exchange structure (right) and used parallel genetic algorithm scheme (left).

Quantity of impulses: 5
Frequencies elimination required: $0.85\,\omega_0$; $1\,\omega_0$; $1.5\,\omega_0$ damping coefficient: 0
Criterial function value reached: 0.0250

Impulse no.	Amplitude	Phase
1	0.1503	0
2	0.1736	2.4776
3	0.1975	3.0949
4	0,3399	5.4923
5	0.1388	8.2632

The obtained sequence of impulses minimizes the spectral amplitude of control impulse for chosen frequencies, generally in the interval between $0.7\,\omega_0$ and $1.6\,\omega_0$. Good characteristics were achieved using relatively few impulses and a low time delay, which makes the realization easier. The results are shown in Figure 9 and Figure 10.

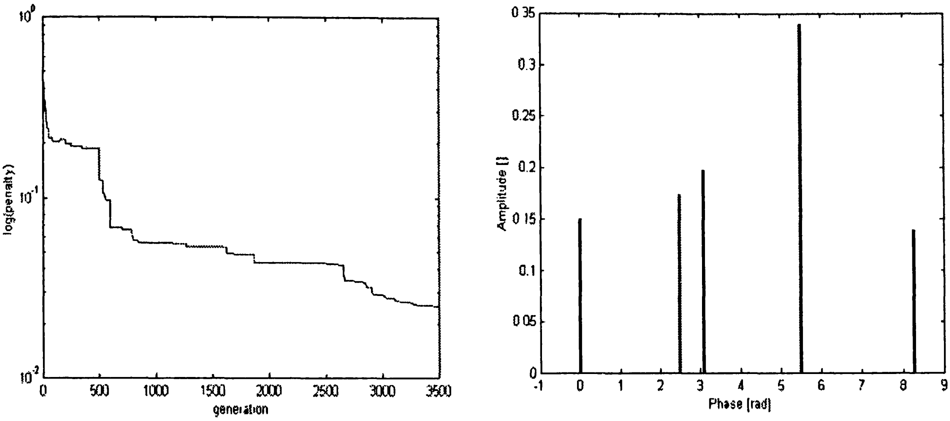

Fig. 9. Penalty continuance of the best individual and the best set of 5 impulses.

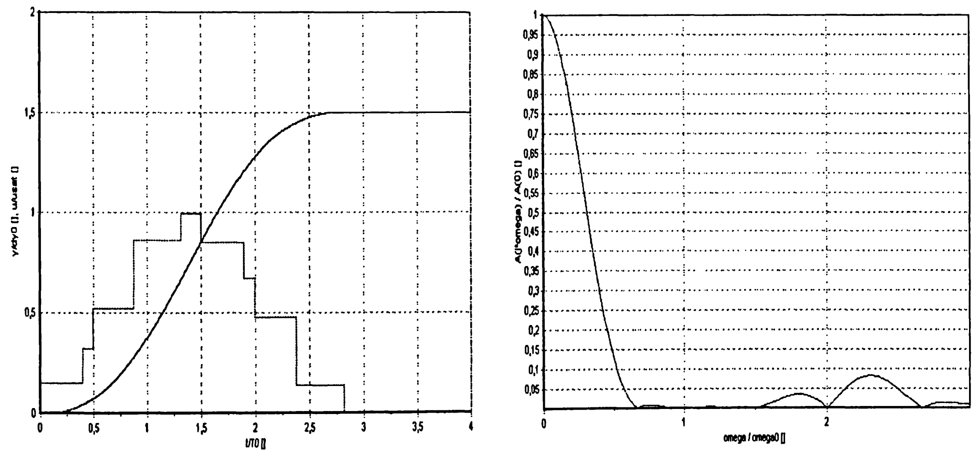

Fig. 10. Control signal, response of the system (left) and spectral density of control impulse (right).

The increase of insensitivity to the change of natural frequency of the system in comparison to the ZVD shaper (usually used as already insensitive type of the filter) is shown in the Figure 11 and Figure 12.

The system response when the GA optimized filter is used accounts similar prolongation of the transient process as in the case of ZVD shaper, the insensitivity to the change of natural frequency (especially when estimated system frequency is smaller than in the real system) is with the GA optimized filter much better.

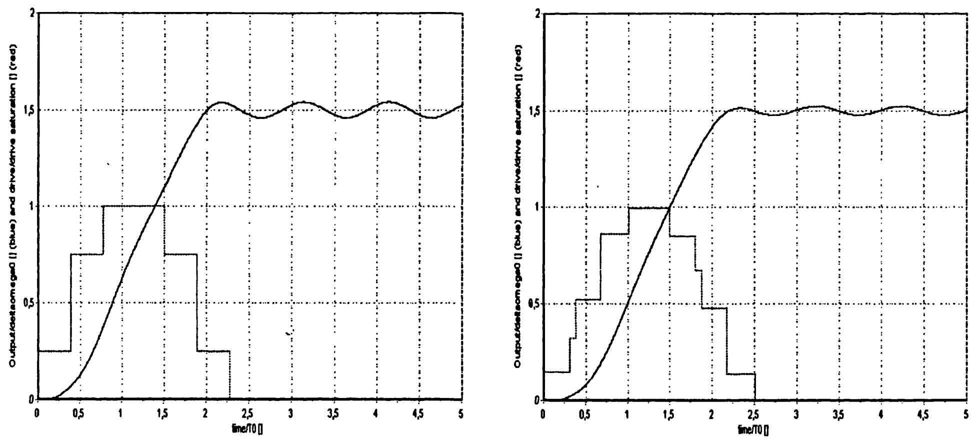

Fig. 11. Control signal and response of the system with 30 % changed natural frequency of the controlled system for ZVD shaper (left) and GA optimized shaper (right).

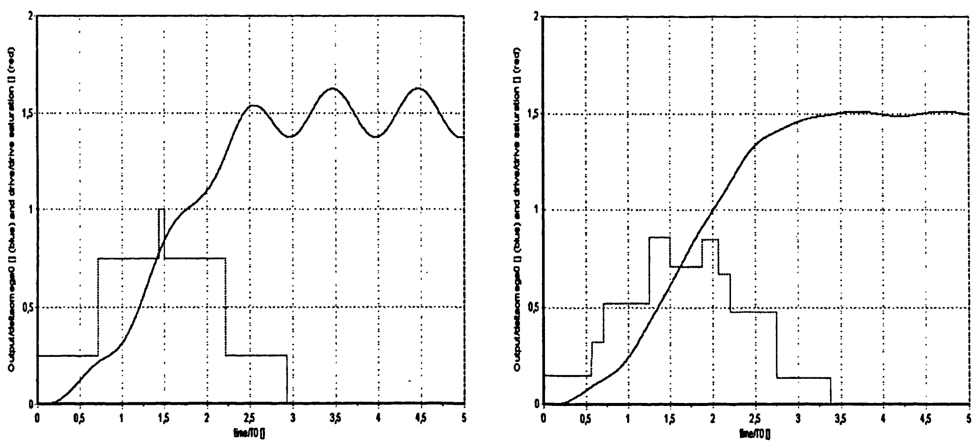

Fig. 12. Control signal and response of the system with −30 % changed natural frequency of the controlled system for ZVD shaper (left) and GA optimized shaper (right).

4. CONCLUSION

The aim of the paper is the presentation of methods suppressing vibration excitation in vibrational systems. Although the basic methods provide a possibility of their complete elimination with a good insensitivity to natural frequency changes, they are fetching a significant time delay into the control process. This is the reason, why new algorithms minimizing the amount of impulses and especially time delay of the discrete filter were developed. Genetic algorithms were effectively used here, the results were verified by simulation. Preserving the delay time and the amount of impulses (according to typically used ZV or ZVD shapers) we gained discrete filters with increased insensitivity to system parameter changes.

This is very important for real industrial applications, as the natural frequency varies here depending on the state of the controlled process. For the case of the crane the length of the cable and for the case of the robot the inertia of the moved mass can be changed usually in the factor that significantly affects the natural frequency and disqualifies the use of the simple filter. Therefore only some adaptive algorithm with the increased robustness can be successfully applied here. Besides, the minimization of the filter time delay can play the important role in the stability of the original path planning algorithm. Proposed numerically optimized digital filters can be successfully applied in these control tasks.

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