FEEDFORWARD CONTROL OF ELECTRICAL DRIVES - RULES AND LIMITS

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Abstract: *Nowadays, there are several application in the field of position controlled electric drives, such as high speed cutting, where traditional cascade control structures provide insufficient accuracy. Therefore, it is necessary either to completely change the control structure (e.g. sliding mode control) or to modify and extend the basic cascade structure. One of those modifications can be feedforward direct branches. Feedforward increase order of astatism without stability influencing but on the other hand it brings other problems regarding to the feedforward technique implementation, system parameters changing or neglecting particular system behavior. This paper describes basic control structures, their features and several mentioned problems related to feedforward control of electric drives.*

Keywords

Feedforward, servodrive, accuracy.

1. Introduction

This article is a part of overall topic called Feedforward Control of Electrical Drives. It is thematically related to the paper with title *An Introduction to Feedforward Control of Electrical Drives* [1]. The main purpose of this paper is to show how to use the most common structures in the field of commercial electrical drives, their features and possibilities of tuning. There is a section describing the limits which can appear during the implementation of the electrical drives in the real word. At the end, there are shown some others forms of feedforward techniques.

2. Structures and their Feautures

A simple structure of the position control adopting a speed feedforward has been shown in [1]. The following chapters will outline how to solve potential problems resulting from feedforward, and how to tune properly the loop in order to get the maximal benefit from feedforward.

The speed feedforward offers faster speed response, but on the other hand causes a speed overshot. One of the possible solutions is to add an acceleration loop and to try to eliminate an error in steady state, which is given by step change of the acceleration. The scheme in Fig. 3 in [1] is then extended and changed according to Fig. 1.

The transfer function of the system is modified as follows:

$$G_\theta(s)=$$

$$\frac{s^3 K_{FF\varepsilon} + s^2 K_{FF\omega} K_{P\omega} + s\left(K_{P\omega} K_{P\theta} + \frac{K_{P\omega} K_{FF\omega}}{T_\omega}\right) + \frac{K_{P\theta} K_{P\omega}}{T_\omega}}{s^4 T_\Sigma J + s^3 J + s^2 K_{P\omega} + s\left(\frac{K_{P\omega}}{T_\omega} + K_{P\omega} K_{P\theta}\right) + \frac{K_{P\theta} K_{P\omega}}{T_\omega}}, \quad (1)$$

and resulting error is given by (2).

As it can be seen from (1), the gain of speed feedforward $K_{FF\omega}$ can affect the gain of the acceleration feedforward $K_{FF\varepsilon}$. Assuming unitary gain of $K_{FF\omega}$, than the gain of the acceleration loop $K_{FF\varepsilon}$ will be equal to J (moment of inertia).

The question is how it will affect the overshoot observed in the structure with the speed feedforward. The answer will provide a simulation realized according to the block diagram in Fig. 1. There is clearly visible impact of all interventions in Fig. 2. It is seen that the required linear increase of speed follows a structure without any feedforward with constant lag. An introduction of the speed feedforward leads to cancelation of the lag, but on the contrary an overshoot occurs. This is caused due to imperfect tracking of the acceleration, which changes to zero when the reference speed reaches steady state. After the introduction of acceleration feedforward the aforementioned undesirable overshoot is reduced to the minimum. In this case the speed will be without any permanent lag as well as without any overshoots.

Note. Scheme in Fig. 1 contains feedforward branches given by gain and differentiator of the relevant order. The block diagram, depicted in Fig. 1, is more suitable for illustration and understanding, but the practical implementation of derivation members would cause noise in the feedforward signal. Therefore, in practice, the desired shape of the derivative position is primarily generated as same order as order desired feedforward and the other references are obtained by its integration. In other words, if we want to use for instance acceleration feedforward, it is possible to generate desired acceleration based on limits of acceleration, speed and position.

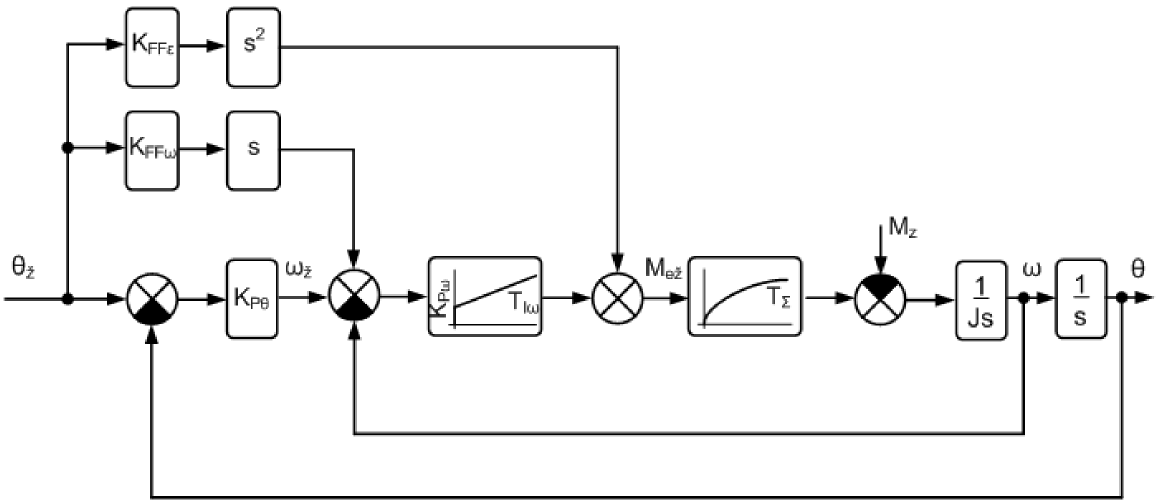

Fig. 1: Block scheme of the position control with feedforward loop of speed and acceleration.

$$e_{\theta\infty} = \lim_{s \to 0} sL\{\theta_{\check{z}}\}L\{e_\theta\} = \lim_{s \to 0} s \frac{1}{s^2} \frac{s^4 T_\Sigma J + s^3 (J - K_{FF\varepsilon}) + s^2 (K_{P\omega} - K_{P\omega} K_{FF\omega}) + \frac{s}{T_\omega}(K_{P\omega} - K_{P\omega} K_{FF\omega})}{s^4 T_\Sigma J + s^3 J + s^2 K_{P\omega} + s\left(\frac{K_{P\omega}}{T_\omega} + K_{P\omega} K_{P\theta}\right) + \frac{K_{P\theta} K_{P\omega}}{T_\omega}}. \quad (2)$$

Then the speed and position references are simply calculated by the integration of an acceleration reference.

Generally speaking, the higher feedforward order and the dimension of reference vector of kinematic variables associated with the feedforward, the lower representation of higher frequencies in the output and hence the error signal, which has a positive impact on the overall system response.

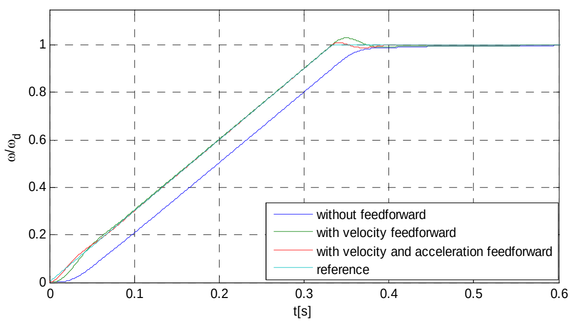

Fig. 2: Speed waveforms - position control with PI speed controller for different modes of operation.

Above mentioned facts describe only one structure of the position control with feedforward loops. There are several types of potential control structures. An example how to set up feedforward loops can be demonstrated on the similar structure, which can be reached by introducing a new PDF controller (PDF – Pseudo Derivative Feedback) instead of standard PI controller [3]. Block scheme is in Fig. 3.

Difference between those two schemes is that the PDF controller, unlike the PI controller, does not entail a zero into the plant. Although, it does not help to decrease the order of the plant as well as increase the dynamic of the system, it has an "attenuation" effect of the above mentioned zero and thus prevents the generation of any overshoot. Another change is in topology. The acceleration feedforward loop is in case of PI controller connected behind the speed controller. In case of PDF controller, the acceleration feedforward loop is summed with speed behind the position controller. The reason of this approach is because of an absence of zero in the speed controller. Impact on the numerator will be the same before and after the speed controller, so that can be used both schemes. By using of a version with PI controller it is impossible to affect the acceleration before the speed controller.

A transfer function related to the scheme in Fig. 3. is as follows:

$$G_\theta(s) = \frac{s^2 K_{FF\varepsilon} K_{I\omega} + s K_{FF\omega} K_{I\omega} + K_{I\omega} K_{P\theta}}{s^4 T_\Sigma J + s^3 J + s^2 K_{P\omega} + s K_{I\omega} + K_{P\theta} K_{I\omega}}. \quad (3)$$

As it has been mentioned before, transfer function of the control without any feedforward loops does not contain any zero points. By adding feedforward loops into the structures is the number of zeros increased up to two.

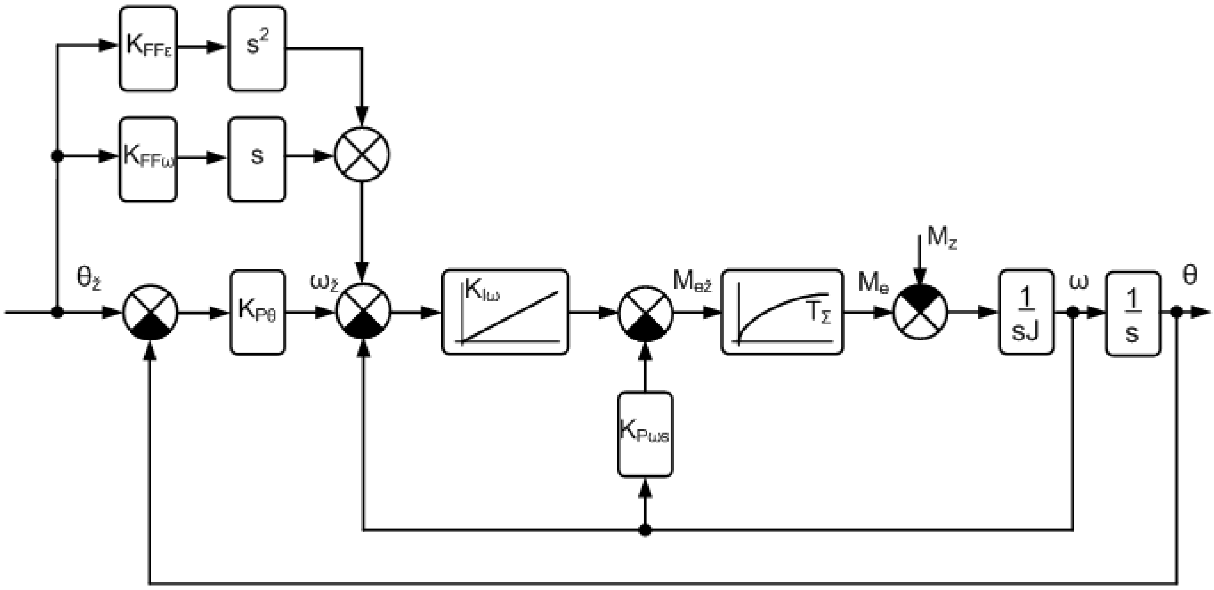

Fig. 3: Block scheme of feedforward position control with speed PDF controller.

Feedforward gains will affect only the coefficients nearby the first and second power, unlike of the first example, where the order of the numerator has been three and all of nonzero power coefficients are affected by feedforward gains.

By using of a Final value theorem it is possible to explain the error in steady state as follows:

$$e_{\theta\infty} = \lim_{s\to 0} sL\{\theta_{\check{z}}\}L\{e_\theta\} = \lim_{s\to 0}\left(s\frac{1}{s^2}\cdot\frac{s^4T_\Sigma J + s^3J + s^2\left(K_{P\omega} - K_{I\omega}K_{FF\varepsilon}\right) + s\left(K_{I\omega} - K_{I\omega}K_{FF\omega}\right)}{s^4T_\Sigma J + s^3J + s^2K_{P\omega} + sK_{I\omega} + K_{I\omega}K_{P\theta}}\right). \quad (4)$$

As it can be seen from (4), by setting $K_{FF\omega}$=1 and $K_{FF\varepsilon} = K_{P\omega}/ K_{I\omega}$ it is possible to cancel some of the powers in the numerator. How such settings take effect on the resulting waveforms can be seen from Fig. 4, which represents the results of the simulation according to the block diagram in Fig. 3. Setting of controllers has been performed by poles placement method [4], (for simplicity, it has been elected four times the real pole).

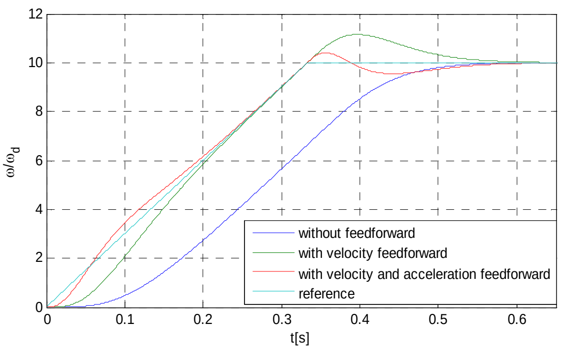

Fig. 4: Speed waveforms – position control with PDF speed controller.

Here can be seen an influence of zero missing in the speed controller under the non-feedforward control (in comparison with Fig. 2.). The speed overshoot under speed feedforward control is more significant and its compensation by acceleration feedforward has a lower effect.

The waveforms of the acceleration in Fig. 5 only confirm previous results assessment.

In this case it is possible to add another loop – a jerk feedforward. According to equation (3) the gain of this loop can be explained as ($J/K_{I\omega}$). It is clear that this way leads to very similar results as it is in case of speed PI controller, because this approach is also based on the compensation of three orders in denominator.

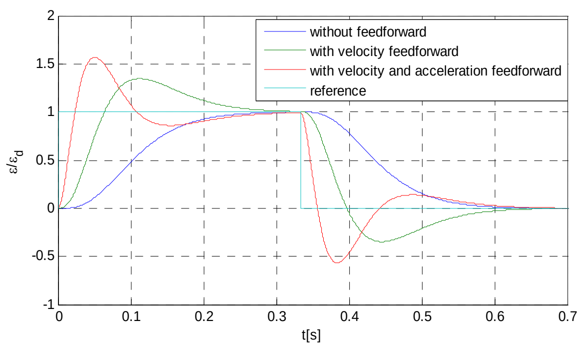

Fig. 5: Acceleration waveforms – position control with PDF speed controller.

At the end of this section, simulation results of the overall system are shown. The simulation represents a position control with saturation of speed and acceleration. During the simulation test a standard speed PI controller has been used and all three structural modifications have been tested.

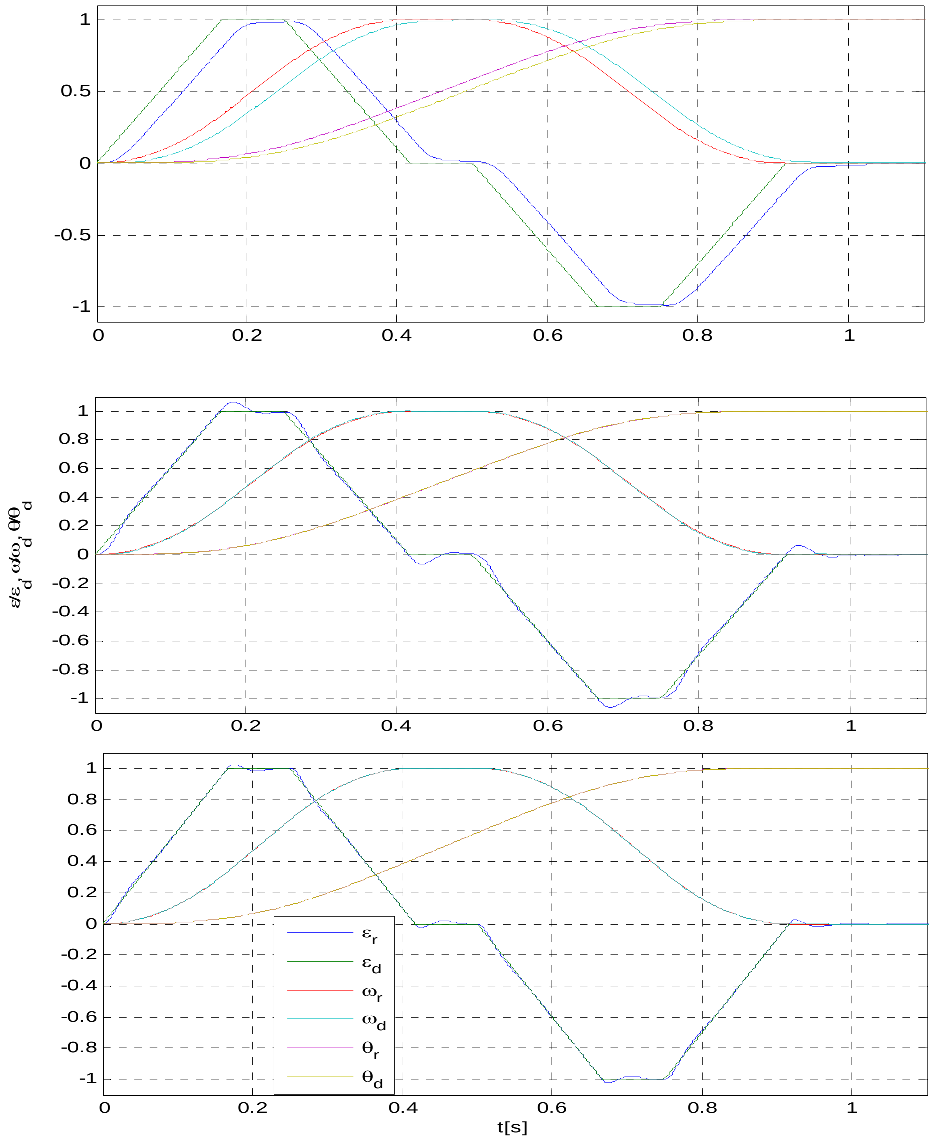

Fig. 6: Waveforms of kinematic signals – position control with speed PI controller under different modes: without feedforward, speed feedforward, acceleration feedforward.

As it can be seen, a significant lag behind the references is pretty successfully eliminated by feedforward loops.

Very useful tool during the control tuning process are logarithmic amplitude and phase characteristics (LAPCH), Fig. 7. Those in Fig. 7 specifically describe the system with the speed PDF controller and again confirm that feedforward reduces the order of the plant (see phase characteristics) and also allows the system to work with a wider bandwidth. In this particular case provides the speed feedforward three times wider bandwidth and the acceleration feedforward even six times wider bandwidth.

Note. If we had continued with another loop (jerk), the bandwidth would be almost 13 times greater!

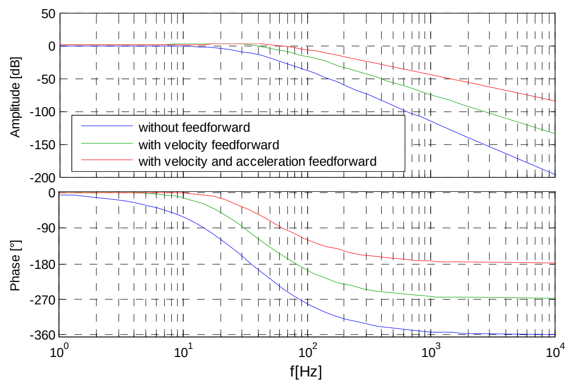

Fig. 7: LAPCH of position control in deferent modes.

Wider bandwidth allows quantities to track the references with lower lag, and also allows additional correction of gains in order to affect the response regarding to the disturbances signals (e.g. load torque). This is essentially the main task of feedforward – to take the responsibility for a tracking of controlled variables. Although it has been mentioned at the beginning, that feedforward does not affect the stability, it is necessary to note that a very small influence is still there. The controllers are not fully employed because the feedforward primary affects the response according to control signals. This could allow setting the parameters of the controller such way, that it would normally cause low values of phase and amplitude security and the state close to the instability. Such idea is up to discussion.

The chapter offers the solutions of the feedforward for two different structures. It is also possible to apply to other structures, and will be achieved very similar results. For instance, it can be a structure combining PDF controller for position and P controller for speed, or PI position controller with speed P controller [5], eventually PID controller positions without speed loop [6].

3. Limitation in Real Application

In previous chapters have been shown principles of feedforward based on the system, which is close to the ideal one. It is certainly important to know the problematic in term of theory, but it may not be enough in practical applications. The practical implementation of the feedforward solutions brings some others problems to be solved. Some of them will be described in the following lines.

The system described in the preceding paragraphs has been simplified and idealized. The inner loop containing the current controller (torque), inverter and motor itself have been replaced by a proportional plant with a transmission delay of the first order. The delay caused by armature has been offset by the controller and the delays counted in the summation constants. Since it is relatively small sum of delays, system approximation with first order delay does not entail substantial error in the system [2]. Totalized time constant includes delays due to inverter, time calculation, signal sampling, time of AD conversion and filtering noisy current signal (transmission delays are approximated by first order delay).

Besides, the real system contains a significant proportion of noise in the sensed currents and angular velocity signals. The speed will be strongly affected by noise if it is obtained by derivation of the position signal. This is a consequence of sampling and final resolution of an encoder. The most common solution is a filter, which is tuned in order to keep the stability of the system, to remove unwanted high frequencies and preserve demanded bandwidth. The ripple of waveforms seen on the next pictures is given by mentioned noise and subsequent filtering (mainly angular acceleration).

One of the most important parameter is the moment of inertia J and the most critical task is its identification. Not only parameters of the controllers (tuned by analytic methods) are dependent on the knowledge of J, but also the parameters of feedforward. If the information about the inertia is not correct, the feedforward will not work properly. This phenomenon can be seen in Fig. 8.

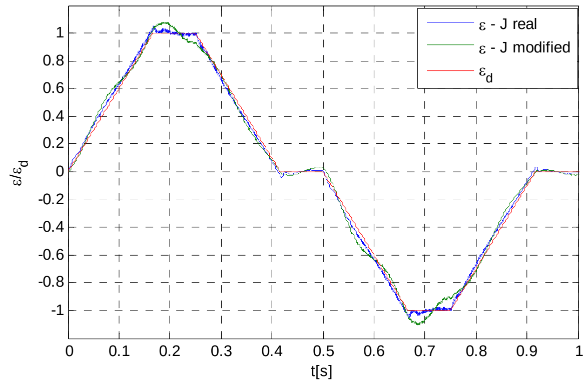

Fig. 8: Speed waveforms – position control with feedforward for right and wrong moment of inertia J identification.

It is clear, that 30 percent error in the identification of J causes an overshoot, which is not acceptable regarding to the high state of astatism.

Another parameter which can secondary affect the quality of the resulting waveform, may be a summary time constant of the inner loop. For example, if we tune the parameters of a servodrive with speed PDF controller by using of pole placement method, it is necessary to know the delay of inner loop. Its incorrect identification causes wrong calculation of parameters of controllers and consequently the gains of feedforward loop, as it is shown in Fig. 9 (60 percent error in the overall time constant identification). This lack is possible to additionally tune. At last, an incorrect identification of the inner loop order may also negatively affect the quality of the control like unexpected overshoots and imperfect demanded trajectory tracking.

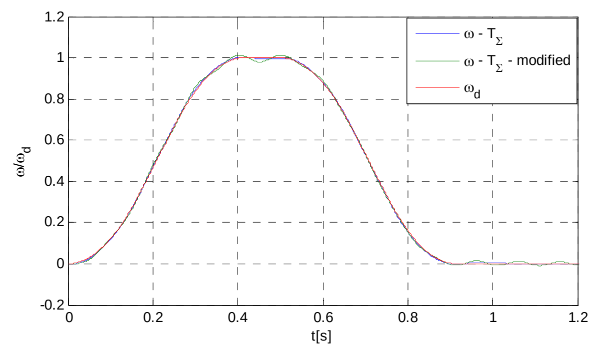

Fig. 9: Speed waveforms – position control with feedforward for right and wrong time constant T_Σ identification.

One of the last mentioned problem that needs to be in solved in practice is related to the delay feedback signal position. Ideally, the signal on the current position is immediately available for further processing. In the real condition, however, stands in the way of several obstacles that prevented it in the way and slowing him. These barriers are related to sampling frequency, conversion time, eventually signal filtration which mean totalized delay for speed loop. It would be useful if control algorithm know about these obstacles. If this information is not used, the desired position is compared with the real one, but delayed what giving rise to error and requires handling of the position controller. In the previous sections, we have said that the main aim is unload the controller from this role. The solution is very simple and is based on increasing delay of the reference signal. It can be seen that exact time delay estimation will be critical. It is possible to used method of gradual optimization or all delay are simply added together (as mentioned above, all delays are replaced by first order lag). These facts are best documented by traces of reference signals without and with delay (Fig. 10).

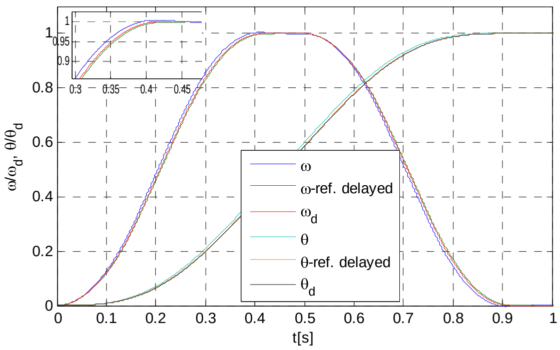

Fig. 10: Speed and position waveforms for control with speed feedforward loop without and with delay in references.

Since the picture is not possible to specify details of the position, Figure 11 provides a comparison of the difference between required and actual value of feedforward without and with delay in references. It is seen that the intervention of the regulator is rapidly reduced. Further reduction is possible if better identification of structures and parameters of the system will be done. These solutions how to compensate overshoot in position control system is being used in more applications [9].

Mentioned facts have concerned the control with feedforward speed signal. If we use the feedforward of acceleration we can also eliminate acceleration overshoot. Figure 13 indicates the location of delay blocks in the control structure.

Finally, it should be noted one more factor which may complicate the practical realization. Reference kinematic variables were generated in the previous sections, in accordance with the sampling loop, in which the feedforward links enter. In real systems, however, references are generated by master reference system (relevant interpolator) and through the appropriate communication interface (Ethernet, SERCOS, EtherCAT, etc..) are transmitted to the servo systems.

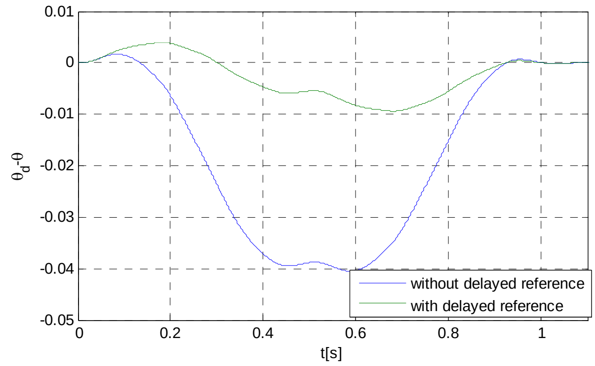

Fig. 11: Waveforms of position error for control with feedforward speed loop without and with delay in references.

The problem is the speed of generation and transmission of information. If sampling frequency of feedforward is twice than sampling of positional loop speed has the following shape (Fig. 12):

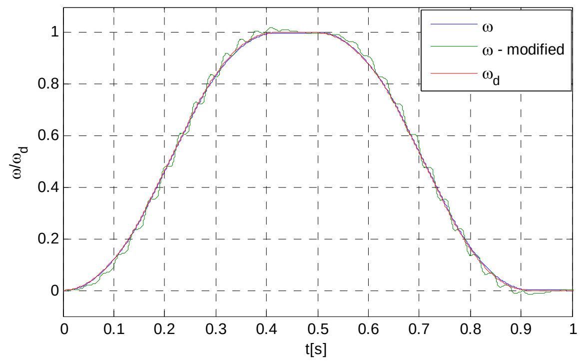

Fig. 12: Speed waveform for position control with feedforward, ω-modified is speed for twice sampling frequency of feedforward than sampling of position loop.

It is clear that the results is unsatisfactory and needs to convert some extra interventions. Most elegant is the use of fast interface (e.g. Ethernet Powerlink) and sampling of feedforward references adapt to sampling of appropriate loop. If it is not possible signal has to modified or assimilated to the sampling of control loop. In this case, we cannot eliminate the introduction of certain errors and delays.

The last part of paper mapped problems that may accompany the application of position control algorithms with feedforward in real terms. Did not seek to appoint all things which can be experienced only highlighted the fact that a practical solution to solve the problem requires a more complex view of the problem. Specific applications bring specific problems that go beyond the scope of this paper.

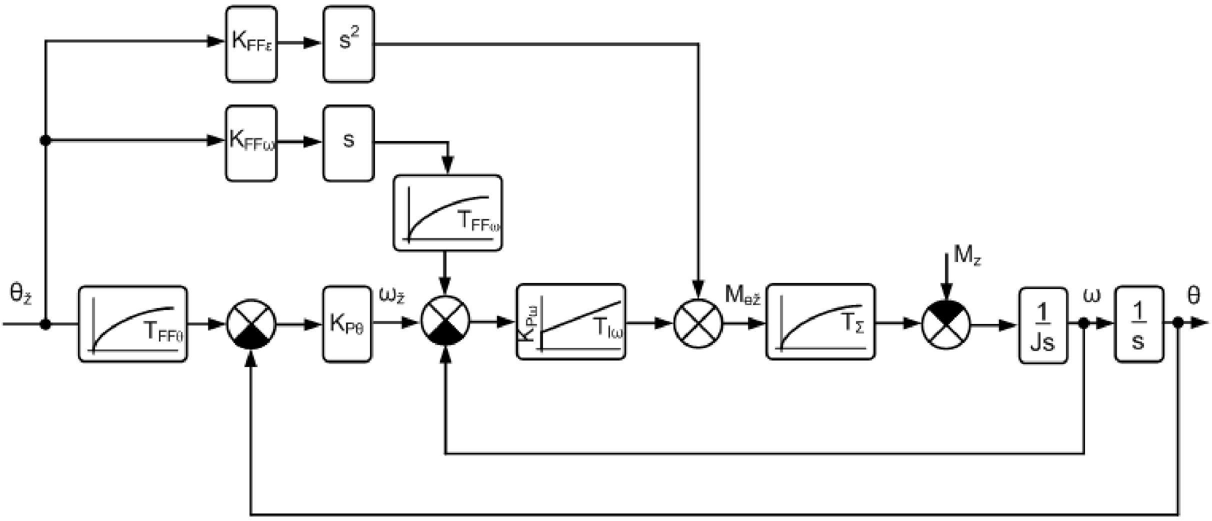

Fig. 13: Position control with speed and acceleration feedforward loops with delay in reference.

4. Other Form of Feedforward

The above forms are not sole way how to implement feedforward loops. In applications, we can encounter with feedforward based on calculating the torque correction signal which is fed to sum block of torque (current) loop. Its input signals are re-reference kinematic variables with the fact that one branch compensates for the dynamic moment $\left(\hat{J}\varepsilon_{\check{z}}\right)$ and second moment of friction forces, which are defined in the simplest case by the viscous friction coefficient $\left(\hat{B}\omega_{\check{z}}\right)$. In some cases, the frictional forces can be described in exact function. It may consist of Coulomb and viscous friction eventually the static component of Stribeck friction model. More demanding applications require a dynamic model of friction. Because component of the viscous friction is function of speed it may be compensated by feedback loop and Coulomb friction and Stribeck friction can be eliminated by feedforward form. Since the acquisition of friction characteristics is relatively complicated, detailed description of this form of feedforward loop will be left to other publications.

The last mentioned form of feedforward is form based on fuzzy logic and neural networks. These can be used, for example. in applications where the acquisition of that friction model is impossible or difficult to implement. Learning algorithm compensates nonlinearities that classical feedback algorithm could not be compensated [7].

5. Conclusion

The paper has a aims to map out some facts regarding feedforward loops utilized in commercial actuators. Indicates what should be thinking and what should be considered in the design of the actuator with feedforward loops (it is mean actuator with high precision positioning), where not only position but also its derivatives are forced to follow the required references. It is discussing the issue solely from the perspective of control variables and associated responses. View of the fault variables will be left to other publications.

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