NUMERICAL CO-SIMULATION IN INDUSTRY 4.0 – CREATING DIGITAL TWIN OF BELT TRANSMISSION WITH NX AND MATLAB

Julian Malaka, Mariusz Hetmańczyk

Silesian University of Technology, Faculty of Mechanical Engineering
ul. Konarskiego 18A, 44-100 Gliwice, Poland

Corresponding author: Julian Malaka, julian.malaka@polsl.pl

Abstract: The subject matter of the research described in the paper is the procedure of creating a digital twin of a mechanism under consideration, representing the dynamic features of the latter. There was suggested a solution based on the use of popular CAE tools – the NX and MATLAB software. A model was built to show the elasticity of the belt and its contact with the transmission pulleys, which accurately reflects the mechanical processes occurring during the operation of the drive system. It was investigated how data obtained in the simulation can be integrated into the flow of information between various digital environments and industrial devices – e.g. within the Industrial Internet of Things (IIoT). The experiments were conducted with the use of the examined solution, and their promising results and conclusions drawn from them are described in the present publication.
Key words: Industry 4.0, digital twin, modelling, Matlab, NX.

1. INTRODUCTION

The digital twin is an important part of the Industry 4.0. It offers an insight into the parameters of products and technological machines even before they are manufactured, as well as during the use thereof. Appropriate tools enable the parallel representation in a virtual environment of what is happening with a given real system.

The classic methods of the analysis of operating devices are based on recording certain physical quantities with sensors, and presenting them, for instance, in the numerical form on diagrams. What is required in order to correctly read the condition signalled in this way is the specialist knowledge of the characteristics of a monitored process or machine and the nominal reference values [1-3].

Physical measurement of the parameters is not necessary, as long as one has a numerical replica of the examined technical system. Its computer model can constitute a kind of a formula to calculate desired quantities on the basis of other data recorded in the work area. The whole takes place in the online mode, which means that a simulative image of certain processes is received by the operator exactly at the moment when they actually occur. The resulting information, thanks to appropriate tools, is presented, for instance, in the form of easily interpretable visualisation.

A simulative numerical model synchronized with a real object – being its digital twin – allows one to determine in real time the parameters of a selected sub-assembly in the situation when physical access to it may be problematic. This situation occurs in the case of belt transmissions, which are a vital part of technological machines, and the condition of which determines the correct course of a manufacturing process [4].

1.1 Concept of digital twin system in the case of belt transmission

When operating the transmission of the type under consideration, it is indispensable to maintain the efficiency of the belt, which needs to be regularly checked. In standard drive systems, the only parameters monitored by hardware are the angular positions of the belt pulleys. Nevertheless, it enables the identification of the factors and consequences of the operation of the elastic transmission element. Thanks to commonly applied encoder sensors, the indicated quantities can be used in digital processing system. They are entered into the numerical calculations as the description of the motion of objects mechanically connected with the virtually replicated component. With the probability corresponding to the quality of the model, information about its (unmeasured) parameters occurring in the detected circumstances is artificially generated. The pool of available data is thus extended by the simulative characteristics of the reaction of the analysed part to the excitations controlled by signals from the measuring system. The user receives information, such as the one on the deformation of a selected section of the belt and the accompanying internal forces, on an ongoing basis. They are essential in diagnostics and – thanks to the digital twin – they can be obtained without the necessity of measuring them. The system described is schematically shown in Figure 1.
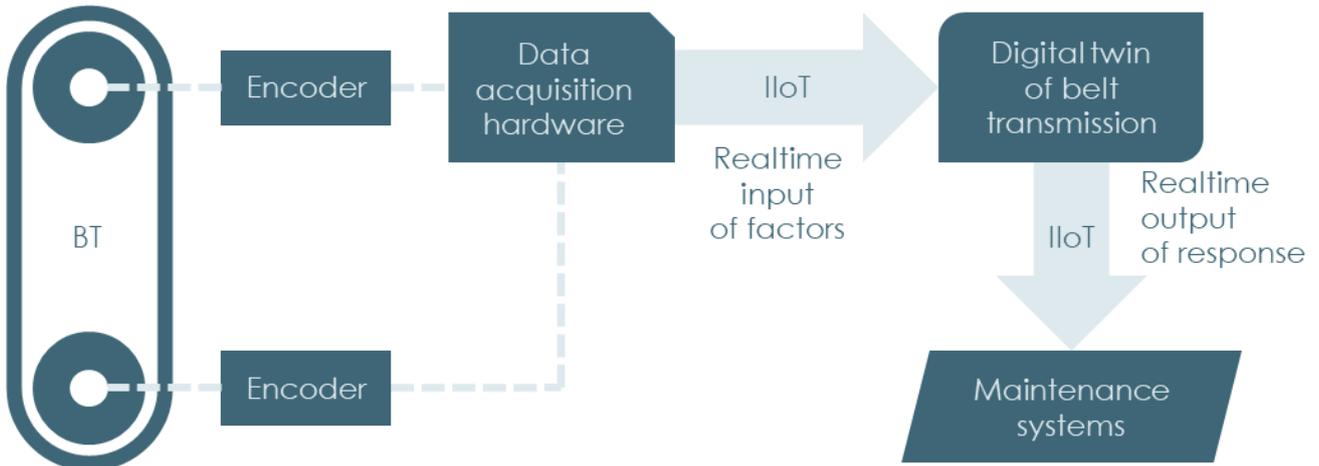
Fig. 1. System of data processing in concept of digital twin of toothed belt transmission (BT)

Generating diagnostic data by viewing simulation scenarios requires an accurate digital replica of the transmission, reflecting belt elasticity. In CAE environments, the dynamic analysis of mechanisms is conducted by means of MBS simulation. The literature repeatedly described the modelling of an elastic component using the Kelvin-Voigt method, which can be applied thanks to MBS [1, 3]. The object under consideration is a lumped parameter system [2]. The belt is divided into identical elements, characterised by the values of mass and moments of inertia [5]. The elasticity of individual components is not taken into consideration – they are perfectly rigid. Between them, there occur springs and dampers [6]. This way, individual bodies form a loop. In the simulation, the conditions of the contact between the pulleys and the belt components are defined. Such coupling of individual elements makes the parts of the elastic object move on a path close to the actual one, observed during the operation of the mechanism [7, 8]. The adopted method of representing the belt implies that the latter is understood as a set of many rigid bodies connected by means of spring-damping elements. The belt then becomes the sub-assembly of the whole device – a

chain, the flexibility of which is achieved thanks to the proper connection of links.

1.2 State of the art

For the creation of the described model as well as the simulation synchronised with actual events, an appropriate set of tools is essential. The Mechatronics Concept Designer module of the Siemens NX program allows one to realise virtual online monitoring; yet, it is mainly limited to the visualization of events detected by sensors. The limitations of this environment do not enable the creation of a multibody elastic belt model featuring desired accuracy and speed of generating the responses to excitations. The Motion module of the same application offers much more possibilities with this regard. Taking into consideration the availability of the "bushing" object, the reactions joining the component solids of the belt are determined much faster when compared to the application of a set of independent spring and dampers. The "general"-type "bushing" attracts the indicated points of two bodies to each other (base and action) according to user-defined parameters of stiffness and damping in each axis (linear or angular one) – as shown in Figure 3.

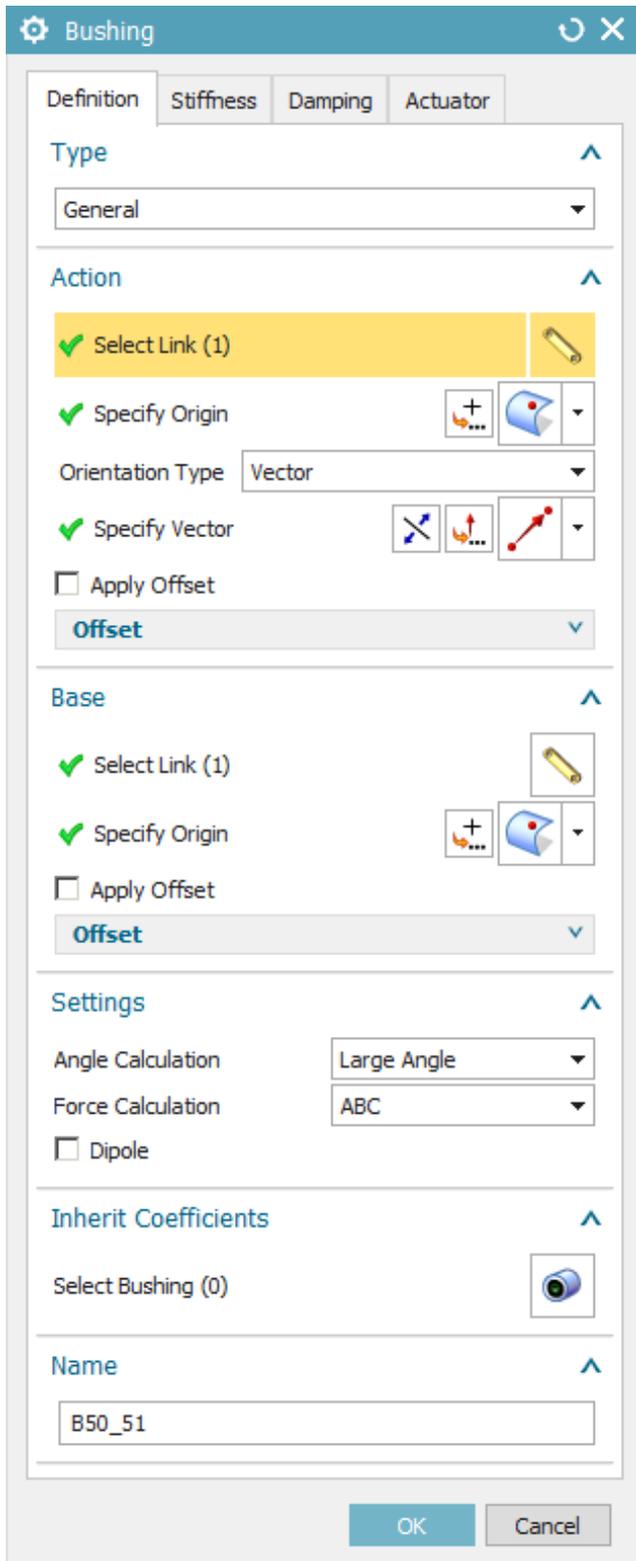Fig. 2. Characteristics of available simulation tools

85

Fig. 3. "Bushing" element defining window

In the situation under consideration, the fact that the simulations are only performed in the offline mode – with no connection to an external source of an ongoing parameter adjustment – constitutes a disadvantage. On the other hand, the possibility of exporting the created model (which is in fact a set of mathematical functions) and using it in the Matlab Simulink program is an important advantage. The exporting can be executed in the module presented in

Figure 4. Matlab Simulink is a programming environment enabling the implementation of real-time operating systems integrated with industrial devices by means of standard communication protocols [10].
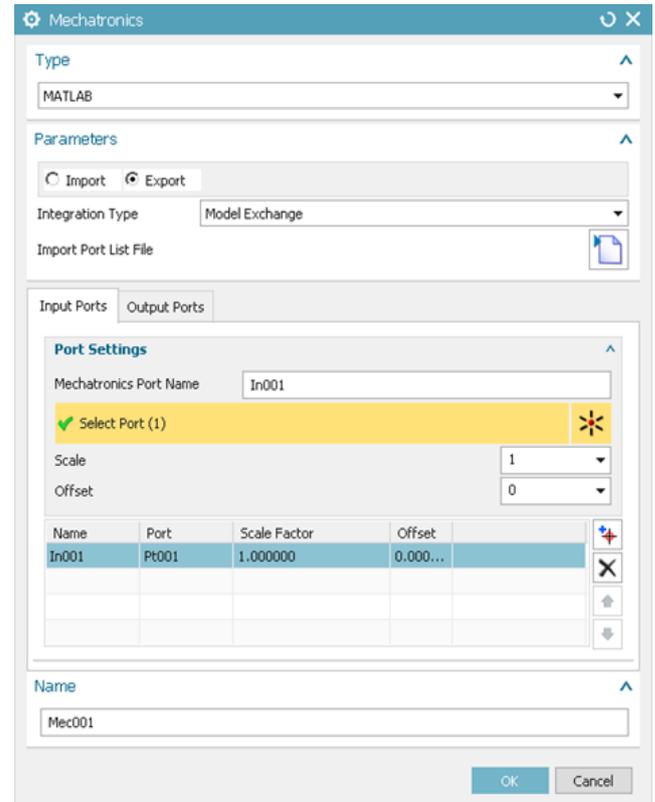

Fig. 4. Model export settings in Siemens NX

Such a combination of data processing tools, characterised in Figure 2, is the basis of the concept of the digital twin described above.

1.3 Research hypothesis and objectives
In connection with the identified capabilities of the Siemens NX and MATLAB software, it was assumed that the co-simulation with the use of these two environments will allow one to meet the digital twin standards. In the case of the drive under consideration, the modelled phenomena are the motion of the elastic belt as well as accompanying deformations and force interactions in its individual parts. The following procedure of creating and running a virtual replica was proposed:
1) creating the model of the mechanism, including an elastic component, using the Kelvin--Voigt method, in the Motion module of the Siemens NX application,
2) adapting the model to the co-simulation by defining the signals:
a) input signals – measured parameters of drive operating conditions (angular velocity of belt pulleys),
b) output signals – calculated belt parameters,
3) exporting the model to the function block of MATLAB Simulink application,

86

4) creating – in MATLAB Simulink environment – a system for the real-time simulation of belt parameters on the basis of previously obtained model and input data.

The steps and their results are schematically presented in Figure 5. The essence of the investigated solution is to ensure that the generated information be:

a) verified – the model after transformation (export to another computing environment) must react to excitations in the same way as the original one [9],

b) obtained in the shortest possible time, enabling an appropriate protective reaction once the overload is detected – it was assumed that there is a threshold of the complexity of computations, related to the multiplicity of the elements of the model (i.e. its degrees of freedom – the number of equations to be solved), at which a delay in obtaining the results appears.
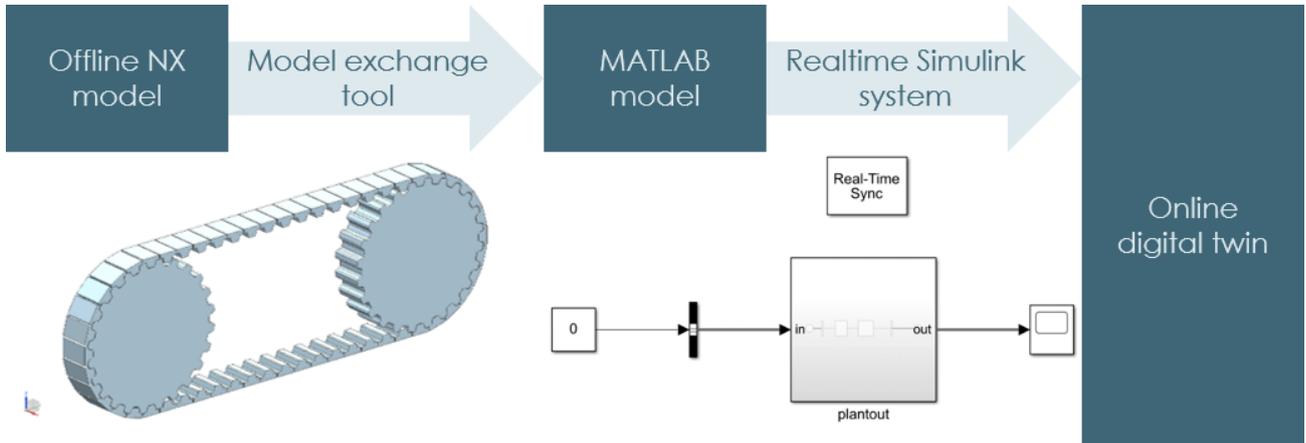

Fig. 5. Hypothetical procedure of creating digital twin

The objective of the researches was therefore to find the answers to the questions:

1) is the transformed model homologous with the original one?
2) what is the maximum complexity of the model (defined as number of the belt elements) available in the real-time condition?

2. METHODS & MATERIALS

There were planned 2 experiments aimed at finding the answers to the raised questions. With a view to conducting them, a model was created in line with the procedure included in the hypothesis. It constituted a research material, which, during the tests, was subject to modifications related to its degree of complexity. The analysis started with the simulation of a fragment of the belt reduced to 6 rigid links connected by spring-damping elements.
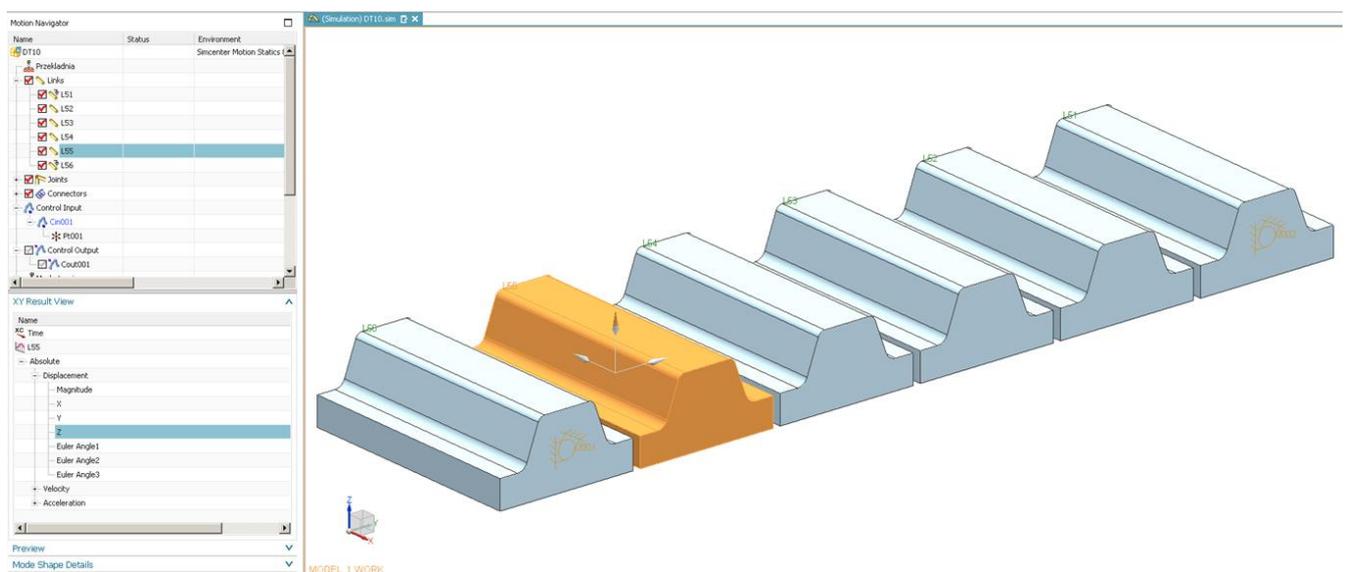

Fig. 6. Basic model being research material

Outermost elements were fixed in all 6 axes. The remaining ones – unconstrained by anything but the interactions which connect them – reacted with displacement caused by their own weight. The object was to be gradually modified towards the full form of the belt, cooperating with the pulleys.

2.1 Experiment no. 1 – model verification

In the Siemens NX environment, there was conducted a simulation of the displacement of a selected link (marked in Figure 6) in the modelled section of the belt. The simulation ran in the offline mode, without being connected to any controllable input data source. The results were available only after the elapse of a predetermined simulation time (unsynchronized with real time). The parameter calculated in this way was the "reference" (Figure 7) in the comparative analysis of the online simulation (in the real-time condition).
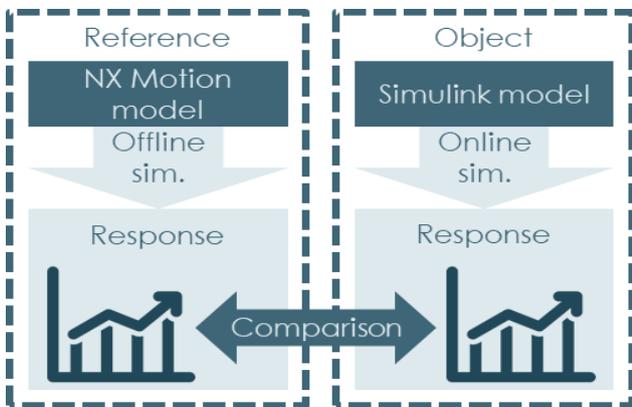

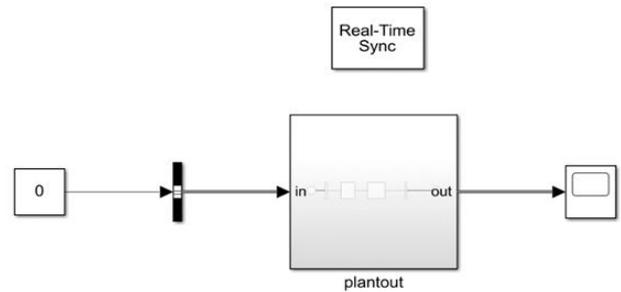Fig. 7. Diagram of procedure of model verification in digital twin

Fig. 8. Investigated model as function block in MATLAB Simulink

According to the hypothesis, the virtual object transferred to the MATLAB Simulink environment (as a "black box" containing a mathematical model, with an input factor and an output response, called "plantout" in Figure 8) was to generate the same course of a selected quantity in time – as a response to identically defined mechanical conditions of its operation.

2.2 Experiment no. 2 – searching for synchronous simulation limit

Experiment no. 2 was conducted in line with the developed algorithm presented in Figure 10. One of its stages is to reduce the model to a minimum. For the applied mechanical interactions to produce any observable result, at least three links were required, including 2 of them – outermost ones – fixed, as one can see in Figure 9.

Fig. 9. Diagram of simplified model for research

In subsequent iterations of the study, the chain of objects forming the elastic belt was enlarged.
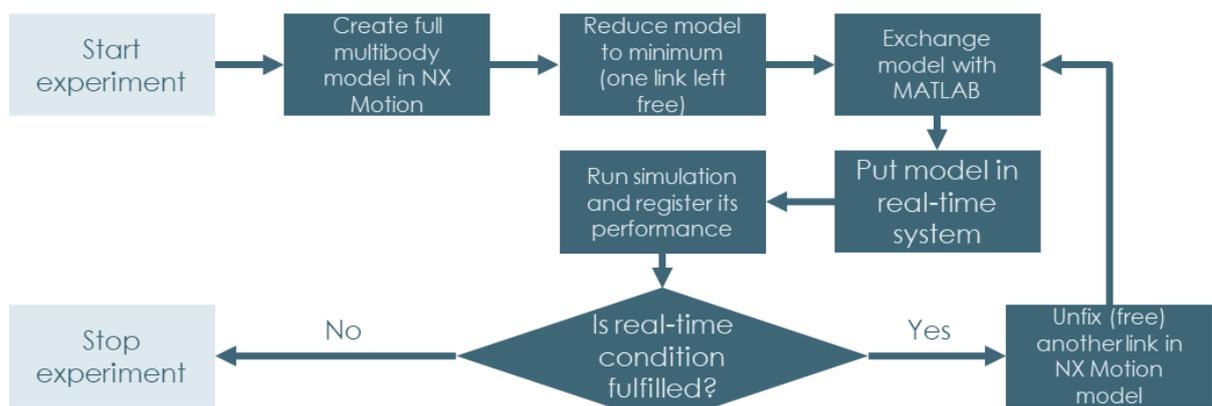

Fig. 10. Algorithm of experiment no. 2

A tool for monitoring the time of waiting for the computation result is available in the target computation environment. The example of its output data is presented in Figure 11. The "Total Time (s)" of the "plantout" calculations cannot exceed the real time of events covered by the simulation, so that the mapping of selected parameters of the replicated object in virtual space does not take place with a delay in relation to reality. "Real-Time Synchronisation" is a delay added artificially to synchronise the speed of changes on the screen with the physical one.

Fig. 11. View of simulation time monitoring tool in MATLAB Simulink

After each attempt completed with meeting this requirement, further free elements were added to the model until the stop condition was reached. The system was observed for 5 seconds. This is an adopted interval for checking the condition related to determined (ultimately by means of measurement) circumstances of the operation of the analysed part of the drive. Therefore, data processing time in a function block containing the dynamic equations of the belt (called "planout") could not exceed the indicated value.

3. RESULTS AND DISCUSSION

The tools used make it possible to save the computation results as a set of samples of a selected simulated parameter in the time domain. This allows them to be presented in the form of charts. This form was chosen in order to present the displacements obtained as a result of experiment no. 1, to juxtapose their courses in one coordinate system and, on this basis, to compare them visually. In experiment no. 2, one numerical value was expected after each iteration expanding the complexity of the model. It was therefore sufficient to put the obtained data in a table.

3.1 Results of experiment no. 1
The below-presented charts pertain respectively to:
1) offline simulation in Siemens NX environment – Figure 12,
2) online simulation in MATLAB Simulnik environment – Figure 13,
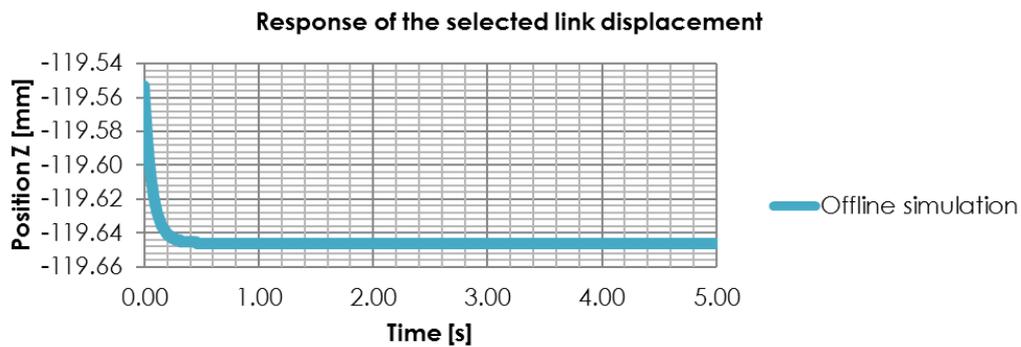3) comparison of results of both simulations – Figure 14.
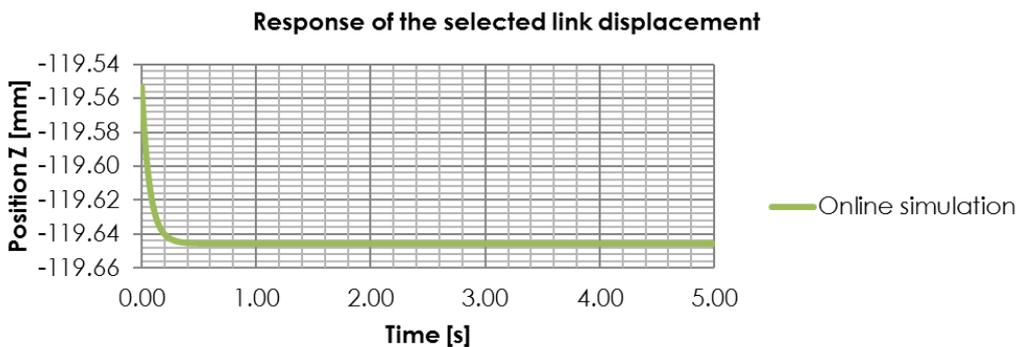

Fig. 12. Results of simulation in Siemens NX Motion

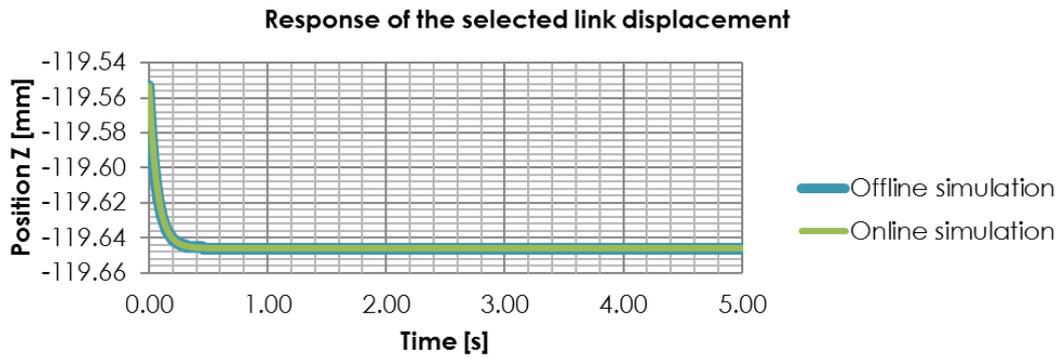Fig. 13. Results of simulation in MATLAB Simulink

89

Fig. 14. Comparison of results of both simulations

Offline computations (in Siemens NX Motion) constituted the point of reference in comparative analysis. The Figure 14 shows that the model converted to a form suitable for the adopted digital twin system generates in real time identical data as the one in an offline simulation.

3.2 Results of experiment no. 2
The form of the model used in the first iteration of the study was schematically presented in Figure 9. The time needed to simulate the behaviour of the analysed system for 5 seconds at certain mechanical actions is displayed on the screen shown in Figure 11. The result of this and the subsequent steps of the experiment are shown in Table 1.

Table 1. Results of experiment no. 2

Iteration	Simulated time	Computation time	Real-time synchronisation
1	5 s	0.190 s	✓
2	5 s	0.231 s	✓
3	5 s	0.328 s	✓
4	5 s	1.691 s	✓
5	5 s	958.633 s (simulation stopped)	✗

In the Figure 15 one can see the window of the tool for measuring data processing time in individual function blocks of the computation system during the last iteration. The stop condition in the applied algorithm of performed actions was then reached.
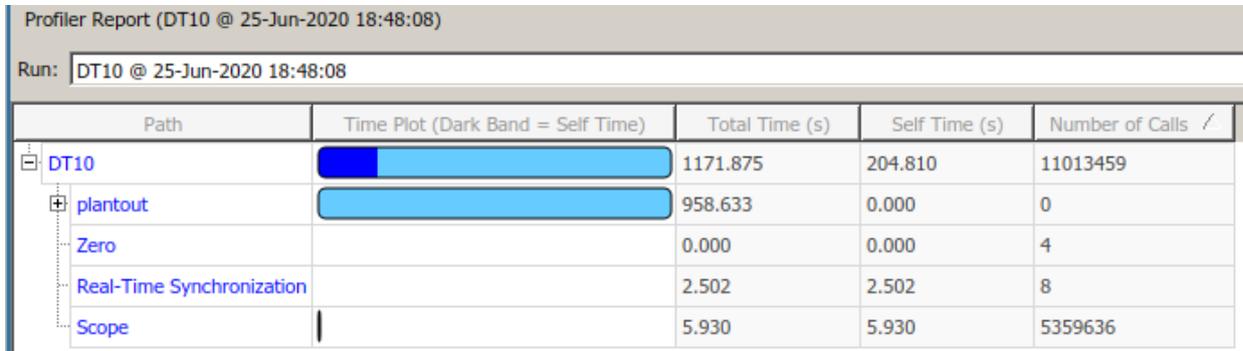

Fig. 15. Report on study of computation time in iteration no. 5

Fig. 16. Form of model used in iteration no. 5

The last trial was conducted with a model extended from the initial one by 4 free links connected to the rest of the belt with "bushing" elements – according to Figure 5.

4. CONCLUSIONS

Transferring the model from the Siemens NX application to MATLAB Simulink in the proposed way did not cause the loss of its quality, understood as the correctness of generating the desired information. Therefore, within the framework of experiment no. 1, there was conducted the verification, the result of which is positive. What is more, by implementing the task in the target environment, the features of the simulation were obtained which are key in the operation of the digital twin. The analysed process is based on output signals (numerical parameters defining mechanical conditions of the replicated system) entered to a

90

computer from measurement systems. It is feasible thanks to standard communication solutions, implemented in the MATLAB program, which guarantee its compatibility and integration with industrial data processing tools. Thanks to using the "Real-Tim Sync" function block, events can be mapped in virtual space at natural pace. Quantities describing a change in the condition of selected elements in response to identified circumstances are calculated before the change actually occurs and displayed in sync with it. However, the critical condition here is an adequately short time of performing the numerical operations defined in the "planout" block. In the case under consideration, with 5 free links – connected with spring-damping elements and only subjected to gravitational acceleration – the computation took too long for the system thus created to be used as a digital twin. Thus, the Kelvin-Voigt model built in the chosen simulation environment did not meet the expectations. It therefore requires further refinement, which constitutes the conclusion after experiment no. 2.

4.1 Further research perspectives

The system under consideration is susceptible to actions improving its computation performance. A device replicated in virtual space can be in reality monitored with more sensors. The measurement of the distance would enable the determination of the displacement of individual sections of the elastic component. Then, these parameters would be excluded from the simulation. It would significantly reduce the complexity of mathematical operations, and thus the computer loading. This way, the desired (missing) information would be generated in shorter time. Nevertheless, it would still be possible to determine the tension, bend and accompanying forces or torques between the links – acting in the "bushing" elements located there and being their characteristic quantities. They are the most important in terms of operation and prediction of the condition of the device, and the used tools make it possible to determine them as the output data. Within the framework of further work, an attempt should be made to develop and review the concept of recording additional parameters and entering thereof from the outside to the digital twin, in order to reduce the computation needs. It would then be necessary to repeat the examination of the response time of the numerical replica to the identified operating conditions of the mechanism.

5. REFERENCES

1. Čepon G., Manin L., Boltežar M., (2009). *Introduction of damping into the flexible multibody belt-drive model: A numerical and experimental investigation*, Journal of Sound and Vibration, **324**, 283-296.
2. Callegari M., Cannella F., (2001). *Lumped parameter model of timing belt transmissions*, 5th AIMETA Congress of Theoretical and Applied Mechanics, Taormina, Italy, Sept., **1**, 1-11.
3. Čepon G., Manin L., Boltežar M., (2011). *Validation of a Flexible Multibody Belt-Drive Model*, Journal of Mechanical Engineering, **57**, 7-8.
4. Pakuła A., (2005) *Wpływ wybranych czynników na trwałość pasów zębatych napędu rozrządu silnika spalinowego*, Archiwum Motoryzacji, **4**, 357-362.
5. Kubas K., (2015). *A model for analysing the dynamics of belt transmissions with a 5pk belt*, The Archives of Automotive Engineering, **67**(1), 189-209.
6. Srivastava H., Haque I., (2009). *A review on belt and chain continuously variable transmissions (CVT): Dynamics and control*, Mechanism and Machine Theory, **44**, 19-41.
7. Adamiec-Wójcik I., Grinke L., (2017). *Metoda sztywnych elementów skończonych i jej modyfikacje*, Modelowanie Inżynierskie, **62**, 5-11.
8. Fischer M., Eberhard P., (2014). *Simulation of moving loads in elastic multibody systems with parametric model reduction techniques*, Archive of Mechanical Engineering, **LXI**(2), 209-226.
9. Karkula M., (2012). *Weryfikacja i walidacja dynamicznych modeli symulacyjnych procesów logistycznych*, Logistyka, **2**, 717-726.
10. Siemens NX software documentation, https://docs.plm.automation.siemens.com/tdoc/nx/12.0.2/nx_help, Accessed on 24.05.2020.