Digital twins of mechatronic machine tools for modern manufacturing

A A Kutin [1]*, V V Bushuev [1] and V V Molodtsov [1]

[1]Moscow State University of Technology «STANKIN», Vadkovskij per. 1, Moscow, Russian Federation, 127994

aa.kutin@stankin.ru

Abstract. The article is devoted to the problem of the development of “digital twins” of technological equipment — it’s specially organized and structured information models. The prospects for the use of digital twins for the organization of digital production and the problems associated with providing an adequate description of real mechatronic technological systems with their help are considered. It is shown that the creation of digital twins of technological equipment is a complex task associated with the integration of information and production technologies; therefore, its main solution is a systematic approach that defines the requirements for mathematical, informational and methodological support of digital productions. The advantages and disadvantages of various approaches to the formation of such models are considered. A combined technique for obtaining digital twins of mechatronic feed drives, forming a system for shaping CNC machines, which uses the results of finite element modelling and experimental data, is proposed. Using the example of drive identification, an experimental result shows the need to develop and implement scientifically based methods for constructing digital twins.

1. Introduction

Digital production accumulates advanced achievements in the field of manufacturing and information technologies and uses the scientific results of the modern interdisciplinary direction - mechatronics. Integration of new information and manufacturing technologies along with the creation of mechatronic technological systems mainly increases productivity and production efficiency.

Project “Industry 4.0” shows that to successfully solving of these problems in recent decades, the concept of a "digital factory" is being realized. In most cases, the term "digital factory" refers to the information model of high-tech production, covering the main directions of advanced manufacturing technologies, new materials and information and communication technologies [1]. This model (figure 1) includes information about all manufacturing processes, as well as the entire amount of information about the product, which can be distributed through the stages of its life cycle. Within the framework of the new paradigm, digital production is a system that supports the full life cycle of manufactured products and is characterized by a common information platform and the use of mechatronic equipment capable of generating information online and adapting to changing tasks. The implementation of the new paradigm requires the development of new methods of research and design of large manufacturing systems, focused primarily on the description of their production and technological state. The analysis of the structure of the CNC equipment should be carried out to determine the influence of physical and technological parameters on the possibilities of high-performance and reliable operation in conditions of "unmanned" production.

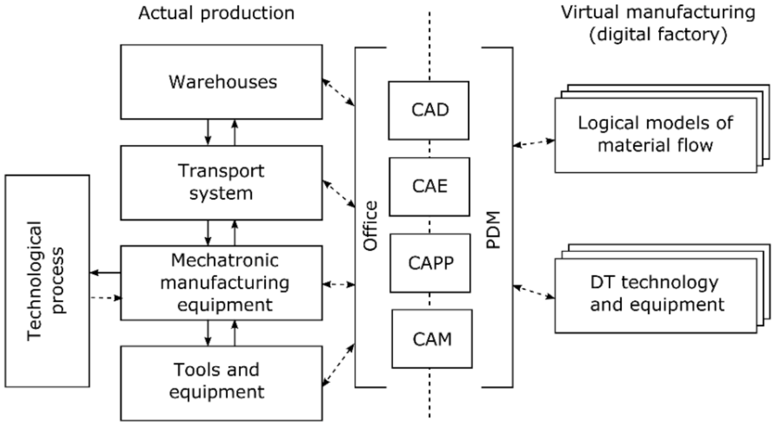


Figure 1. Modelling of technological processes of machining production

A fundamental problem is the lack of development of "digital twins" (DT) of CNC equipment – virtual model includes geometric model of the machine; a set of calculated data of parts and components, information about materials and technological processes of manufacturing. This model (figure 2) is the basis for informational support of the life cycle of technological systems in digital production, including the formulation of a technical task, the description of information and logistic links of a system operation, the quantification of performance indicators, the simulation of the system operation, processes of manufacturing products.

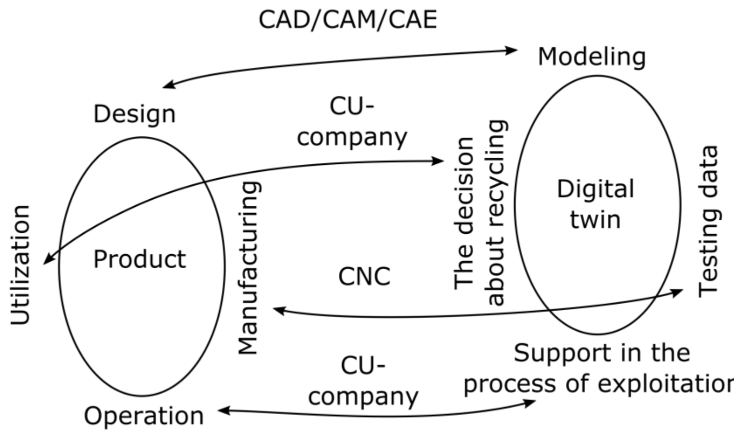


Figure 2. Information support of the product life cycle

Digital twins of mechatronic technological systems (MTS) will allow to solve a complex of problems, assessing the suitability of technological equipment for manufacturing parts of the required accuracy, preparing control programs that take into account the specific features of each machines, the formation of requirements for the designing of new equipment (figure 3). Such a variety of applications is explained by the fact that "digital twins" in structure are sufficiently adequate models of these objects, which makes it possible to obtain objective information about them and to form fairly complex control laws, in accordance with many input parameters that changing with time.

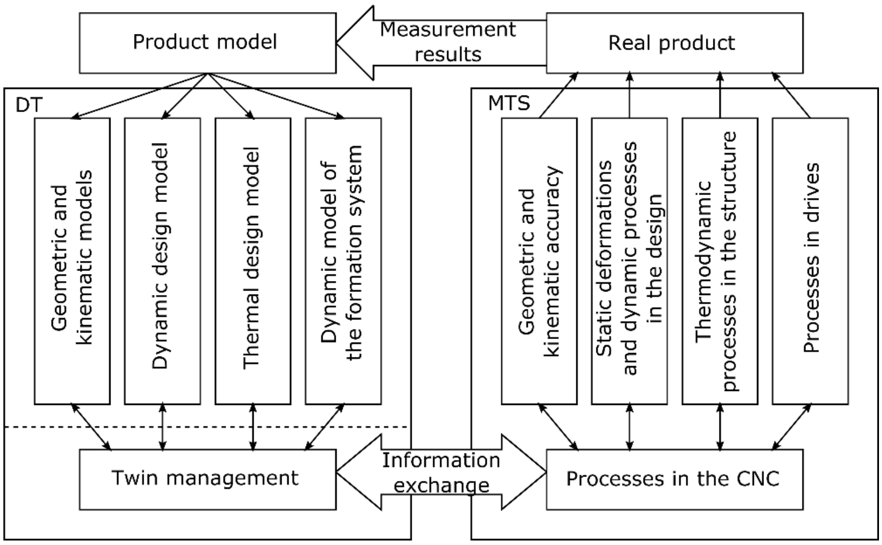


Figure 3. Digital twin mechatronic process system

2. Theory and Methods

The creation of digital twins of technological equipment is a complex task connected with the integration of information and manufacturing technologies, therefore the main approach is the systematic approach that determines the requirements for the mathematical, informational and methodical support of digital production. For their implementation it is necessary:

– to identify the relationship between the operational characteristics of the mechatronic system for the shaping of modern technological equipment, the designing parameters and control systems for the drives;

– to offer mathematical models for simulation and analysis of dynamic processes in mechatronic systems for shaping modern technological equipment and to develop methods for parametric synthesis and identification that provide specified operational properties of machine;

– develop the necessary software, create databases and provide recommendations that ensure the implementation of adequate reality sets of mathematical models of all stages of technological processes of forming the products of mechanical and physicochemical treatment.

It is very important that the digital twin includes tools for solving the problems of production process planning, including the control programs for CNC machines. The methods of CNC machine control, which allow to take into account the specific operational features of an equipment and adapt it to the requirements of a specific technological process, significantly expand the production possibilities and therefore their development is one of the promising directions in the implementation of new modern digital production technologies.

When machining precision parts with hard-profile surfaces, their contours are the result of axis movements of the tool and workpiece. Drives in mechatronic systems for forming CNC machines ensure the coordination of these movements. The task is transferred to them through the information network of the control device. The transition from mechanical to information connections made it possible to substantially increase the flexibility of the equipment and the different surfaces realized on the machine while simultaneously increasing the accuracy of machining, as the effect of the errors in the mechanical links of the kinematic chains ensuring the coordination of movements in CNC-free machines was ruled out. However, the dynamic processes in the drives, and the lag when operating the information network, have a direct impact on the output precision of the part.

The dynamic quality of the feed drives depends significantly on the elastic properties and distributed inertial characteristics of their mechanisms, since resonance phenomena appearing in the mechanical part of the drive prevent the increase in the speed and position contours to the required level. Despite the importance of the problem, it has not been studied enough, both theoretically and experimentally.

Resonance phenomena in drives with ball screw, which are the most popular type of traction devices for machine tools, are caused, as a rule, by axial and torsion oscillations in the design of these gears. The intrinsic frequencies of the axial oscillations of the moving assembly located in the band of the transmission of the position loop from (30-40 Hz to 200 Hz) or in the immediate vicinity of it have a direct influence on the quality of the machining. Resonance phenomena in torsion vibrations of rotating elements of the traction device structure (screw, coupling, engine rotor, etc.) arise at frequencies from several hundred to several thousand Hz. They practically do not appear on the moving node, but can lead to loss of stability of the speed loop and limit the possibility of its tuning [2].

Modern design and analysis tools, such as SolidWorks, MATLAB, ANSYS, and NX Motion Software, allow to simulate and analyze the design of modern machines at the designing stage. However, the finite element modeling built into modern computer engineering systems cannot be used directly in the modeling of the federate control loops, due to its cumbersomeness, redundancy and closeness [3, 4]. Dynamic models of mechatronic systems in MATLAB Simulink allow taking into account dynamic processes in the control circuits of feed drives, but obtaining adequate models of the mechanical part is a complex problem.

Models that allow describing the processes in the mechanical part of the drive with high accuracy, can be created on the basis of information about the natural frequencies and modes of the object's oscillation obtained from the experimental frequency characteristics or by calculation as a result of finite element modeling using means of modal analysis [5, 6]. The main drawback of these models is that they do not reflect the actual physical structure of the object, in fact representing a black box in which the connection between the input and the output is given by some abstract mathematical function - the modal series. For this reason, they are not used in the designing of feed drive mechanisms, although they can be effective enough when selecting and configuring its control loops.

A satisfactory description of the dynamic processes in the mechanical part of the drive with minimal resources is provided by models of the form

$$\left.\begin{array}{c} J_1 s^2 \varphi_1(s) = M(s) - k_{1,2}(s)[\varphi_1(s) - \varphi_2(s)] \\ \vdots \\ J_i s^2 \varphi_i(s) = k_{i-1,i}(s)[\varphi_{i-1}(s) - \varphi_i(s)] - k_{i,i+1}(s)[\varphi_i(s) - \varphi_{i+1}(s)] \\ \vdots \\ J_n s^2 \varphi_n(s) = k_{n-1,n}(s)[\varphi_{n-1}(s) - \varphi_n(s)] - M_c(s) \end{array}\right\},$$

(1)

where Ji and $\varphi_i(s)$ – the moment of inertia and the angle of twisting of the i-th rotating mass, i = 1, ..., n; M(s) and Mc(s) – moments on the engine side and resistance forces; $k_{i,i+1}(s) = b_{i,i+1}s + c_{i,i+1}$ – a complex parameter that determines the elastic and dissipative coupling between adjacent masses; $c_{i,i+1}$ and $b_{i,i+1}$– stiffness and damping coefficient of the corresponding part of the structure. Determination of the parameters of such models on the basis of experimental data or finite-element modeling results is described in detail in [7].

The problem of determining the unknown values of the moments of inertia of the concentrated masses and the rigidity of the elastic constraints of such a system reduces to a joint solution of the inverse problems of eigenvalue problems for it and an analogous system with a rigidly fixed rotor of the type

$$([\tilde{\alpha}] - x_i[E])\{\Psi\}_i = \{0\},$$

(2)

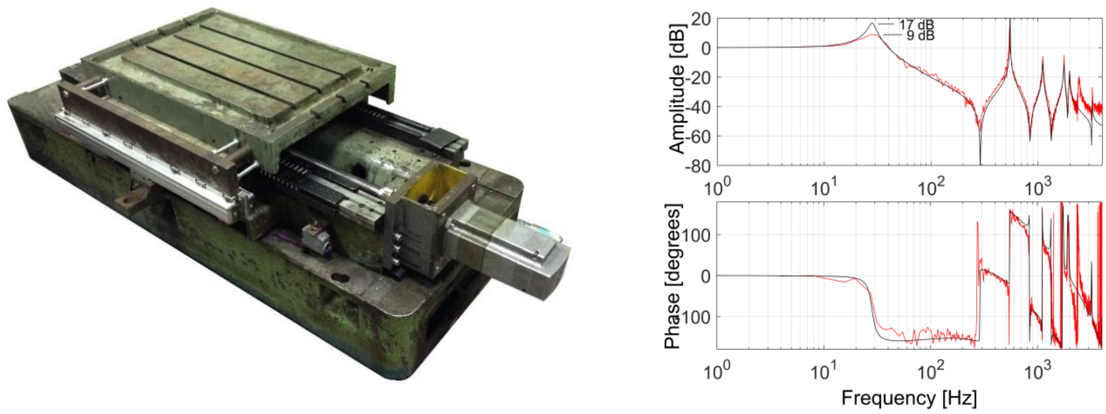
where $[\tilde{\alpha}] = [M]^{-1/2}[C][M]^{-1/2}$ – is the matrix of the squares of the partial frequencies, [M] and [C] – are the matrices of masses and rigidity, $\{\Psi\}_i = [M]^{-1/2}\{\Phi\}_i$, xi ≥ 0 and $\{\Phi\}_i = [\Phi_n \cdots \Phi_1]^T$– are the i eigenvalues and the vector.

The algorithm for determining the dimensions and parameters of the system includes the following basic steps:

1. Using finite element simulation or experimentally, nonzero eigenvalues of the rotating part of the drive with a free (pole) and fixed rotor (zeros) are determined.
2. For non-zero eigenvalues of poles and zeros, using the recurrence relations obtained from Newton's formulas for determining the power sums of the roots of a polynomial, the coefficients of the characteristic polynomials of matrices $[\tilde{\alpha}]$ for systems with a free and fixed rotor are determined.
3. From the coefficients of the characteristic polynomials of these matrices computed at the 2nd step, the values of the squares of the partial frequencies are found using the recursive computational procedure [8].
4. The unknown moments of inertia of concentrated masses and the rigidity of elastic bonds are determined on the basis of information about the total moment of inertia, the rotating elements of the mechanical part of the drive.

3. Results
As an example of the application of the developed method, a parametric identification of the model of the mechanism of the experimental stand presented in figure 4a was carried out using poles and zeros obtained experimentally.

To obtain the frequency characteristics of the drive, the model of its mechanical part (1) was used, which, in combination with a fairly simple model of the drive control loops described in [9], forms a mathematical model of the dynamic system of a multi-circuit electromechanical feed drive. The model of control loops takes into account delays in the transmission of information in current loops, speeds and positions that have a significant effect on the dynamic processes in them. figure 4b shows a comparison of simulation results in the MATLAB environment with the experimental frequency characteristics of the drive.



(a) (b)

Figure 4. Stand design (**a**) and identification results (**b**)

4. Conclusions
It can be concluded that the development of methods and tools for creating digital twins is an important scientific and technical problem that is of decisive importance for engineering in general. The main difficulties are connected with the establishment of interrelations between the performance characteristics and design parameters of mechatronic systems made in the form of models and functional relations, and methods for their parametric and structural approximation.

Based on the research carried out by the authors, as well as the work of other researchers, we highly need for the development of "digital twins" of equipment for specific technological production processes, which allows us to conclude that the relevance, prospects and great practical significant are such works.

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