SYNERGETIC DEVELOPMENT OF MACHINE TOOLS

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Looking at modern machine tools from a design point of view, we observe that a number of their basic characteristics and methods used for their optimised design are the same. This even applies to very different categories of machines with different proportions, dimensions, parameters and specific structures. The project introduced in this paper—Synergic machine tool design (SMTD – aims to find such shared characteristics and use them in creating a knowledge and simulation system: SYNTOS. From an application point of view the system is oriented towards the support and development of new machine tools, with a special focus on the early stage involving the design of machine tool structures and drives. The aim is to assess a wide range of options linked to different initial requirements, and to systematise them for the purposes of selecting the definitive solution. During this selection process, the purpose is to provide the user with a number of dependences that make it possible to assess different configurations of machine drives and whole machine tool structures. The project has been implemented in cooperation between CTU-RCMT, Kovosvit MAS, a.s. and TOS Varnsdorf, a.s., with support from the Ministry of Industry and Trade of the Czech Republic (MPO).

Keywords
synergy, simulation, database, mechanical structure, drive

1. Motivation and General Description of the SMTD Project

Modern methods for complex motion axis modelling which involve the interaction between the mechanical structure and the drive make it possible to simulate dynamic motion axis parameters and observe the influence of all motion axis parameters on machine tool behaviour [Altintas 2011]. Since the creation of such models is complicated and the time available in the design stage limited, it is possible to create only a limited number of machine configuration options and predictions of machine tool characteristics. Another limitation of current complex models lies in the fact that these models are not linked to suitable database and design tools that would make it possible to automate the selection of optimum solutions.

The verification of simulation models using measurement results makes it possible to draw more general conclusions concerning the suitability of individual structural and conceptual solutions for motion axes, while obtaining the required parameters. By processing such results a combined system supported by results from measurements and simulations can be created which allows, in the early stages of designing a new machine tool, for selecting the most suitable kinematic configuration of motion axes and their structural characteristics, as well as the most suitable drive design. A combined knowledge and simulation system makes it possible to evaluate large numbers of possible motion axis options and their expected parameters. Such analysis is relevant for the stages between the issuance of technical requirements for a new machine tool (e.g. by the marketing department) and the start of development and design work, or for critical re-assessment of existing solutions (see Fig. 1).

The analysis makes it possible to select, for the development and design stage, the appropriate solutions in terms of obtaining the best possible mechanical properties of the motion axes from the point of view of their path control, taking into account the design and production limitations. The designers thus do not have to perform such ‘routine’ tasks as iterative computations for each case, and can use their creative potential to make qualified decisions, selecting from a set of proposed sub-optimum solutions.

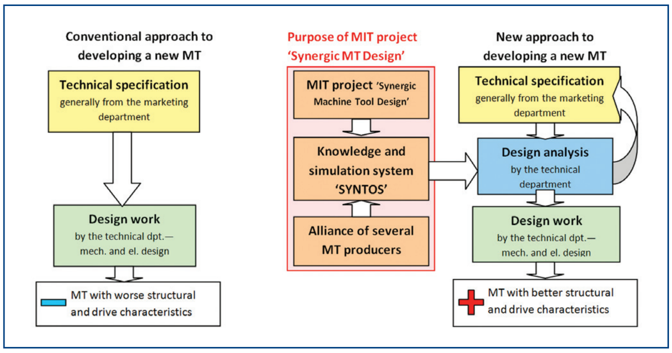


Figure 1. *Illustration of the differences in machine tool design using the conventional approach and the approach based on the SYNTOS knowledge and simulation system*

In the machine tool industry, like in the car industry, different configuration tools exist which make it possible to assess some of the machine tool characteristics. Those are the tools with the closest link to issues addressed in this paper. Typical examples include the European NEXT project [Nemeth 2009] which has led to the creation of a machine configuration tool including auxiliary technical and economic calculations, intended primarily for the sales sector (it uses existing machine tool groups). Integration of the configuration tool with optimisation tools for a large set of possible solutions is shown in [Zatarain 1998], where possible machine tool configurations for three-axis milling applications are computed, and simplified optimisation based on stiffness links between individual machine tool groups is performed. A very sophisticated solution has been introduced by a Bologna and Florence University team [Tani 2006]. This approach already involves some parameterisation of existing solutions, and thus offers a more comprehensive set of options. The final solution is then selected from this set of options using coupled FEM simulations. On a commercial basis, complex modelling tools linked to a library of mechanical machine tool parts are used by the company Trumpf [Nieding 2011]. The solution presented below in detail differs from the above-mentioned configuration tools in the following aspects:

- Models of machine tools and machine tool groups are always optimised for specific input parameters (see chapter on Parametric Optimisation of Base Structures). Thus, also the options that have not been implemented yet are taken into account, which is the basic precondition for their use in the design stage.
- Verification measurements on real machine tools have been used to create the models.
- The drive generation system is linked to a large database of components.
- The system introduces comparisons of individual solutions based on obtained eigenfrequencies, mass, and price.

2. Characteristics of the SYNTOS Software

The SYNTOS software—the outcome of the project entitled Synergic Machine Tool Design—has been developed for use in the early stages of machine tool design. It consists of functional modules and algorithms which will be described in the following chapters. The software has been developed in cooperation with leading czech machine tool producers: Kovosvit MAS, a. s., and TOS Varnsdorf, a. s.

It is focused on the milling and drilling sector. It should also be noted that SYNTOS is an open system, which means that it is possible to add new machine tool types. The overall structure of the system is depicted in Fig. 2.

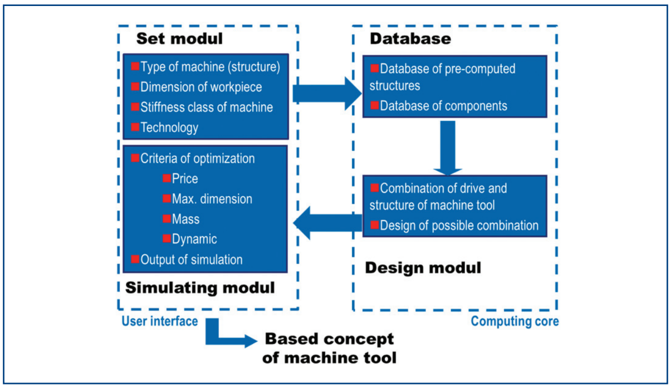


Figure 2. *Structure of the SYNTOS software*

The user first defines the input parameters using the data entry panel (see chapter on Input Parameters). Processing of this data yields a set of suitable bearing structure options (see chapter on Parametric Optimisation of Base Structures) from the database. Within the design module, possible drive configuration options are assigned to the selected mechanical structures (see chapter on Drive Design). The result is a set of solutions that meet the input conditions (parameters). The solutions are further filtered according to optimisation criteria and limiting parameters defined in cooperation with Kovosvit MAS and TOS Varnsdorf. The remaining options are arranged in graphic dependences according to their properties; this means the dependence and sensitivity of individual options are observed in relation to price, dynamic properties, mass, etc. (see chapter on Selection of Definitive Option). The software concept has been designed to enable a comparison of different drive structures, and thus whole milling machines, within a period of maximum five days. The software solution consists of the MATLAB software and the MySQL database system. The end user – Kovosvit MAS and TOS Varnsdorf in our case – works with a compiled, auto-run version of the software without the need to install the MATLAB software. To fill the database with base structures it is possible, in addition, to use the ANSYS FEM solver. The database is filled with base structures of vertical milling machines based on the MCV type (Kovosvit MAS) and horizontal milling machines based on the WRD configuration (TOS Varnsdorf). There is a single methodology for creating the structures, based on repeating the task described in the chapter on Parametric Optimisation of Base Structures; it is therefore easy to add new machine types or bearing structures (portals, columns, tables, etc.) to the database.

3. Input Parameters

The input parameters must include the basic specification of requirements defined by the marketing department and understandable for the design department. This specification may become the source of numerous problems in a new machine tool (many examples of this exist in practice) and may lead to the machine tool being uncompetitive and unmarketable. The reason is that the specification of parameters from the marketing department entails serious design complications and non-standard procedures which make the machine tool expensive. Feedback on input parameter changes needs to be available and the sensitivity of the resulting machine tool properties to these parameters needs to be observed. This requires computations for a large number of options and an efficient system for classifying and filtering these options, which is ensured by other modules of the SYNTOS software.

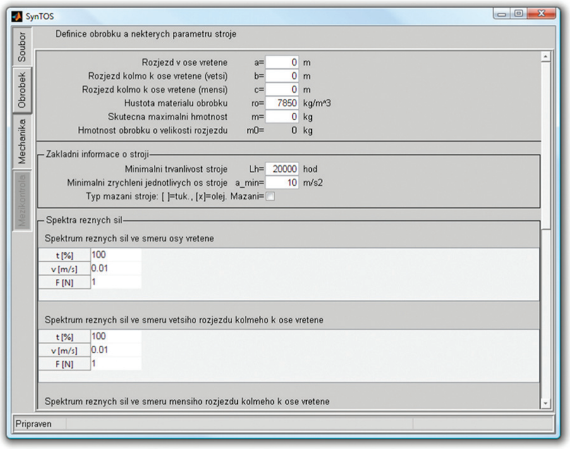
Maximum workpiece size and mass are entered in the input parameter module. Based on this data, pre-computed base structure options that are most closely correlated with the required dimensions are selected from the database (see chapter on Parametric Optimisation of Base Structures). Then, load spectra, required acceleration, and service life are entered. These parameters are used by the design module to optimise the ball screw drives (see chapter on Drive Design). A screenshot of the data entry panel for input parameters is shown in Fig. 3.

4. Parametric Optimisation of Base Structures

The possibility to quickly explore a large number of options while being able to change the input parameters means, in fact, creating the desired feedback between the design department and the marketing department. The design department can compare and evaluate the options generated by the SYNTOS software and provide the marketing department with qualified cost-benefit estimates for the specified input parameters. To be able to make computations for a large number of options within a short time span (five days), a parametric optimisation method for base structures has been developed. First, a map of possible workpiece sizes is defined for selected milling machine types. The sizes are deliberately selected in small discrete steps and, in addition, the functional limits go beyond the usability of the machine tools. This ensures that for each desired practical solution a near point always exists in the mesh of dimensions. Along with the dimension meshes, machine stiffness classes are defined; this broadens the range of possible options and enables comparison within the required precision limits (statistic deviations). The classification of machine tools based on attainable directional stiffness at the point between the tool and the workpiece is mentioned e.g. in [Stephenson 2006], [Bach 2006]. Thus, we obtain an important sensitivity parameter as part of the general evaluation. Three stiffness classes have been defined for the observed milling machines (low 50 N/μm; medium 100 N/μm; high stiffness 150 N/μm). These values have been defined using results from measurements at Kovosvit MAS and TOS Varnsdorf. Then, the whole machine tool is divided into 'machine groups'. These are defined on the basis of their interchangeability with other machine types. For a given machine type it is important that these machine groups are independent of one another in terms of geometry and properties. In our particular case of MCV milling machines, these groups are: the column group (column and spindle head), and the table group (cross slide and table). The group constituting the machine bed is subordinate to both of these groups, which means that the bed part can be defined through the size and mass of these two groups. This is why the bed is not taken into account in further optimisation steps. Only one group exists for the WRD horizontal milling machine type – the column group (movable column with spindle head) – as it is responsible for all three movements on the X, Y, and Z motion axes (movable column with spindle head). More machine types (configurations) can be divided in this way. The following Fig. 4 shows the selection of a concept for a machine tool and machine groups in the SYNTOS environment.

Individual machine groups are then subjected to geometric parameterisation. A simplified FEM model, determined by a set of geometric parameters, is created. The parameters and their dependences are defined by design and computing specialists (from Kovosvit MAS and TOS Varnsdorf). They determine the design degrees of freedom, generally selected from experience or with the help of test computations. These parameters include e.g. the number of ribs, the column width and high, the width of side, etc. (see Fig. 5.).

Before the simplified parametric model, a complex model (mechanical structure and control) is created and verified through measurements on a corresponding real machine. The measurements were performed on Kovosvit MAS and TOS Varnsdorf machines. They were drive measurements testing the frequency characteristics.



Definice obrobku a nekterych parametru stroje

Rozjezd v ose vretene a= 0 m
Rozjezd kolmo k ose vretene (vetsi) b= 0 m
Rozjezd kolmo k ose vretene (mensi) c= 0 m
Hustota materialu obrobku ro= 7850 kg/m^3
Skutecna maximalni hmotnost m= 0 kg
Hmotnost obrobku o velikosti rozjezdu m0= 0 kg

Zakladni informace o stroji
Minimalni trvanlivost stroje Lh= 20000 hod
Minimalni zrychleni jednotlivych os stroje a_min= 10 m/s2
Typ mazani stroje: [ ]=tuk., [x]=olej. Mazani= ☐

Spektra reznych sil

Spektrum reznych sil ve smeru osy vretene

t [%]	100
v [m/s]	0.01
F [N]	1

Spektrum reznych sil ve smeru vetsiho rozjezdu kolmeho k ose vretene

t [%]	100
v [m/s]	0.01
F [N]	1

Spektrum reznych sil ve smeru mensiho rozjezdu kolmeho k ose vretene

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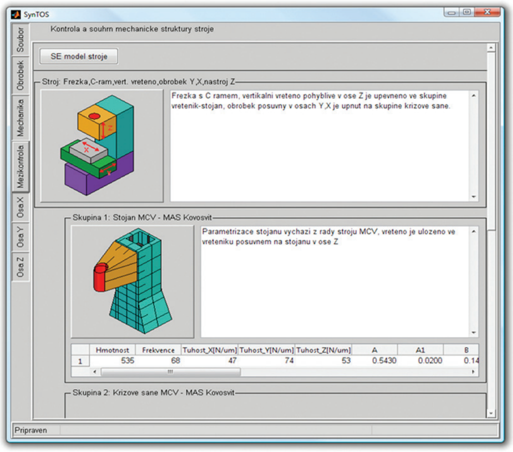
Figure 3. *User interface – specification window for workpiece size and other parameters*



Kontrola a souhrn mechanicke struktury stroje

Stroj: Frezka,C-ram,vert. vreteno,obrobek Y,X,nastroj Z

Frezka s C ramem, vertikalni vreteno pohyblive v ose Z je upevneno ve skupine vretenik-stojan, obrobek posuvny v osach Y,X je upnut na skupine krizove sane.

Skupina 1: Stojan MCV - MAS Kovosvit

Parametrizace stojanu vychazi z rady stroju MCV, vreteno je ulozeno ve vreteniku posuvnem na stojanu v ose Z

	Hmotnost	Frekvence	Tuhost_X[N/um]	Tuhost_Y[N/um]	Tuhost_Z[N/um]	A	A1	B
1	535	68	47	74	53	0.5430	0.0200	0.14

Skupina 2: Krizove sane MCV - MAS Kovosvit

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Figure 4. *Selection window for machine and machine group concepts in the SYNTOS software*

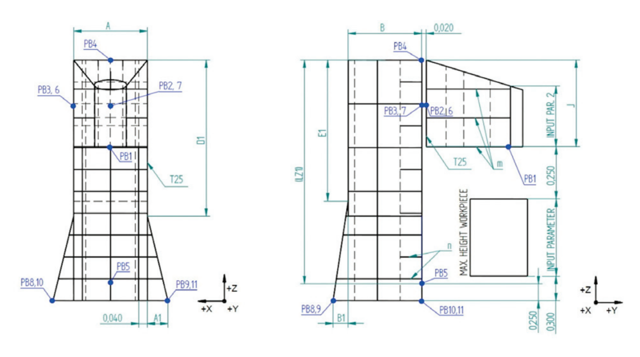

Figure 5. *Example parameterisation of a MCV-type column*

This step makes it possible to determine the mechanical and control properties of the machine. It is possible to observe the critical eigenfrequencies within selected machine groups and their relation to the control performance [Vesely 2008]. Using the verified complex model, the simplified parametric model is adjusted so that it is able to simulate comparable results for specified geometric parameters corresponding to the measured machine. The parametric models are implemented in the optimisation cycle. By using the Monte Carlo methods, parameter sensitivity and gradient method [Ghisbain 2009] the geometric parameters are changed in order to conform to the objective function

$$H_n = \min(m)_{f_n}^{f_{n+1}} \;\wedge\; H_n \in (k_T)\,,$$

which serves to find the machine group H_n with the minimum mass m in a given frequency interval $<f_n - f_{n+1}>$ (this applies to the first critical eigenfrequency), corresponding to a given stiffness class k_T. Thus, we obtain a discrete distribution of Pareto-optimum options, as shown in the graphic representation in Fig. 6 on the left hand side; this means the Pareto-optimum solutions are part of the envelope of possible solutions. The ideal case would be to look for solutions within a continuous interval of frequency and stiffness values, which, however, would prevent the process from being automated.

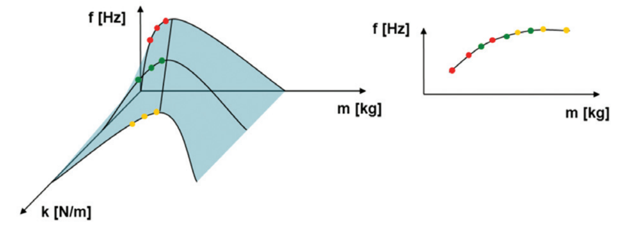

Figure 6. *Pareto envelope of possible solutions for mechanical structures, depending on the first critical eigenfrequency, mass and stiffness class (3D on the left; 2D on the right)*

Switching to a 2D representation (Fig. 6 on the right) yields a very important dependence between machine group mass and attainable first critical eigenfrequency. This chart is used to select the final solution for a specific machine group. This is where the skills of design and computing specialists are used, as the specialists have to assess the *mass of the structure in relation to the eigenfrequency*. As auxiliary functions, they can use price calculations based on mass, and the possibility to export a CAD model consisting of geometric parameters linked to the individual options. To reduce the number of selected options, it is possible to activate auxiliary filters which put together options with similar mass and limit the maximum and minimum solutions. A chart for a specific case (the input parameters define an existing machine configuration) is shown in Fig. 7. The chart shows all of the points of the Pareto-optimum solution for MCV column. Through subsequent filtering the options marked with crosses are removed. For the sake of illustration, a point characterising the configuration of a real machine has been inserted. This clearly shows that the set of computed solutions determines the limit within which also the existing solution is situated. To find the optimum (a single solution), the Pareto set has to be clearly ordered. This can be achieved by using a criterion defined by the mass-frequency ratio which unequivocally determines the relative quality of the structures. A point for which this *ratio has a minimum value* (ROP) can be found on the envelope. This is necessarily also the structure with the smallest ratio possible—depending, of course, on the accuracy of the numerical method. The ratio optimum point (ROP) is available to the user as another auxiliary function to help them select the definitive machine group configuration

$$q_{\min} = \min\left(\frac{m_i}{f_i}\right).$$

The dependences mentioned here (mass, frequency, stiffness) are evaluated for the whole workpiece size mesh. They are stored in a database in the form of modal matrices which can be used to generate the mass, inertia and frequency characteristics of a given machine group [Hatch 2001]. It is also possible to export selected mechanical structures into a CAD environment where, already at this stage, the user can evaluate and select a structure by shape (e.g. taking into account the placement of other peripheries).

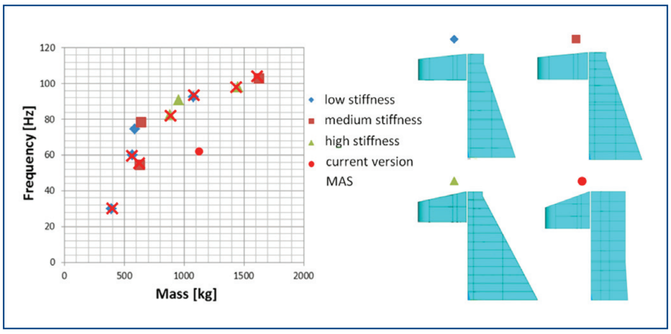

Figure 7. *Pareto-optimum solution for MCV column*

Drive Design

By following the procedure described above the user chooses a suitable solution for the mechanical structure, i.e. selects the machine concept, stiffness class and specific machine groups based on the ratio between the mass and the first critical eigenfrequency. Certain criteria that need to be met in the design process (such as forces, acceleration, etc.) are known from the original design brief. Thus, all the necessary parameters for the drive design are known, including the mechanical structure to which the drive is coupled. In the computing environment of the SYNTOS software this coupling is realised with reduced modal matrices of the mechanical structure, linked to the corresponding input and output variables from the mechanical model of the drive.

The aim of the drive design is to find a suitable configuration and select specific drive components for each axis with a view to meeting the criteria specified in the design brief.

The design module uses a component library which, in fact, consists of component producers catalogues copied into Excel spreadsheets in a predefined form and containing all of the parameters relevant for the computations. As the data is stored in the form of a spreadsheet, it is easy for the user to update and add to it. From the point of view of the SYNTOS environment structure, the spreadsheet is part of the database, although it is saved as a separate file.

Computation Method Used

The computations are performed in steps, going from one machine axis to the next. First, it needs to be specified which kinematic configurations are relevant for a given axis. As the number of the components considered is relatively small, it is possible to make the computations for all options resulting from the combinations of allowable components. The decision as to whether a component is allowable is made by the user in the filtering module. Filters define the range of components from the library to be used for the computations.

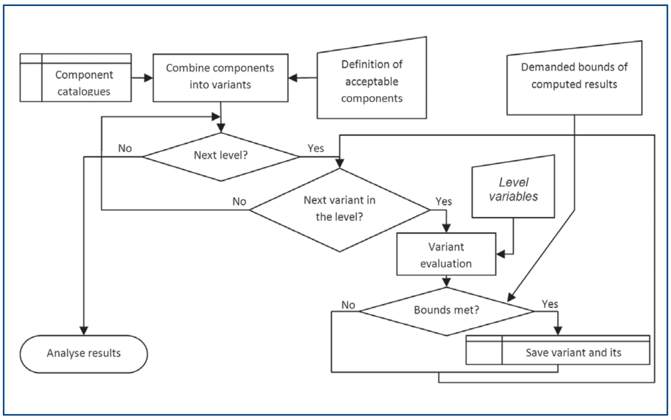

Figure 8. *Software diagram*

As shown in Fig. 8, the computations are always performed for options described in terms of the catalogue values for each parameter (e.g. for a ball screw these values include its diameter D_{SR} , lead h , axial contact stiffness of the ball nut k , dynamic load capacity Ca , allowable nxD factor $nD_{\max}$). Computational variables, which are the same for all options, are added to these values.

Results are computed for each option, including achievable force, acceleration, rapid feed rate, first locked motor frequency, and reduced mass, as well as results for individual components, such as ball screw life, screw buckling check, critical revolutions, etc. For each option these results are confronted with the original requirements. The dynamic behaviour of the axis model is described through the first locked motor frequency which makes it possible to assess axis control quality [Soucek 2004].

If an option meets all of the specified criteria, it is saved for further processing. Again, the set of all options corresponding to the specified input conditions forms a pareto envelope of optimum solutions. To compare the results we use a similar graphic representation as for the mechanical structure of the machine Fig. 7. As this is a complex structure composed of the drive mechanics and the machine mechanics, the eigenfrequencies are replaced with first locked motor frequencies, and the structural mass is replaced with reduced mass represented by the geometric coordinate of a given motion axis.

5. Selecting the Definitive Option

The definitive option is selected primarily using graphic dependence (Fig. 7). The advantage of such dependence lies in the fact that it compares standardisable parameters able to measure the quality of different structures. The user can thus assess the effect of strengthening the dynamic properties on the total mass and price of the motion axis being designed. Motion axes can be compared within one machine, or between different machine (machine group) concepts. The following extended selection algorithms based on filtering and comparison functions are also available:

- Selection based on frequency characteristics (similar frequency spectra of the motion axes lead to balanced control properties)
- Selection based on reduced mass (the motion axes are balanced in terms of energy)
- Selection based on drive components used (unification of motion axes)
- Other (selection based on maximum acceleration, service life,…)

While it is possible to automate the evaluation of the definitive machine configuration by setting weight coefficients corresponding to the required parameters, the problem arises of how to set these weight coefficients. They reflect the experience of the design engineers, the volume of machine tool production, the customer's requirements, the management objectives, and other variable factors. The approach whereby the user has to take an active part in selecting the final solution makes use of the design engineers' creative potential, the marketing skills of the sales department and, not least, the management skills of the managing staff. The selected option then represents the necessary compromise made between these departments. When the SYNTOS software is used, the design stage is not constrained by having to choose from a limited selection of only a few options without the possibility to quickly change a machine parameter and observe the sensitivity of the options to the change.

Conclusion

The SYNTOS software tool has been developed within the project entitled Synergic Machine Tool Design, supported by the Ministry of Industry and Trade of the Czech Republic. The potential of this tool is best used in the machine tool design stage. It is based on a knowledge and simulation database which includes a large number of optimised solutions for machine tool mechanical structures and drive components. A dedicated computational method for filling the database – parametric optimisation of mechanical structures – has been created as part of the project. This makes it possible to add new mechanical parts to the database, and thus extend the scope of application of the SYNTOS software. The database is linked to algorithms for evaluation, filtering and comparison which help the end user to select the definitive solution for a machine and drives. Within a relatively short time span (approximately five days) several machine tool options can be compared, including drive designs, possible configuration of construction, estimated price, and other parameters. Thus, only options that have been checked for deficiencies from several points of view make it to the design stage. This significantly reduces the risk of implementing a solution with unexpected properties which may lead to major design changes in the mechanical structure itself, as well as the drive structure. Working in the SYNTOS environment is a benefit in itself: the end user can systematically monitor the effects of the parameters they select on the resulting properties of the machine or machine group being designed.

References

[Altintas 2011] Altintas, Y., et al.: *Machine tool feed drives*, CIRP Annals – Manufacturing Technology, 2011

[Bach 2006] Bach, P.: *Optimization of efficiency of machine tool* (in Czech), Habilitation, 2006

[Ghisbain 2009] Ghisbain, P.: *Application of a Gradient-Based Algorithm to Structural Optimization,* Massachusetts Institute of Technology, 2009

[Hatch 2001] Hatch, M. R.: *Vibration Simulation Using Matlab and Ansys*, Chapman & Hall/CRC, Boca Raton, 2001

[Nemeth 2009] Németh, I., Püspöki, J., Arz, G., Marvulli, S., Merlo, A., Arrieta, J., Ricondo, I., Molina Benitez, F.: *Development of a Machine Tool and Manufacturing System Configurator*, The 7th International Conference on Manufacturing Research (ICMR09), University of Warwick, UK, September 8-10, 2009

[Nieding 2011] Nieding, P.: *Simulation of machine tool with influence of structural dynamic* (in German), SimTech WCM, Trumpf Werkzeugmaschinen GmbH + Co. KG, 2011

[Soucek 2004] Soucek, P.: *Servomechanism in the machine tools* (in Czech). CTU of Prague, Prague 2004

[Stephenson 2006] Stephenson, A., D., Agapiou, J., S.: *Metal Cutting Theory and Practice*, 2nd ed., Taylor and Francis Group, 2006

[Tani 2006] Tani, G., Bedini, R., Fortunato, A., and Mantega, C.,: *Machining centers for high speed machining: a new design approach,* Proc. of the CIRP-2nd Intenational Conference, High Performance Cutting (HPC), Canada, 2006

[Vesely 2008] Vesely, J., Sulitka, M.: *Machine Tool Virtual Model*, Proceedings of the International Congress MATAR 2008; Part 1, pp. 115 – 122; Prague; Czech Republic, 2008

[Zatarain 1998] Zatarain, M., Lejardi, E., EgatiaModular, F.: *Modular Synthesis of Machine Tools*, CIRP Annals – Manufacturing Technology, Volume 47, Issue 1, Pages 333-336, 1998

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