Methods and possibilities of a virtual design for actively controlled smart systems

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Abstract

The objective of this paper is to present an overall approach and to point out the methods and possibilities of a virtual design for actively controlled smart systems with the intention to use the suggested approach and methods for the subsequent prototype and real active systems development. The suggested methods of the virtual design are computer aided, including different software tools used to generate models necessary for the overall virtual design. The basis of the approach is an overall finite element (FE) or a multi-body system (MBS) model of the smart system including the passive parts of the machine or structure as well as the actuators and sensors and the control algorithm.

Keywords: Virtual design; Smart systems; Overall design; Finite element modelling; Multi-body systems model; Active vibration control

1. Introduction

With the development of the computer aided design techniques, the virtual design as one of the preliminary phases in the process of the overall design in engineering gains more and more significance. Usually the design in engineering starts with a preliminary computer model of the system under consideration which is extended and completed through the subsequent design steps until the final system is available as a virtual computer model. Such a virtual model is used to optimize the system until a prototype is really built. The optimization usually includes the mechanical behaviour, such as statics, strength of materials, dynamics, lifetime, safety, etc. Electric and electronic components, as well as control and several other components, are usually developed separately and consequently it is not possible to study the overall behaviour of the system under realistic operating conditions. The future holistic design of a system requires the development and application of a new methodology, where it is important to extend the 3D product model of the system and its components by the most important physical models, such as mechanical, thermal, fluid, electric and magnetic models, the control electronics, the power supply as well as by models describing the general operating and environmental conditions of the system. In the overall design in engineering the manufacturing process, the production logistics and even the recycling have an essential influence, which also has to be taken into consideration. The integrated product management system which can be created automatically is also required in the holistic virtual development process and consistently the user dependent partial models of the product are necessary as well. The product model in general covers the product geometry as well as functional, technological and other features.

This paper presents steps and methods of such an integrated development process, which has partially been realized at the chair of the authors, including besides the CAD software different analysis tools, such as the finite element analysis (FEA) software COSAR and ANSYS, the MBS software SIMPACK and the controller design tool Matlab/Simulink. For the required data exchange between different tools, special data interfaces were created as well. Especially the finite element software COSAR (see:
The main research objective of our group in the field of smart structures is the development of the equations of motion for these structures. The finite element method (FEM) is widely used for the development of the equations of motion for smart structures. These equations can be derived using the established design tools for piezoelectric controlled smart structures. In this paper, we are applying a model based optimal LQ controller, including additional smart systems properly. In this paper, we are applying a model based optimal LQ controller, including additional smart systems properly. In this paper, we are applying a model based optimal LQ controller, including additional smart systems properly. In this paper, we are applying a model based optimal LQ controller, including additional smart systems properly.
This approach has been used to develop a comprehensive library of multi-field finite elements: 1D, 2D, 3D elements, thick and thin layered composite shell elements, etc. (see Fig. 1) which was implemented in our finite element package COSAR for the simulation of the static and dynamic structural behaviour of smart structures.

The main features of the finite element software COSAR which make it convenient for modelling and analyzing of smart structures can be summarized in the following way: (a) the software possesses a large library of multi-field finite elements for appropriate modelling of different structures; (b) special pre-processors are included, which enable automatic generating of the electro-mechanical coupled finite element models; (c) for solving the special types of coupled equations in the time domain the numerical tools are included, as well as (d) the tools for modal reduction of the number of equations; (e) bi-directional connection between the finite element software COSAR and the Matlab/Simulink for the control design purposes is realized through developed data interfaces and (f) a special post-processor is developed for graphical representation of the results.

3. Virtual design of smart machine components using the MBS approach

In the design of smart machine components, such as tool machines, robots, measurement machines etc., the influence of large movements (e.g. rotations) on the dynamic behaviour and the accuracy has to be taken into consideration. For this reason the application of a multi-body system (MBS) approach is preferable. We are using the SIMPACK software as a basis for the virtual design developments, including elastic finite element models, control electronics, different types of active and passive joints, bearings, actuators and sensors, different types of excitation, etc. Several of such extensions are not available in the standard MBS software, but they can be added via special user defined interfaces.

An interesting field of smart structures concepts are machine tool systems, where vibrations caused by the manufacturing process can reduce the accuracy of work pieces. There are different kinds of additional actuators and sensors available, such as hydraulic, pneumatic, magnetic, electric, piezoelectric, optic, etc. actuators, which can be integrated into the structure together with appropriate control electronics to fulfill special tasks. Special attention is paid to piezoelectric actuators as well as to magnetic actuators, which can be used to realize a high precision control of machine tools. The theoretical basis of modelling piezoelectric and magnetic actuators in the frame of a finite element approach can be found in the literature (see e.g. [8,12,13]). Therefore, only the brief explanations regarding implementation of such models in the MBS software are given in this paper.

Piezoelectric ceramics such as stack actuators or thin patch actuators can be described on the basis of the mechanical and electric balance equations and the coupled electro-mechanical constitutive equations. This approach was extended recently by the authors to include hysteresis and creep [25] and integrated in the MBS software SIMPACK using a Fortran user interface.

The authors have also included new models for magnetic actuators in SIMPACK based on the description of the user defined force elements [14]. Magnetic actuators, e.g. magnetic bearings, are highly nonlinear, where special attention has to be paid to creating a relatively simple but correct force element. The static magnetic force in the air gap can be described on the basis of the MAXWELL equations. In relation to MBS simulations it is often appropriate to describe magnetic actuators or magnetic bearings as one-dimensional magnetic force elements, which generally calculate the static forces beyond the magnetic saturation of the material. The input data of such a force element, which we have developed recently, are the geometry, the material data of the permanent magnet, the magnetic leakage flux and the B–H-graph or permeability of the material. A further input parameter is the electric current of the coil.
Here a static parameter, a function or a controller output can be included [14].

4. Controller design as a part of an overall virtual design procedure

Controller design represents an important part of an overall virtual design procedure. Actively controlled systems necessarily involve active components in terms of actuators and sensors, together with an appropriate control law, which enables adapting of the controlled system behaviour to desired requirements and environmental conditions. Regarding the possibilities for the controller law, which enables adapting of the controlled system actuators and sensors, together with an appropriate control systems necessarily involve active components in terms of the type of the disturbance function.

4.1. FEA development of the reduced state space model for the controller design of smart structures

As revealed in Section 2, the FEA approach to modelling of smart structures results in a model of a structure in the form (5). This model possesses a large number of degrees of freedom, which are often not convenient for the controller design. One of the software tools integrated with the FE system COSAR (as mentioned in Section 2) enables the reduction of the number of equations describing the behaviour of the structure (and at the same time the order of the obtained model) retaining the sufficient information for its accurate description. The modal truncation is accepted as a suitable technique for the reduction of the number of equations in the state space model. The technique we have used is based on the solution of the eigenvalue problem for the equation of motion (5). Limited number of the eigenmodes of interest is taken into account, while the remaining modes are truncated. The modal truncation is justified by the fact that flexible structures possess a low-pass characteristic, which allows neglecting high-frequency dynamics. Solution of the linear eigenvalue problem results in the modal matrix \( \Phi_m \) and the spectral matrix \( \Omega \), where \( \Phi_m \) is ortho-normalized with \( \Phi_m^T \Phi_m = I \) and \( \Phi_m^T K \Phi_m = \Omega \). Generalized displacements \( q \) are transformed into modal coordinates \( z \) using the following relation:

\[
q(t) = \Phi_m z(t),
\]

which applied to (5) results in a decoupled system of equations in modal coordinates \( z \):

\[
\ddot{z} + \Delta z + \Omega z = \Phi_m^T F
\]  
(7)

where \( \Delta = \Phi_m^T D \Phi_m \) represents the modal damping matrix.

In the modal truncation procedure the modal displacement vector \( z \) is partitioned into two parts: \( z_r \) which contains selected \( r \) modes and \( z_u \) which contains the remaining truncated modes:

\[
z = \begin{bmatrix} z_r(t) \\ z_u(t) \end{bmatrix}
\]

(8)

The modal damping and stiffness matrices as well as the modal matrix are also partitioned in an appropriate way:

\[
\Omega = \begin{bmatrix} \Omega_r & 0 \\ 0 & \Omega_u \end{bmatrix}, \quad \Delta = \begin{bmatrix} \Delta_r & 0 \\ 0 & \Delta_u \end{bmatrix}, \quad \Phi_m = [\Phi_r, \Phi_u].
\]

(9)

Then from (7)–(9) after appropriate transformations, taking into account (5) and introducing the modal reduced state vector:

\[
x(t) = \begin{bmatrix} z_r(t) \\ \dot{z}_r(t) \end{bmatrix},
\]

(10)

the modal reduced model is obtained in the state space form:

\[
\dot{x}(t) = A x(t) + B u(t) + E f(t)
\]

(12)

where \( A \) denotes the state matrix, \( B \) is the input matrix and \( E \) is the disturbance coupling vector. The measurement equation in the state space form is obtained in a similar way. Restricting the model to \( r \) selected mode shapes and taking into account the partitioned modal matrix and the reduced modal state vector (10), the measurement equation is expressed in the form:

\[
y = [C \Phi_r \ 0] \begin{bmatrix} z_r(t) \\ \dot{z}_r(t) \end{bmatrix} = C x(t).
\]

(13)

Eq. (13) in this form commonly used in the control theory corresponds to the general form of the output equation:

\[
y = C x(t) + D u(t) + F f(t)
\]

(14)

when control and external inputs do not influence the outputs. State and output equations (12) and (13) represent continuous-time state space model of the piezoelectric structure in the form convenient for the controller design.

4.2. Discrete-time optimal LQ controller with additional dynamics and tracking properties

One approach to the controller design developed and applied by the authors [4,16] is an optimal tracking system with additional dynamics, which is in authors’ opinion a successful means for the vibration suppression in smart structures. The controller design includes available a priori knowledge about occurring disturbance type contained in the additional dynamics. Such an a priori knowledge is available in terms of the type of the disturbance function.
which has to be rejected or whose influence should be suppressed by the controller. Periodic disturbances with frequencies corresponding to the eigenfrequencies of the smart structure can cause resonance and their suppression is therefore important. They are taken into account via the additional dynamics.

A discrete-time state space equivalent (15) of the state space model (12) and (14) developed through the FEM procedure and modal reduction is used for the controller design.

\[
\begin{align*}
\dot{x}_i[k + 1] &= \Phi x_i[k] + \Gamma u_i[k] + \omega[k] \\
y_i[k] &= C x_i[k] + D u_i[k] + F w[k]
\end{align*}
\]

(15)

Using the a priori knowledge about the disturbance class, which has to be suppressed, the model of the disturbance is represented in an appropriate state space form, where the disturbance is assumed to be the output of the state space representation. The poles \( \lambda_i \) of the disturbance transfer function are used to define the additional dynamics using the coefficients of the polynomial:

\[
\delta(z) = \sum_{i=1}^{m} \frac{\delta_i z^{-i}}{(z - e^{\lambda_i T})^m} = \delta_1 z^{-1} + \cdots + \delta_n z^{-n}
\]

(16)

where \( m_i \) represents the multiplicity of the pole \( \lambda_i \). Additional dynamics is expressed in a state space form:

\[
x_i[k + 1] = \Phi_i x_i[k] + \Gamma_i e[k];
\]

(17)

where \( x_i \) is the vector of the state variables for the additional dynamics, \( e \) is the error signal and:

\[
\Phi_i = \begin{bmatrix} -\delta_1 & 1 & 0 & \cdots & 0 \\ -\delta_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\delta_{n-1} & 0 & 0 & \cdots & 1 \\ -\delta_n & 0 & 0 & \cdots & 0 \end{bmatrix}, \quad \Gamma_i = \begin{bmatrix} -\delta_1 \\ -\delta_2 \\ \vdots \\ -\delta_{n-1} \\ -\delta_n \end{bmatrix}.
\]

(18)

For the multiple-input multiple-output (MIMO) systems additional dynamics is replicated \( q \) times (once per each output). Replicated additional dynamics is described by:

\[
\overline{\Phi} \overset{\text{def}}{=} \text{diag} \left( \Phi_1, \ldots, \Phi_q \right),
\]

\[
\overline{\Gamma} \overset{\text{def}}{=} \text{diag} \left( \Gamma_1, \ldots, \Gamma_q \right).
\]

(19)

The discrete-time design model \((\Phi_i, \Gamma_i)\) is formed as a cascade combination of the additional dynamics \((\Phi_i, \Gamma_i)\) or \((\overline{\Phi}, \overline{\Gamma})\) and the discrete-time plant model \((\Phi, \Gamma)\):

\[
x_d[k + 1] = \Phi_d x_d[k] + \Gamma_d u_d[k];
\]

(20)

\[
\Phi_i = \begin{bmatrix} \Phi^* & 0 \\ \Gamma^* C & \Phi^* \end{bmatrix}, \quad \Gamma_i = \begin{bmatrix} \Gamma \\ 0 \end{bmatrix}, \quad x_d = \begin{bmatrix} x_i[k] \\ x_i[k] \end{bmatrix}
\]

(21)

for MIMO systems. For the design model (20) the feedback gain matrix \( L \) of the optimal LQ regulator is calculated in such a way that the feedback law \( u[k] = -L x_d[k] \) minimizes the performance index (22) subject to the constraint (20), where \( Q \) and \( R \) are symmetric, positive-definite matrices.

\[
J = \frac{1}{2} \sum_{k=0}^{\infty} (x_i[k]^T Q x_i[k] + u[k]^T R u[k]).
\]

(22)

The feedback gain matrix \( L \) is afterwards partitioned into

\[
L = \begin{bmatrix} L_1 & L_2 \end{bmatrix}
\]

(23)

so that \( L_1 \) corresponds to the state space model of the structure, and \( L_2 \) to the modelled additional dynamics.

5. Virtual actuator/sensor design and placement optimization

Design of actuators and sensors is one of the crucial problems in smart structures development. It is connected with solving different questions regarding the type, size, number and placement of actuators and sensors. The actuator/sensor locations are important among other issues for the controllability and observability of a controlled structure and exert a major influence on the efficiency of the control system and the required control effort to satisfy a given design criterion. Difficulties arise from the relationship between the position of the actuators and the control algorithm used. The position and the operation mode of actuators/sensors influence the dynamic behaviour of the structure itself, which has to be taken into account.

In the process of the smart structures virtual design it is meaningful to develop a tool for the automatic virtual placement and optimization of actuators and sensors. In the distributed control of continua (e.g. plate and shell structures attached with piezoelectric wafers) the automatic estimation of an optimal actuator and sensor shape as well as their placement is a very complex problem and it has not been fully solved yet. Research towards the solution of this problem for the distributed control of continua (e.g. plate and shell structures attached with piezoelectric wafers) has been performed at the chair of the authors (for details see [5,6]). As a starting point for the structural design with respect to the actuator/sensor placement it is assumed that the specification of the structure itself is known, including the objective of the controlled behaviour, external disturbances, the frequency range, etc. The number and positions of the required actuators and sensors are estimated using the controllability and observability indices of the \( k \)th natural mode [17] expressed in the form of Eq. (24).

\[
\mu_k = \phi_k^T \bar{B} \bar{B}^T \phi_k.
\]

(24)

The placement of actuators and sensors must guarantee the controllability and observability of a structure. A system is completely controllable if \( \mu_k > 0 \) \forall k, where \( \mu_k \) should be as high as possible.
Based on the results of the eigenvalue analysis at each structural point, the modal strains, and consequently, the modal electric voltage are calculated yielding the controllability index $\mu_k(x_P)$ of the $k$th mode at the structural point position $x_P$. The best positions $x_P$ for the control of the first $r$ eigenmodes are the positions with the highest overall controllability index:

$$\mu(x_P) = \prod_{k=1}^{r} \mu_k(x_P).$$

Pre-selected actuator/sensor positions can be modified further through a mathematical optimization process. The optimization problem is defined by the objective function, by design variables and their restrictions. Position of the piezoelectric actuators and sensors represents the design variables, which are restricted within the area of the mechanical structure. In our opinion the evaluation of the transfer function as well as the state space vector provide a useful criterion. The optimal placement of the actuators is connected with the optimal controller design, so that both processes should be handled together. In our opinion, an optimal controller can be designed by using the concept of the state space feedback (LQ-controller). The stability of the whole optimization is determined by the sensitivity analysis. The objective function should define a useful criterion to minimize the vibrations of the mechanical structure. We tested different objective functions, where we finally preferred the transfer functions between structural points which provided acceptable results in several test examples.

6. Coupling between different design tools

Mentioned modelling and simulation tools for the virtual design of actively controlled structures are coupled via appropriate interfaces which enable data exchange. A schematic representation of possible couplings is given in Fig. 2.

6.1. Coupling of CAD with mechanical simulation

It is generally accepted that the prerequisite for continuous computer aided engineering is the integration of the product data throughout the product development. A suitable basis for modelling and integrating product data is offered by the product data technology, which is characterized by an explicit association with the product, and not by the process of planning and manufacturing. Since 1987, work has been in progress under the auspices of the International Standards Organization to develop a standardized product data model called STEP. Meanwhile STEP is general accepted, applicable and safe, which has been proven by numerous applications in industry. The coupling of CAD systems with FEA or MBS systems as well as special pre-processor software via STEP is one of the favourite possibilities nowadays. Of course, there are several problems connected with such a data exchange between FEA, MBS and CAD and we are still far away from an integrated product data management system, which is required for future applications [18]. Whereas the pre-processors of FEA tools, e.g. FEMAP, have a good access to CAD software, this is in general not the case in MBS software. The
reason is that the solution based on a MBS model only requires information about the mass and mass inertia for each body as well as the connections between the bodies and the fixed environment. The real geometry only helps to better understand the solution by applying an animation of the dynamic behaviour of the system. There are many different MBS systems available on the market [19]. We are using the MBS software SIMPACK, which has been designed to simulate the nonlinear dynamic behaviour of structures consisting of rigid and flexible parts. Due to its modular open structure it is well prepared to include control design software as well as other new features [20]. In our experiences the FEA software is well suited to design controlled smart structures especially in lightweight applications. Recently, the research group of the authors has extended a commercial FEA tool – COSAR (see: www.femcos.de) to design smart structures including integrated piezoelectric actuators and sensors and control electronics [21,22]. On the other hand the MBS software taking into account also flexible parts represents an excellent tool to design smart machine systems performing large movements (tool machines, robots, etc.).

6.2. Coupling between the controller design/implementation and modelling/design tools

Developed control laws can be implemented in the FEA software as well as in the MBS software. In MBS software this is a standard task, whereas such possibility is not available in standard FEA codes like ANSYS or ABAQUS. As mentioned in Section 2 for our FEA software COSAR a bidirectional data interface was developed, which also allows to integrate developed time independent control laws in the FEA code by applying the control matrix L or the control law in the form of a C code. In the MBS software SIMPACK there are several possibilities available to implement a control strategy. The simplest ways are (a) the application of the control elements, which are directly available in the software, (b) the generation of the state space matrices derived form a linearized MBS model, which can be transferred to Matlab/Simulink. However, these control strategies are limited and often insufficient in special applications. In such cases SIMPACK offers an interface to different controller design tools, e.g. to Matlab/Simulink in order to perform a co-simulation. If one sample time period is elapsed both solvers are forced to stop and interconnecting vectors are exchanged. A complex model can also be calculated in SIMPACK, if the control loop is imported via a data interface, which automatically creates a Simulink model by applying the Real-Time Workshop using the supplied configuration files that can be incorporated fully within SIMPACK.

As a connection between the virtual development and the final implementation, the real time behaviour of actively controlled systems can also be investigated and tested using Hardware-in-the-Loop (HiL) systems. They offer the possibility to substitute parts or the complete virtual model of the investigated object by real components, while retaining the virtual environment and to investigate the behaviour of the system under conditions which correspond to a great extent to real operating conditions. One possibility for using such a system is a HiL system with dSPACE which integrates the control system with appropriate control laws realised in Matlab/Simulink environment, real object under investigation mainly with actuators and sensors included and a set of virtual auxiliary devices, which can simulate (among other functions) various data acquisition and monitoring tools, as well as AD and DA converters.

7. Examples

7.1. Vibration control of a funnel-shaped structure

Active control in the sense of vibration suppression was developed for a funnel-shaped shell structure (see Fig. 3), the inlet part of the magnetic resonance tomograph (MRT) produced by Siemens [4,16,23]. The aim of the design was the reduction of transmitted vibrations from the cylindrical body of the tomograph to the funnel-shaped inlet using piezoelectric actuators and sensors. Six actuator-groups and six sensors attached to the surface of the funnel (Fig. 4) have been designed based on a finite element model of the funnel, which takes into account the coupled electromechanical behaviour in the piezoelectric patches as well as the control electronic.

In the final optimized realization, the positions of actuators and sensors (see Fig. 3) are denoted as 1L, 2L, 3L for the left-hand side actuators and sensors and 1R, 2R, 3R for the right-hand side ones. Applying described overall design procedure, control of the three selected eigenmodes (corresponding to the eigenfrequencies \( f_1 = 9.573 \text{ Hz}, f_2 = 23.333 \text{ Hz}, f_3 = 31.439 \text{ Hz} \)) was performed in the sense of the vibration suppression in the presence of excitations. Controller used for the vibration suppression is an optimal

Fig. 3. Funnel shaped part of a MRT, produced by Siemens.
LQ tracking system with additional dynamics described in Section 4. As a worst study case the excitations are selected as sine signals with frequencies corresponding to the eigenfrequencies of the funnel.

The results of the optimal LQ controller design and implementation (response of the sensor S1R and control signal of the actuator A2R in the presence of the sine excitation with the frequency equal to the first eigenfrequency) are represented in Fig. 5. The response in the absence of control is characterized by obviously greater vibration amplitudes in comparison with the controlled case. Several further design studies where performed, which demonstrate the advantage of an overall virtual design strategy.

7.2. Circular table with magnetic bearings as part of a machine tool

Fig. 6 represents a circular table as a part of a machine tool system [24]. The table consists of two main parts: a support and a rotor. The support includes magnetic bearings to levitate the rotor for small translations along the main axis and the rotation about the horizontal axis and a torque engine for control of the large rotation about the vertical axis. On the upper side of the rotor a clamping plate is fixed by an angle change facility to permit lateral buckling. During high-precision machining with a required accuracy of some μm undesired deformations can considerably reduce the quality of the manufacturing process.

Such undesired deformation can occur due to the following reasons.

- Static deformations due to the mass (weight) of the work piece, the mass of the rotating table, the rotor, the clamping devices, etc.
- Dynamic deformations due to stochastic excitations of the magnetic bearings.
- Dynamic deformations due to an asymmetric position of the work piece at the table.
- Deformations due to the metal cutting operations, which induce high static and dynamic forces acting in horizontal and vertical direction at the work piece.
- Static deformations due to changing thermal influences during operation.

Fig. 5. Signal of the sensor S1R and the actuator signal A2R of the controlled device excited by the first eigenfrequency; in the time interval from about one to eight seconds the controller was switched off.
There are two different possibilities to increase the accuracy of the manufacturing process in order to ensure a high quality of the work piece. The first possibility is to use active components of the machine system, such as electric motors, magnetic bearings, hydraulic components etc., which are primary components of the system. These components can be additionally used as actuators for controlling undesired actions of the system. The second possibility is to add new smart components, such as piezoelectric stack actuators, which are additionally integrated into the machine system, e.g. to actively damp parts of the system.

In order to demonstrate the active damping of undesired vibrations of the circular table during operation 12 additional piezoelectric stack actuators (see Fig. 7b) have been integrated into the upper part of the clamping plate (see Fig. 7a). The stack actuators are excited with a sinusoidal voltage in a range of ±50 V and a frequency close to the first eigenfrequency of the system. Fig. 8 shows the vibration amplitudes perpendicular to the plate surface at two different points. These amplitudes are larger than the amplitudes caused by the undesired additional vibrations due to the operation of the tool machine, which are not damped by controlling the magnetic bearings. Consequently, such additional piezoelectric stack actuators provide a secondary possibility to increase the manufacturing quality of such machines. The technical realization and testing of the developed configuration is under progress.

8. Conclusion

An overall virtual design approach for smart structures and high precision machines has been presented in this paper in order to reduce vibration and noise and to increase the accuracy. The basis of this approach is an overall finite element model (FEM) or a MBS model of the smart system, where both models can be generated from a CAD model. The model includes the passive parts of the machine or structure as well as the actuators and sensors (e.g. piezoelectric patch actuators or stack actuators), joints and bearings (e.g. magnetic bearings), different types of excitations, etc. It is also very important to include the control in the design process, e.g. in order to study the controlled behaviour of the system if different types of excitations, disturbances or environmental conditions are influencing the system. To demonstrate the advantage and the potential of such an approach two industrial problems –
a smart funnel of a MRT and a circular table of a machine tool – are discussed in the paper.

As conclusions of our investigation it can be stated that in the moment, software and technology tools are not flexible enough for specific and economic deployment for industrial requirements. Contemporary general purpose software tools are mostly beyond what future technological developments really need. Especially the virtual holistic development process still represents a challenge. In the future the development process should be guided and supported by a virtual development platform, where e.g. modelling starts with the CAD data and virtual mock-ups to get geometry, kinematics and functionality descriptions, as well as a subdivision into domains and modules. The domains will be discretized applying a FEA and/or MBS approach, where the level of detail is automatically selected in accordance with the objectives of the approach. The overall model can be consistently extended by sub-models, such as electric, hydraulic, pneumatic and other parts, different types of actuators and sensors, control electronics, etc. The assembly of structural members (domains and modules) will be programmed in a very simple way through an application programming interface in a language chosen by the user. The precision of modelling and computation and necessary scaling should be self-regulated to the greatest possible extend.

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References


Fig. 8. Vibration amplitudes perpendicular to the plate surface at two different points (15532 and 15537, see Fig. 7), if the stack actuators are excited with a sinusoidal voltage in a range of ±50 V.


