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SIMULATION AIDED DESIGN OF INTELLIGENT MACHINE TOOL COMPONENTS

By integrating sensors and actuators, intelligent machine tool components can be realized, which allow the monitoring of machining processes and machine tool states and an active influencing of process conditions. In the design and layout of these intelligent machine tool components, their mechanical structure and the functional performance of the sensor and actuator sub-systems have to be optimized. As an example, a sensor and actuator integrated fixture system for clamping large but sensitive aerospace structural parts is presented here. In order to investigate the major influences of design approaches on the behaviour of the workpiece and fixture, especially with respect to vibrations and process stability during milling, multiple test rigs and prototypes for basic analyses and machining tests were developed and realized. Experimental and Finite Element Analysis (FEA) results are presented and discussed. Process simulations were conducted taking the dynamic behaviour of the clamped workpiece at different processing steps into account. This simulation can be used for predicting the limits of the process stability. An approach of sensor and actuator integration is described and test results are shown. The paper introduces a principle design and layout methodology for similar intelligent machine tool components.

1. INTRODUCTION

Modern CNC machine tools represent sophisticated mechatronic systems on which extremely high demands are made regarding machining performance, quality of parts, reliability and availability as well as effectiveness with respect to production costs, resource and energy consumption. Considering process planning information as major input, process machine interactions as the essential functional parameters and assuming that the geometry and surface characteristics of a machined workpiece constitute the relevant output, mechatronic machine tools are embedded as core elements within complex machining systems (Fig. 1).

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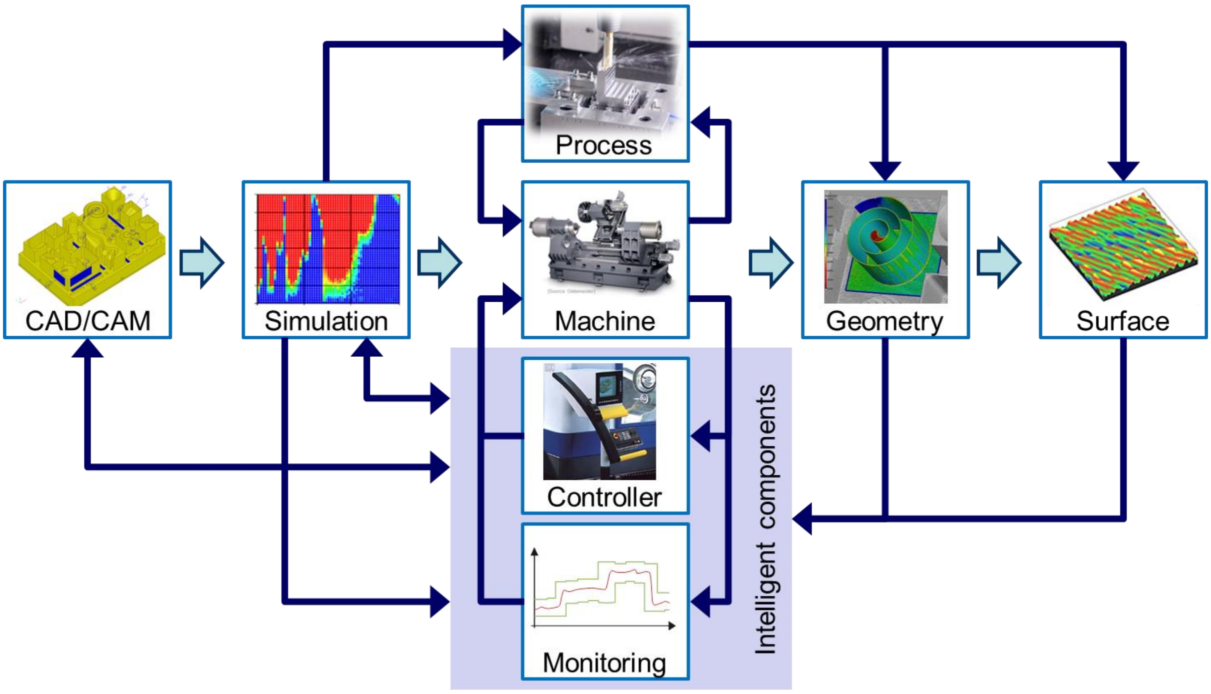


Fig. 1. Self-optimizing machining system

Starting from the desired workpiece geometry and initial NC code, a comprehensive process optimization can be conducted by means of process simulation techniques [1]. For this purpose, advanced simulation approaches can take process machine interactions and machine control behaviour into account [2]. The most relevant process machine interactions imply machining forces and process dynamics [3] as well as thermal and thermo-mechanical effects [4]. The optimized process layout is physically implemented by the real machine which carries out the actual machining process. During machining, the whole machine tool system including its mechatronic components (e.g. main spindle, feed drives, encoders, and controller) is involved in carrying out the processing tasks. Furthermore, process conditions and machine tool states can be monitored by means of an analysis of control internal information and additional sensor signals [5],[6],[7],[8],[9]. Offline process simulation can be applied to define monitoring thresholds and assessment criteria [10]. Furthermore, monitoring data can be used in adaptive control loops in order to immediately adjust and optimize machine behaviour and process conditions [11],[12]. These adaptive optimization approaches can be implemented on either the machine level [13],[14] or by mechatronic and adaptronic machine components [15],[16],[17],[18],[19]. By predicting the geometry and surface quality of the machined workpiece, taking the behaviour of the process, workpiece and machine into account, in principle, a ‘pre-control’ becomes possible, which allows a process layout and mechatronic setup that is directly optimized with respect to the process results [20],[21]. Furthermore, the effect of an active mechatronic process influencing can be estimated [22].

Providing sensing capability, data processing and control electronics and algorithms, as well as integrating actuation functionality for influencing and adjusting machine and process conditions, the mechatronic and adaptive systems mentioned above are also called ‘intelligent’ systems in scientific literature [23],[24],[25],[26],[27]. Often artificial intelligent approaches are utilized in related signal processing and control strategies [28],[29]. Also, realizing self-organization led to the naming of ‘intelligent manufacturing systems’ [30],[31]. Jedrzejewski and Kwasny discussed ‘machine tool intelligence’ in [32] with a special emphasis on control, digitization and virtualization systems. Intelligent machine functions shall enable self-optimisation of process conditions with respect to productivity, part quality and production costs (including energy consumption). For achieving such self-optimizing capability, a certain degree of autonomy has to be given to the machines, components and control systems. Self-optimization in particular includes an adaptive compensation of disturbances and error effects which influence the manufacturing processes.

Since the ‘intelligent’ sensor and actuator integrated systems and components possess additional functionality and, thus, additional degrees of freedom in system layout, higher effort is necessary during design and optimization compared to conventional components. With respect to the integration of intelligent components into machining systems as depicted in Fig. 1, a more comprehensive consideration of the system interactions is essential.

Hatamura et al. discussed the design of an intelligent machining center in [33]. The concept development process (Fig. 2) at first consists of an analysis and decomposition step in which the required performance is allocated to the distributed elements of the total system structure.

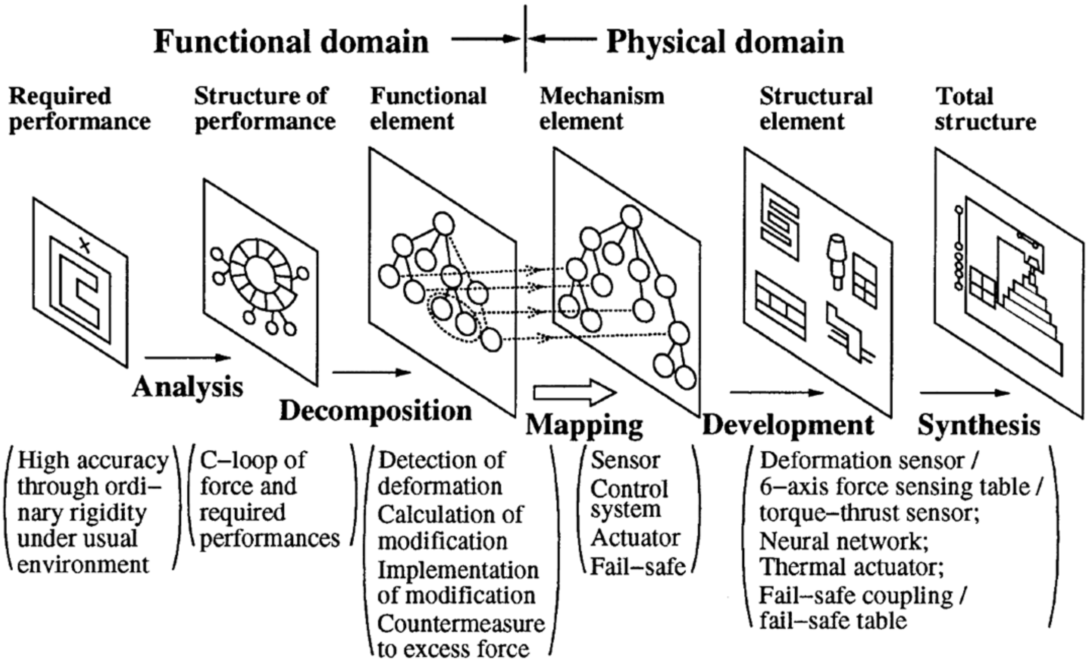


Fig. 2. Fundamental concept development process in the design of an intelligent machining center [33]

In a mapping step, the decomposed sub-functions are connected to the physical mechanism elements. These elements are afterwards designed in detail and synthesised to the total machine structure. Although this concept allows a systematic design procedure and it reduces the complexity of the overall layout task by decomposition, a drawback is the lack of considering interactions between the system elements and between the overall system and the processes the system is designed for.

A well-known design method for mechatronic systems is represented by the ‘V-model’ (Fig. 3) and described in the VDI standard 2206 [34]; see also [15]. The functional interaction of domain-specific design approaches is analysed by modelling and simulation during the development phase. By this, a higher degree of maturity can be achieved with the integrated mechatronic product. Several iterations and optimization loops can be conducted, each following similar design procedures.

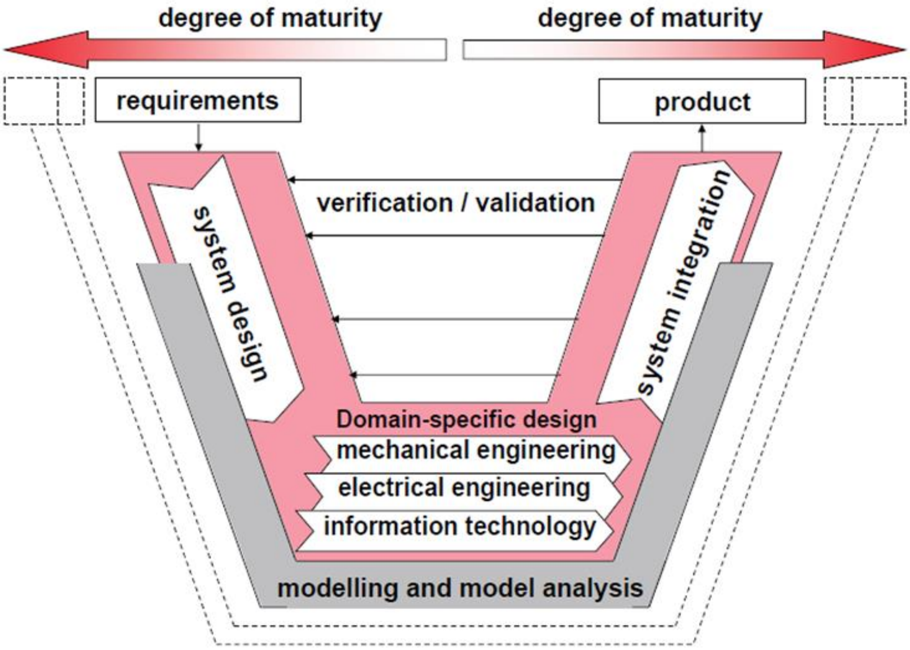


Fig. 3. V-model for the design of mechatronic systems [34]

The complexity of a mechatronic design even increases when cognitive and sensory functions shall be included into an intelligent system. Dumitrescu, Anacker and Gausemeier introduced a framework for the integration of cognitive functions into intelligent systems in [35]. In order to take interactions of the mechatronic functions with the environment and external influences into account, comprehensive simulations are necessary. Barbieri et al. therefore proposed a ‘W-model’ for the integrated design of mechatronic systems emphasising the analysis of the virtual system behaviour (Fig. 4) [36].

Furthermore, multiple simulation runs enable parameter studies and system optimization within the development phase (Fig. 5) [37]. For optimization, system assessment is necessary based on an evaluation of the characteristics and performance of the system with respect to pre-defined requirements and application related functional indicators. This could also be combined with artificial intelligence techniques [38].

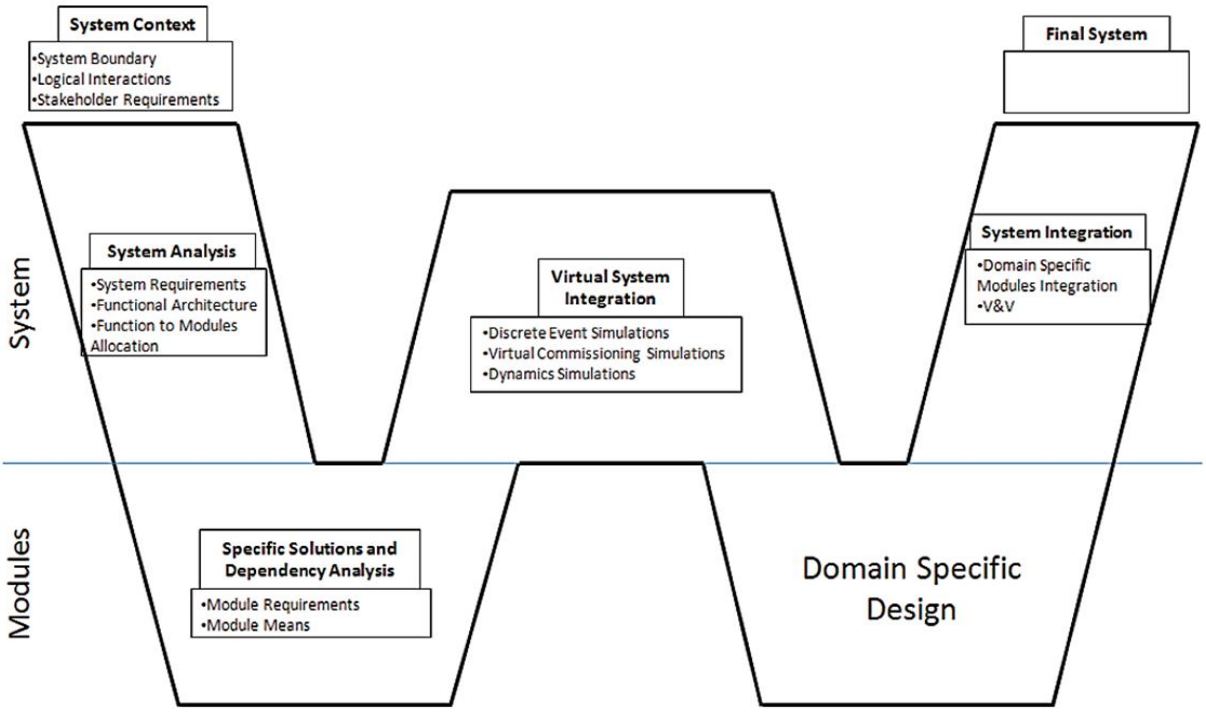


Fig. 4. W-model for simulation integrated design of mechatronic systems [36]

Simulation aided design approaches are also applied intensively in the machine tool sector [39],[40],[41],[42],[43],[44],[45]. For example, Huo et al. presented an integrated design and modelling approach in [42], where the functional properties of the machine tool are considered in detail during the development phase (Fig. 6). However, the integration of ‘intelligent’ components is not considered by these methodologies.

In this paper, sensor and actuator integrated ‘intelligent’ fixtures for clamping aluminium structural parts for the aerospace industry are introduced and discussed. The work presented here is part of the European research project ‘Intelligent Fixtures for the manufacturing of low rigidity components - INTEFIX’ (www.intefix.eu). In addition to exemplary technical solutions which overcome challenges in workpiece clamping regarding vibrations, deformations and positioning, design and optimization methodologies for intelligent fixtures are a major objective of the project. Sensor and actuator integrated fixtures can be understood as typical intelligent subsystems for modern machine tools. Fixtures for workpiece clamping are an essential part of machining systems. Main functional tasks of fixtures and clamping systems are: to define the location (position and orientation) of a clamped workpiece in the workspace of the machine tool; to maintain this defined location even under the influence of static and dynamic mechanical and thermal loads; to guide these loads as an integral element of the machine structure inside the force flux [46].

Nowadays, fixtures and clamping elements with integrated sensors for monitoring tasks are available [17],[47],[48]. Furthermore, active fixtures enable an actuated movement of clamping points, e.g. for adaption to distorting workpiece shapes [29],[49],[50], or to excite the workpiece in order to improve process conditions [51],[52].

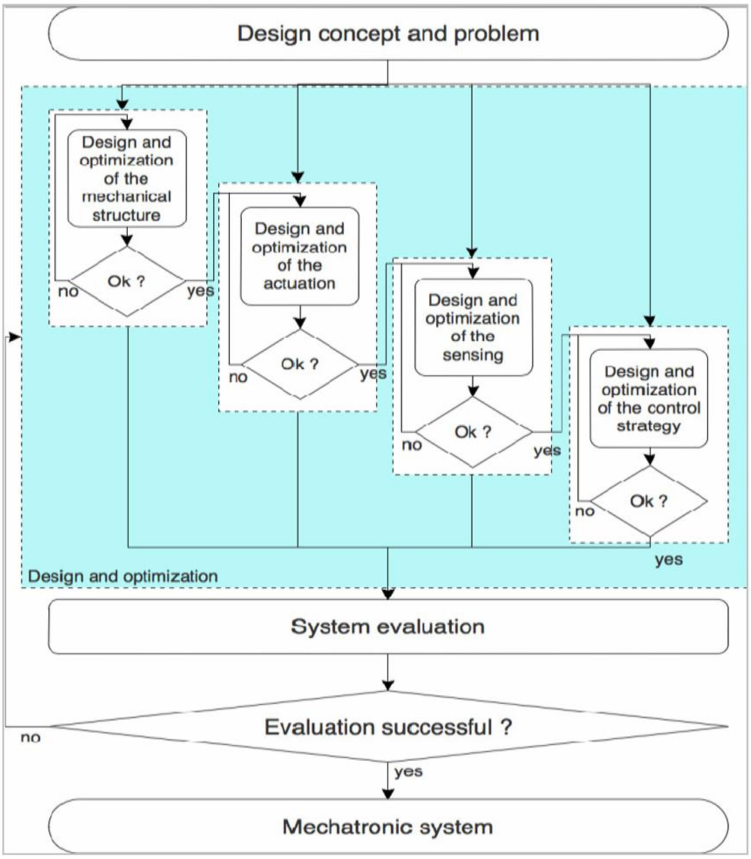


Fig. 5. Optimization-based design approach for mechatronic systems [37]

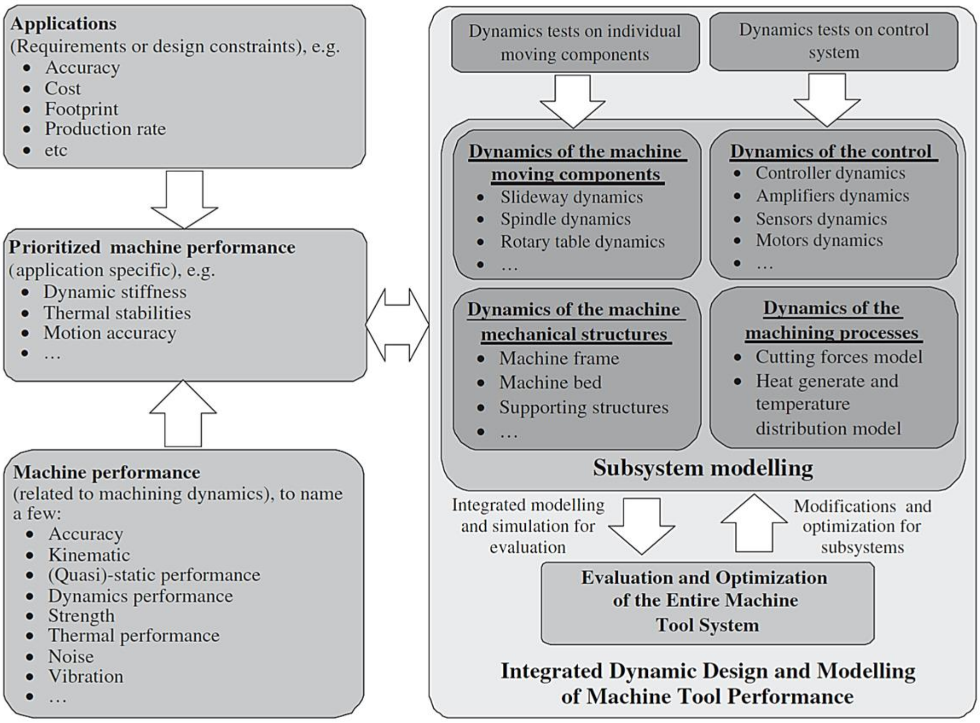


Fig. 6. Schematic of integrated dynamic design and modelling approach [42]

Extensive research work addresses strategies for optimizing clamping configurations [53],[54],[55],[56],[57]. Fixture design can be supported by numerical calculation and simulation [58],[59],[60]. The dynamic behaviour of the fixture and the clamped workpiece which affects the process stability has to be considered in particular [61],[62],[63],[64]. In summary, design methodologies for fixtures can be regarded as an ongoing topic, especially in view of intelligent fixtures [65].

2. CASE STUDY ON INTELLIGENT FIXTURE

In this paper, the analysis of an intelligent fixture design is based on a case study dealing with the clamping of thin-walled aluminium structural parts for aerospace applications. Especially thin-walled workpieces are affected by distortions due to residual stresses which are induced or delivered during the machining processes [66],[67],[68],[69]. The reference workpiece is a structural aluminium part with a length of 1,970 mm, width of 100 mm and height of 48 mm (Fig. 7). The final workpiece is machined out of an aluminium block by several milling process steps. After completed machining, removal of the clamps and demounting the workpiece off the fixture, distortions occur which lead to a bended shape with a height difference of up to 10 mm between the centre and the edges of the part. These distortions are not necessarily distributed evenly about the length of the workpiece. In order to reduce the resulting shape deviations, several re-clamping steps are currently conducted in which the workpiece is dismounted off the conventional fixture, turned and clamped again in order to allow machining from both the front and the rear side.

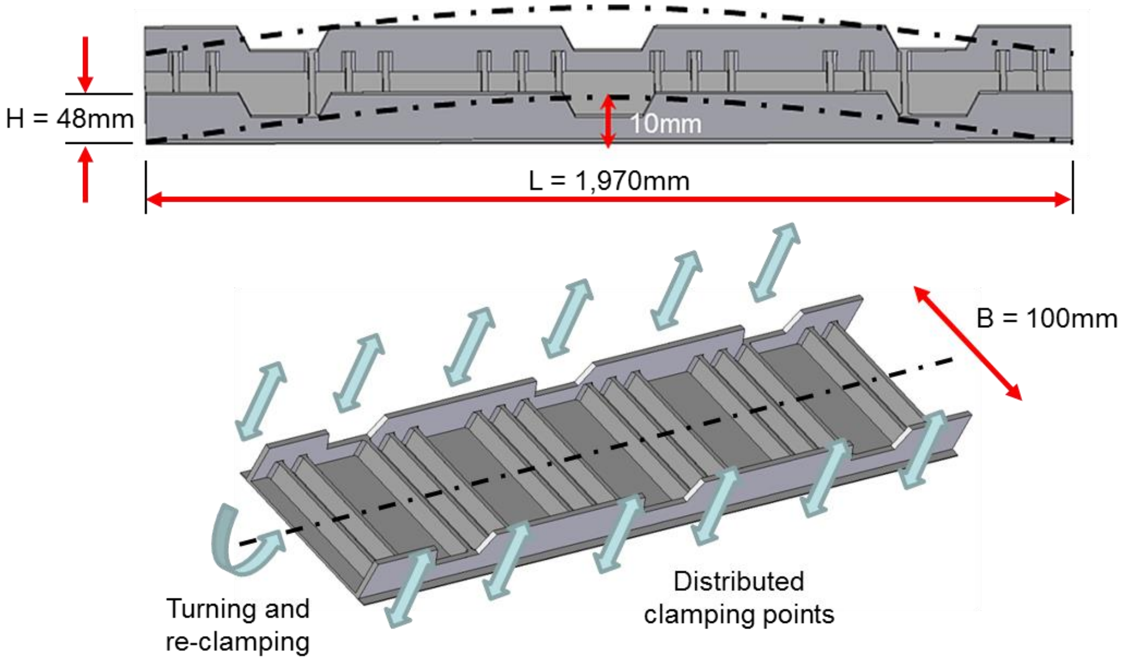


Fig. 7. Reference workpiece from aerospace industry

The aim of this procedure is to achieve an uniform distribution of residual stresses and, thus, minimized distortions. However, this manual re-clamping is a costly and time consuming solution to overcome the given problem. Furthermore, the re-clamping not always leads to acceptable results in terms of workpiece shapes which satisfy the tolerances defined by the customers.

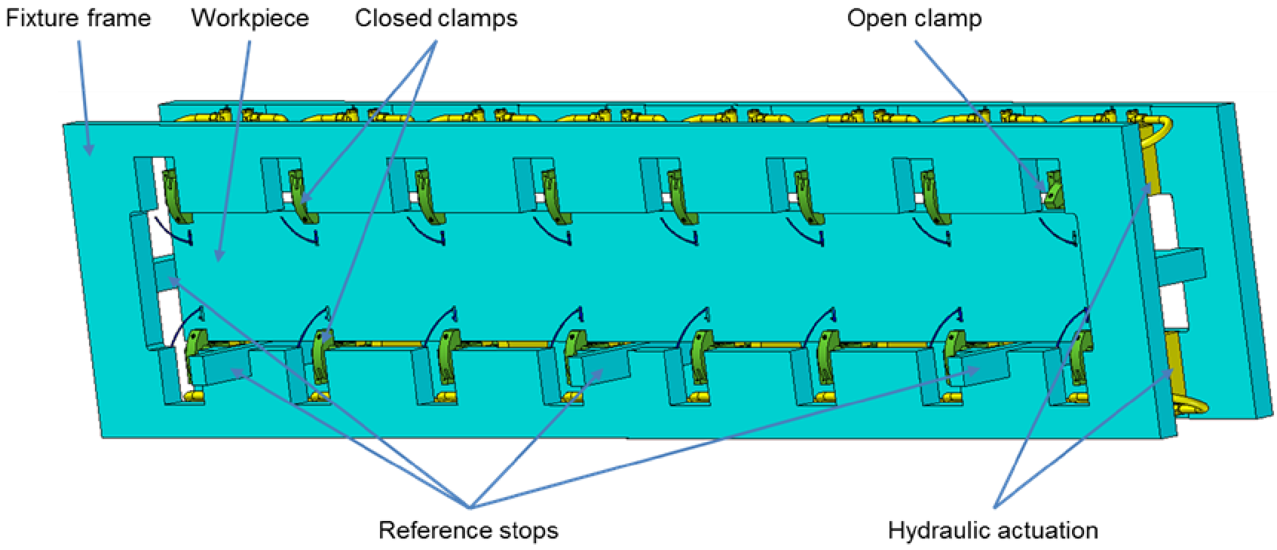


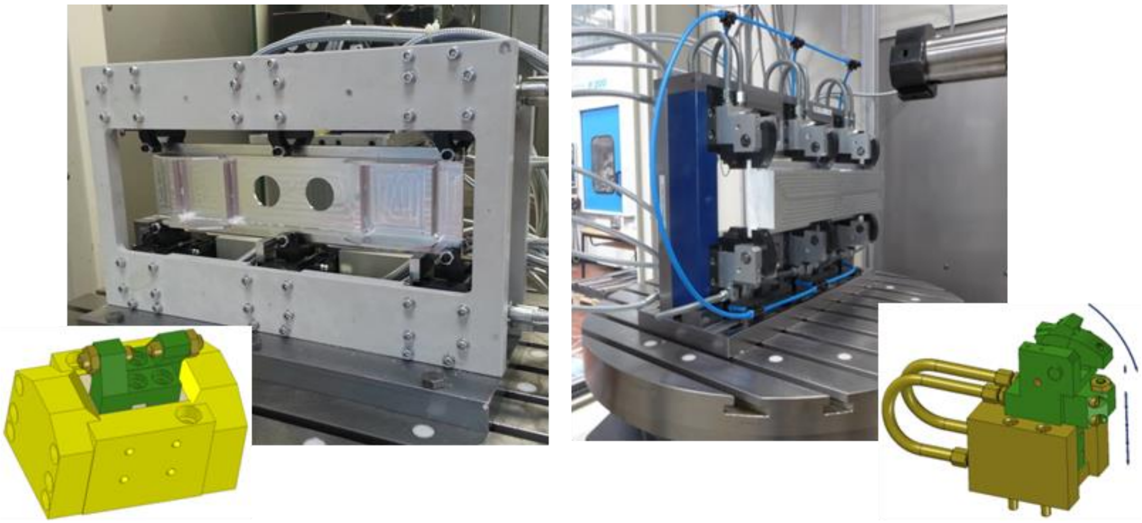
Fig. 8. Concept distributed clamps and workpiece [70]

Within the INTEFIX project, an approach is investigated which is based on the application of a fixture frame that integrates several adjustable clamping elements (Fig. 8). The fixture frame holds the workpiece in an upright position, so that accessibility of the clamped part from the front and the rear side is provided. This allows automated both-sided milling operations inside a horizontal machining centre with a rotary table. The adjustable clamping elements allow an adaptation of the locations of the clamping points to distorted shapes of the clamped workpiece by floating degrees of freedom (DoF). By this, a relaxation of the workpiece at intermediate states of the total machining process becomes possible. Thus, residual stresses can be compensated and the final distortions can be reduced. During the milling operations, the floating DoFs of the clamping elements are blocked by hydraulics. In order to align the locations of the clamping points actively, additional hydraulic actuators are integrated into the fixture system which move the floating clamps separately. For an adaptation of the clamping point locations to distorted intermediate workpiece shapes, a controlled positioning of the floating DoFs is necessary. To obtain measurement signals for position and force control, sensors are integrated into the actuation sub-systems. Consequently, by sensor, actuator and control integration, the fixture provides the additional ‘intelligent’ functionality to adapt itself to occurring distorted part shapes.

Nevertheless, the main task of the fixture system is to fixate the clamped workpiece during the milling processes and to allow stable cutting conditions at economically acceptable material removal rates. This necessitates the consideration of the machining scenarios during the design and development phase of the intelligent fixture. In order to integrate the analysis of the process behaviour into the fixture layout, a simulation system for the analysis of the milling process including the behaviour of the fixture system was developed and exploited. In addition, multiple test rigs were built in order to allow a systematic development of the fixture and a verification of process simulation approaches.

3. TEST RIGS AND EXPERIMENTS

For keeping the costs and effort of the realization of experimental setups relatively small, downsized test rigs were built which allow investigations of the principle characteristics of the fixture frame approach (Fig. 9). The size of the test rigs is characterized by a width of B = 500 mm and a height of H = 390 mm. The first test rig consists of steel frame elements and six distributed ‘PosiFlex’ floating clamps provided by company Roemheld. These clamping elements possess a floating DoF with a stroke of 6 mm. Clamping forces of up to 7 kN can be achieved at 250 bar hydraulic pressure. The second test rig integrates floating clamping claws with up to 10 mm stroke and clamping forces of up to 7.5 kN. Both test rigs were investigated by means of FEA, experimental modal analysis and machining tests. Table 1 and table 2 summarize the first natural frequencies obtained by experimental modal analyses for the first and second test rig, respectively. The measurements consider different states of the workpiece, starting with the raw part and ending up with the finished part. Also, with the first test rig, the influence of the clamping pressure was analysed at 150, 200 and 250 bar. As can be seen, for the first test rig the natural frequencies depend more significantly on the workpiece state compared to the second test rig. The influence of the clamping pressure appears to be negligible.



‘PosiFlex’ floating clamp
(2x 6 mm; 7 kN at 250 bar)

Floating clamping claw
(8 mm / 10 mm; 7,5 kN at 250 bar)

Fig. 9. Test rigs for experimental investigations of the fixture frame approach

Table 1. Natural frequencies of the first test rig with PosiFlex floating clamps

Mode ↓	Clamping pressure [bar] →	Natural frequency [Hz] Workpiece state								
		Raw part			Intermediate step			Final part		
		150	200	250	150	200	250	150	200	250
1		127	125	126	127	130	129	126	129	126
2		291	285	290	234	234	233	224	224	224
3		630	635	630	652	659	649	636	636	642
4		780	785	781	754	757	754	751	751	752
5		1027	1022	1020	988	988	987	983	987	996
6		1367	1345	1347	1298	1302	1274	1042	1010	1050
7		1521	1521	1511	1531	1523	1507	1517	1483	1513
8		1621	1605	1604	1604	1608	1609	1606	1598	1609

Table 2. Natural frequencies of the second test rig with floating clamping claws

Mode	Natural frequency [Hz] Workpiece state					
	Raw part	Intermediate step 1	Intermediate step 2	Intermediate step 3	Final part	Without workpiece
1	138	145	141	148	146	130
2	296	298	294	300	300	263
3	619	600	603	615	619	345
4	777	760	745	714	715	500
5	973	966	971	984	984	587
6	1288	1278	1277	1304	1350	899
7	1514	1557	1553	1549	1448	1413
8	1859	1786	1783	1826	1827	1833

The second test rig provides comparable natural frequency values for the first two eigenmodes without a clamped workpiece and with a clamped raw part. These eigenmodes are the bending (pitching) mode of the upright fixture frame and the displacement of the upper part of the frame structure in longitudinal direction, deforming the rectangular frame to a parallelogram. The low dependency on the state of the clamped workpiece reveals the self-sufficient stiffness of the frame structure.

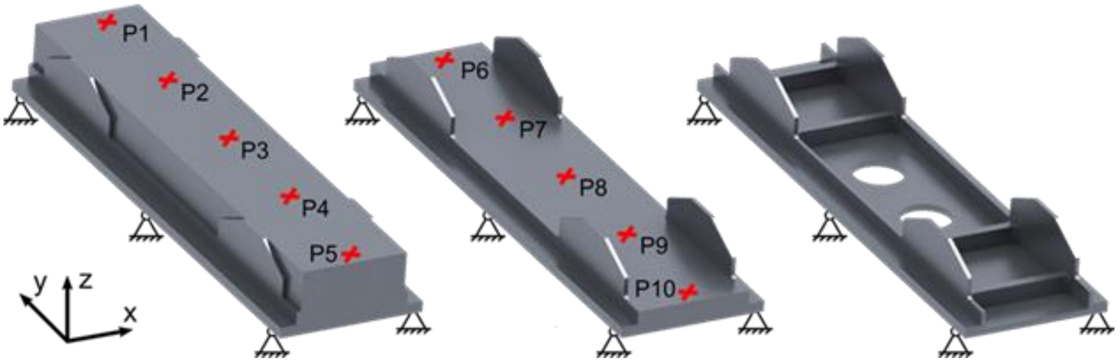


Fig. 10. States of a test workpiece clamped in second test fixture

In order to analyse the influence of different workpiece states with respect to process stability limits during milling, process simulations were performed which consider the dynamic compliance of the clamped parts inside the fixture frames. In Fig. 10, three workpiece states are depicted which were analysed with the second test rig [70].

The stability calculations were carried out considering three different types of milling tools [70]. Fig. 11 shows the resulting stability diagrams. It can be seen that in this case the process stability is predominantly limited by the dynamic behaviour of the tools and not by the compliance of the fixture or the workpiece. Furthermore, clearly different stability borders occur for the different workpiece states (visible through the blue curves in the upper parts of the diagrams). Consequently, the different workpiece states have to be considered in the layout of the fixture system.

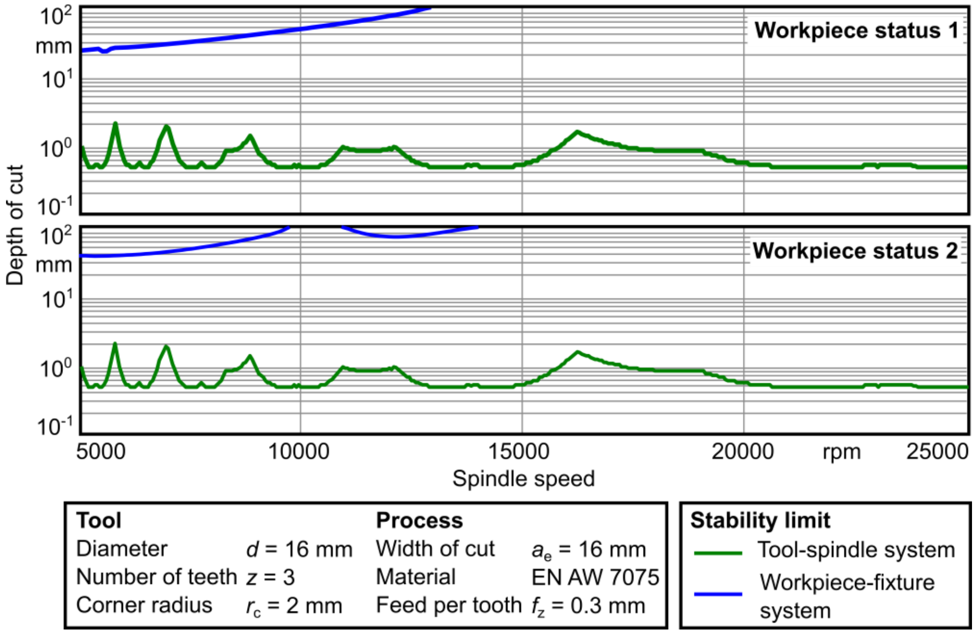
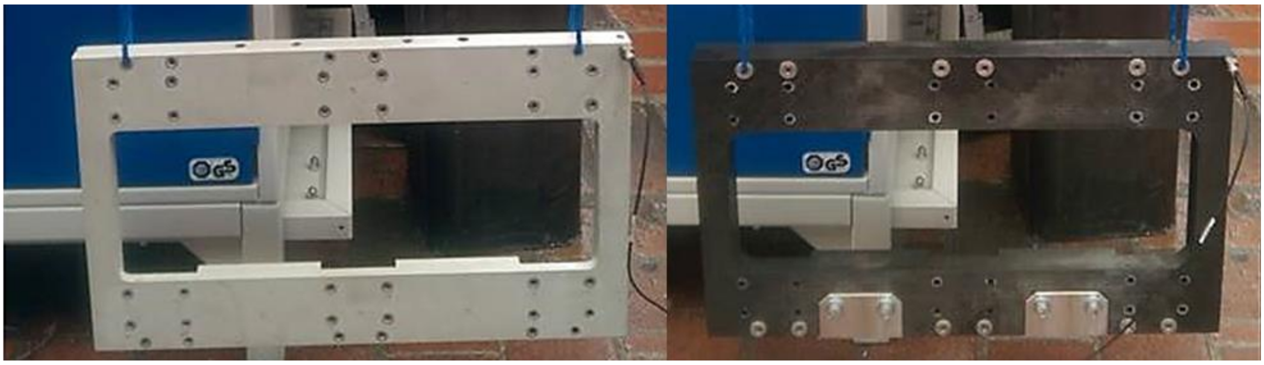


Fig. 11. Simulated stability diagrams for different process scenarios

In a variation of the first test fixture, the steel frame was substituted by a CFRP frame for analysing the effect of improved material damping properties. At first, the single CFRP element was compared to the steel component by means of experimental modal analysis (Fig. 12). Significantly higher natural frequencies and damping ratio values could be recognized showing the high potential of the material substitution.

The CFRP frame was afterwards mounted into the test rig and modal analysis of the complete system was conducted (Fig. 13). Although the single CFRP element provides enhanced dynamic characteristics, the complete test fixture, incorporating CFRP frame components instead of the steel parts, shows lower natural frequencies and less damping. This can be explained by the properties of the chosen interfaces between the frame elements and the ground plate of the fixture. Whereas the steel frames are connected to the bottom plate by distributed screws, the CFRP frames are mounted in brackets which are screwed onto the plate. This obviously leads to a reduced dynamic stiffness of the overall structure.



Eigenmode	Steel		CFRP	
	Natural frequency in Hz	Damping ratio in %	Natural frequency in Hz	Damping ratio in %
1	211	0.08	295	0.52
2	269	0.06	482	0.22
3	396	0.09	587	0.36
4	564	0.04	714	0.42
5	656	0.05	851	0.17
6	712	0.03	976	0.32
7	770	0.03	1216	0.38
8	977	0.02	1364	0.37
9	1068	0.03	1533	0.47

Fig. 12. Comparison of steel and CFRP frame element for first test fixture

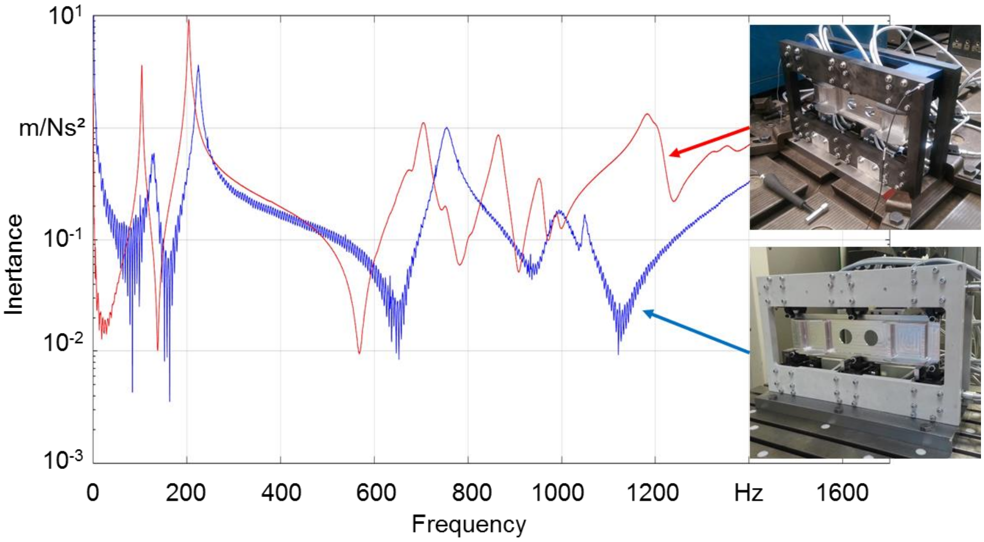


Fig. 13. Comparison of steel and CFRP test fixture

Regarding the adaptation of the clamping point locations to intermediate workpiece shapes, a sensor and actuator system is required which enables the measurement of the workpiece distortion forces and which can actively move and adjust the floating DoF of the clamping elements. For actuation, double acting hydraulic pistons are integrated into the second test fixture (Fig. 14) and the final prototype. The pistons are connected to the floating clamps by links at which strain gauge sensors are mounted for actuation force measuring.

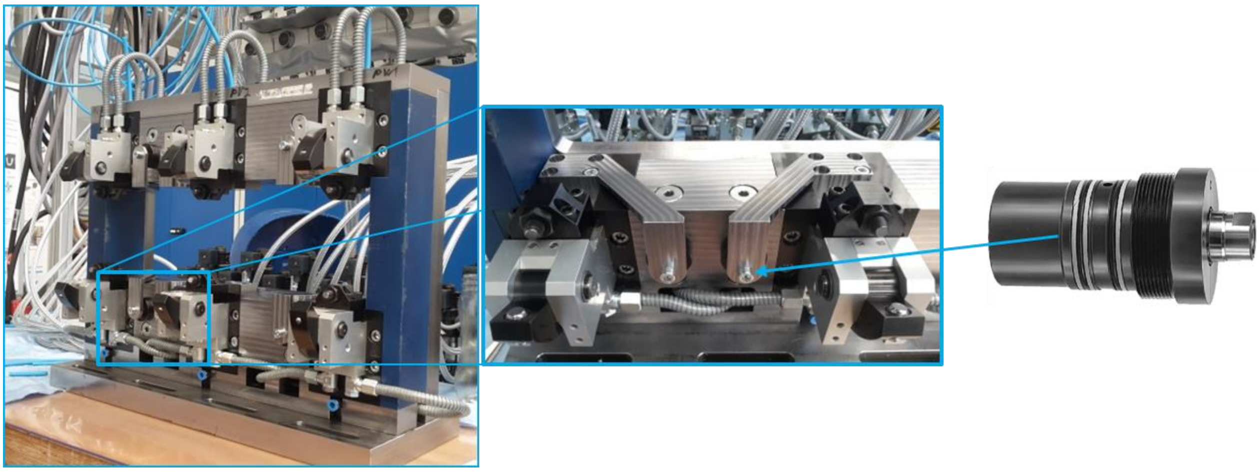


Fig. 14. Integration of hydraulic actuators for clamping element positioning

In order to allow the experimental analysis of the attached strain gauge sensors, a test rig was built in which a bending beam with a length of 1 m is clamped by a sensor and actuator integrated clamping claw (Fig. 15). By moving the clamping claw within its floating DoF, the bending beam is deformed and consequently stresses occur which act as forces against the actuation mechanism. The bending motion is measured in the test rig by an eddy current sensor. The forces which are applied at the floating clamp are measured by the strain gauge sensors and an additional reference force sensor. Exemplary sensor signals are depicted in Fig. 16. Obviously, the signals obtained by the strain gauge sensors are sensitive with respect to the bending of the test beam which represents the distortion forces of a clamped workpiece inside the fixture. Based on this sensor and actuator setup, the control scheme shown in Fig. 17 can be implemented for the adaptive compensation of workpiece distortions at intermediate processing steps.

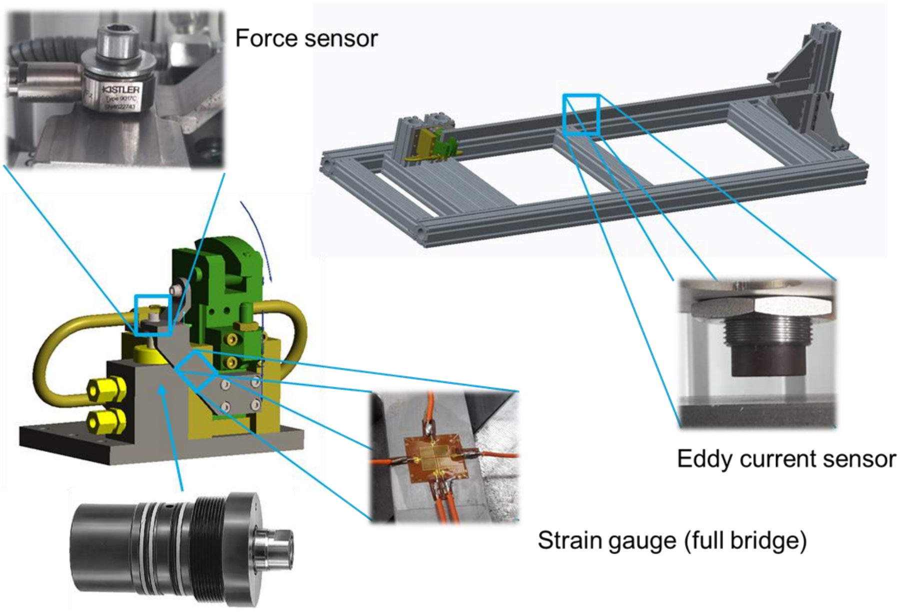


Fig. 15. Sensor integration and bending beam test rig

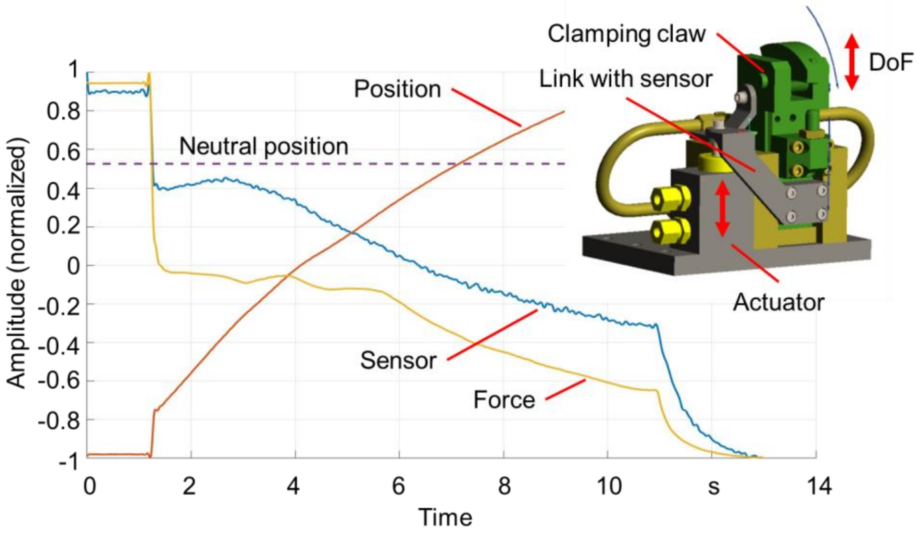


Fig. 16. Measured sensor signals

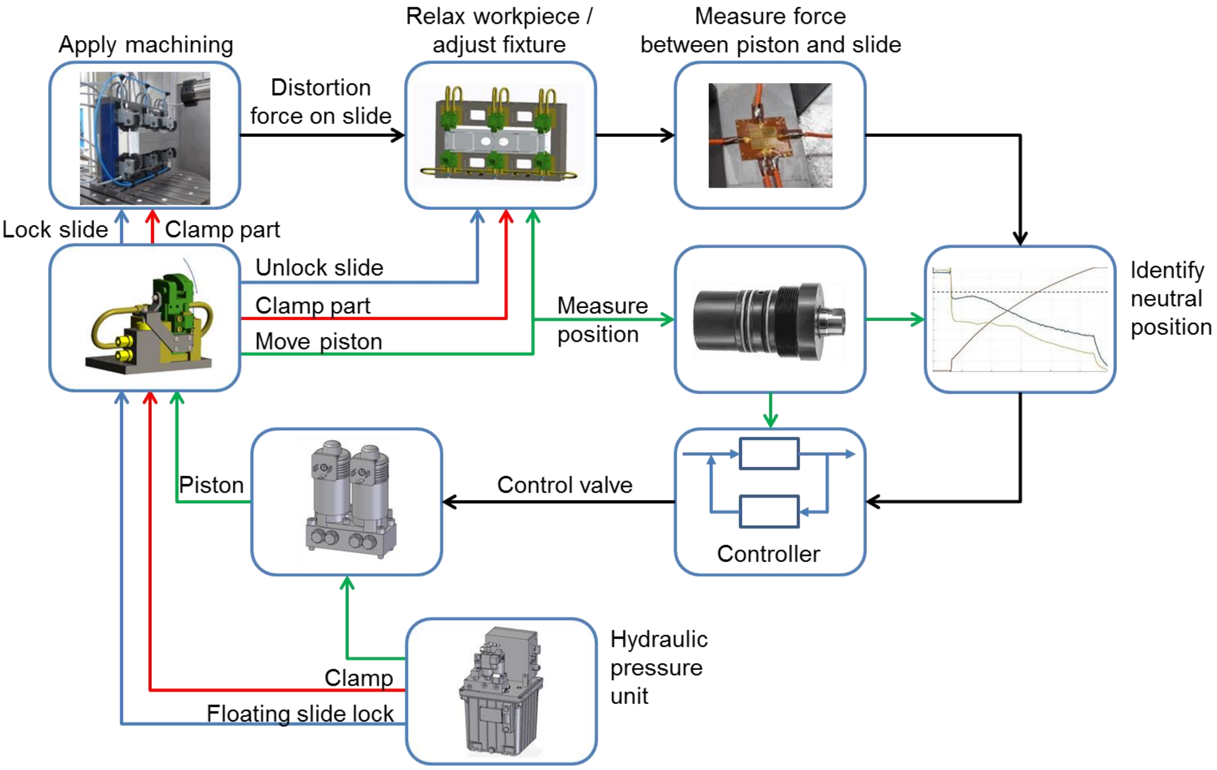


Fig. 17. Control scheme for workpiece relaxation

4. PROTOTYPE OF INTELLIGENT FIXTURE

Based on the gained experiences and the obtained analysis results, the final prototype of an intelligent fixture for clamping the real workpiece, which is defined by the industrial case study within the INTEFIX project, was designed and realized (Fig. 18).

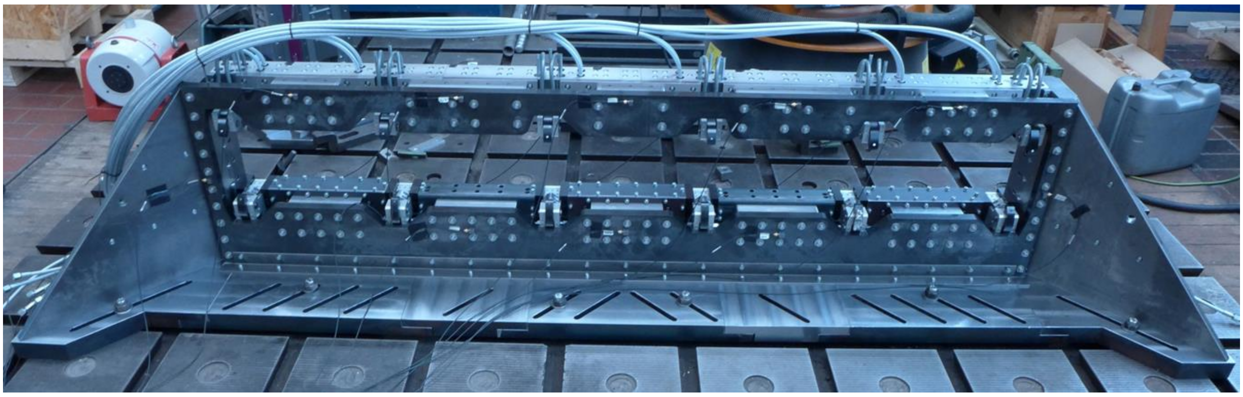


Fig. 18. Final prototype of the intelligent fixture

The prototype fixture consists of a metal frame structure with open profiles which provide a beneficial bending and torsional stiffness. The upright frame is supported by side walls in order to increase the system stiffness with respect to pitching. Furthermore, an additional CFRP frame is attached to the metal frame as a damping element (Fig. 19). The overall size of the fixture amounts to B = 2,860 mm and H = 555 mm.

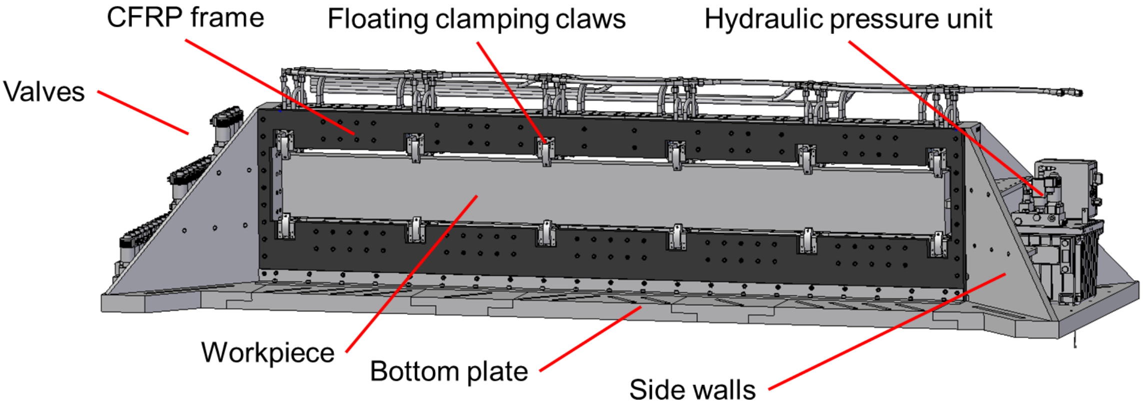


Fig. 19. Structure of the intelligent fixture

The frame structure integrates 12 floating clamping claws which are connected to hydraulic actuators via sensor equipped links as described above. The prototype fixture includes a hydraulic pressure unit and the necessary valve system for controlling the clamps and actuator pistons. This final prototype allows comprehensive experimental investigations regarding the requirements of the case study and the general intelligent fixture approach. Results of an experimental modal analysis of the prototype fixture without a clamped workpiece are depicted in Fig. 20 (red and black curve; excitation at drive point 44 in horizontal z-direction, orthogonal to the fixture frame surface).

The first natural frequency appears at approx. 64 Hz and belongs to a bending mode of the upper traverse of the frame structure in vertical direction (y-direction). Table 3 summarizes the dynamic characteristics of the prototype fixture frame without workpiece.

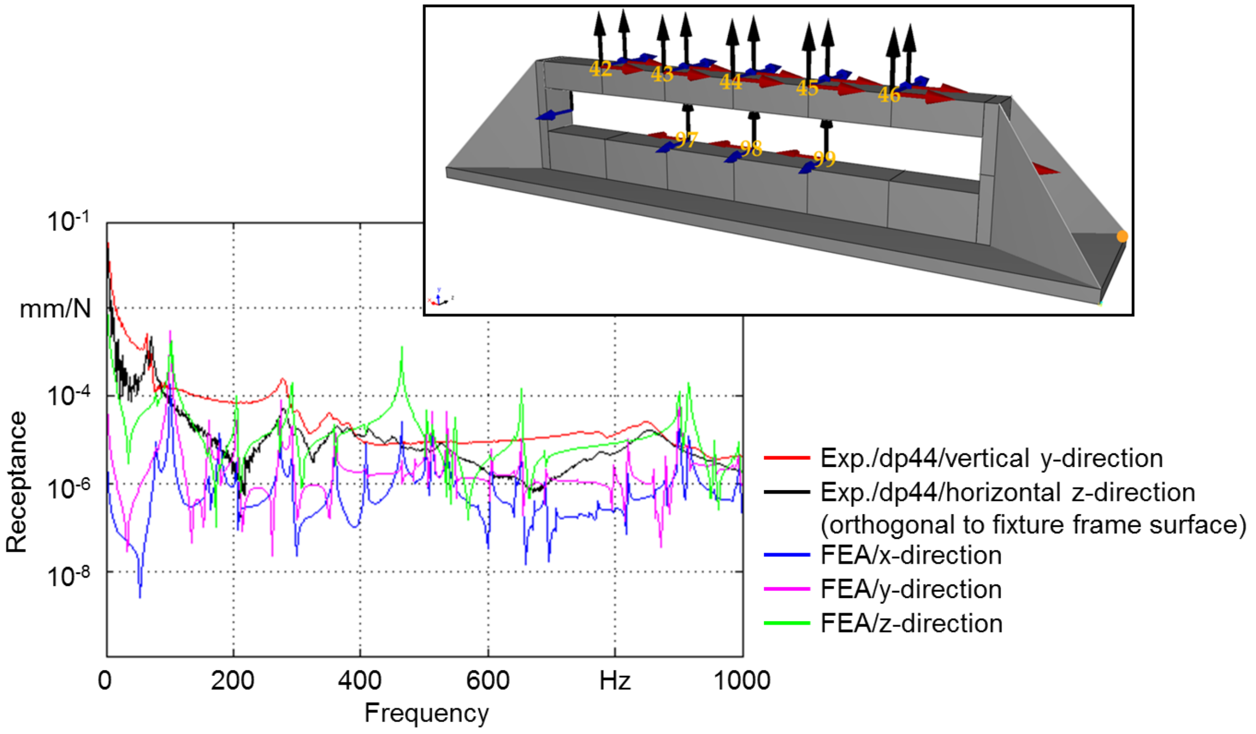


Fig. 20. Results of the experimental modal analysis of the fixture prototype without a clamped workpiece

Table 3. Results of dynamic analysis at prototype without workpiece

Mode	Natural frequency [Hz]	Damping ratio [%]	FEA natural frequencies [Hz]
1	64	1.5	86
2	71	1.9	104
3	149	1.8	252
4	209	1.1	276
5	279	1.9	421
6	352	1.9	462
7	548	1.3	506
8	675	1.7	528
9	779	1.2	559
10	849	1.8	591
11	928	2.6	745

The dynamic behaviour of the fixture frame was also simulated by means of the FEA. In Fig. 21 the first two eigenmodes of the simulated fixture are shown. As indicated in Table 3, the first natural frequencies are over estimated by the FEA results. This can be explained by the simplification of the simulation model, especially with respect to the internal interfaces and mechanical contacts between the fixture elements. However, he comparison verifies that FEA results can be exploited for an appraisal and evaluation of the fixture performance during the design phase.

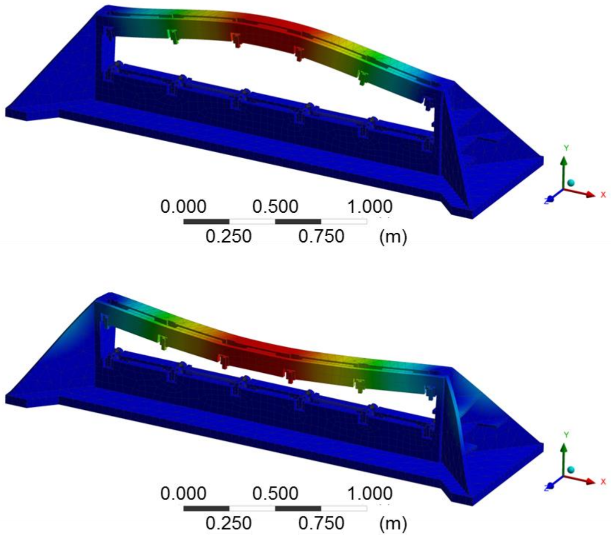


Fig. 21. Finite Element Analysis of the fixture prototype without a clamped workpiece

5. SIMULATION BASED SYSTEM ANALYSIS

Finite Element Analysis was also conducted for the virtual fixture prototype considering a clamped raw part and a clamped workpiece after completed machining. Fig. 22 shows the results for the first three mode shapes. Based on this, also the dynamic response at different points of the clamped workpiece when excited by an estimated sinusoidal process force can be calculated. Fig. 23 depicts harmonic response shapes when the workpieces are excited at nodes close to the mid of the parts.

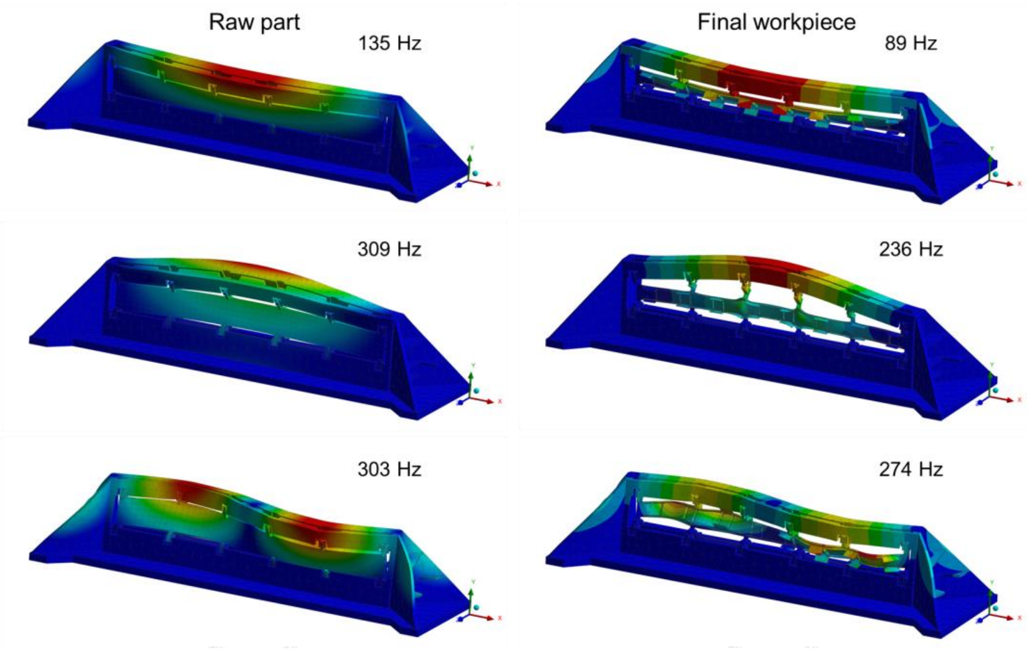


Fig. 22. FE-based modal Analysis of the fixture prototype with a raw and final part

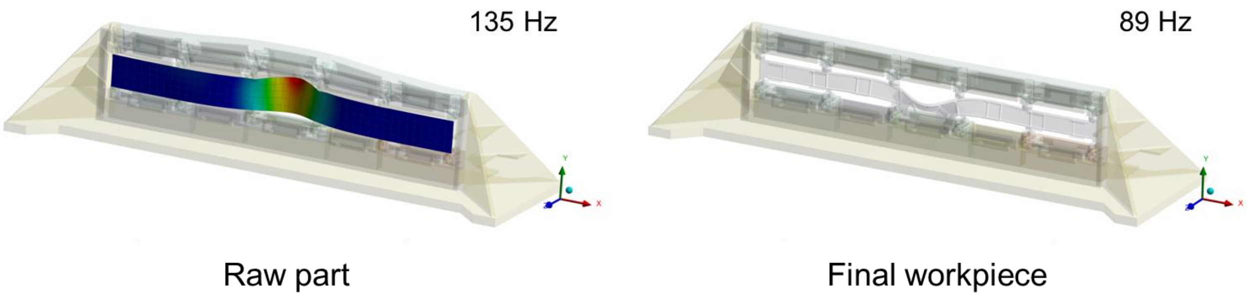


Fig. 23. Harmonic response of the clamped workpieces when excited at middle position

As can be seen in Fig. 23, the harmonic response of the clamped raw part results from an interaction of the dynamic behaviour of the part and the fixture frame. In contrast, the harmonic response of the final workpiece is dominated by the compliance of the workpiece itself whereas the fixture frame has minor influence.

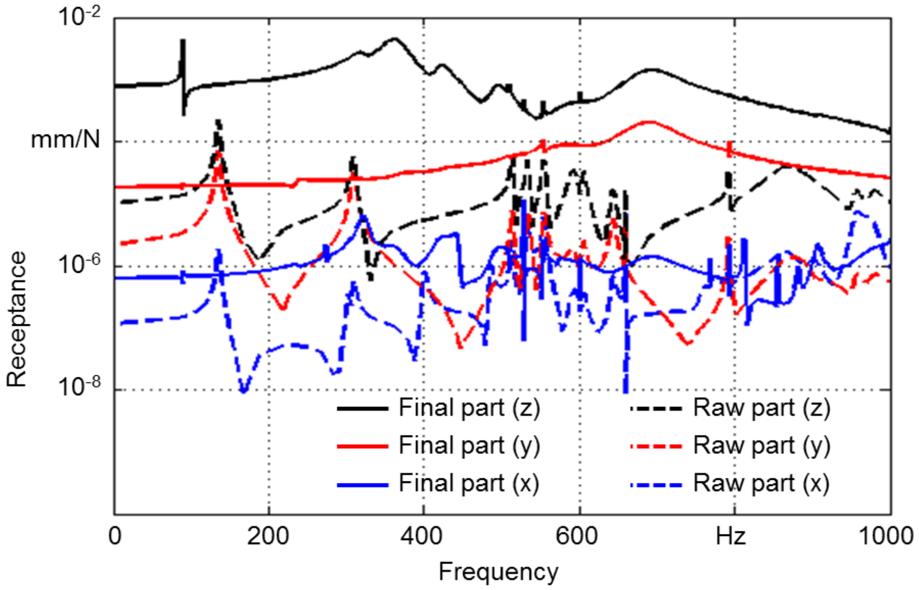


Fig. 24. Comparison of Frequency Response Functions (FRFs) for a clamped raw and final part

The FRFs (excitation in z-direction, responses in all directions) are compared in Fig. 24. The behaviour changes significantly with the state of the workpiece. Furthermore, the harmonic response depends on the excitation point at the workpiece. In Fig. 25 responses for an excitation in z-direction at point 1 (mid of workpiece) and at point 2 (left side of the workpiece) are depicted.

The FEA results expose essential characteristics of the fixture. However, in order to achieve acceptable computation times and stable solutions, a number of simplifications are necessary. The initial CAD model of the fixture system includes more than 100 contact areas which have to be parameterized carefully for an accurate FE modelling. Since also non-linear contact phenomena are involved, the computation time is extremely high. Even with a simplified geometry (avoiding e.g. curvatures, irrelevant boreholes and chamfers) the FEA model includes more than 1 Million nodes. Here, most of the contacts inside the workpiece-fixture system were neglected and assumed to be rigid. Still, non-linear contacts between the workpiece and the clamping elements remain. Thus, the calculation of a single frequency response function with one selected load direction takes more than 4 ½ days (applying an Intel® Core™ i7-5960X processor with 3.0 GHz).

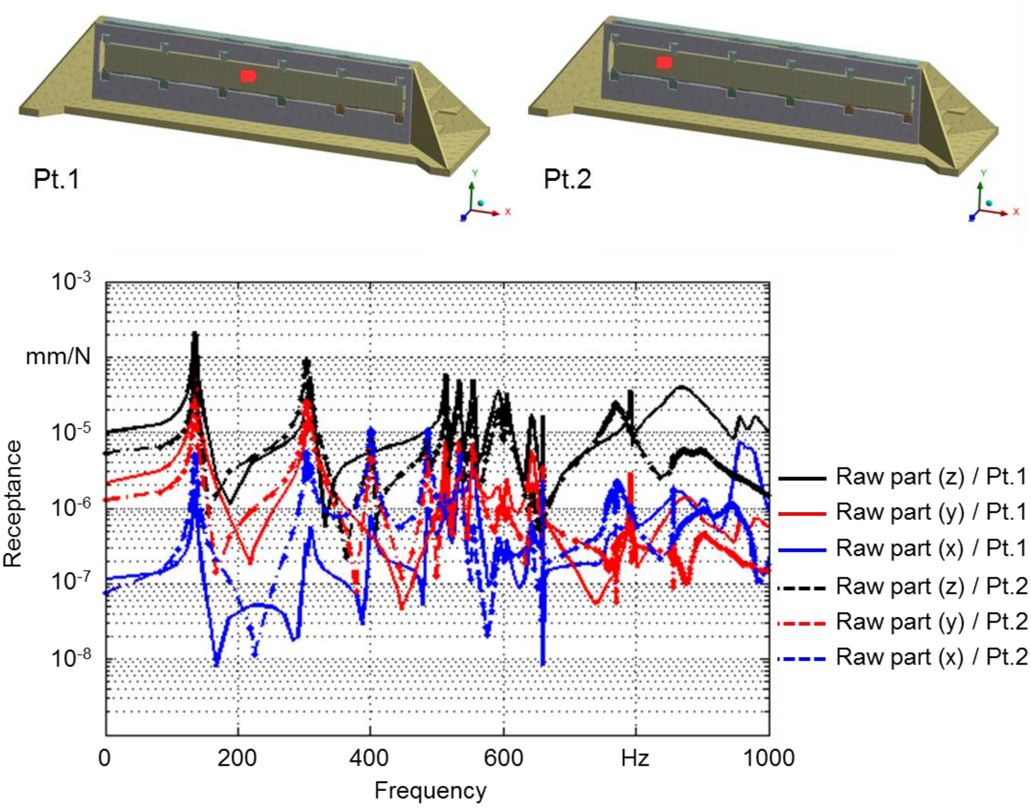


Fig. 25. Comparison of FRFs for different excitation points

Another challenge in modelling the fixture system is the appropriate consideration of material and structural damping. Material damping for the steel components of the fixture can be parameterized by the beta and alpha coefficients of the Rayleigh damping which can be derived from literature [71] or which can be identified by basic experimental modal analysis of a steel specimen. In principle, the same approach can be followed for the aluminium alloy of the clamped workpiece. Regarding the integrated CFRP frame, a more complex derivation is necessary which considers the properties of the fibres and matrix, the fibre volume content, the combination and alignment of layers and the number of layers resulting in the thickness of the component. Consequently, orthotropic stiffness and damping values can be obtained and used in the FE model. The internal structure of the CFRP frame component provides additional degrees of freedom regarding an optimization of the dynamic fixture properties. This can be exploited in future work.

6. SIMULATION BASED PROCESS ANALYSIS

The FEM simulated dynamic behaviour of the fixture system can be used to predict forces and deflections during the cutting process. This information is very helpful for the designer of the fixture system due to the possibility to evaluate the fixture rigidity already during the design process. Effects like surface errors, regenerative chatter, or the tool load can be estimated, which offers the opportunity of highly customized, lightweight, and reasonably priced fixtures.

To acquire these data, a geometric-physical process simulation was used in the presented work, which is based on the constructive solid geometry (CSG) technique for modelling the chip shape by intersecting the model of the tool and the workpiece [72]. The determined chip shape is used to calculate the process forces by utilising the uncut chip thickness [73]. The dynamic behaviour of the tool and the workpiece together with the fixture can be modelled by using an oscillator-based method [74]. Thus, for setting up a simulation project, the following input parameters are needed:

- Parameters for the calibration of the force model
- Modal parameters describing the dynamic behaviour of the tool and the workpiece (including the fixture)
- Tool paths of the intended milling process
- Geometry of the tool and the workpiece.

To illustrate the capabilities of the used process simulation, Fig. 26 shows a screenshot of the simulation of a workpiece section. The current process forces, the deflections of the tool and the surface error of the workpiece that is caused by the deflections of the tool and the workpiece are depicted as well.

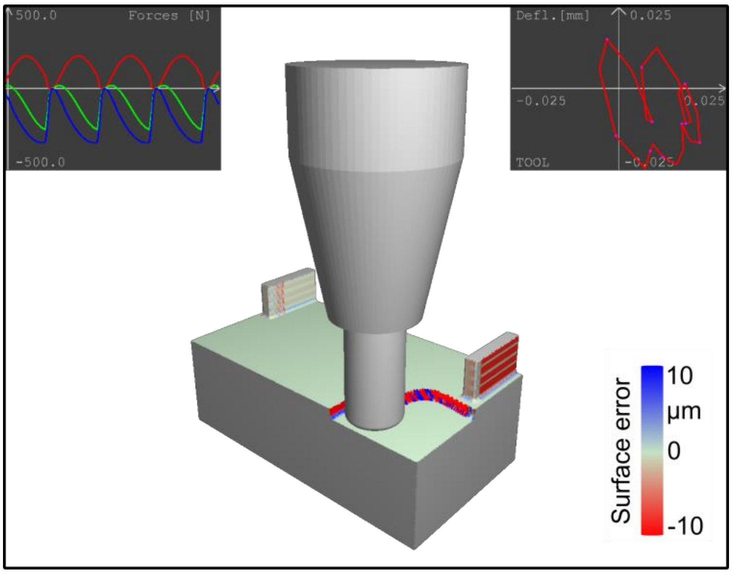


Fig. 26. Process simulation of a section of the test workpiece with a visualisation of the current process forces, tool deflections, and the surface errors

The required frequency response functions are typically measured with experimental modal analysis techniques like the impulse hammer method. However, the FRFs of the fixture system, which are intended to be used during the milling process, cannot be measured in the design phase. For this purpose, the utilisation of FEM calculated FRFs is an appropriate instrument to acquire the required data for the parametrisation of the simulation model.

For the design of the described fixture (Fig. 18), several results of the presented simulation system were used. For the simulations a typical roughing process with a tool diameter *d* = 16 mm was chosen as test process. In Fig. 27 simulated process forces for this typical process are shown with and without taking the dynamic behaviour of the workpiece and the tool into account.

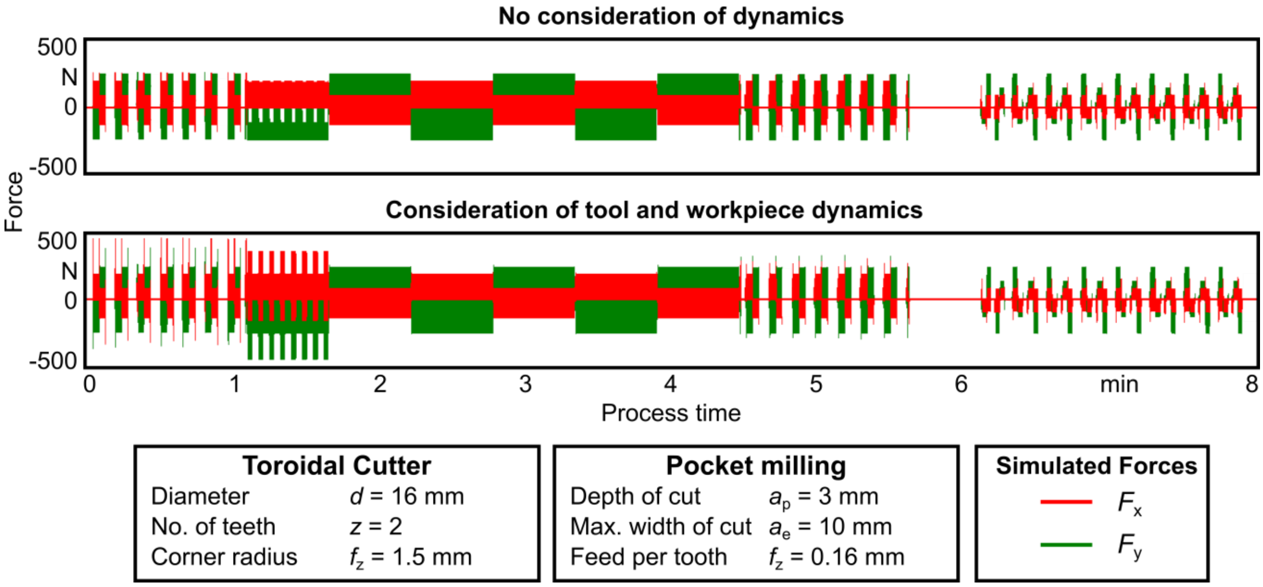


Fig. 27. Comparison of simulated forces with and without taking the FEM calculated modal parameter values into account. One layer of the pocket milling process (roughing) of the demonstrator workpiece is shown

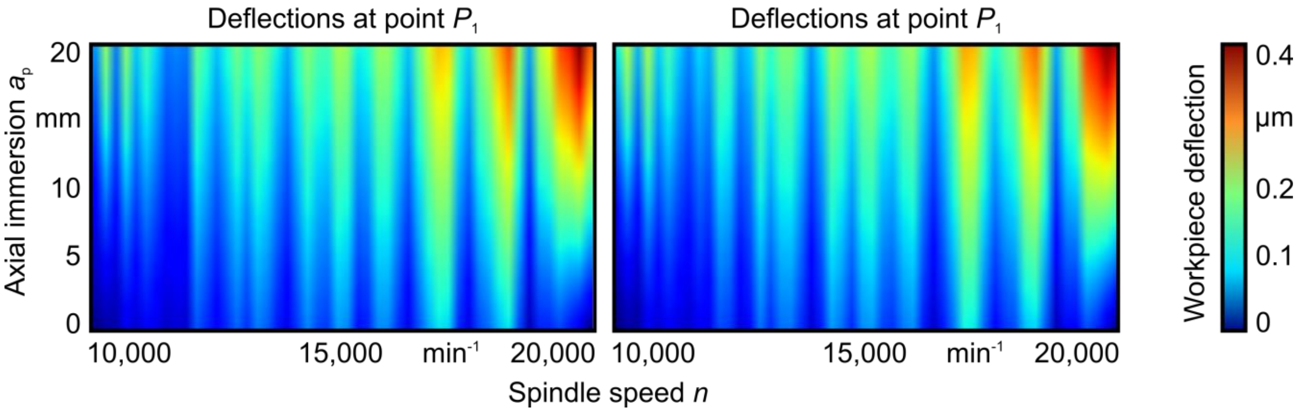


Fig. 28. Comparison of simulated workpiece deflections at point P_1 and point P_2 (cf. Fig. 25) on the workpiece not taken the tool dynamics for varying process parameter values into account

The higher process forces predicted with the consideration of tool and workpiece dynamics at particular sectors of the process can be explained by the occurrence of chatter vibrations. The layout of a fixture with the assumption of chatter-free processes would lead to an underestimation of the occurring process forces and hence to a fixture layout, which might be not stiff enough. Even in chatter-free processes, there are slight deflections in every fixture system. To give the designer the possibility to evaluate these deflections, charts for varying process parameter values can be calculated, which depict the maximal deflections of the workpiece.

In Fig. 28 exemplary charts are depicted where the tool dynamics are neglected since the milling tools are often not defined at this early stage in the design process. Comparing the charts for point P1 and P2 (cf. Fig. 25) only slight differences are visible. The maximal deflection (0.4 μm) is very low. Nevertheless, different spindle speeds lead to different deflections and higher immersions of the tool result in higher deflections.

The advantages of the combination of FEM-based simulations for predicting the modal parameter values of the workpiece and simulations of the milling process is the possibility to estimate the behaviour of a planned fixture system at an early stage of the design process. The designer has an efficient tool to calculate occurring forces and deflections under consideration of the dynamic behaviour of the tool, the workpiece, and the fixture system. However, the quality of the process simulation results are strongly dependent on the FE-based prediction. The validation of the simulation results can only be made when the fixture is already built and fundamental modifications of the fixture design are impractical. For this purpose, the presented workflow requires a certain level of expert knowledge.

7. SIMULATION AIDED DESIGN METHODOLOGY

The presented case study revealed the potentials but also the challenges of a process simulation aided design methodology for mechatronic ‘intelligent’ machine tool components. Process simulations allow a detailed consideration of the real functional environment during the design and optimization of the regarded mechatronic system. For enabling accurate process simulations, both representative process conditions and relevant system properties have to be identified and analysed in order to allow realistic model parameterization. An initial simulation setup can be implemented for the selected process scenario and the mechatronic system by using analytically derived, experimentally obtained or estimated initial modelling parameter values. Uncertainties in the system modelling significantly affect the quality of the process simulation results when coupling the models via an exchange of system simulation results. Nevertheless, the coupled virtual process and system description can be used for improving the system design. Furthermore, specific test rigs can be defined which allow a more detailed analysis and identification of process and system parameters. Consequently, the design method does not necessarily lead to a final prototype or product directly, but involves specific experimental intermediate analysis steps. Exploiting these intermediate experiments, calibration of the model and an improvement of the simulation accuracy becomes possible. By use of these calibrated simulation models, an optimization of the final prototype, product and process can be achieved.

Based on these experiences, an approach of a simulation aided design methodology can be proposed which consists of two parallel layers: a process layer and a system layer (Fig. 29 and Fig. 30). At both layers, firstly the application scenarios, requirements and boundary conditions are to be defined. In order to provide meaningful process simulation results for the system development, process analysis is necessary in order to obtain initial values for the process modelling. In parallel, a decomposition of the system regarding functions, components and process interactions takes place. Process modelling can then be conducted based on the process analysis information and simulated system properties considering the limitations as discussed above in this paper. Vice versa, simulated process loads can be applied on the system model in order to assess the performance of the system. An intermediate experimental testing step can be inserted in which simulation results are to be verified, and an improved parameter identification can be achieved. Both, the process and the system simulation can be updated by newly identified parameters and calibrated with respect to experimental data. Finally these revised models can be utilized to optimize the processes in consideration of the properties of the mechatronic system and to optimize the mechatronic system in consideration of the realistic process conditions.

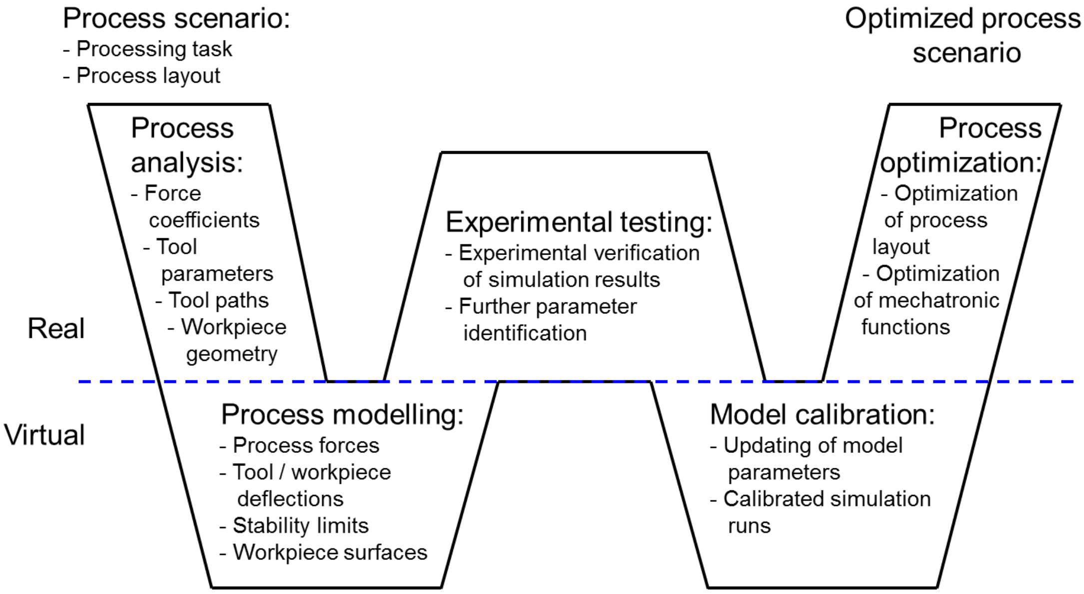


Fig. 29. Process related part of the design methodology

The information flow between these two parts of the design method can be understood as an inherent linking of both layers (Fig. 31). At each step of the parallel design progress, requirements and specifications as well as intermediate results and system properties are communicated. This also allows multiple iteration loops in each phase of the development, including e.g. the consideration of parameter variations or of several constructive approaches, related test rigs and experiments. The complex and permanent information exchange is depicted in an abstracted way in Fig. 32.

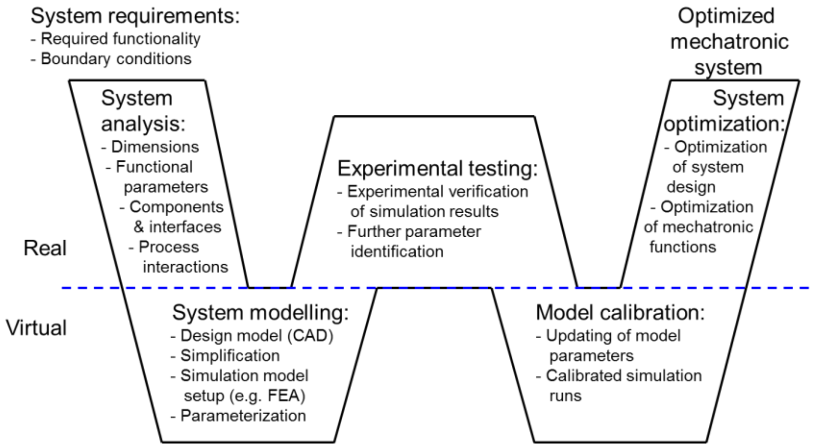


Fig. 30. System related part of the design methodology

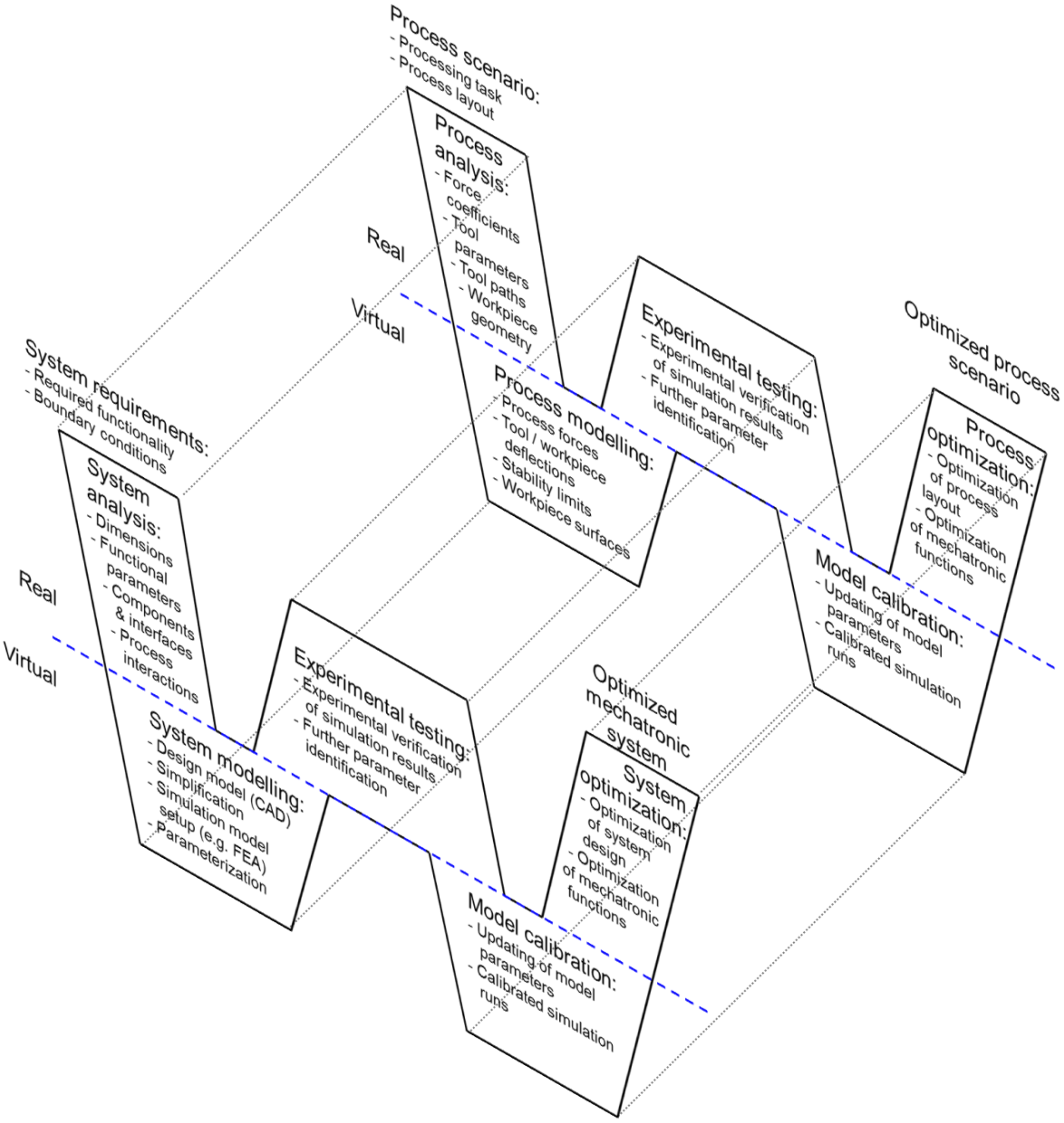


Fig. 31. Concept of the simulation aided design approach

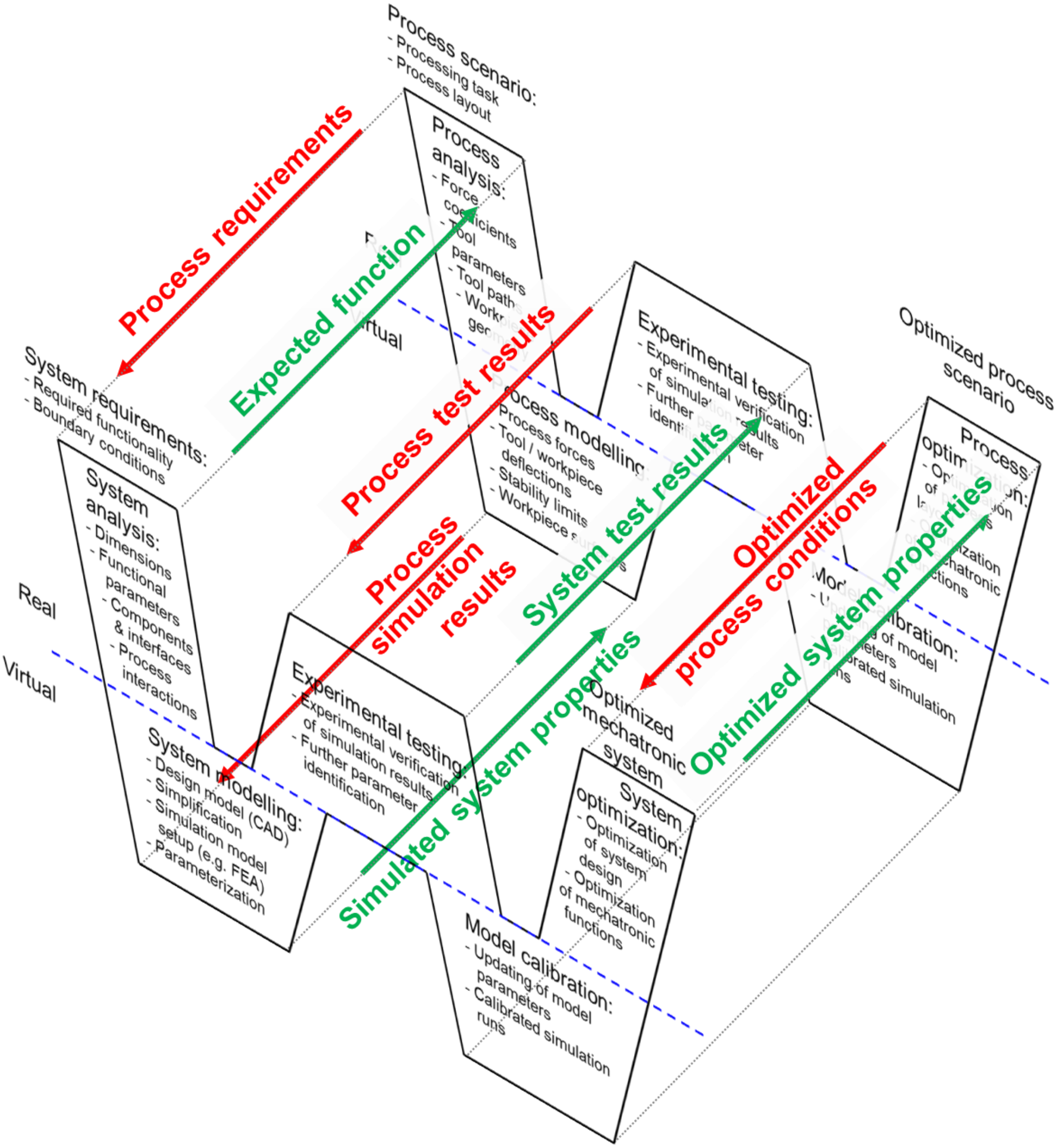


Fig. 32. Communication within the simulation aided design approach

For ‘intelligent’ systems there will not only be one system layer but multiple layers for each functional component of the overall system. For each sub-system which interacts with the machining process, a similar structure as depicted in Fig. 32 could be established. Certainly, the layer of the overall system which comprises the functional properties of the sub-systems has a dominant role in the design concept hierarchy and it therefore summarizes the characteristics of the combined intelligent component.

8. CONCLUSIONS

This paper firstly gives an overview of known design methods for mechatronic products. It can be concluded that these methods are limited with respect to the development of sensor, actuator and control integrated ‘intelligent’ systems. Furthermore, the lack of detailed consideration and assessment of the functional properties with respect to the desired process performance is discussed. A case study of an intelligent fixture for machining of aerospace structural parts is introduced and its functional elements are described. For the design and optimization of this exemplary machine tool component, a simulation aided approach was followed. This approach incorporates detailed process simulations for analysing the application related characteristics and performance of the system. Preconditions, challenges and limits of this design approach are discussed. However, the potentials of the simulation aided design approach are obvious. Based on the experiences made, a concept of a simulation aided design methodology for intelligent machine tool components is proposed. In future application of this methodology to various machine tool sub-systems, its applicability will be analysed.

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