Chapter 10
Recent Developments in Hardware-in-the-Loop Testing

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Abstract Future applications of mechatronic systems will be characterized by a high degree of digitization enabling the integration of numerous innovative functions. The validation and reliability analysis of such complex systems often requires the realization of cost intensive full system prototypes and the evaluation of field tests. Innovative technologies are therefore integrated slowly in industrial sectors that focus on system reliability. Hence, there is a strong interest in a reliability orientated development and test process for complex mechatronic systems.

The integration of real-time simulations in test environments allows efficient development and verification of the individual components of a mechatronic system in many cases. Currently, this especially applies for the test-driven development of embedded control units and their corresponding software. A reduced number of field tests, the automated run of test procedures and the application of error injection methods can be achieved by the widely used Hardware-in-the-Loop (HIL) technique. In signal level HIL tests, an existing control unit is connected to a virtual real-time simulation of the residual system. If however the device under test includes a mechanical or power electrical interface, the coupling of the test object to a virtual residual system requires the application of a mechanical or power electrical HIL interface. Current activities aim for this extension of In-the-Loop technologies for the validation of mechanical and power electronic subsystems.

This paper highlights the potential of combined signal level, mechanical level and power electrical HIL tests for the validation of complex mechatronic systems in an early phase of design. The paper also points out the key topics of test-driven development, real-time simulation and the realization of hybrid test environments by means of mechanical and power electrical HIL interfaces.

Keywords Hardware-in-the-loop · Hybrid testing · Real-time substructuring · Development of mechatronic systems · Early stage validation

10.1 Introduction and Motivation

While digitization has led to many innovations in the consumer goods sector, digital technologies are integrated much slower into specific products in sectors like machinery and plant engineering, energy technology, or the automotive industry. Usually in those sectors there are considerably higher demands on reliability, safety and machine availability compared to consumer goods. Furthermore, future applications of mechatronic systems will be characterized by a high degree of digitization enabling the integration of numerous innovative functions (e.g. an interaction between several mechatronic systems on different physical domains or cyber-physical systems). Often a model based development process is utilized due to the potentially high system complexity and the mutual interaction between different subsystems. The iterative increase of the simulation model's accuracy and the related early stage validation of numerical submodel by means of accompanying laboratory tests is one focal point within the model based design process.

The assessment of the function and system reliability of the drive train and generator of a wind turbine for example requires the close analysis of the interactions between the generator itself, the support structure, the power grid and the dynamic behavior of the rotor blades. Until today, an overall system validation requires a field test of the completely installed

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wind turbine. According to manufacturer's information, a measurement campaign takes up to 12 months and leads to costs up to one million Euros. Many other sectors are facing similar challenges: The automotive industry usually realizes extended early stage test phases with over 100 pre-series vehicles. Also, in machinery and plant engineering there are extensive and challenging test and commissioning phases especially for control-oriented applications in the context of Internet of Things (IoT) and Industry 4.0 (e.g. intelligent picking systems or force controlled Machine to Machine interaction). In this context, changing environmental conditions, ad hoc networking, and reconfiguration are destined to create major challenges with regard to model uncertainty and not suitable laboratory tests during early stage design.

If the overall system's functionality and related models can only be sufficiently validated at the end of the development phase, the introduction of disruptive technologies is slowed down or even prevented. Test and validation methods for innovative functions or products based on digital technologies (e.g. complex, interconnecting systems in terms of smart home, smart city, smart grid, autonomous driving or smart structures) are often inadequate or non-existent. Therefore, incremental innovations are often preferred in developing reliable products. New technologies and processes for the systematic derivation of testing environments for development-accompanying tests which assist the model based development process are thus a key factor for sustainable innovativeness. An appropriate, early stage test and validation method for complex mechatronic systems can provide an additional economic value as the effort for extensive overall system tests or field tests can be reduced. Furthermore, early stage and sufficient validation increases the development speed without constraining reliability objectives. It is a mutually beneficial process as early stage numerical simulation and premature experimental validation are moving closer together. As soon as new numerical models are available, they serve the design of more accurate test environments which for their part help to identify more detailed numerical models of the device under test due to the enhanced boundary conditions throughout the experimental investigation. Even more relevant results can be gained by including critical test cases from requirements analyses in tailored test environments.

In summary, there is a strong need for a development process for complex mechatronic systems that integrates validation tests from an early stage concept phase until component test on system level. This allows for high model accuracy during every step of system development and for the detection of critical aspects during system design. Applying such a design process, a test environment is derived from the system's requirements prior to the development of the actual component. Currently, this approach of test-driven development is widely used in software development and it is characterized by short development cycles. Comparative studies showed that the error rate in the final product can be reduced up to 50% using test-driven development [1]. For complex real-time embedded systems, hardware-in-the-loop (HIL) simulations allow for an early stage model and functional validation without having the overall system available in physical hardware. A first HIL test environment was realized more than 50 years ago for a realistic validation of the Gemini mission's embedded control system because a field test (i.e. the rocket launch) would have been an unreasonable burden. Within this HIL environment the embedded control system was connected to a real-time simulation of the avionics, the sensors and flight dynamics [2]. The HIL test method has gained currency especially in automotive and aviation industries since then. However, it is mostly used for the validation of embedded control hardware and their respective software. These ideas and methods create the foundation for the proposed concept of a test-driven and model-based development process for complex mechatronic systems. The following sections give a brief introduction to model-based development and highlight current activities and research issues in HIL testing.

10.2 Model-Based Design and Virtual Testing

The realization of mechatronic systems often results in a large number of basic system considerations in early stage design, which especially applies for innovative solutions. For a given application, each of the possible approaches then again might be realized by means of different actuators as well as sensors and control principles, resulting in an even larger number of potential system setups. On the one hand, this is desired since the additional degrees of freedom during early stage design allow for resolving constraints and enhancing functionality. On the other hand, the resulting diversity has to be handled within the design process.

Another challenge can result from the fact that beside the intended interactions between the various subsystems within a mechatronic system also unwanted interdependencies might occur. In vibration engineering, the excitation of mode shapes at higher frequencies due to a nonlinear behavior of the actuator is a common example. For the development of an active vibration control system, the overall system comprising the excitation, the mechanical structures, the actuators, the sensors as well as digital signal processing has to be considered during early stage design. Hence, a model-based design process is applied more frequently. A suitable methodological approach for a model-based design process for active vibration control systems is presented in Ref. [3].

The key component of a model-based design process is an integrated system simulation which is continuously adapted regarding its level of detail and with respect to the current development phase. These phases are organized along the entire development process for complex mechatronic systems [4]. In a first step, the model describes the initial topology based on elementary submodels. A basic structure can be initially derived from requirements engineering in early stage design. As the system progressively becomes more firmly established, the submodels are then successively replaced by more precise descriptions of the components. The iterative increase in model complexity thus supports the clarification of specific tasks as well as the assessment of basic system setups. At a later stage of development, an integrated system simulation supports the design and virtual test of specific components. However, the generation and validation of individual component models remains a challenge during the design of complex systems since the behavior of a component might strongly depend on its interaction within the overall system context. Summarizing, this leads to three crucial points for the model-based design and testing. Beside the design and validation of simulation models, which represents the physical behavior of the technical system, consistency throughout the entire process is mandatory and traceability of the defined requirements from the design phase till the integrity tests has to be ensured. A holistic model-based approach aggregates these three crucial points and reduces time-to-market and design costs while maximizing quality due to mature products, which meets the defined requirements.

10.3 Hardware-in-the-Loop Testing

Recent developments in hardware-in-the-loop (HIL) testing are focusing on combining the method of test-driven development and the model-based design methods for complex mechatronic systems. The key objective is an overall development method that allows the systematic derivation of HIL test environments based on system requirements. Within the HIL test environment, the device under test (DUT) interacts with a real-time simulation of the respective rest of the system (ROTS) which provides a high level of flexibility due to the rapid interchangeability of the underlying real-time simulation models. The integration of multiphysical HIL simulations allows the real-time emulation of mechanical, electrical or informational boundary conditions within the test environments and improves the early validation and iterative increase in model accuracy during system development. A distinction is made between signal-level, (electrical) power-level and mechanical-level HIL simulation depending on the interface between the physical and the simulated numerical subsystem [5, 6]. Figure 10.1 illustrates the above mentioned basic concepts based on an example of a controlled electromechanical system.

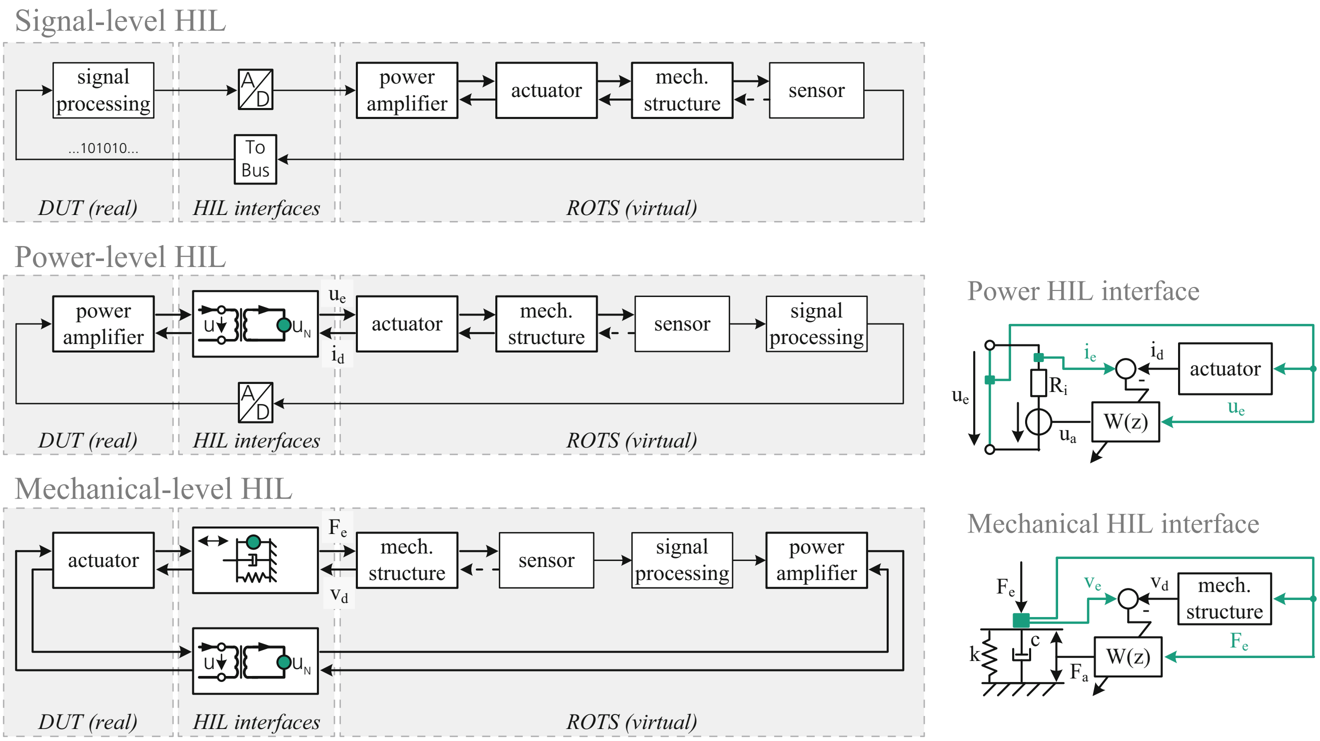


Fig. 10.1 Signal-level, power-level and mechanical-level hardware-in-the-loop test environment (left) and realization of electrical power-level and mechanical-level HIL interfaces (right)

A *signal-level HIL* simulation (sHIL) comprises an interconnection of a physical subsystem (i.e. signal processing) and a virtual residual system at signal level. Signal-level HIL simulation is an often applied method in automotive and aviation applications. The concept of (electrical) *power-level HIL* simulation (pHIL) summarizes HIL procedures which include a significant exchange of electrical power within the interface between the physical subsystem and the residual simulated system. Current activities also focus on power-level HIL tests for power electronic applications in the megawatt range. *Mechanical-level HIL* simulation (mHIL) enables the close analysis of the mechanical interaction between a yet unrealized mechanical structure and an existing mechanical substructure or actuator system in the HIL test environment. Apart from a few exceptions, primarily simplified mechanical load tests with mechanical shakers are used to qualify the mechanical strength not taking into account the interaction between the DUT and the ROTS.

10.4 Current Activities in Hardware-in-the-Loop Testing

There are special challenges related to the further establishment of the test-driven and model based development method for complex mechatronic systems, the real-time simulation of a heterogeneous, multiphysic ROTS and the realization of electrical and mechanical HIL interfaces of high bandwidth and power and signal HIL interfaces for highly interconnected systems. The following subsections will discuss the focal priorities in detail.

10.4.1 Integrating Test-Driven Development into a Model-Based Design Process

At present time digitization, rising complexity and strong multidisciplinarity are growing challenges for the development of innovative technical products. This led to an increased perceptibility of systems engineering, especially Model-Based Systems Engineering (MBSE), in these areas. With this background, there took place a rapid development of methodologies and processes in order to develop complex products systematically. Estefan presents some Model-Based Systems Engineering methodologies [7].

MBSE activities aim on offering a guided process for a system to develop. Consistency from requirements to the actual system needs to be provided. The rising importance of modeling for systems engineering processes in this context is obtained by the MBSE initiative [8].

Starting with requirements, basically three development phases occur in this design process of intelligent systems. A system design phase in early stages is followed by a domain-specific design phase. After achieving a specific solution for each discipline concerning the specified requirements, the system integration phase completes the process. Particularly to support developers in the early conceptual phases, partial models are established [9]. According to SysML, a system model can contain different elements. In the CONSENS notation a set of eight coherent partial models is suggested. CONSENS represents a specification technique for mechatronic systems, which starts with focusing all the important stakeholder of a system to ensure that all the necessary requirements are captured. This is done by considering all the outside influences of the targeted system. To fulfil the requirements, which are included in the associated partial model, CONSENS defines functions, which are structured in form of a functional hierarchy. The structure of active principles shows an abstract solution to fulfil the defined functionality. Elements within their relations between each other and disturbances are implemented in the active structure. Furthermore, the behavior of the system is build up.

Beside the system model, which is the central model inside an MBSE approach, the model-based development can be conducted by the V-Model as a description of a model-based development process [4]. To develop the simulation models the first step is to regard the system architecture. This architecture is used, to define the architecture of the simulation model. This enables a clear and comprehensible development of simulation models and submodels, which could easily be allocated to the related components. The V-Model envisages a phased validation of the component to the system. The special challenge consists in the diversity of the components (electrical, mechanical, software) and the complexity of the systems. For such systems, there are no conventionally established schemes for the universal function and property modeling [10].

An approach for solving these challenges is a test-driven development, which is currently only established in the area of software development and enables high-quality, reliable and at the same time a short development time of innovative software products through systematic test definitions at partial and overall system levels [11]. Henke et al. presents a holistic approach for virtual commissioning of a turn-milling-center. The approach encompasses the MBSE activities beginning with a system model and covers requirements engineering in four level of detail. With a systematic generation of test cases by the House-of-Quality and the application of Model- and Hardware-in-the-Loop scenarios the test depth for programmable logic controllers and NC controllers can be enhanced significantly [12].

A transfer of the method of test-driven development to mechatronic systems that integrate energy interfaces is a subject of current research. The different methods of HIL testing allow for an early stage validation of the different components of mechatronic system within its system context and under more realistic conditions. In this context, also test cases for the overall system gained from requirements engineering or preliminary failure mode and effects analyses can be integrated into HIL test environments. Critical operating states can thus be reproducibly investigated prior to field tests of the actual system.

10.4.2 Simulation Tools and Model Generation

An efficient modeling strategy enables and enhances the development process of mechatronic systems and especially vibration control measures in an essential manner. Using a model-based system development, different specifications and measures can be compared with respect to their capability. Once a promising concept is defined, passive or active measures, control concepts or other components can be designed and proven virtually. Moreover, the integration of real-time simulations in test environments allows an efficient verification of the individual components of a mechatronic system. This especially applies for the test-driven development of embedded control units and their corresponding software. In signal-level HIL tests, an existing control unit is connected to a virtual real-time simulation of the residual system. Expanding these methods to devices under test that include a mechanical or power electrical interface, the coupling of the test object to a virtual residual system requires the application of a mechanical or power electrical HIL interface.

For holistic system simulations of mechanical structures, power electronics, and active components, i.e. actuators and sensors, the usage of an impedances-admittances layout of the system simulation model is highly recommended. The advantages are an easy exchangeability of single system components due to standardized interfaces and the possible combination of mechanical, electrical and hydraulic components [3, 13]. The components themselves are represented at different detailing levels, thus defining a certain detailing level of the holistic system. Complex multidisciplinary coupled dynamic systems can be consistently built up in system simulation in dependence of the particular stage of development [14, 15]. The independently modeled subsystems can be derived from various modelling approaches, e.g. electronic circuit, multi body and finite element simulation or can be determined by system identification methods based on experimental testing.

Starting from detailed and modular built up system models, real-time simulation models are generated. The ROTS models are created by extracting the subsystems and components under test, which can easily be done by an automated process due to predefined and standardized interfaces according to the modelling strategy. Consequently, the necessary system states for the coupling between virtual and real subsystems result directly from the ROTS model.

The generation of real-time models is a substantial part for HIL simulations, since a realistic testing of components and subsystems is highly dependent on the exact numerical emulation of the ROTS. Numerically efficient models with reduced number of states and degrees-of-freedom that simulate the dynamic behavior at the system boundaries are required. On the one hand they can be based on the physical properties of a system; on the other hand models with reduced complexity can be generated from existing models by means of mathematical methods [16]. For mechanical structures, simplified continuous models with sufficiently similar input and output behavior can be derived using model order reduction techniques [17]. The use of time-discrete, order reduced models offers the potential to eliminate existing limitations in the dynamic range of HIL applications. Recent research activities deal with the automated generation of high-frequency real-time simulation models for multiphysical coupled problems. As the simulation models are used in different applications along the design process, there are several models with different detail level. To design sustainable processes, the simulation models are created modularly, by using an object-oriented approach. This enables to work with basic model classes, which are extended for the special applications. Changes in these base-classes causes an automatically change in each specialized model, so that the effort for these changes is minimized. Furthermore, different levels of details can be handled easily and serve the dynamic adaptation of simulation model properties during run-time (model reconfiguration).

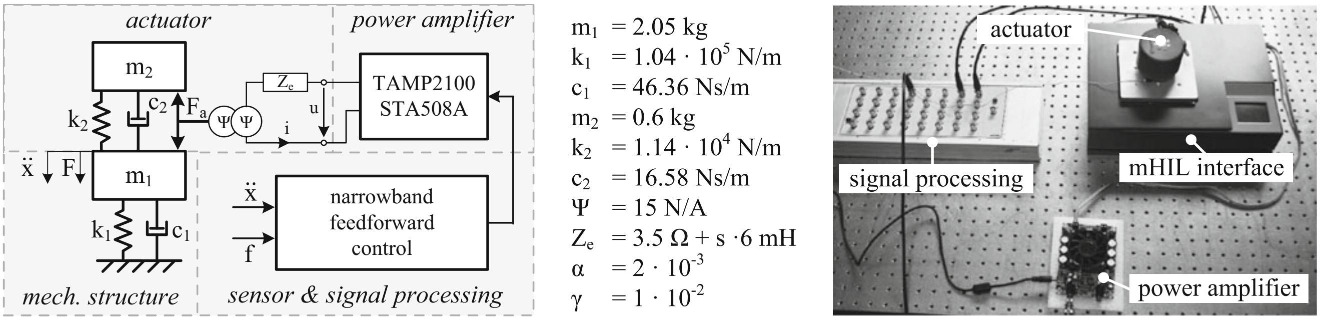
10.4.3 Realization of Hybrid Test Environments

The third focal point is the development and realization of HIL interfaces for the real-time emulation of informational, electrical and mechanical signals, loads and boundary conditions. Signal-level HIL (sHIL) and model-based testing are widely used in automotive and aviation industries for the test of embedded control units [18, 19]. Current activities are focusing in increasing the bandwidth of sHIL tests up to 1 kHz for the evaluation of controllers used in vibro-acoustic applications like active noise and vibration control. This is achieved by identifying parasiteric characteristics (i.e. dead times of analog-digital and digital-analog conversion, filters and signal processing) and either self-learning or static compensation measures [20]. Present work is also concerned with the model-based development in production and automation engineering [21] and addresses the automated generation of simulation models for the validation of control systems within a virtual commissioning environment (e.g. by physical three-dimensional virtualizations [22]). Consistent validation methods for communication in IoT or Industry 4.0 are increasingly demanded by users, expert committees and researchers [23]. An important issue concerning interconnected elements is a robust and flexible communication between all these system-elements. There are standards used to set up a communication between heterogeneous elements. In the context of machine engineering and in automotive applications field buses (e.g. CAN or Profibus) or Ethernet-based protocols (e.g. EtherCAT or OPC-UA) are applied typically for distributed control, data mining or simple information sharing. Concerning functionality tests of complex distributed systems the test of communications structures becomes an important discipline. Varying latencies jitter effects and communication breakdown have strong influences on the stability of closed-loop control and impairs the interaction of distributed systems. The functionality can be investigated by Hardware-in-the-Loop tests with fault injection for communication restrictions. Henke et al. describe a pattern-based approach for design and testing of distributed control systems for autonomously driven railway vehicles [24].

Besides power-level HIL (pHIL) tests also standardized validation procedures for power electric devices (e.g. electromagnetic interference, short circuit, reversed voltage, or discontinuities in supply voltage) exist (e.g. [25]). Power-level HIL test methods are especially getting important whenever the device under test shows a strong interaction with its electrical load or its power supply. Power-level HIL has thus been realized for the early stage validation of power electronics applications [26–30] also in the megawatt range. However, in many applications the bandwidth of the power-level HIL simulation is restricted due to the controller's stability constraints. For the emulation of low bandwidth signals either open-loop [29] or closed-loop control is used [26, 27]. The emulation of mechanical boundary conditions is achieved by mechanical-level HIL (mHIL) simulations. Purely passive substructures for the emulation of the mechanical ROTS only provide a low degree of accuracy [31, 32]. Semi-active [33] and active mechanical HIL interfaces [34] offer a greater flexibility compared to passive substructures. Active mechanical HIL interfaces are used in the automotive sector or energy technology [5, 35–37], in mechanical engineering [38, 39] or in civil engineering. The dynamic and the bandwidth is often limited due to the actuator types being used or the applied control method (usually $D = 10$–20% and $f_{max} = 30$ Hz). In order to allow for a flexible use of pHIL and mHIL simulations with active controlled HIL interfaces, current activities focus on the transfer of the model based development of smart structures for the development of active pHIL and mHIL interfaces [40, 41]. This also includes the derivation of design catalogs for adjustable mechanical elements [42], actuators, adaptive admittance control and power electronics. Due to the strong interaction of the desired numerical behavior of the ROTS and the dynamic properties of the device under test, adaptive feedforward control of pHIL and mHIL interfaces is an essential component for high bandwidth, high dynamic and robust pHIL and mHIL environments [34, 41, 43, 44].

10.5 Application Example: Early Stage Validation of an Active Vibration Control System

The potential of combined model based development and signal-level, power-level and mechanical-level HIL testing is investigated for an exemplary active vibration control (AVC) application. Figure 10.2 illustrates the basic HIL scenarios. A primary structure (m_1, k_1 and c_1) is excited by an external force F. A linear chirp signal from $f = 20$ to 200 Hz within 20 s is chosen for exiting the primary structure. An inertial mass actuator (m_2, k_2, c_2, Ψ and Z_e) serves the cancelation of the



$m_1 = 2.05$ kg
$k_1 = 1.04 \cdot 10^5$ N/m
$c_1 = 46.36$ Ns/m
$m_2 = 0.6$ kg
$k_2 = 1.14 \cdot 10^4$ N/m
$c_2 = 16.58$ Ns/m
$\Psi = 15$ N/A
$Z_e = 3.5\,\Omega + s \cdot 6$ mH
$\alpha = 2 \cdot 10^{-3}$
$\gamma = 1 \cdot 10^{-2}$

Fig. 10.2 Test set-up for the investigation of hybrid simulation environments (left) and realization of the test rig in the laboratory (right) acceleration $\ddot{x}$. The actuator is driven by a low-cost amplifier namely the TAMP2100 from Sure Electronics. The actuator's control signal is computed by the narrowband feedforward FxLMS algorithm [45] whereas the normalized adaptation step size α and the leakage weighting factor γ serve the adjustment of the control performance. Digital signal processing is realized by means of a dSPACE DS1005 rapid control prototyping system with a sampling frequency of 10 kHz. Analogue eighth order Butterworth filters ($f_{3dB} = 4$ kHz) are used for anti-aliasing and reconstruction filters.

A key challenge during the design of an AVC system is the strong interaction (i.e. power exchange) between the components of the mechanical and electrical domain. Therefore, this interaction has to be considered at an early stage of development since the strong interaction and feedback between the components significantly influences the design of the actuator and the power amplifier. Furthermore, the adaptive narrowband feedforward controller implements a numerical model of the cumulated transfer function of the overall system. Hence, the controller's performance also strongly depends on the accuracy of the underlying model.

In order to investigate the overall system's performance and to evaluate the accuracy of the numerical models, an experimental setup, a signal-level (sHIL), an electrical power-level (pHIL) and a mechanical-level HIL (mHIL) test environment is realized. The structure of the respective HIL simulation is based on the topologies illustrated in Fig. 10.1. The results are then compared with the results obtained from a numerical investigation. The focus is not on optimal model accuracy at this stage but rather on the detection of stronger deviations between the respective HIL investigation and the numerical models derived from early stage model-based development. In order to increase model accuracy during different stages of system development, the numerical models can be detailed subsequent to the respective HIL investigation. The mechanical HIL interface [41] is realized by an in-parallel arrangement of a variable stiffness element (continuous adjustment between 12 and 840 N/mm) and a voice coil actuator with a peak force of 350 N. The power electrical HIL interface [40] comprises a pulse-width-modulated current controlled H-bridge amplifier ($I_{max} = \pm 2$ A, $U_{max} = \pm 30$ V) which is based on the BTN8982 evaluation board.

Figure 10.3 summarizes the results of the investigations by means of an order cut of the remaining acceleration at the primary structure and the apparent power at the output of the power amplifier. The results show a good accordance between the initial and not yet adapted numerical simulation, the different HIL setups and the experiment. However, there are some slight deviations between the numerical model and the respective validation setup. Regarding the remaining acceleration at the interface, there are some model deviations within the numerical model in the higher frequency range above 100 Hz compared to the signal-level HIL test. This can be caused by a not yet considered dead time within the digital signal processing unit. The deviations between the numerical model, the experimental setup and the mechanical-level HIL test are getting even more noticeable. Besides the overestimated damping within the numerical model of the primary structure (deviations at 40 Hz), there is a second resonance frequency between 20 and 40 Hz that has not been considered yet. One of the most significant deviations is the higher power demand of the power amplifier especially in the frequency range above 60 Hz which can be caused by a larger inductive load of the actuator. The deviations between the mechanical-level HIL test and the experiment in the frequency range between 80 and 160 Hz might be caused by a parasiteric stick-slip effect within the mechanical HIL interface. This, however, requires a further investigation.

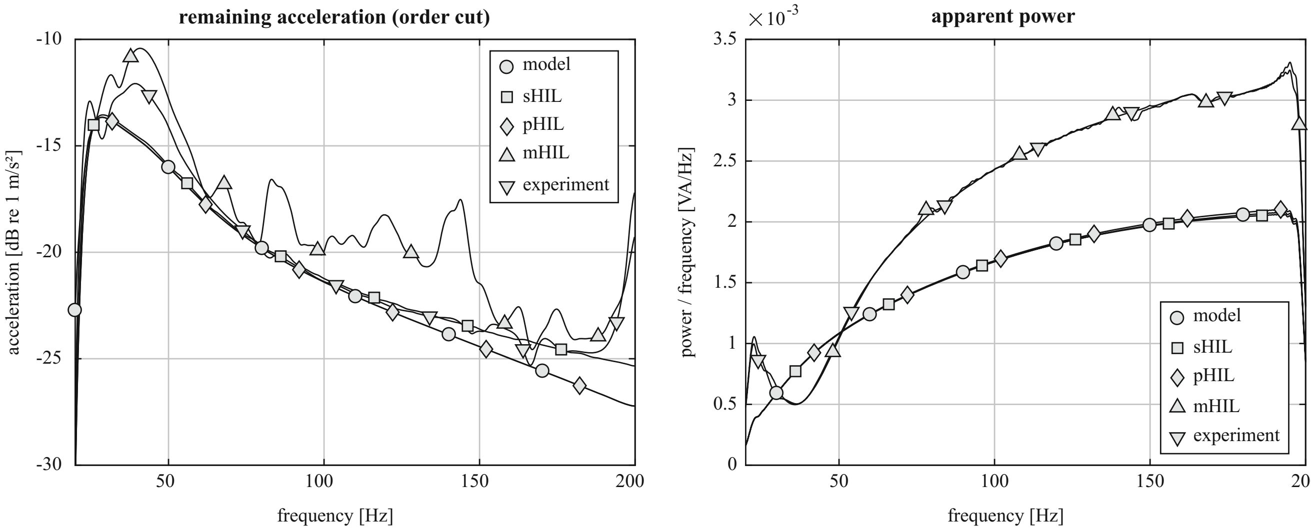


Fig. 10.3 Order cut of the remaining acceleration $\ddot{x}$ of the primary structure (left) apparent power (one-sided cross spectral density) at the output of the power amplifier (right)

10.6 Conclusion

There are growing challenges for the development of innovative technical products such as digitization, rising complexity and strong multidisciplinarity. In this context, multiphysical hardware-in-the-loop (HIL) testing is deemed to be an integral part of early stage validation and future methods of system development. Besides the further establishment of the test-driven and model-based development method for complex mechatronic systems, there are special challenges related to the real-time simulation of a heterogeneous, multiphysical systems and the realization of electrical and mechanical HIL interfaces of high bandwidth and power as well as signal HIL interfaces for highly interconnected systems.

The flexible combination of numerical, signal-level, mechanical-level and electrical power-level HIL simulations throughout the design and development of a mechatronic system allows the early stage validation of numerical models and already realized components.

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