Towards Mechanical Vibration Control by Dynamically Adaptive Impedance Elements in Vibration Testing

Ansatz zur mechanischen Schwingungsbeeinflussung mittels Dynamisch Adaptiver Impedanzelemente in der Versuchstechnik

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Abstract

The interface properties are a key factor in the vibration behaviour of technical systems, making it relevant in vibration testing. The potential of *Dynamically Adaptive Impedance Elements* (DAIEs) as interfaces between the test bench and the test object is derived from two distinct fields of application: the vibration reduction of lightweight structures in the aircraft cabin and the vibration analysis of handheld devices in the human-machine interaction. DAIEs are semi-active interface elements that enable the adaptation of the interface stiffness and damping during testing, thus facilitating the replication of multi-steady-state as well as transient behaviour in the testing environment.

Kurzfassung

Die Schnittstelleneigenschaften haben einen entscheidenden Einfluss auf das Schwingverhalten von technischen Systemen, sodass die Berücksichtigung in der Versuchstechnik erforderlich ist. Das Potenzial von *Dynamisch Adaptiven Impedanzelementen* (DAIE) als Schnittstelle zwischen Prüfstand und Testobjekt wird anhand von zwei unterschiedlichen Anwendungsfeldern aufgezeigt: der Schwingungsreduktion von Leichtbaustrukturen aus der Flugzeugkabine und der Schwingungsanalyse von handgehaltenen Geräten in der Mensch-Maschine-Interaktion. DAIE sind semi-aktive Schnittstellenelemente, die eine Adaption der Schnittstellensteifigkeit und -dämpfung im Versuchsbetrieb ermöglichen, sodass multistationäres und transientes Verhalten effizient und reproduzierbar in der Prüfumgebung abgebildet werden kann.

1. Introduction – Interface Elements in Vibration Testing

In vibrating systems, the interfaces between the system in focus and the operating environment are a key factor for the dynamic behaviour of the overall system. The vibration excitation is transmitted through the interfaces onto the system in focus or from a vibration source into the environment. In vibration testing, careful consideration has to be placed into the design of the interfaces between the system in focus, respectively the test object, and the testing environment, respectively the test bench [1]. A variation of the interface properties has an impact on the vibration behaviour of the tested product [2]. Generally, three different approaches are viable in the testing environment:

1) *Rigid interfaces:* The interfaces are chosen not to interfere with the vibration excitation and transmit it as undisturbed as possible from the testing environment onto the test object [3]. Usually, the interfaces are designed as stiff as possible, so they come close to a rigid body [3]. It is detrimental that the interfaces do not experience a resonance of their own in the tested frequency range [2], [3]. No over-testing or under-testing is desired [2].
2) *Realistic interfaces*: The interfaces are supposed to resemble the real boundary conditions of the operating environment closely [4]. The mechanical properties, such as stiffness, damping and inertia of the original interfaces have to be precisely known and implemented in the interfaces of the testing environment, which often poses a considerable difficulty [4].
3) *Optimised interfaces*: The interfaces in the testing environment are deliberately used to influence the vibration transmission and alter the vibration response of the test object. The interfaces get included into the system's outer boundary. An optimisation of the vibration behaviour is possible through a holistic focus on the overall vibration system consisting of the test object and the interfaces [5].

In general, a reproducible and well-known behaviour of the interfaces must be ensured, because they are used to analyse the dynamic characteristics of the system in focus, thereby averting potential error propagation [6].

2. Aim of the Approach

The testing effort is often substantially increased in testing scenarios, which are aimed at realistically replicating the original interfaces of the specific application [4] or at the optimisation of the interfaces to influence the vibration behaviour of the test object [5]. Individual interface elements have to be developed, manufactured, characterised and mounted in the testing environment for every test object [5]. This leads to a large setup time between tests. Additionally, vast numbers of tests are often necessary to identify the proper combinations of interface properties to reach the required vibration response of the test object [5]. Especially, the determination of damping effects is challenging and usually done by testing [7], [8].

To reduce the testing effort, interface elements are needed that enable an efficient variation of mechanical impedance over a large range of values [9]. Therefore, *Dynamically Adaptive Impedance Elements* (DAIEs) are developed and investigated in the project DynaVal (see the Acknowledgement). DAIEs are mechatronic elements which contain stiffness and damping mechanisms that allow for a separate semi-active adaptation (Figure 1). Consequently, the mechanical impedance [10]

$$MI(f) = \frac{F}{\dot{u}} = \mathrm{i}\,2\pi f\, m + \frac{k}{\mathrm{i}\,2\pi f} + d \tag{1}$$

of the interface is adapted (damping d, frequency f, force F, imaginary unit i, stiffness k, moving mass m, velocity $\dot{u}$). Only elements of dynamically adaptive or semi-active type are considered, where the interface properties, stiffness and damping, can be changed during operation, but the interface forces do not result from a driven actuator in constant need of external energy supply. For a distinction between passive, semi-active and active systems in vibration control, please refer to [11] or [12]. Two different applications for DAIEs are studied: The dynamic testing of lightweight structures in the context of aircraft interior monuments and of handheld devices such as power tools.

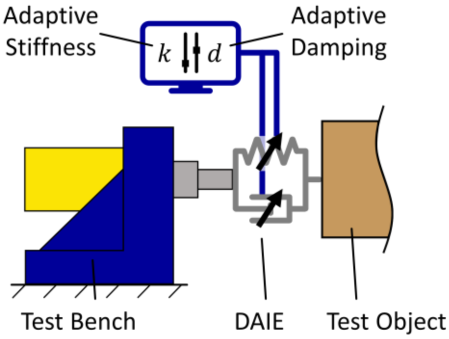

Figure 1: Concept of DAIE as adaptive interface element between test bench and test object

3. Point of Origin – Adjustable Impedance Elements (AIEs)

In the preceding project AIProVE (funded by the Deutsche Forschungsgemeinschaft DFG, German Research Foundation, project number 399922375), *Adjustable Impedance Elements* (AIEs) have been investigated, which permit a manual adjustment of their mechanical impedance over a wide range of values [13]. For more details on the developed AIEs, please refer to the AIE design catalogue [14]. The AIEs have been applied to vibration testing of lightweight structures to achieve a reduction of the maximum amplitudes at resonance (as describes in the section *AIEs for Testing of Lightweight Structures*) and to the development of a hand-arm model (HAM) for replicating the mechanical properties of the human hand-arm system (HAS) in testing of handheld devices (as describes in the section *AIEs for Testing of Handheld Devices*).

AIEs for Testing of Lightweight Structures

One field of application for the AIEs is vibration testing of aircraft interior monuments. In the case of the windmilling event, a potentially critical low-frequency but high-amplitude vibration excitation is introduced into the aircraft structures [15]. The windmilling arises from a sustained engine imbalance (SEI) after a blade loss, while the rotation of the shut-down engine persists due to the airflow of the moving aircraft [16]. A frequency of 17 Hz with a substantial amplitude is typical [15]. During testing, a frequency range from 2 to 30 Hz should be addressed [17]. Even when the windmilling event does not imply a direct threat to the airworthiness of the entire aircraft, potential safety issues can result nevertheless. The vibration excitation is transmitted from the engine through the primary structure into the cabin. First, this can cause overloading and a possible failure of interior monuments. Second, violently vibrating interior monuments within the immediate surroundings of the passengers and the crew can pose a threat to their physical integrity.

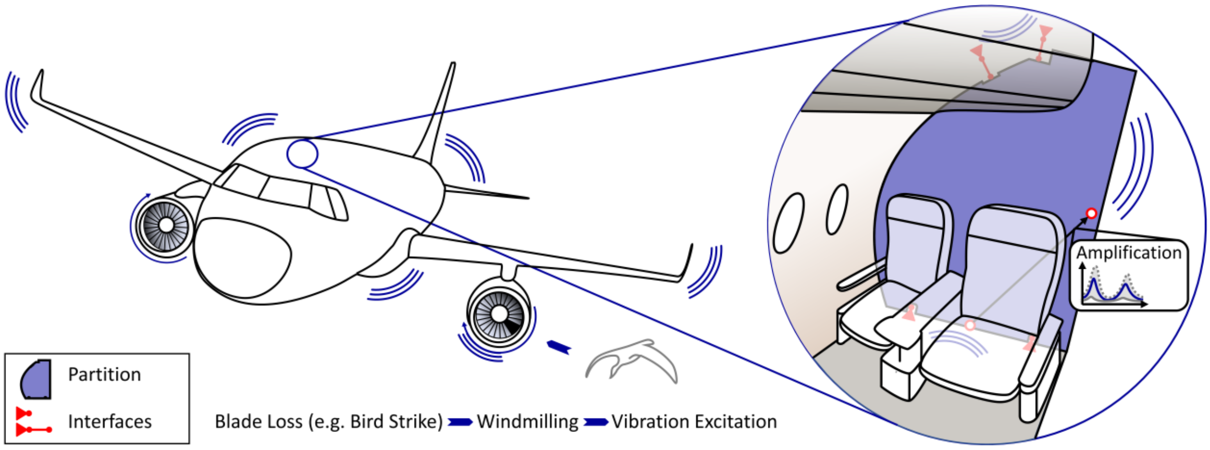

Figure 2: Application example – amplification of an aircraft partition with rigid interfaces due to windmilling

A measure to reduce these threats can be a vibration reduction of the aircraft's interior monuments [5]. The dynamic behaviour of lightweight structures is highly sensitive to the mechanical properties of the interfaces to their surroundings [1], [9]. Therefore, the approach of optimising the mechanical properties of the interfaces is promising towards an effective vibration reduction [5]. This involves a large number of tests with various interface elements, which represent different stiffness and damping values [13], to find the interface properties leading to a large vibration reduction. This would cause an infeasible effort during testing and certification regarding the variety of interior monuments. Therefore, the prevailing practice at present is to subject most interior monuments to static testing only [18]. When dynamic tests are conducted, often rigid interfaces between the test bench and the tested structure are used [13], [19], leaving potential for reducing vibrations untapped. To enable testing of lightweight structures under variation of the interface properties without the need for multiple interface elements with different stiffness and damping values, AIEs can be deployed to limit the testing effort, as only one AIE per interface is necessary to represent different stiffness and damping values [5], [13].

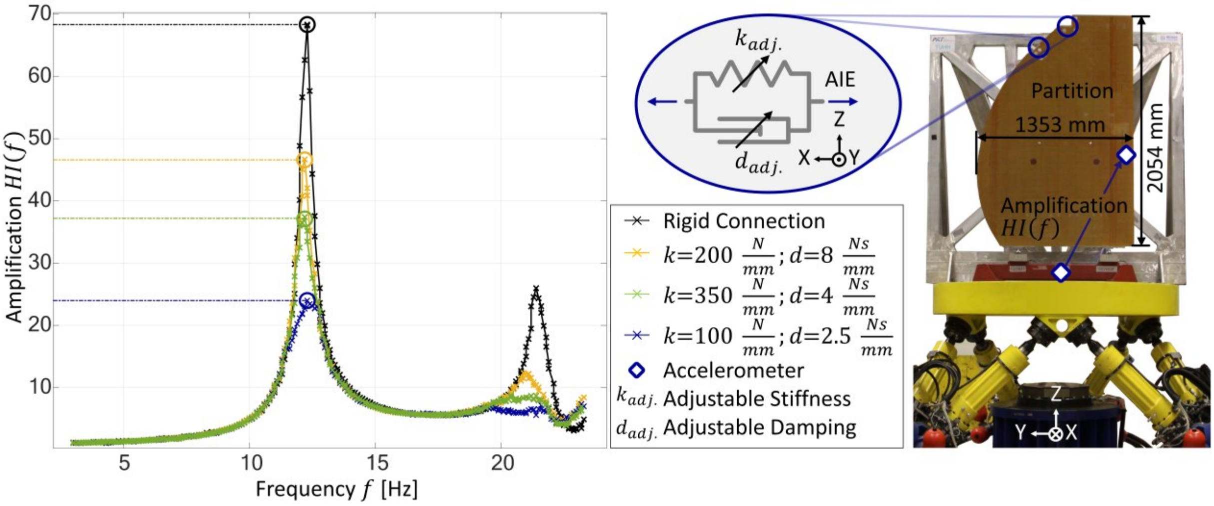

Figure 3: Vibration reduction of aircraft partition by AIEs, measured FRFs of the amplification amplitude for different settings of the AIEs compared to the rigid connection, based on [20]

An application example for the approach of vibration reduction in lightweight structures by AIEs is a partition under dynamic loads in the windmilling scenario (Figure 2). This example is studied by HEYDEN ET AL. [20] and briefly described below. In Figure 3, the test setup and measured frequency response functions (FRFs) of the amplification are shown. The partition has been attached to the test bench by two rigid interfaces at the bottom and two interfaces at the top, which are equipped with AIEs. The AIEs enable an individual adjustment of the interface stiffness and damping. The test bench has been excited with a translational sine sweep from 3 to 23 Hz at a constant acceleration amplitude of 2.5 m/s^2 and a rate of 0.1 Hz/s in the X-direction. Accelerometers have been placed at ten different positions on the test setup. Here, only the sensors at the base and at the location of the maximum vibration response in the first resonance are considered (see Figure 3, right). FRFs of the form

$$HI_{base \rightarrow output}(f) = \frac{\ddot{u}_{output}}{\ddot{u}_{base}} \tag{2}$$

are calculated from the FOURIER-transformed acceleration signals $\ddot{u}$ of these sensors and represent the vibration amplification from the excitation of the base to the response of the partition at the indicated location. The amplitude curves are plotted for different stiffness and damping values of the AIEs (Figure 3, left). As a reference for determining the achieved vibration reduction, the AIEs are set rigid to prevent their relative motion. This condition comes closest to the original tie rods, which are used as interfaces between the partition and the surrounding aircraft structures. Two resonances occur in the tested frequency range, although the first resonance is in focus here. Its amplification is reduced by 65% (from 69.3 to 23.9) with both AIEs set to a stiffness of $k = 100\ \mathrm{N/mm}$ and a damping of $k = 2.5\ \mathrm{Ns/mm}$ [20].

To achieve vibration reduction, the optimal combination of interface stiffness and damping is to be determined individually for each product, which usually leads to a large number of tests [5]. A FEM simulation is used to identify a promising range of stiffness and damping (more information in [20], [21] and [5]). Within that range, AIEs are applied to vary the interface properties in a grid for analysing the vibration reduction experimentally. A total replacement of tests by simulations is not feasible, since damping behaviour cannot be modelled precisely [22]. The interdependence between the dynamic behaviour of the interfaces and the tested product variants leads to different loading of the structure depending on the interface properties, thus testing cannot be avoided [5].

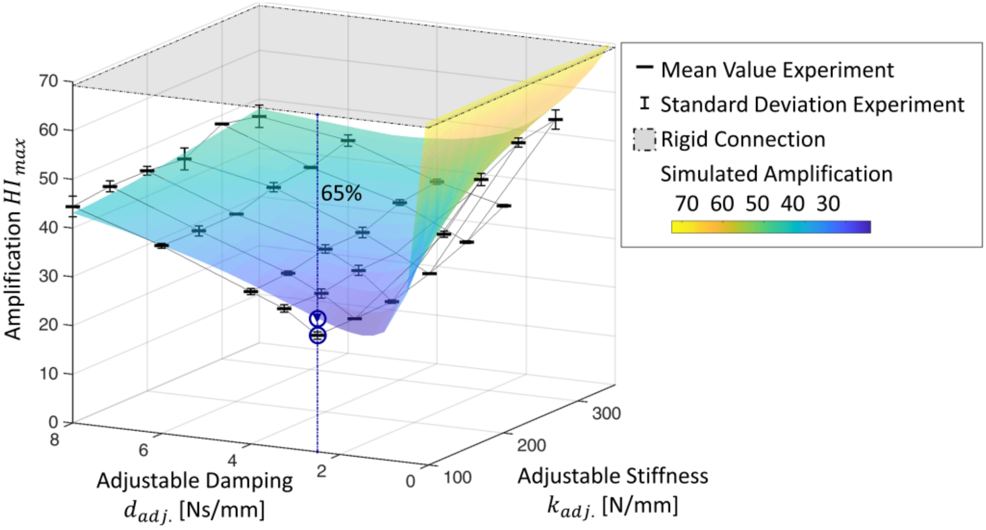

Figure 4: Comparison of experimental and simulated parameter studies of the maximum amplification at the first resonance over interface stiffness and damping, based on [20]

The experimental and simulated parameter studies of the amplification in the first resonance of the partition are compared in Figure 4 and are found to match well. The stiffness is confined to a lower limit of $k = 100\ \mathrm{N/mm}$, since lower values would cause an impermissible deflection due to static loads [5]. In the case of the partition, the largest vibration reduction results from the lowest considered interface stiffness. However, this is not the case for every lightweight structure (see [23]) and therefore no generic design rule should be derived from that. For more information on the process of reaching a large vibration reduction of lightweight structures by AIEs, please refer to HEYDEN [5].

AIEs for Testing of Handheld Devices

The human-machine interaction is a crucial aspect in the development of handheld devices, as the user is in direct physical contact with the device during operation. Therefore, the work results as well as the function of the device are affected by the human-machine interaction [24], [25], as the device is controlled by active interactions through muscle activity, but also influenced by various changing factors of passive interactions, e.g. the stance, the anthropometry, as well as the grip and push forces [26]. Furthermore, it must be ensured that the user is not harmed as a consequence of the behaviour of the handheld devices. A recurring vibration exposure can be the cause of illnesses of the hand-arm system (HAS) [27]. Consequently, the vibration emission of the handheld devices, such as power tools, must be analysed. An approach to avoid the uncertainty of the user behaviour and physique during vibration testing of the human-machine interaction and increase the reproducibility of measurements is the replacement of the passive user interactions by a physical hand-arm model (HAM, Figure 5) with equivalent effect [13], [28].

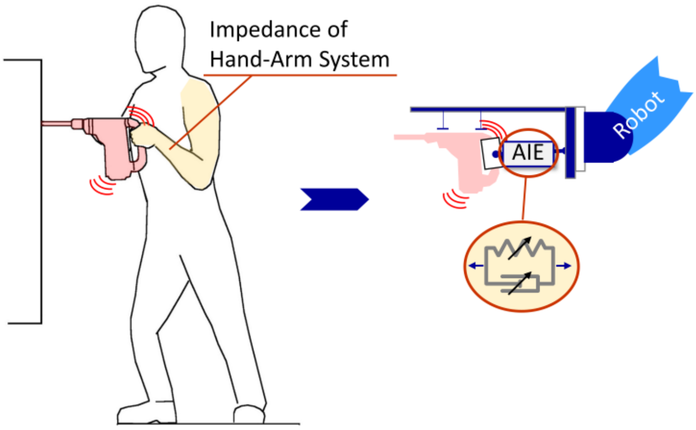

Figure 5: Impedance of the HAS of the user operating a handheld device (left) is reproduced by a physical HAM (right) on an automated power tool test bench (APP)

HAMs consist of masses, spring and damper mechanisms, which are designed to reproduce the mechanical impedance of the human HAS in a defined operation point (Figure 5) [29]. HAMs with fixed, non-adjustable properties are presented by [30], [31]. Generally, translatory as well as rotational degrees of freedom can be addressed by HAMs (see [32]), though this contribution is focused on HAMs with a translatory degree of freedom. Since the mechanical properties of the human HAS scatter among a user group and to enable testing of interactions with the device under various boundary conditions, HAMs with adjustable properties are proposed [13]. LINDENMANN [29] presents such a HAM based on an AIE, which features an adjustment of the mechanical impedance as well as a separately adjustable push force.

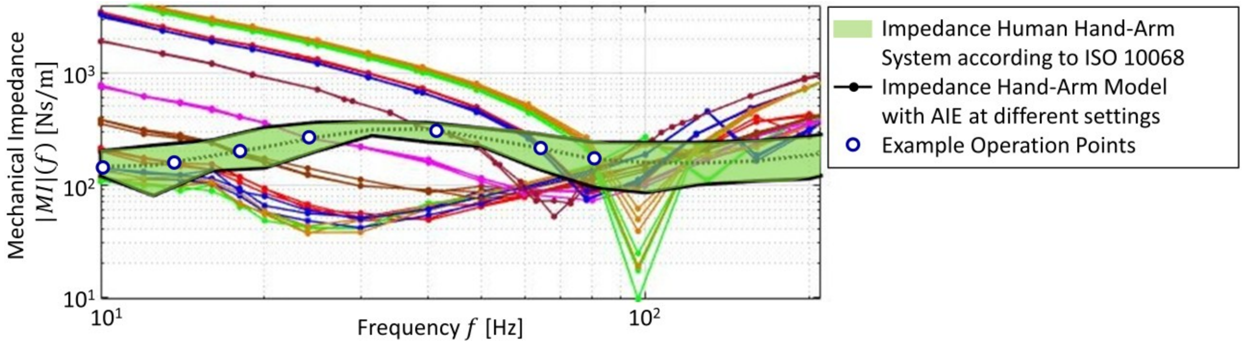

Figure 6: Mechanical impedance of the human HAS according to ISO 10068 [33] compared to the impedance of the HAM based on an AIE at different settings, based on [29]

The range of adjustable impedance achieved by the HAM based on an AIE [29] is compared to the impedance of the human HAS according to ISO 10068 [33] in Figure 6. In the frequency range up to 100 Hz, the impedance curves of the HAM at different settings match the impedance of the HAS at specific frequency points. The HAM can be deployed for testing of handheld devices at these steady-state operation points. Changes in the frequency during testing with the HAM away from the steady-state operation points would result in a deviation from the impedance of the HAS, since the setting of the HAM cannot be changed during operation due to the manual adjustment. The shallow slope of the impedance of the HAS over the entire frequency range shown in Figure 6 leads to challenges in its reproduction in a physical HAM with the current state of the art. According to the model parameters of ISO 10068 [33], a moving mass of a few grams is required.

4. Potential of Dynamically Adaptive Impedance Elements (DAIEs)

AIEs enable a simple and reproducible variation of interface properties in vibration testing of lightweight structures and handheld devices. Due to the manual adjustability, AIEs are only suited for setting the stiffness and damping in a steady state. However, this leads to challenges and demands for further development: Although simple, the manual adjustment results in a setup time before each test, which accumulate to a considerable effort during extensive test series [5]. Additionally, AIEs are unsuitable for applications where the interface properties have to be changed during operation [23], [29]. Those two disadvantages of AIEs lead to the need for DAIEs, which are interface elements with the ability to adapt the mechanical impedance during operation and enable the reproduction of multi-steady-state or unsteady interface properties [5]. A multi-steady-state vibration control of technical systems will be permitted by the dynamic adaptability of the DAIEs (see section *DAIEs for Testing of Lightweight Structures*), as an efficient variation of the interface properties during testing procedures is being achieved and thus the development of products with optimised vibration behaviour is being facilitated. In this context, multi-steady-state refers to an adaptation of interface properties during testing within a series of steady-state operation points, which represent various boundary conditions. The effective vibration control of products with a large number of variants or multiple operation points requires extensive parameter studies of the interface properties [5]. These parameter studies are only viable with a reasonable amount of testing effort when the variation of the interface properties is automated to a certain degree.

In several applications, interface properties change over time (see section *DAIEs for Testing of Handheld Devices*). When these unsteady interface properties of a specific application have to be reproduced in the testing environment, interface elements are needed that are capable of adapting their mechanical impedance during an ongoing test. To meet this demand, DAIEs are needed to ensure efficient and reproducible testing conditions [5].

DAIEs for Testing of Lightweight Structures

Aircraft interior monuments come in a large number of variants. Different attachments such as screens, literature pockets or baby bassinets can be added and cause an altered vibration behaviour of the monuments [7], [34]. In the context of vibration reduction, all the combinations of various attachments have to be considered as variants and the interface properties with the highest potential for vibration reduction have to be determined individually [5]. Parameter studies over the interface stiffness and damping have to be carried out for each variant [5]. Between every combination of stiffness and damping to be tested, the interface elements need to be adjusted. In the process of obtaining a performance map (as shown in Figure 4) through a parameter study over the interface stiffness and damping, an immense testing effort is accumulated, if AIEs with their manual adjustment are used. Each manual adjustment of the AIEs requires the test bench to be shut down, as personnel must enter the danger zone. In the case of the hexapod test bench (Figure 3 on the right), the adjustment of the AIEs involves recurring working at height, so fall protection for the personnel should be ensured.

Interface elements, which permit multi-steady-state properties through an adaptation during operation, would result in a more efficient change of the interface's dynamic behaviour [35]. DAIEs would cause a significant reduction in testing effort [5], as multi-steady-state testing is a key factor towards enabling extensive parameter studies of product families on an industrial scale. The adaptation process between different settings of stiffness and damping could be automated using DAIEs, which would render a shutdown of the test bench for the adaptation process and personnel entering the danger zone obsolete. The efficient, reproducible and randomised execution of the large number of tests caused by various combinations of product variants and interface properties could be facilitated by DAIE [5].

In some cases, multiple resonances of a lightweight structure occur in the relevant frequency range of its specific application and have to be reduced. When the parameter combinations of interface stiffness and damping with a large potential of vibration reduction determined by simulated parameter studies (similar to Figure 4) differ considerably for the different resonances, an adaptation of the interface properties during operation is needed [23]. By multi-steady-state testing using DAIEs, an adaptation of the interface properties during testing is possible, so each subsection of the overall frequency range can be tested with the specific stiffness and damping values, which are promising for the vibration reduction of the resonance occurring in that subsection [23].

DAIEs for Testing of Handheld Devices

Often in the human-machine interaction, a shift over time is observed, which can result from various influencing factors such as fatigue, changes in posture, push and grip forces [36] or changes in the vibration frequency of the handheld device due to different revolution speeds [37]. Hence, the impedance of the HAS to be reproduced varies over time. The existing HAM based on an AIE is only suitable to reproduce the mechanical impedance of the HAS according to ISO 10068 [33] within steady-state operation points, as shown in Figure 6. As a result, the acting harmful vibrations could be confounded and worse could be underestimated during power tool testing, rendering the derived conclusions regarding the occupational safety false. Therefore, a HAM is needed that enables an adaptation of the impedance during operation. By developing a HAM based on a DAIE, both multi-steady-state and unsteady behaviour could be analysed in the testing environment. Multi-steady-state testing would facilitate efficient, reproducible and randomised investigation of the human-machine interaction in various operation points by automation without the need for manual adjustment, e.g. users of different genders, different levels of push and grip force, posture or revolution speeds of the device. Unsteady testing would enable the reproduction of whole work cycles in the testing environment, including fatigue of the user. The aim is a full replication of the impedance of the human HAS over the frequency as shown in Figure 6.

5. Conclusion and Outlook

In this publication, the potential of DAIEs as interface elements in vibration testing is described. DAIE enable a dynamic adaptability of the interface properties during testing (semi-active elements). Two different applications are considered: Testing of aircraft interior monuments and handheld power tools. In both cases, the need for an efficient and reproducible adaptation of the interface stiffness and damping during testing is derived. DAIE would facilitate multi-steady-state testing, such as automated parameter studies over the interface stiffness and damping, in order to achieve a vibration reduction of variant lightweight structures. Additionally, the reproduction of the unsteady mechanical impedance of the human HAS would be enabled for vibration analysis in the human-machine interaction between users and handheld devices.

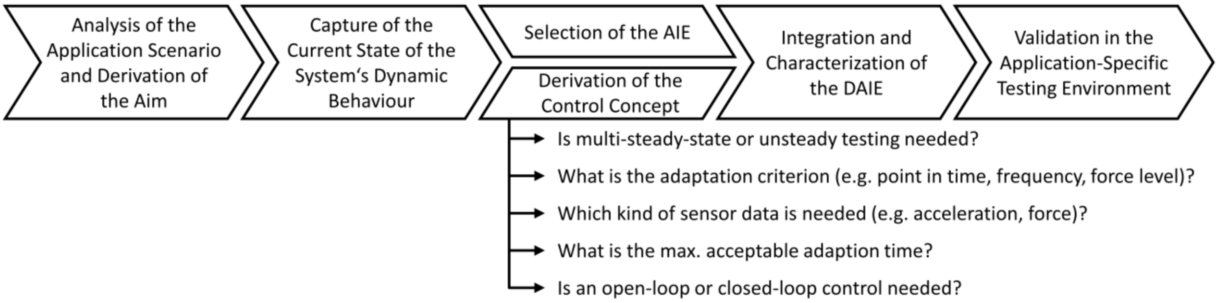

Figure 7: Approach for the development of DAIE for vibration testing

The proposed DAIE will be developed, investigated in both fields of application and presented in future publications, according to the generic approach shown in Figure 7. The application specific approaches by Heyden [5] for the vibration reduction of lightweight structures using AIE and by Lindenmann [29] for the replication of the mechanical impedance of the human HAS in a HAM based on AIE are generalized and expanded into a generic approach for DAIE. In contrast to AIE, a control concept has to be derived for DAIE, in which application specific requirements have to be considered. Whether multi-steady-state or unsteady testing is required, affects the adaptation criterion, the kind of sensor data needed, the acceptable adaptation time and the demand for an open- or closed-loop control.

6. Acknowledgement

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