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AN APPROACH FOR THE MODEL BASED MONITORING OF PIEZOELECTRIC ACTUATORS

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Abstract. *Piezoelectric actuators are used in a wide range from mechatronic applications like fuel injection to the field of smart structures for micropositioning or noise and vibration suppression. However, due to increasing demands for reliability and safety of technical systems, fault diagnosis and structural health monitoring become important. Therefore, the on-line diagnosis of piezo actuators is an essential challenge when developing smart structural systems for industrial as well as automotive or aerospace applications.*

Model based monitoring systems can provide detailed information about the current status of a technical system [1]*. In this work, an approach for model based monitoring of piezoelectric actuators is examined. The main idea is to use the measurement of the electrical impedance of the actuator to receive information about possible damages. Because of the electromechanical coupling, this measure includes information about the electrical parameters as well as the mechanical parameters of the actuator. At hands of a simulation, basic studies on damage scenarios of electromechanically coupled systems are accomplished.*

Methods for model based fault diagnosis of the system are developed and implemented with the help of adaptive digital filters [2]*. These should provide parametric models of the input impedance function, possibly on-line in parallel to the operation of the piezo transducer in a vibration control system. The signal processing algorithms are developed taking into account the possibility of implementation of a real-time capable embedded standard hardware, i.e. the computational effort of the diagnostic system. Measurements on piezoelectric stack actuators used in smart systems for vibration decoupling help to improve the simulation. The monitoring system is implemented on rapid prototyping controller hardware and is tested in an experiment on monitoring of the piezoelectric actuators.*

1 INTRODUCTION

The integration of monitoring and fault detection systems is increasingly taken into account in the development of mechatronic systems and smart structures. Model based fault detection methods have been proposed, e.g. in the field of automotive applications[1]. They are based on tracking the changes of a parametric model of the system in case of damage.

In many systems, piezoelectric actuators are applied. For example, piezoelectric stack transducers are used to design stiff active mounts for vibration control in various applications[3]. In this work, a model based monitoring system for such a mount will be examined. With the help of the electromechanical analogy it is possible to develop models for piezoelectric transducers[4,5]. These can help to examine the influence of the damages, i.e. changes in the physical parameters, on the model parameters. Because of the electromechanical coupling of the piezo actuator, its electrical input impedance gives information as well about the electrical parameters as well as about the mechanical parameters and the mechanical structure coupled to the actuator, and with detailed modeling it is possible to identify also material constants[6]. Therefore, the impedance is often used in structural health monitoring systems[7]. Here, the electrical input impedance of an integrated piezo actuator will be examined for its properties as a measure towards damage diagnosis.

The possibility of monitoring mechanical systems with adaptive digital filters has been investigated in several applications[8]. In this work, adaptive filters will be applied for the parameter identification of the electrical impedance. Since in smart structures, control algorithms are often based on digital signal processing, the implementation of the monitoring system with similar signal processing methods offers the possibility for an integration of both the vibration control and the diagnosis, which can lead to a fully integrated smart structure.

The paper is organized as follows: First, the electromechanical model for a piezoelectric stack actuator will be presented and the result is compared with respective measurements. After that, the approach of adaptive digital filters for model based monitoring is introduced and afterwards examined at hands of a simple example using the developed piezo model to simulate different damage scenarios. In section 5, the impedance monitoring method is experimentally tested in an application, an active piezo interface for vibration decoupling with the help of real-time signal processing.

2 LINEAR DYNAMIC MODEL OF A PIEZO ACTUATOR

A parametric model of the piezoelectric actuator is the basis for the development of a model based monitoring method. A suitable way to implement a model of an electromechanical transducer system is the electromechanical analogy. This method implements a linear model, yet it is including the electromechanical coupling of the piezo transducer. It is assumed, that the actuator can be modeled as a lumped mass-spring-system. This assumption is valid for small signals and for the frequency range up to the first longitudinal resonance of the actuator.

The method allows for representing a system which consists both of mechanical and electrical subsystems with electrical circuit diagrams. In the first step, the actuator mass is neglected, while only the mechanical stiffness k_p, damping b_p, the electromechanical coupling coefficient α and the electrical capacitance C_p are considered. Then, for the piezoelectric actuator, a representation by a two-port network can be found (Figure 1).

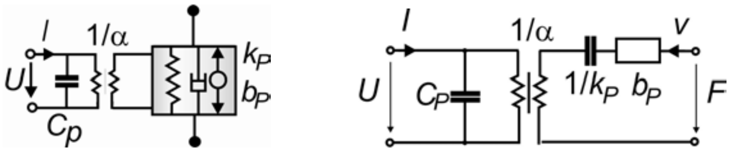

Figure 1: Electromechanical equivalent circuit of a piezo transducer

This network can be described by several matrix formulations[9]. Here, the impedance matrix **Z** is of special interest:

$$\begin{bmatrix} U \\ F \end{bmatrix} = \begin{bmatrix} \dfrac{1}{j\omega C_p} & \dfrac{\alpha}{j\omega C_p} \\ \dfrac{\alpha}{j\omega C_p} & \dfrac{k_p C_p + j\omega C_p b_p + \alpha^2}{j\omega C_p} \end{bmatrix} \begin{bmatrix} I \\ v \end{bmatrix} \tag{1}$$

To examine the properties of this modeling method, the comparison to an admittance measurement of a piezoelectric stack actuator with free-free boundary conditions is used (Figure 2). The model parameters of a piezo stack can be calculated from the physical and geometrical parameters:

$$C_p = \varepsilon_{33} \frac{A_p}{l_p} n_p^2 \tag{2}$$

$$k_p = E_p \frac{A_p}{l_p}$$

$$\alpha = d_{33} n_p k_p$$

Here, A_p is the cross-section, l_p is the length of the actuator and n_p is the number of layers, which are stacked mechanically and electrically connected in parallel. The necessary physical parameters are the Young's modulus E_p, and the piezoelectric material constants d_{33} and ε_{33}. The mass m of the actuator is concentrated into two lumped masses in a way, that the first longitudinal resonance frequency matches the resonance of the resulting mass-spring system. In the equivalent circuit, this mass is represented by

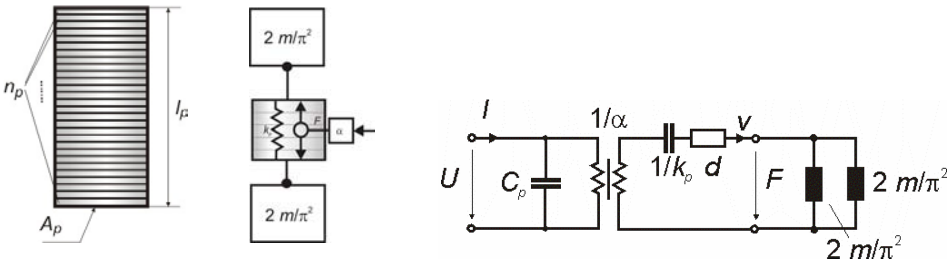

Figure 2: Piezo stack actuator, mechanical and electromechanical representation.

terminating the two-port network with an inductance (Figure 2). With the resulting terminating mechanical admittance

$$Y_{mech}(j\omega) = \frac{\pi^2}{2j\omega m}, \tag{3}$$

the electrical input admittance can be calculated:

$$Y_{in}(j\omega) = j\omega C_p \frac{(j\omega)^2 + (j\omega)\frac{d\pi^2}{m} + \frac{\alpha^2\pi^2}{mC_p} + \frac{k_p\pi^2}{m}}{(j\omega)^2 + (j\omega)\frac{d\pi^2}{m} + \frac{k_p\pi^2}{m}}. \tag{4}$$

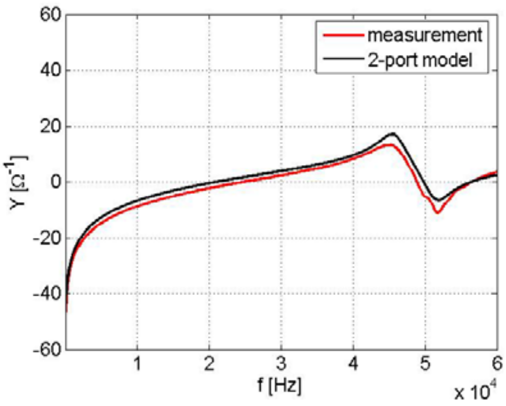

Figure 3: Comparison of an admittance measurement and the electromechanical model

With the help of the parameters of the actuator, which are taken from the material data sheets, the admittance can be evaluated numerically and compared to an admittance measurement (Figure 3). Because the real parameters differ slightly from the data sheet, a numerical optimization of the model parameters is done. After the adjustment of the parameters in order to enhance the precision of the model, both the measured and the calculated admittance match quite well up to the first resonance frequency at above

40 kHz. Obviously, the admittance represents the capacitive property of the electrical part of the system as well as the dynamical mechanical properties.

3 APPROACH FOR MODEL BASED MONITORING OF THE PIEZO

Since the electrical admittance function includes the important electric and mechanical properties of the piezo actuator, there is a motivation for using it as a monitoring parameter for damage detection in piezoelectric actuator systems. The concept is based on a standard procedure for model based diagnosis. The system is excited by a suitable test signal, the response from the system is measured and a parametric model is identified from the input and output data. In this work, the focus is on the identification of parametric models as damage features with adaptive digital filters (Figure 5).

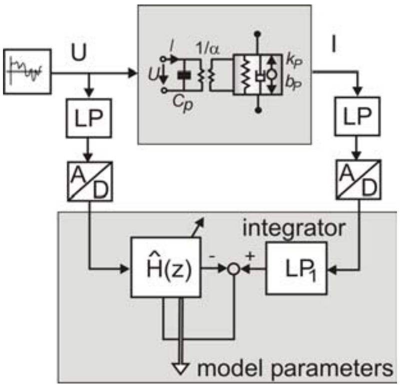

Figure 5: Identification of parametric models with adaptive digital filters

The admittance function shows a capacitive behavior over the whole frequency range. This may lead to problems in the convergence of the adaptive filters regarding the modeling of the resonance of the piezo system. Therefore, instead of the admittance the monitoring system identifies a time-integrated version of the admittance:

$$H(j\omega) = \frac{Y_{in}(j\omega)}{j\omega} \tag{5}$$

For integration of the system output, a first-order low pass filter with a cut-off frequency far lower than the interesting frequency range is used, which can be easily added to the digital filter system (Figure 5). The adaptive filter will provide a time discrete model of the transfer function $H(j\omega)$. Because of its recursive characteristics, an IIR (infinite impulse response) filter should model the function with a minimum of parameters:

$$\hat{H}(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{1 + a_1 z^{-1} + \ldots + a_N z^{-N}}\,. \tag{6}$$

4 SIMULATION OF AN EXAMPLE

To test the described concept in simulations, a piezo actuator system is considered, which consists of the piezo stack used before with an effective mass of m = 0.2 kg added to one side and fixed to the ground on the other side. The actuator mass itself is therefore small against the coupled mass and can be neglected without introducing a relevant error. Because of the simulation of the components as one- or two-port networks, the simulation is easily enhanced, if more complex mechanical loads are to be considered (Figure 6).

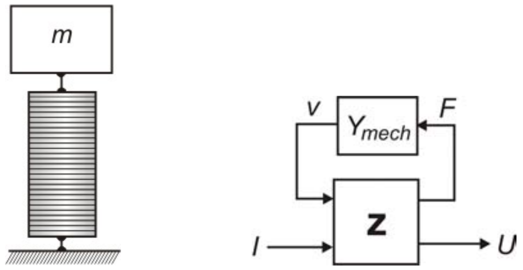

Figure 6: Test example of a mechanically loaded piezo and network representation

Assuming a sampling interval T, the ideal model is given by the transformation of the transfer function into the time discrete domain, which is received with the help of the impulse invariance transformation:

$$H(z) = \frac{C_p - \left(\frac{\alpha^2 \operatorname{Im}\{p\}}{\omega_0 C_p m} - 2\operatorname{Re}\{p\}\right) z^{-1} + |p|^2 z^{-2}}{1 - 2\operatorname{Re}\{p\} z^{-1} + |p|^2 z^{-2}} \tag{7}$$

$$\text{with } \omega_0 = \sqrt{\frac{k_p}{m}} \quad \text{and} \quad p = e^{-dT/2m + j\omega_0 T}$$

Therefore, an adaptive filter with three coefficients in the numerator and in the denominator should be able to identify the transfer function.

As an adaptive filter algorithm, the recursive-least-squares algorithm is chosen, which possesses fast and precise convergence properties. Indeed, it is suitable only for a small number of coefficients for real-time implementation because it requires a computational effort of order I^2, when I is the order of the filter[10].

The simulation is set up in *Simulink* to study all interesting effects in the time domain. It includes two different sample rates, a higher rate to simulate the electromechanical system, and a lower rate for the digital signal processing. Therefore, also low-pass filters for anti-aliasing and reconstruction are included (Figure 7). Because their amplitude and phase response affects the transfer function characteristics together with the band-limited excitation around the resonance frequency of the system, the filter order has to be chosen

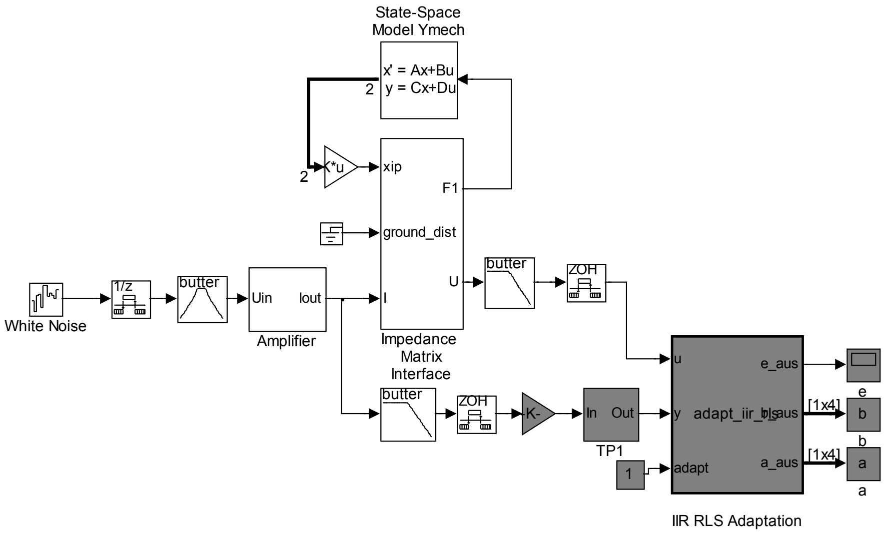

Figure 7: Time domain simulation of the piezo monitoring system

higher than expected from the direct calculation of the time-discrete transfer function (equation 7). A tradeoff between a precise model and a modest computational effort is found for orders M = 6 and N = 4 (Figure 8). With this configuration, several damage scenarios and their effect on the model parameters are studied. Probable damages in a piezoelectric actuator system are the decrease of electrical capacitance, mechanical stiffness or electromechanical coupling. Therefore, these cases are examined in the simulation. Obviously, the adaptive filter estimates the two conjugated complex poles and zeros of the system, which are positioned near the unit circle in the z-plane, and the model is stable (Figure 8).

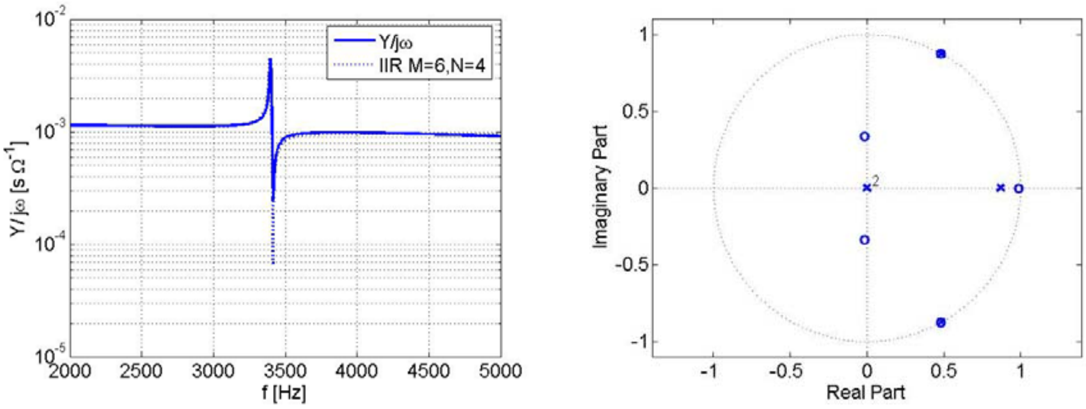

Figure 8: FRF of the system and by the adaptive filter identified model, pole-zero plot of the model

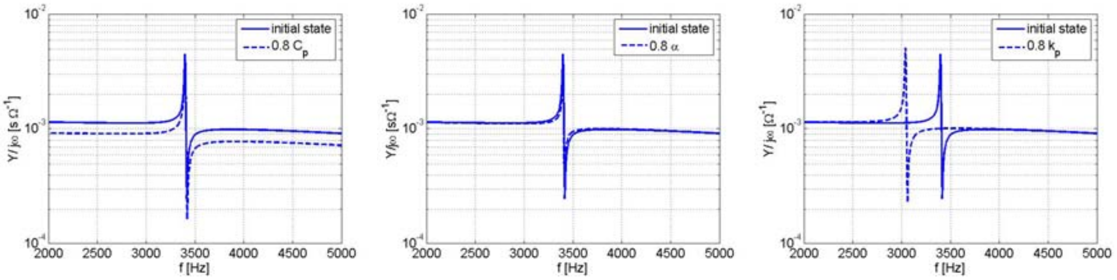

Figure 9: Comparison of transfer functions for initial and damaged state

To evaluate the influence of the damage cases, a gradual decrease up to 20% of each of the parameters is assumed. For the maximum damage, the transfer functions are compared to the ones of the undamaged case (Figure 9).

As a simple damage index, the normalized distance between the filter parameter vectors for the initial and the damaged state is chosen. This is done separately for the numerator and denominator:

$$D_a = \sqrt{\frac{\sum\left(a_n - a_n^{(i)}\right)^2}{\sum a_n^{(i)}}} \tag{8}$$

$$D_b = \sqrt{\frac{\sum\left(b_n - b_n^{(i)}\right)^2}{\sum b_n^{(i)}}}$$

For the three cases, the respective indices are calculated and plotted against the percentage of parameter change (Figure 10). Obviously, the decrease of C_p results mainly in a change of the numerator coefficients. This matches with the expectations, because the capacitance represents the static offset of the transfer function.

The decrease of α has the smallest effect on the damage indices, but as can be seen in Figure 9, for this damage case the transfer function shows only a small variation against the initial state.

The decrease of the mechanical stiffness k_p leads to a lower resonance frequency of the piezo system. Since not only the poles, but also the zeros of the transfer function are influenced by this parameter change, there is an effect on the damage indices of both the nominator and denominator, which is in same order of magnitude. Thus, the approach of monitoring the piezo actuator system with an adaptive digital filter system seems to be suitable for damage detection in different damage cases.

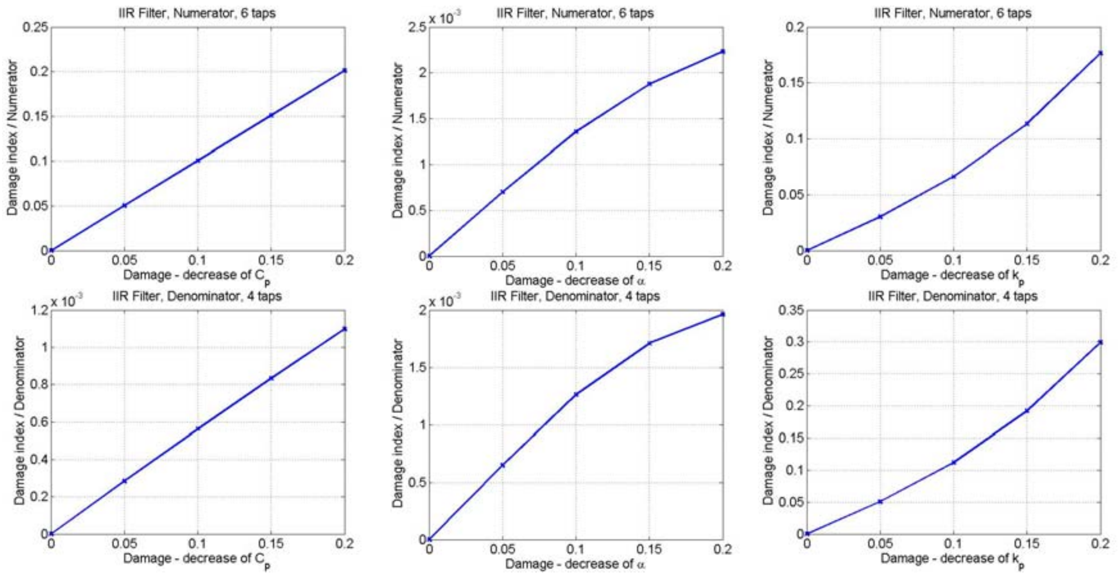

Figure 10: Numerator and denominator damage indices for the studied cases

5 EXPERIMENTAL STUDY ON AN ACTIVE PIEZO INTERFACE

The developed monitoring approach is tested at hands of an active piezo interface for active vibration control (Figure 11). It is designed for automotive applications, where it can be used to decouple excitations of the car body through the engine, the gearbox, aggregates, drive shafts, or the tire/road contact. The realization with stiff piezoelectric stack actuators makes the direct integration into different systems possible, because the interface can bear large static loads. To make the application in the harsh environments of automotive systems possible, the piezo actuator system is designed to resist against oils, liquids, etc. and to withstand misuse loads in the lateral directions of about 3 kN. The active interface is able to control three degrees of freedom, one translation in z-direction and two rotations about the x- and y- axis (Figure 12).

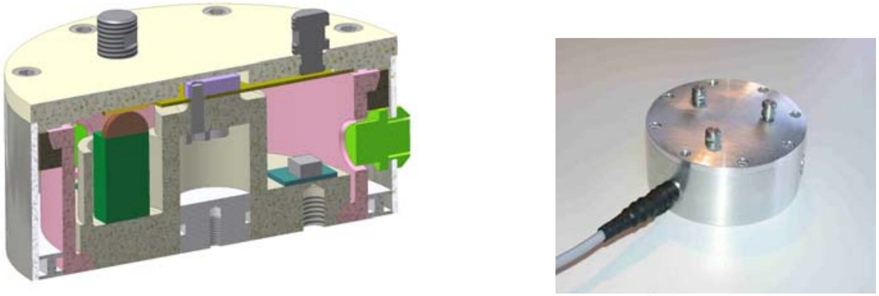

Figure 11: Piezoelectric interface for active vibration control

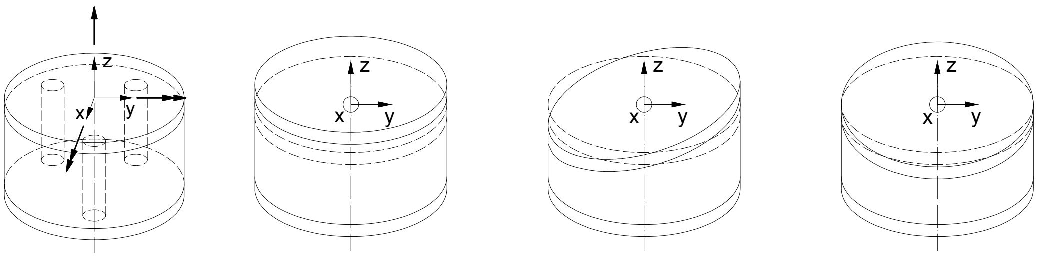

Figure 12: Position of the actuators (left), control of the three degrees-of-freedom

The control of the three degrees of freedom is realized by arranging three actuators on a circle, which can be driven separately. In the studies presented here, only the translational degree of freedom is used, thus all three actuators are connected in parallel and driven with the same voltage. The mechanical set up of the interface consists of the piezoelectric interface itself, and a mass of m_{add} = 0.3 kg mounted to one end in order to simulate a structure coupled to the system.

The signal processing for testing of the piezo monitoring system follows the principle shown above (Figure 5). For realisation of the adaptive digital filter system, a *dSpace* rapid control prototyping system is used running at a sampling frequency of 20 kHz, which implements the algorithm with the help of automatic code generation from the simulation code (Figure 7). The input current of the piezo system is measured using a shunt resistor.

First, the adaptive system identification of the piezo interface in the initial state is tested. A proper frequency range and a number of filter coefficients of the adaptive IIR filter is chosen in order to get a good approximation of the monitored transfer function with a low number of coefficients. Here, a number of $M = 9$ coefficients for the numerator and N = 4 for the denominator was found (Figure 11). Obviously, in the real application the damping seems to be higher than in the preceding simulations.

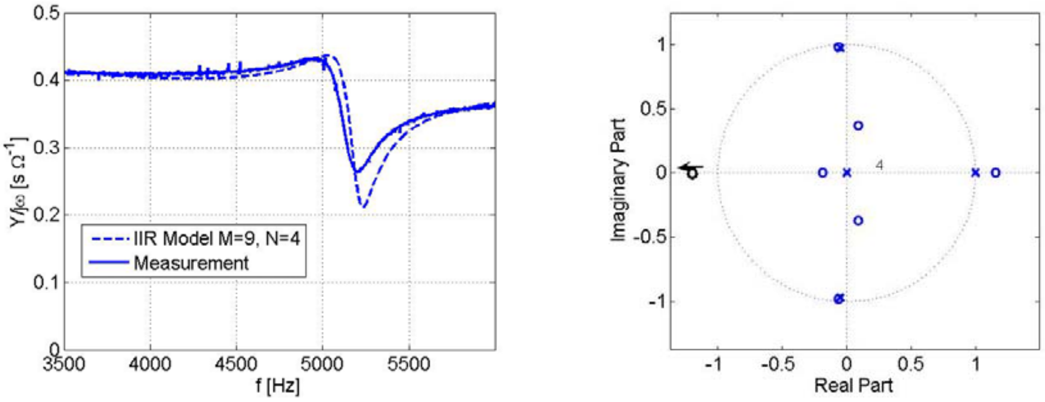

Figure 11: Monitored transfer function and adaptively identified model, pole-zero plot of the model

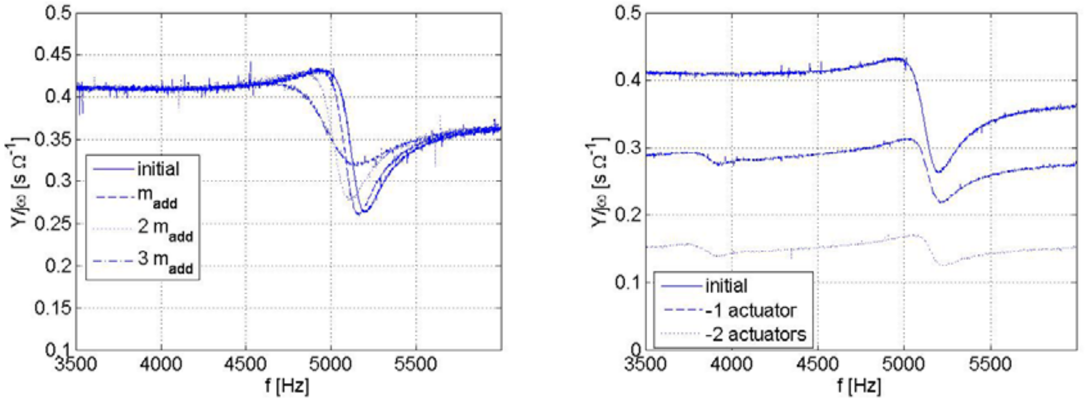

Figure 12: Transfer functions with added masses (left) and disconnected actuators (right)

Because in this work the piezo interface should not be damaged irreversibly, some simulations for damage scenarios have to be used. Instead of decreasing the piezo stiffness, a small amount of mass ($m_{add} = 0.02$ kg) is mounted to one end of the interface, similarly leading to a decrease of the resonance frequency (figure 12, left). As a second damage, the piezoelectric actuators are disconnected successively, which leads to a loss of electrical capacitance (figure 12, right).

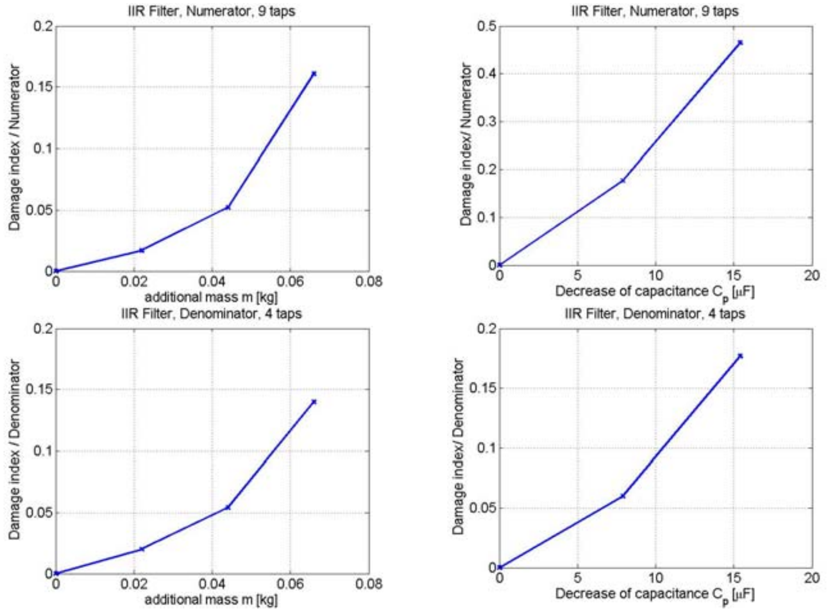

Figure 13: Damage indices for the experimental damage cases

In every situation, the identification with the adaptive filter is done and the damage index (equation 8) is calculated. A decrease of the resonance frequency affects both the numerator and denominator damage index, while a loss of capacitance influences the numerator damage index more than the denominator damage index (figure 13). This matches somewhat with the results received from the simple simulation example (figure 10), but the different damage cases are not as clearly distinguished than in the simulation.

6 CONCLUSIONS

In this paper, an approach for model based monitoring of a piezo actuator system was examined. With the help of the electromechanical analogy, a simulation model for a piezo stack actuator was set up and the calculated electrical admittance was compared to a measurement, which lead to good results. At hands of a simple simulation built up with the help of the actuator model, the method for monitoring of the electrical admittance with the help of adaptive filters was tested. Different damage cases were studied in the simulation. At last, the monitoring system was tested experimentally with the piezo interface. The adaptive filter system was implemented on real-time capable hardware and different damage scenarios were treated. The adaptive filter system could detect the changes in the system characteristics, while the results showed the same characteristics like the results received in the simulations. Therefore, the method seems to be suitable for implementation as a monitoring system for piezo actuator systems.

In order to fulfill the requirements of an integrated smart structure, the monitoring algorithm has to be implemented on low-cost embedded hardware. This will be one focus of the further work. Another important topic will be the refinement of the electromechanical simulation of the actuator system. Therefore, the piezo actuator model will be integrated into a multi-body-simulation to develop a dynamic model of the multiple-degree-of-freedom piezo interface system under consideration of the electromechanical coupling effects. Furthermore, the simulation of the actual application scenario will be possible by integration of dynamic models of the coupled structures. This allows for simulation of the admittance monitoring system more complex application scenarios. When it is possible to model realistic damage scenarios and predict the influences on the parameters of the adaptive filter, a detailed damage diagnosis can be implemented using suitable algorithms. The monitoring method will have to be examined in a fatigue test of the actuator system for further improvements, and at last tests in the actual application will take place.

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