Robust Tuned-Mass-Damper design for viscoelastic materials

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Abstract

Component tolerances in system design of high precision mechatronic systems such as mirrors in projection optics for lithography can lead to system performance losses during qualification of series production. Consequently, significant costs occur for solving out of specification situation. Therefore, a robust design of mechatronic systems is necessary, where the tolerance effects on system performance are investigated. For example, in high precision positioning systems tuned-mass-dampers (TMDs) are used to prevent instabilities of the control loop due to undamped structural dynamics. These dampers are often made of viscoelastic materials, which are strongly sensitive to temperature and the manufacturing process such as geometry and the material properties. Occasionally, a Monte-Carlo simulation is used for investigating the system performance with tolerances. However, in high precision mechatronic systems there are several tolerances, where you cannot guarantee a robust performance within a Monte-Carlo simulation in finite time. For that reason, we use the µ-analysis [1], an optimization-based approach to investigate robust performance of a controlled system. This approach can guarantee robustness for many tolerances. For that reason, we present the use of the µ-analysis for large mechanical structures with viscoelastic damper materials. The temperature, geometrical and material tolerances are considered within the µ-analysis.

For the use of the µ-analysis a nominal dynamic model is extended with parameters for the tolerances. In high precision positioning systems dynamic models are derived from finite element analyses due to small displacements. Thus, tolerances are added by stiffnesses and dampers in a feedback loop. In order to cover temperature uncertainties of viscoelastic materials, the feedback loops are extended by the frequency dependent description of the Young's modulus $e(s)$, see Figure 1. The dynamic behavior of the Young's modulus of the viscoelastic material is often determined by a frequency response function measurement, also known as the dynamic mechanical analysis (DMA). To analyze the impact on the position control, a dynamic model is fitted into the measurement data. Temperature changes can be modeled by frequency scaling of the dynamic Young's modulus. For viscoelastic material the

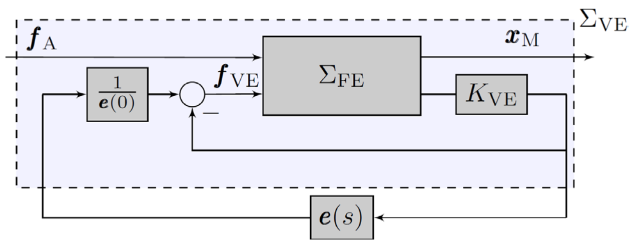

Figure 1. Considering viscoelastic materials in dynamic models by a feedback of a frequency-dependent Young's modulus.

Williams-Landel Ferry model is a state-of-the-art approach for shifting frequencies of the Young's modulus [2]. A frequency shift can be realized by scaling the poles and zeros of the Young's modulus.

In this contribution, the robust system performance of a position-controlled system is analyzed by the μ-analysis. In order to use the corresponding framework, uncertainties are represented in a feedback structure as depicted in Figure 2. The mechanical system from actuator forces to position measurements are combined with two feedback loops for the position controller and the uncertainties. The Δ block represents the tolerances of the viscoelastic material, where we consider structured uncertainties, diagonal blocks for each tolerance scaled to $-1 \ldots 1$. Plant and Controller combined to the nominal system Σ_N.

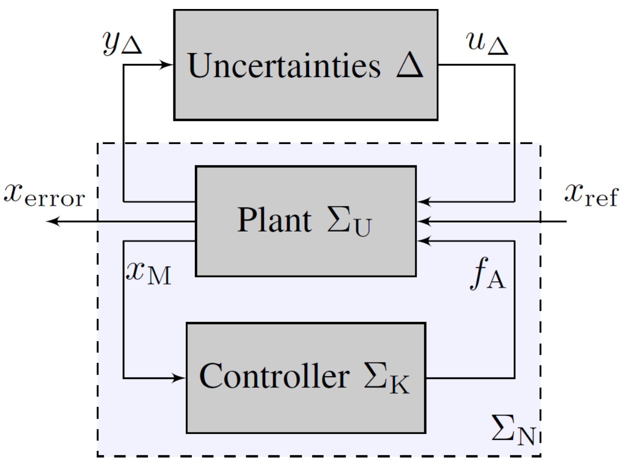

Figure 2. Generalized plant representation of the mechatronic system for the μ-analysis framework**.**

For studying the robust performance, the output sensitivity of the control loop is used, the transfer from reference to servo error signal, a quantity for the distance from open-loop function to the critical point of the Nyquist stability criterion. The structured singular value, also known as μ is defined by

$$\mu(\mathbf{M}) = \frac{1}{\inf\{\sigma_{\max}(\Delta) | \det(I - \mathbf{M}\Delta) = 0\}},$$

where $\sigma_{\max}$ denotes the maximum singular value of the block matrix Δ and M the transfer matrix with respect to the uncertainties. If the nominal system is stable and $\mu(\mathbf{M}) < 1$, the system is robust stable.

The robustness analysis of viscoelastic materials for temperature, geometrical and material tolerances is applied for a three mass-spring system to illustrate the method. In Figure 3 the spring-mass system is depicted.

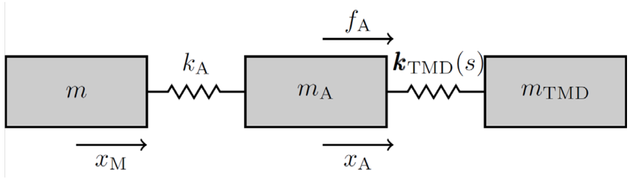

Figure 3. Depiction of a three mass-spring system example to analyze robust performance with viscoelastic materials.

A mass m is controlled by an actuator with a clearly smaller mass m_A and stiffness k_A. The resonance frequency is significantly higher than the cross-over frequency of the control loop, but it causes instabilities without damping. For that reason, the actuator is damped by a tuned-mass-damper (TMD), which is modeled by a mass m_{TMD} and a frequency dependent stiffness $k_{TMD}(s)$. The position controller is tuned for a cross-over frequency of 160 Hz. For the geometrical and material tolerances we assume 20 % deviation at the maximum. Moreover, two temperature intervals for a robust (22 °C … 27 °C) and non-robust case (22 °C ... 37 °C) are considered. In Figure 4 the used Young's modulus and the results for the different tolerances are depicted.

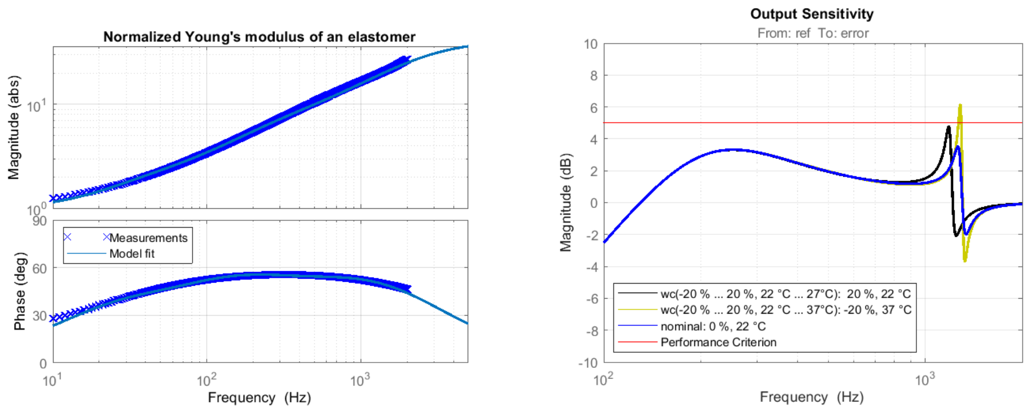

Figure 4. On the left a comparison of the measured Young's modulus of an elastomer and the fitted transfer function. On the right the determined output sensitivity is represented with different worst case parameters, for the nominal, robust and non-robust case based on the µ-analysis.

In this contribution a method is shown to analyze robust performance of mechatronic systems with viscoelastic damper materials with respect to TMDs. Moreover, temperature effects can be covered within the robustness analysis by taking in account of the frequency-dependent effect of the Young's modulus.

References

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[2] John D. Ferry and Henry S. Myers,“Viscoelastic Properties of Polymers ,”J. Electrochem. Soc. 108 142C, 1961