Subproject A6: „Investigation of a micro-electromechanical bandpass filter based on a tongue array”

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Introduction

In this contribution, essential results are summarized which were developed in subproject A6 “Virtual prototyping of micro-electromechanical actuators” of the Sonderforschungsbereich SFB 379 in the second half of 2003 (after delivery of the result’s report 2001-2003). These investigations are related to the tongue array presented in subproject A4 of the SFB 379. Such arrays can be used as bandpass filters. Every tongue represents a special frequency range. The tongues can separately be controlled by changing the offset voltage used for measuring the capacitances. Thus, the system’s transfer behaviour (input: stilt excitation, output: tongue’s excursions calculated backward from capacitances) can theoretically be designed in a nearly arbitrary way (see result’s report 2001-2003 of subprojects A4, A6).
In the optimization process during the system’s design, electromechanical interactions are neglected and a simplified model of the mechanical system is used. These simplifications induce unknown effects in the behaviour of the complete bandpass filter. These effects were examined in subproject A6 using an example array consisting of five tongues. This array shall realise a perfect bandpass (unity gain) in a frequency range from 2.0 to 2.7 kHz. Outside this region, the damping shall have a maximum value (rectangular nominal bandpass, see Fig. 1 left). The observed frequency range is between 1.5 and 3.2 kHz. The quality factor of a solitary cantilever beam was assumed to 10. For the optimization process, a simple model consisting of five spring-mass systems was used because its transfer function with direct excitation (i.e. given time depending function for stilt displacement) is explicitly known. Based on results of prior research work (see result’s report of subproject A6), a logarithmic distribution of the tongue’s eigenfrequency was chosen. For the specific example used here, the optimization process yields the frequencies 1.95, 2.14, 2.36, 2.59, and 2.85 kHz. The amplitude’s weights belonging to are –0.058, 0.1, 0.044, 0.09, and –0.07 V (see Fig. 1 right). Hence, the offset voltages to be used for capacitance measurement should pairwise have the same ratios. With the bandpass filter considered here, the 2nd to 4th tongue are mainly used to realise the filter’s pass-band and the 1st and 5th tongue (with negative weighting) are used for the damping in the stop-band of the filter. The bandpass realised with this model is shown in Fig. 1 on the left side.

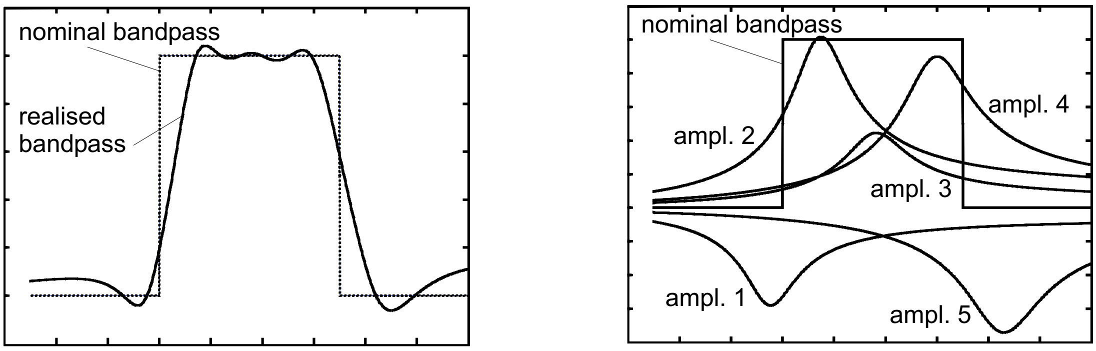

Figure 1: Result of optimization (spring-mass model)

In the following, several optimization results are assorted for this example of a bandpass filter. The calculated frequencies and amplitude’s weights are used in all simulations. But the system’s transfer behaviour is determined by the more detailed models.

Models not considering the electrical subsystem

For detecting the bandpass filter’s behaviour using dynamic simulation, different models were implemented. The amplitude’s characteristic curves were always calculated by varying the excitation frequency in steps of 500 Hz in the observed frequency range between 1.5 and 3.2 kHz. After the transient process is faded away, the tongue’s amplitudes can be determined and added up according to their weights. This way, the amplitude’s characteristic curves shown in the following were developed by multiple simulation procedures.

Spring-mass system

First, the spring-mass system used for the optimization process was also realised in the simulation tool alaska for reference reasons. The characteristic curves of the amplitudes resulting from the explicit formulation of the transfer behaviour were able to be developed from the dynamic simulation, too. Fig. 2 (on the left: linear scale, on the right: logarithmic scale with lower border at $10^{-1.3}$) shows the complete transfer behaviour of the system (input: excitation at the spring, output: displacement of point mass relatively to excitation).

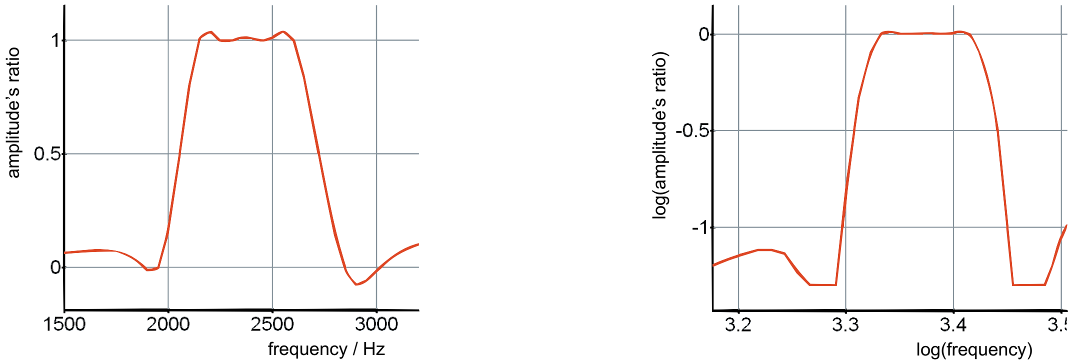

Figure 2: Simulation with spring-mass system

Deformable beam with point mass

In a first model refinement, every tongue was represented by a deformable silicon beam fixed to the stilt at one end. A point mass is attached to the beam at the other end. All beams have the same shape (666 µm long, 20 µm wide, 2 µm high). The tongue's eigenfrequencies are adjusted to the values mentioned above by appropriate mass values of the point masses. The assumed quality factor was realised by corresponding damping forces. The stilt was excited with an amplitude of 10 nm. The complete transfer behaviour of the system resulting from the dynamic simulation (input: stilt excitation, output: displacement of point mass relatively to excitation) is shown in Fig. 3 with linear or logarithmic scale, respectively. Because of the very small excitation amplitude, there are nearly no differences between the spring-mass system and the beam-point mass system.

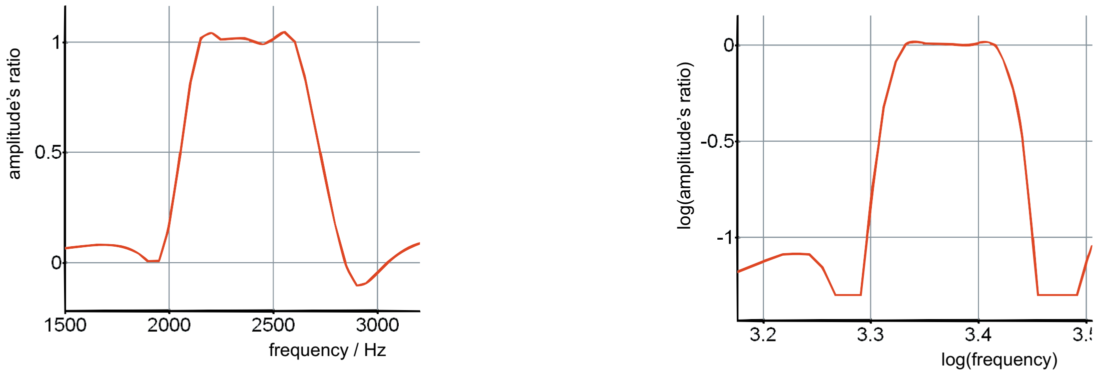

Figure 3: Simulation with deformable beam and point mass

Deformable beam and rectangular solid

The second refinement of the model was implemented using a rigid body (rectangular solid) as vibrating mass. Because of the possible rotation of the body, a second (parasitic) eigenfrequency occurs besides the first (purposed) one at every tongue. The ratio of both frequencies strongly depends on the shape of the solid and on the length proportions of solid and beam. For the longest solid, a length of 600 µm was chosen (with a width of 150 µm and a height of 30 µm). The first eigenfrequency of the concerning tongue was tuned by an appropriate beam length (217.4 µm). Using the same beam length with the other tongues, their first eigenfrequencies were adjusted by suitable lengths of the rectangular solids.

The complete system's transfer behaviour was ascertained considering only the displacement of the solid's centre of mass. Occurring rotations were neglected. The result is shown in Fig. 4 (input: stilt excitation, output: displacement of the solid's centre of mass relatively to excitation). Again, there are nearly no differences regarding the shapes of the characteristic curves (e.g. gradient near critical frequencies) compared with the linear spring-mass system. However, a comparison of the pass-band's levels shows that the purposed unity gain is not reached if the amplitude's weights of the optimized linear spring-mass system are used.

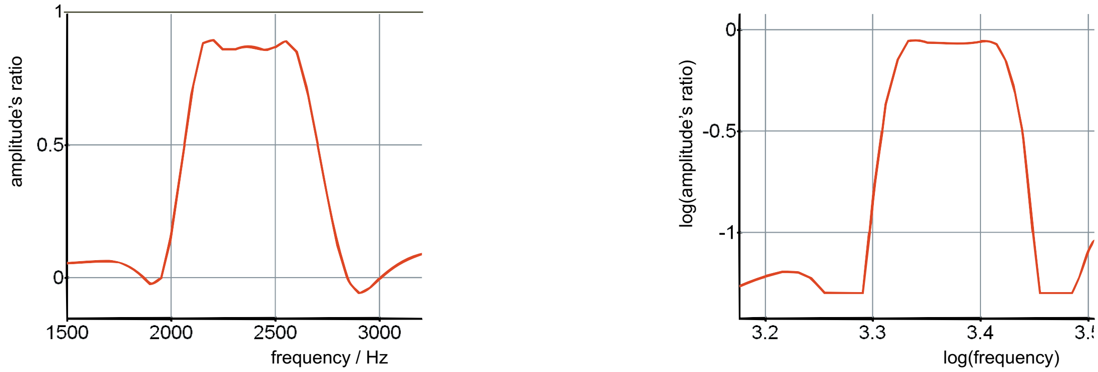

Figure 4: Simulation with deformable beam and rectangular solid

Models considering the electrical subsystem

In this section, two models are introduced which consider electrical components besides the mechanical structure. This way, both systematic measuring errors and electromechanical interactions are included in the behaviour. The mechanical subsystem of every tongue contains again beam and rectangular solid (see section above). The electrical subsystem mainly consists of a measuring capacitor (with voltage source and ohmic resistor) which is formed by a fixed electrode and the solid.

Dependencies of capacitances

The value of a tongue's capacitance depends on both the displacement of the solid's centre of mass and the rotation angle of the rigid body. The determination of the capacitance in the simulation model is carried out considering both dependencies (see different models of capacitances of micro mirrors in the result's report 1998-2000 of subproject A6 of the SFB 379). But from a measured capacitance, only one of both values can be calculated in reverse direction. Because the main influence comes from the displacement of the solid's centre of mass, the backward calculation is based on a capacitor with parallel plates. Hence, there is a systematic error between real and calculated displacement of solid's centre of mass. This effect may influence the complete system's behaviour of the bandpass.

With a first electromechanical model, the described systematic error was included in the dynamic simulation. The basic distance between the plates is assumed to 3 µm. Length and width are taken from the solid. The electromechanical interactions were still neglected, i.e. the assumption was made that the offset voltages used for measuring the capacitances have no influence on the tongue's motion behaviour. The corresponding results are shown in Fig. 5. The reason for the good conformity with the results without consideration of the systematic error is the large distance between first and second eigenfrequency (ratio is about 1:15 or 1:20). If the shape of the beam or that of the rigid body are varied then this distance can be smaller which could result in larger measurement errors.

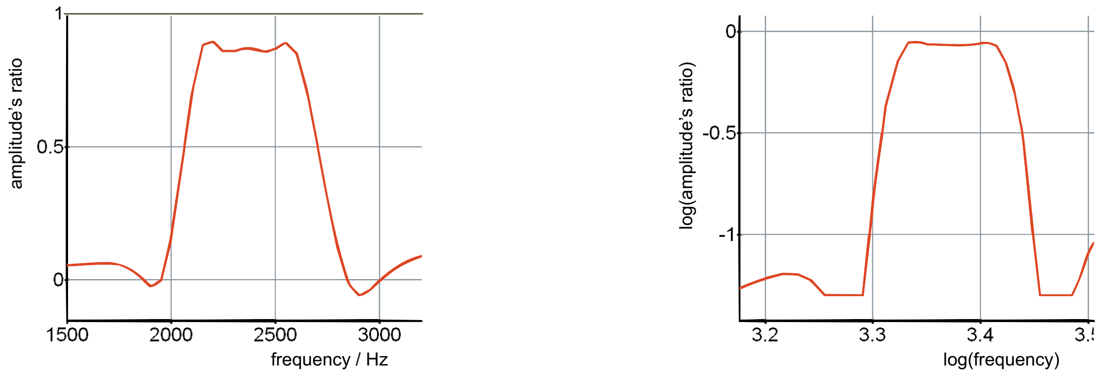

Figure 5: Simulation with model of capacitances

Influence of offset voltage

In a second electromechanical model, electromechanical interactions were additionally included. Neglecting the transient procedures of the electrical subsystem, the influence of electrical charges at the capacitances on the mechanical subsystem were especially respected. If a capacitance is measured then electrically produced forces and torques are applied on the movable plate. These cause disturbances of a tongue's dynamic behaviour. This influence strongly depends on the value of the offset voltages. In Figs. 6 to 8, amplitude's characteristic curves are presented using voltages of 0.1, 0.2, and 0.3 V. But especially Fig. 8 shows that the properties of the filter will be impacted negatively or may be lost completely if the voltage is too high.

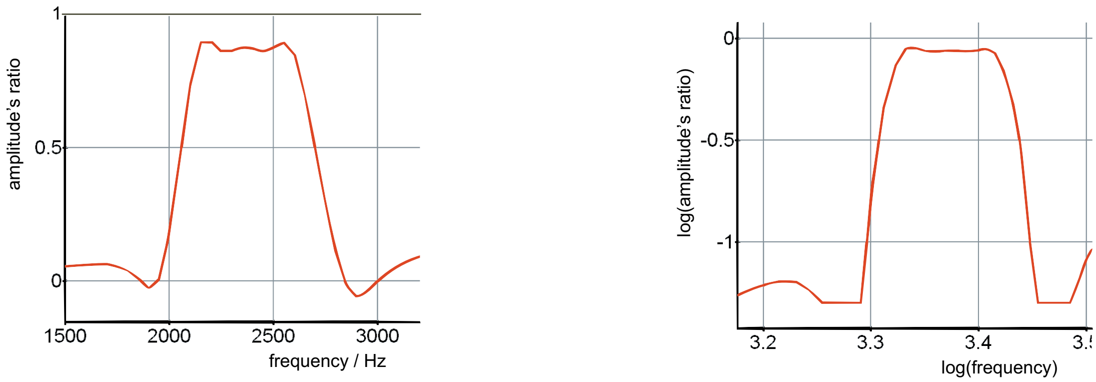

Fig. 6: Simulation considering electromechanical interactions (small voltage)

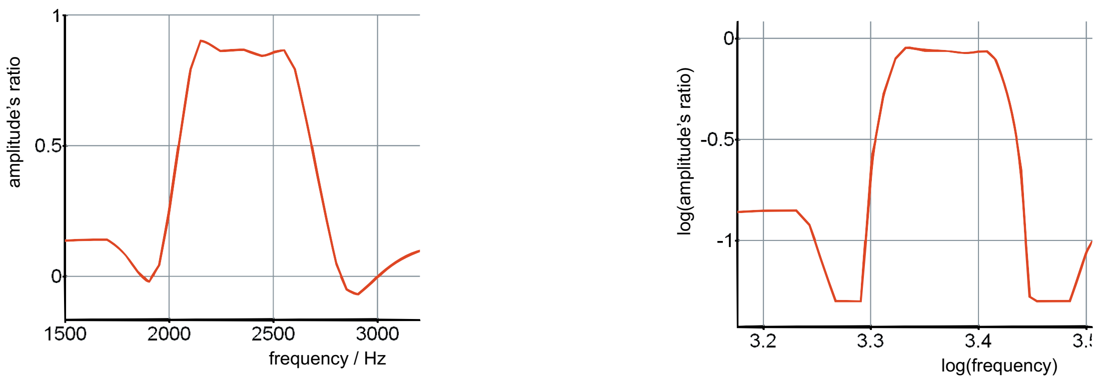

Fig. 7: Simulation considering electromechanical interactions (medium scale voltage)

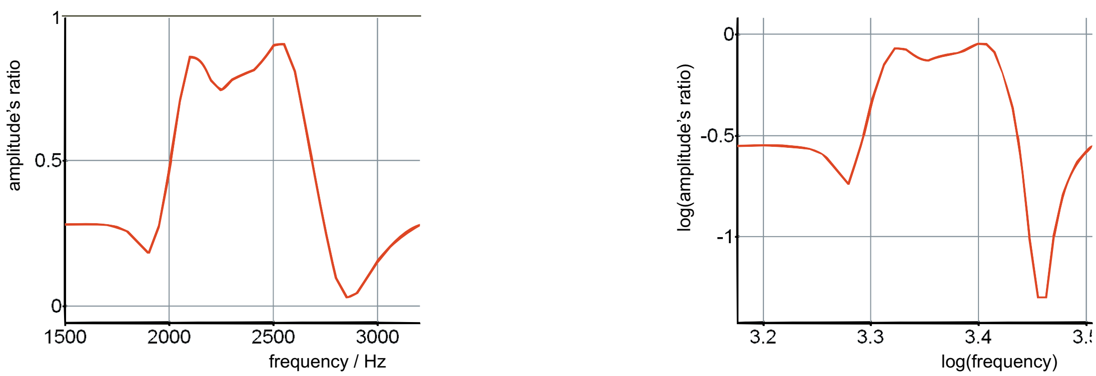

Fig. 8: Simulation considering electromechanical interactions (high voltage)