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Vibration Behavior of Ceramic Hot Gas Filter Elements: Analysis and Characterization of Mechanical Properties

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Introduction

In the combined cycle technology for advanced coal fired power plants at high temperatures up to 950 °C the removal of particles from the stream to the gas turbine is carried out with ceramic filter elements. These elements consist often of siliceous bonded coarse grained silicon carbide. A stable long term operation of the filter elements leads to the demands on good resistance towards thermal, mechanical and chemical loading.

The structure of ceramic filter elements consists usually of a highly porous support which ensures the mechanical strength and a layer which operates as the functional part for the particle removal. Thereby the lifetime of the whole element is mainly determined by the lifetime of the support material and not by the functional layer. The durability of the support is limited in principal by materials degradations leading to a decrease of mechanical properties.

The decrease or an immediate fracture of a filter element sometimes could be observed. It is assumed that immediate fracture or a crack growth of existing flaws can be caused by vibrations of the filter system. However, it is not possible to measure the vibrations of the filter elements during operation. To get an idea of the vibration behavior of the ceramic elements finite element analysis for the stress and strain behavior for different frequencies as well as experimental investigations in some model experiments were made.

Objectives

The objective of this study is to evaluate the mechanical properties of the cylindrical ceramic filter elements under vibration. These vibrations with different frequencies and amplitudes occur particularly in up/down-turning periods and during pulse cleaning but even under regular operation conditions. The geometry of a filter element with a wall thickness of about 10 mm, an outer diameter of 60 mm and an overall length of about 1500 mm with a porous support structure is not typical for ceramic materials. Therefore the risk of mechanical fatigue is high. As a result of the theoretical calculations an optimization of the element geometry shall be achieved. The optimization has to take into account the possibilities for an industrial fabrication of the elements, the possibility of a substitution in existing filter systems and of course a high filter area similar to the usual geometry has to be guaranteed.

Approach

At first a FEM-calculation was performed for the standard filter geometry assuming values for damping of the system and mechanical properties of the material. Based on these calculations variations of geometry and materials properties were made to minimize the risk of fracture.

Afterwards an experimental set-up was developed to investigate the vibration behavior of filter candles under a broad range of relevant frequencies and amplitudes at room temperature to increase the operational reliability of the whole plant. With the experimental equipment it was possible to determine the natural frequencies (eigenfrequencies) of the filter candles mounted on a part of a typical tube sheet and to test the long-term operation at these frequencies. The results can reveal local stresses and the fatigue behavior under these conditions and can deliver important data to improve filter candle design, candle fitting and material selection. Furthermore the experimental result validates the FEM-calculations.

Project Description

The mounting of a single filter element was simulated using the FE-program Abaqus^{TM} for the geometry of a standard filter element which is commercially available from the Schumacher Umwelt- und Trenntechnik Company, Germany. The overall length of the element is 1500 mm, the outer diameter is 60 mm and the wall thickness is about 10 mm. Due to the construction two possibilities for the stimulation of vibration are existing. On the one hand the filter element can pulsate due to oscillations in the gas stream, on the other hand vibrations from the filter system itself can influence the filter elements through the mounting. It is assumed that the vibrations through the mounting are critical. The mounting allows vibrations in horizontal and in vertical direction.

The FE-calculation to evaluate local strain, stress and the natural frequencies of the filter elements for the chosen geometry and alterations of this geometry was performed using an amplitude of 1 mm introduced at the mounting position. The frequencies were varied from 1 to 200 Hz for sinusoidal loading (see figure 1). The boundary conditions for the material were chosen with respect to standard materials like siliceous bonded silicon carbide. The density is 1.9 g/cm^3 whereas the Youngs-Modulus is about 34 GPa (see table 1). To simulate the mounting conditions a geometry shown in figure 2 was chosen with a simulated loading to the top to fix the filter element. Between filter element and plate a seal is mounted. The coefficient for damping ξ was chosen as 5%.

The experimental verification of the calculated results shall be performed by using an experimental setup with a mounting of one filter element similar to those in a commercial filter system. To accelerate the filter element at the position of mounting a shaker was installed. An overview and some details of the experimental setup are shown in figure 3. In figure 4 the position of acceleration sensors to measure the acceleration at different points of the element is drafted. The frequency of stimulation was varied in the range of 1 to 500 Hz. Up to now a comparison of the values for eigenfrequencies for several filter elements produced in one batch and a first test for long term vibration to provoke a failure of an element were performed.

Results

FE-calculation

Firstly the values of natural frequencies and the modes of vibrations were calculated. It can be assumed that the vibrations in the filter systems are in the region of 1 to 200 Hz as the maximum value. The calculation for the above defined standard element has resulted in a first natural frequency of 19 Hz and a second natural frequency of 119 Hz in consideration of the basic values for density, porosity, the Young´s modulus and the possions ratio. The third natural frequency is at 329 Hz and the fourth one at 460 Hz. In regard to the order of natural frequencies shown in Figure 5 the local stresses are maximum at the top of the elements where the element is fixed at the mounting plate (see Figure 6).

Thus it can be assumed that either during start-stop cycles of the plant or during operation the vibrations in the filter system are of the magnitude of the natural frequencies. Therefore high local stresses will be generated. Different possibilities to reduce the stress and to modify the stress distribution are existing. First of all one have to think of alternations of the material. Taking into account that a changing in materials properties are counterproductive for the resistance against high temperature deformation or the filtration efficiency the possibilities for variations are very small.

If the Youngs-modulus is increased, the values for natural frequencies are shifting towards higher values. However, such a shifting results also in an increase of stress. For example an increase from a Youngs-modulus of 25 GPa to 50 GPa results in an increase of maximum stress by a factor of 2, whereas the second natural frequency of a standard element with a length of 1500 mm shifts from 100 Hz to 150 Hz. If the density of the material is increased too, the natural frequencies will decrease. For example an increase of density from 1.9 g/cm^3 to 2.5 g/cm^3 will decrease the second natural frequency from 119 Hz to 100 Hz. Remarkable is that the maximum stress is not affected by the increase of density. A variation of poisons-ratio in a reasonable interval from 0.1 to 0.3 has no effect to frequency or to maximum stress.

The calculated stress depends strongly on the assumed coefficient of damping. Therefore the absolute values should not be overestimated and will not be mentioned in this publication, except if it is necessary for a better understanding. Moreover the comparison between the stress levels for different geometry should be considered as it is shown as follows.

It is obvious that a variation of length results in a variation of natural frequencies. This is well known from the behavior of a lot of components. In our example the first natural frequency will change from 43 Hz for an element length of 1000 mm to 11 Hz for an element with a length of 2000 mm. The behavior of maximum stress has not such a clear dependency. The resulting maximum stress value for the different length of elements is shown in figure 7. It can be seen that the maximum stress is three to four times higher at a length of 1000 mm (at 43 Hz) compared to the stress at a length of 2000 mm (at 19 Hz). It can be concluded that the length of an element should be chosen with regard to the expected frequency of vibration in the filter system. If it can be assured that the frequency in the system will always be lower than a certain value the length should be chosen as short as possible; always taken into account that the cost for the filter system will increase due to more effort to mount the single elements when the same filtration area will be achieved.

In addition to the length of an element the variation of inner or outer diameter (and therefore the thickness of the element which can influence the pressure drop during filtration) can influence the behavior at system vibrations. An increase of wall thickness will always result in a decrease of the values for natural frequencies. When both the inner and the outer diameter are changed and the wall thickness is constant at 10 mm the frequencies will changes too. A variation from 60 mm outer diameter to 70 mm outer diameter leads to a small increase in natural frequencies. However, the maximum stress increases too.

Another possibility to change the natural frequencies and the maximum stresses is given by the mounting of additional weight to the filter elements. This can be achieved for example by using a thick bottom section which is not useful for the filter operation. The effect is, however, small. In table 2 the results for variation of maximum stress and natural frequencies caused by alterations of material properties and the geometry of the filter element are summarized.

A change of the geometry to conical elements would favorable the stress level and the stress distribution. This can lead to a reduction of the risk of mechanical fatigue. But such a variation necessitates new production facilities and maybe new constructions for mounting. Additional the effective filtration area has to taken into account.

Experimental

A set of siliceous bonded silicon carbide filter elements with properties similar to those described for the finite element calculations was investigated in the above mentioned experimental device. Firstly the values of natural frequencies at one filter element were measured. The obtained values were in good correlation to those calculated in finite element analysis as well as in analytical calculations.

Secondly the variations of frequencies within one batch of element production were investigated. Figure 8 shows as an example the spectrum of frequencies for three elements. It is obvious that the three elements are similar with respect to the values of natural frequencies as well as for the values of acceleration. The example is shown for the acceleration sensor located at the bottom of the element in the direction of vibration at the top of the filter element.

However, it can be seen that the second natural frequency which was calculated to 119 Hz for the investigated elements is not exact located at these value. Moreover due to the small deviations in shape and geometry a high acceleration was measured for a broad range of frequencies. In addition it could be observed that the acceleration has different maximum values at similar frequencies. Therefore the risk of fracture due to vibrations differs from one element to other elements.

One of the elements was chosen for performing long term vibrations experiments. Due to experimental demands the experiment was interrupted every hour. The external frequency was chosen as the second natural frequency of the element while the acceleration was constant at 1 g. After more than 20 hours of operation no alteration of the spectrum of natural frequencies could be measured. No fracture could be observed. Unfortunately due to some problems with the experimental equipment further results are missing yet.

Summary

In addition to the thermal loading a mechanical fatigue can be caused by vibrations of the filter systems or vibrations of plant components which are connected to the filter systems.

The highest local stresses will occur at the values of natural frequencies. Therefore this level was investigated.

It is assumed that the vibrations in the filter systems are in the region of 1 to 200 Hz as the maximum value. FEM-calculations for a standard element yield to a first level of natural frequency at 19 Hz and a second level of natural frequency at 119 Hz. At these values the local stresses have a maximum at the top of the elements where the candle is fixed to the tube sheet.

The simulation of different geometries shows that a reduction of length leads to a significant shift of the natural frequencies to higher values. The local stresses, however, are sometimes even higher than for standard elements. A variation of the inner and outer diameter to acceptable values leads only to slight changes of the natural frequencies but yield to significant reductions of stresses. A change to conical elements or an adaptation of additional weights is a promising approach to reduce stress levels and to optimize stress distributions. The analysis of geometry has shown that changes in filter design can influence significantly the vibration behavior of the filter elements and therefore the operational reliability of the whole filter system. Some variations are possible without changes of material, which could also lead to alterations in the mechanical performance and filtration efficiency.

In some basic experimental investigations the main results of the simulation were confirmed. The calculated values of natural frequencies were in the same order of magnitude as the measured ones. However in these investigations no fracture of a filter element could be achieved yet.

Future Activities

The FE-calculations were finished, however, the experimental confirmation of the theoretical results is only done yet for the values of natural frequencies. Therefore more long term experiments with respect to investigate the growth of natural flaws in the elements have to be performed. Afterwards some variations of geometry should be experimentally investigated. For doing this it is in some cases necessary to produce new filter elements which is a high effort. However, some experiments maybe can be performed by adding small additional elements to the existing geometry.

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Figures and Tables

See next pages.

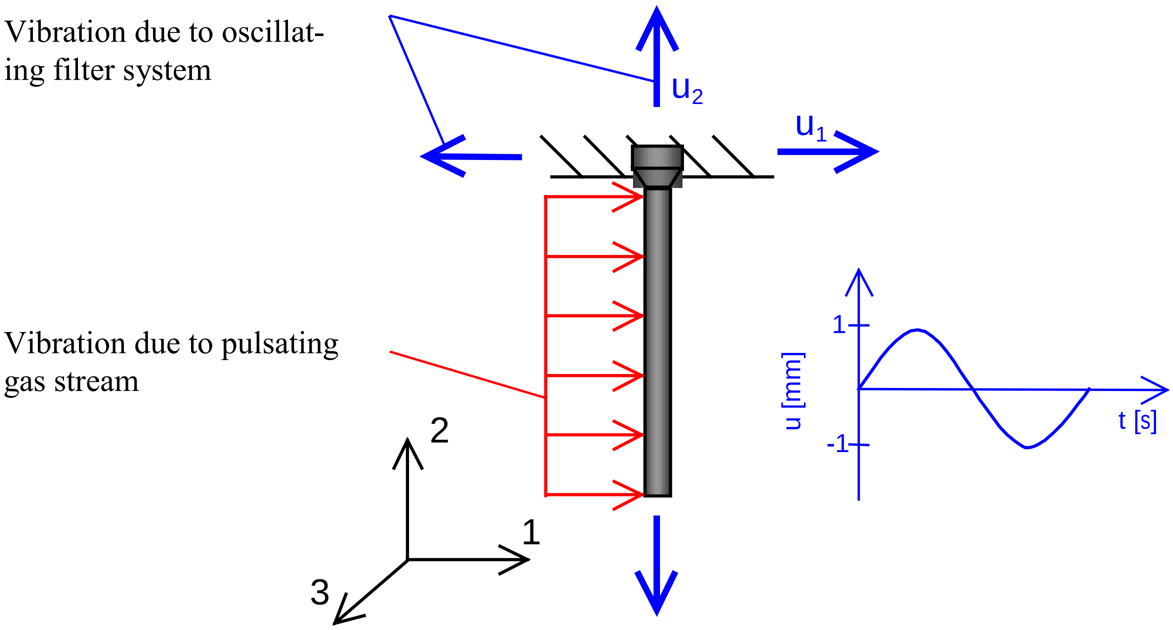

Figure 1: Mechanical boundary conditions for the FE-calculation.

Youngs-Modulus E	34 GPa
Poisson-ratio υ	0,2 (assumed)
Density ρ	1,9g/cm^3
Porosity	~37%
Strength	~20MPa (measured in 4-point bending mode)

Table 1: Properties of the silicon carbide materials used for the Finite-Element-calculation.

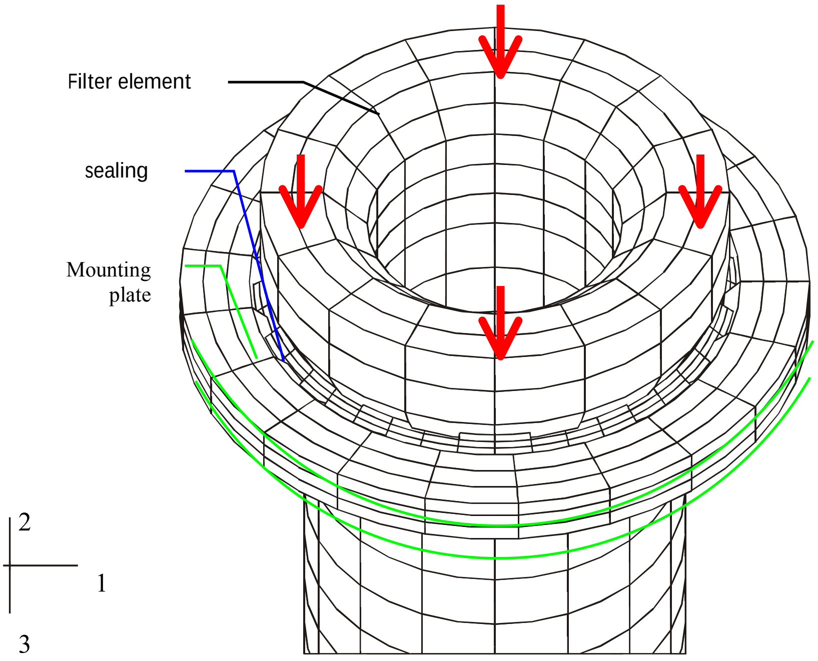

Figure 2: Mounting of Elements.

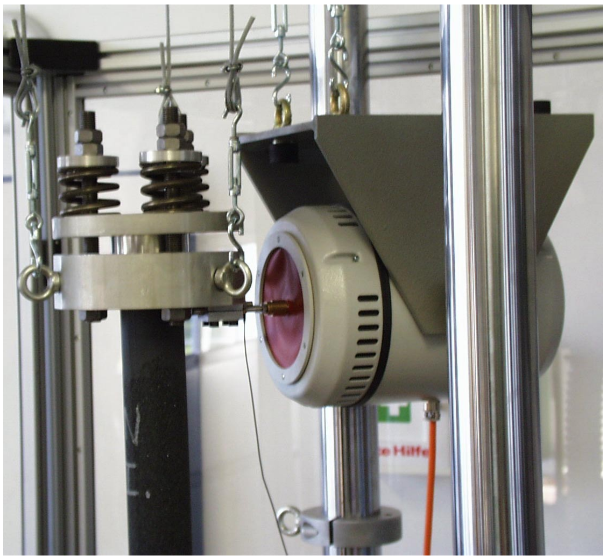

Figure 3: View of the experimental setup for the investigation of vibration behavior and detail of the acceleration drive coupled to a filter element.

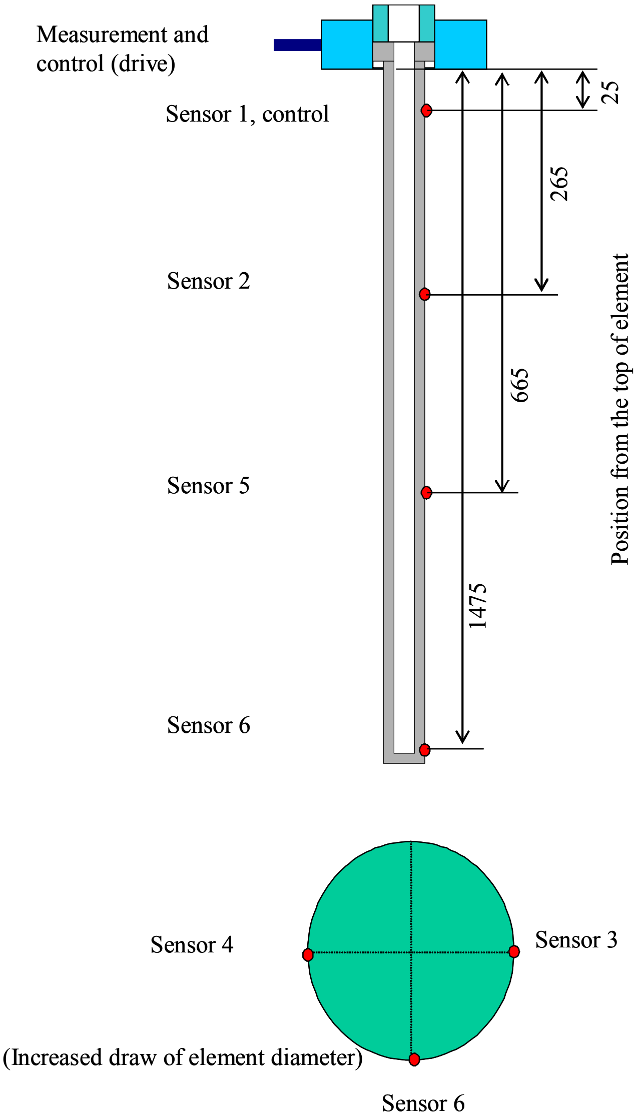

Figure 4: Positions of acceleration sensors at the filter elements.

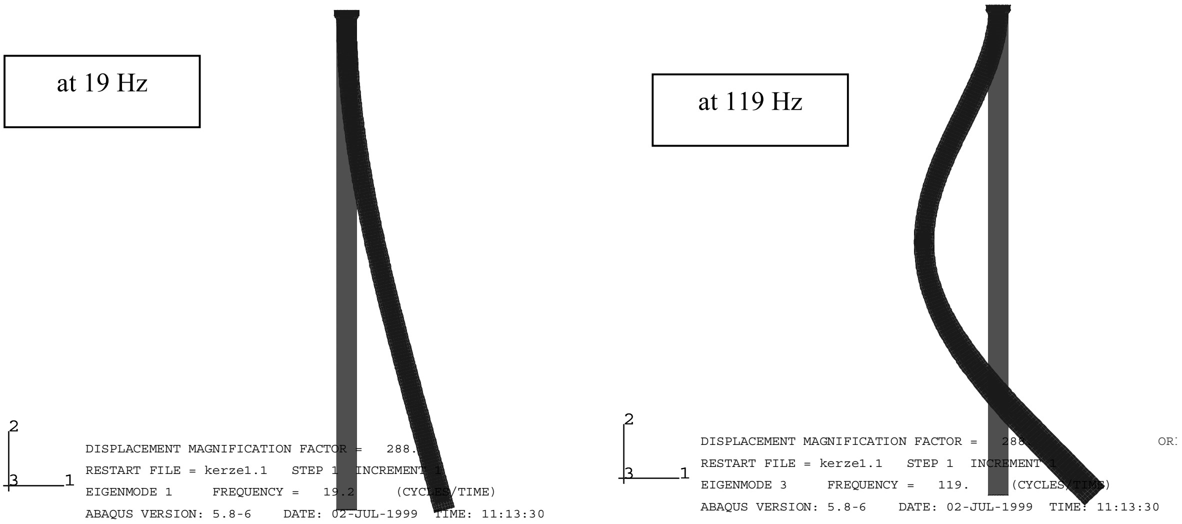

Figure 5: Modes for the first and the second natural frequencies of a standard element with a length of 1500 mm an 40/60 mm inner /outer diameter.

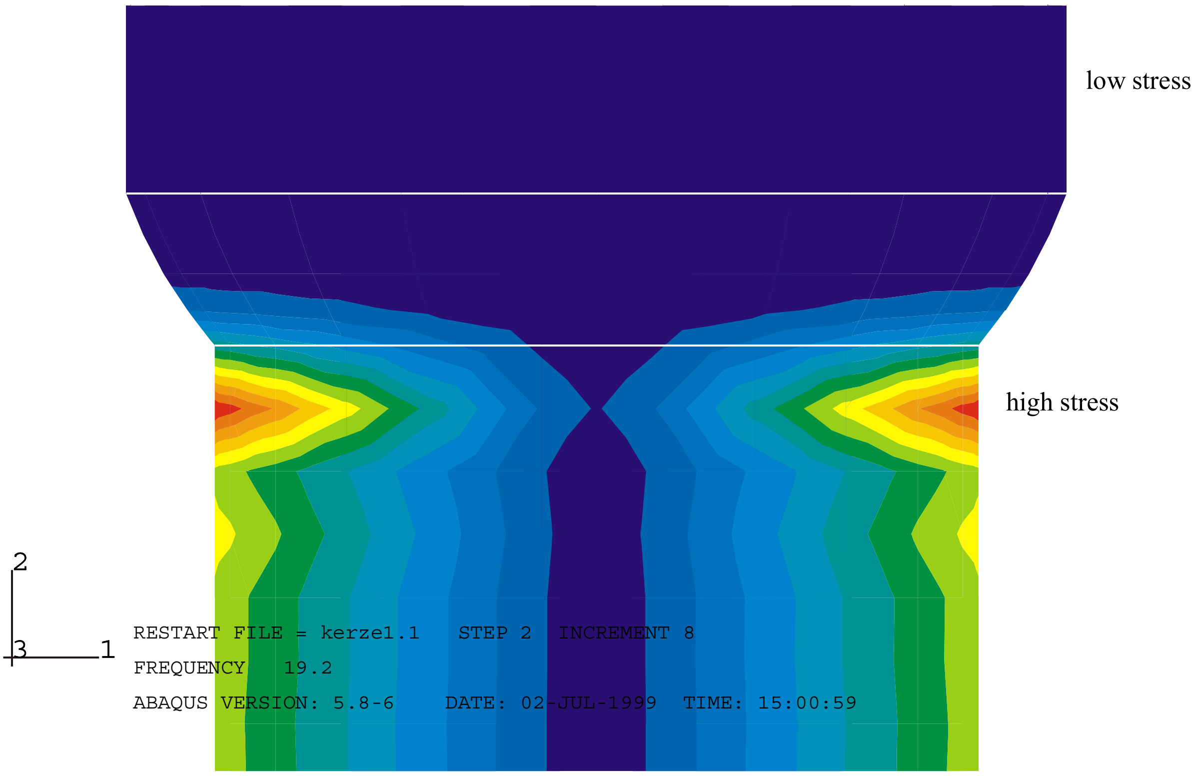

Figure 6: Stress distribution at the top of a filter element.

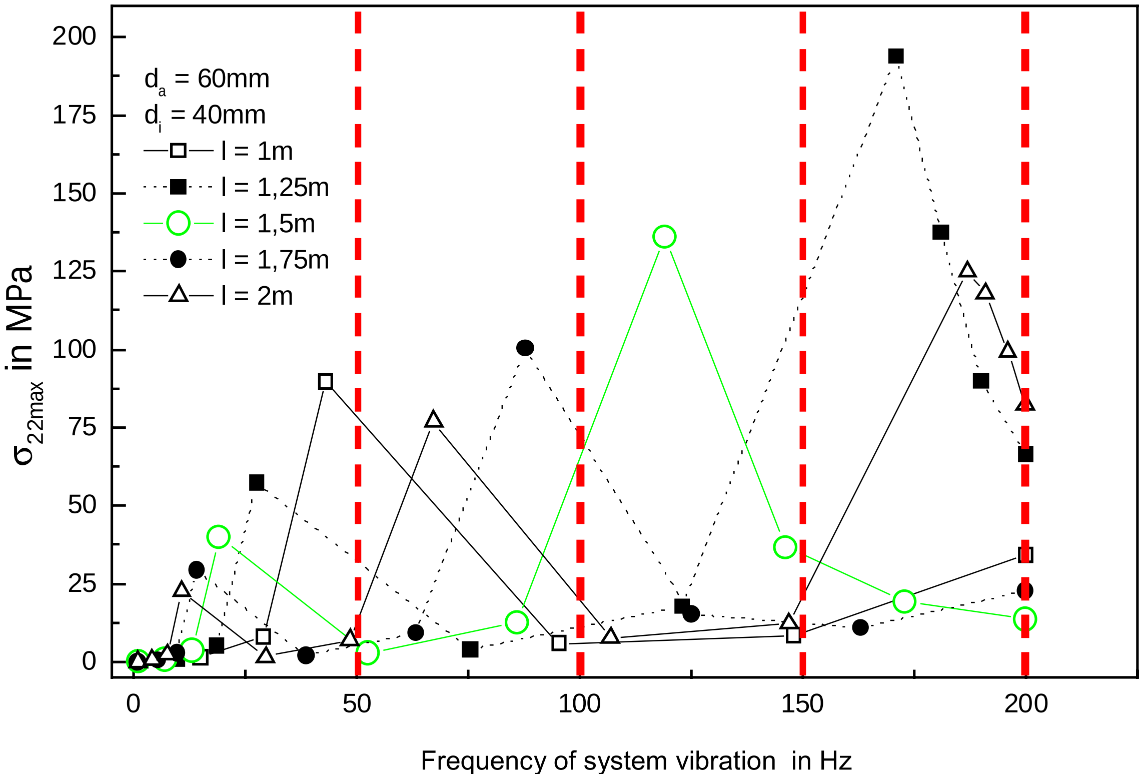

Figure 7: Effect of element length to maximum stress at different frequencies.

Increase of:	Natural frequencies	Maximum stress level
Youngs-modulus	↑	↑
Density	↓	↔
Possion-ratio	↔	↔
Length	↓	see results
Outer diameter	↑	↑
Inner diameter	↑	↓
Weight at the bottom	↓	↓

Table 2: Variation of maximum stresses and natural frequencies caused by alterations of material properties or the geometry of the filter element.

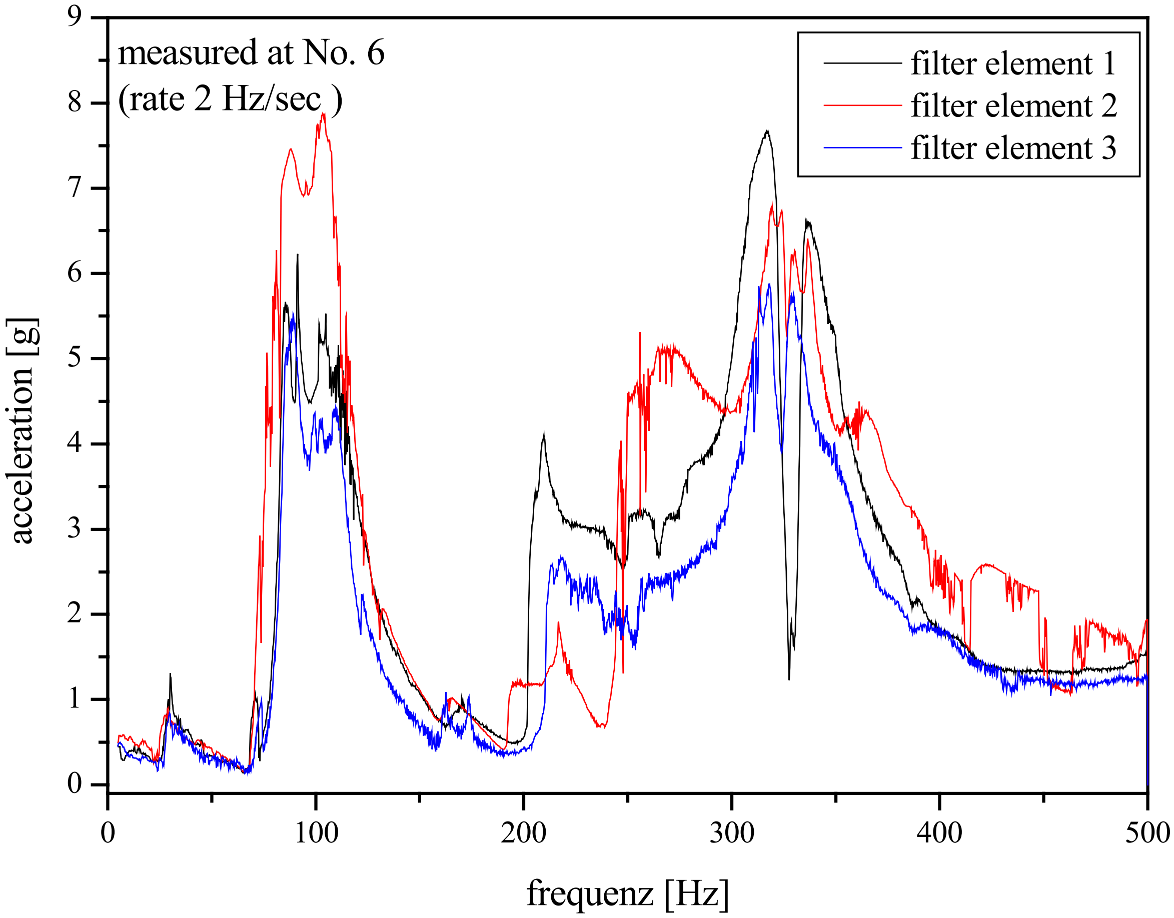

Figure 8: Values of acceleration for three filter elements (all elements from same batch).