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Acoustics of Rocket Combustors Equipped with Absorber Rings

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The performance of absorbers dissipating acoustic energy in rocket combustion chambers is investigated experimentally in cold flow tests. Applying procedures already used in a former investigation on the damping of eigenmodes in a combustor equipped with one absorber, the investigation is extended to absorber rings composed of multiple absorbers. It is shown by experiments and numerical modal analysis that due to the coupling of the additional resonance volumes of the absorbers and the cylindrical combustor the eigenfrequencies of the system are shifted to lower values. For typical lengths of absorbers tuned to the 1T-mode peaks are found in the resonance spectrum that do not correspond to the frequencies of cylinder modes. A general systematics of an absorber ring with N absorbers tuned to the 1T-resonance is presented. Measurements of the damping rate of the modes as a function of the absorber length have been done and are compared with admittance data derived from numerical modal analysis.

Nomenclature

A	area
D	diameter
f	frequency
L	length
m	mode number
N	number of absorbers
P	perimeter
R	radius
λ	wavelength

Subscript

A	absorber
C	combustor

I. Introduction

The development of combustion instabilities originating from the transfer of energy from the combustion process into acoustic excitations of the combustion chamber constitutes a severe risk for rocket combustors. If the evolution of instabilities cannot be suppressed for instance by proper tuning of the propellant injection process specific devices may be added to the combustor in order to dissipate acoustic energy and thus achieve stable and save operation of the engine.

Quarter-wave cavities are an example for such damping devices.[1–3] Usually multiple $\lambda/4$-cavities are mounted on the circumference of the chamber liner near to the injector faceplate. Although the adjustment

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of the length of these absorbers seems to be straight forward using basic principles, in practice the tuning of the cavities appears to be a difficult task. In former investigations[4,5] it has been shown that with the application of a single quarter-wave tube to a combustion chamber the eigenfrequencies of the combustor differ significantly from cylinder modes which are usually assumed to reflect the basic properties of the eigenmodes of rocket combustors. Due to the coupling of an additional resonance volume to the cylindrical combustor its eigenfrequencies are shifted to lower values. In preliminary investigations of a chamber equipped with an absorber ring consisting of 40 absorbers a similar phenomenology has been found.[5]

This paper presents a systematic analysis of a combustion chamber acoustically coupled to an absorber ring with absorbers of identical length. In cold flow experiments the resonance frequencies of the combustion chamber with absorber ring are determined and compared to the situation of a combustion chamber without absorber ring. As will be shown the coupling of the absorber ring to the resonance volume of the chamber significantly changes the resonance frequencies of the chamber.

In previous work on a combustor with one absorber numerical modal analysis has been shown to contribute essential information for the understanding of the experimental results.[5] Similarly for the configuration with an absorber ring a systematic numerical modal analysis of the coupled acoustic system is done and the eigenfrequencies are determined as function of the absorber length. By analyzing the spectra of absorber rings with different number of absorbers a general behavior is found how the resonances of the coupled system are organized. A rough approach is used for a qualitative evaluation of absorber admittance in order to address the question of damping behavior.

II. Test Setup

A. Combustion Chamber and Absorber Ring

The acoustic coupling of an absorber ring with a cylindrical combustion chamber has been investigated in a model combustor used in the frame of the steam generator development program at DLR Lampoldshausen.[6] In figures 1 and 2 the steam generator model combustor and the absorber ring are shown. For the analysis of tangential modes a closure plate has been mounted inside the steam generator chamber in order to shorten the length of the resonance volume as shown in the sketch in figure 3. With the closure plate the frequencies of the longitudinal modes are shifted to higher values thus they do not interfere any more with the frequencies of the tangential modes in the investigated frequency region. The frequencies of the tangential modes are practically not influenced by the application of the closure plate.

The resonance volume was filled with ambient air during the tests. The measured frequencies are therefore about a factor of 4 below that expected in hot fire tests.

The absorber ring consists of 42 absorbers. The distribution of the absorbers around the circumference is symmetrical, however at three circumferential positions there is a gap between neighboring absorbers and thus the perfect symmetry is broken. The diameter of the absorbers was 8mm and the length of each absorber can be adjusted individually. In the frame of the activities up to now, all absorbers were tuned to identical length. The mesh used for numerical modal analysis is shown in in figure 4.

B. Instrumentation

For the investigations presented here the injector head of the steam generator had been replaced by a face plate. The face plate has two ports for the mounting of a microphone and a loudspeaker. The microphone and the loudspeaker can be seen figure 2 in the upper and lower part of the face plate respectively.

Acoustic waves can be generated in the resonance volume by exciting the loudspeaker with specific signals. A synthetic white noise signal is used to obtain an overview over all resonances during one measurement. For the analysis of individual modes also single frequency excitation is applied. The loudspeaker is operated for a short time interval and then switched off. The following decay of the acoustic wave is then recorded by the microphone. The signal is Fourier transformed to obtain frequencies and damping characteristics of the excited modes. The approach has been described in more detail in the work of Oschwald et al.[5] which was treating the performance of a single absorber.

Figure 1. Steam generator combustion chamber.

Figure 2. Absorber ring mounted to the steam generator.

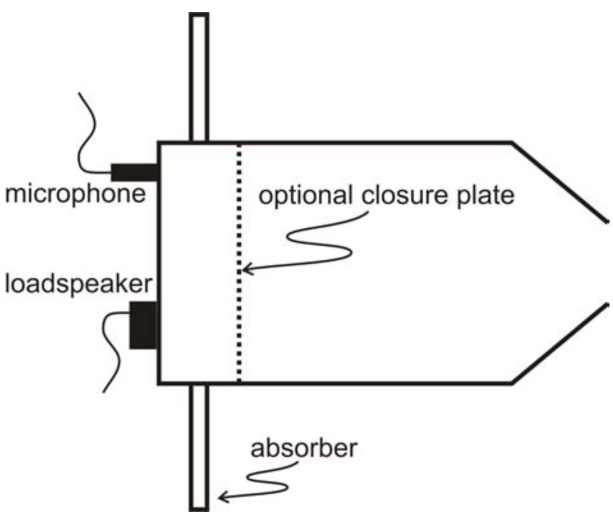

Figure 3. Sketch of steam generator setup.

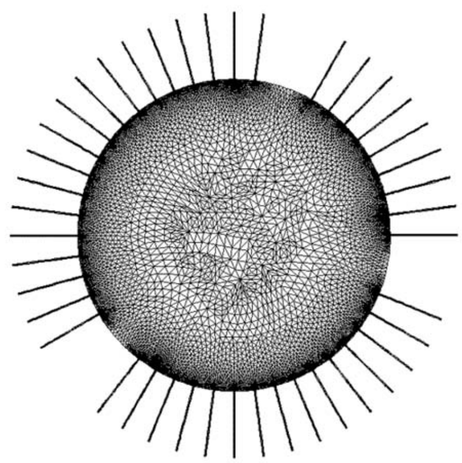

Figure 4. Mesh used for modal analysis of the combustor with absorber ring.

III. Numerical Modal Analysis

A. Resonance frequencies

Eigenmodes of the coupled acoustic system consisting of combustor and absorber ring have been investigated by numerical modal analysis using the commercial software FlexPDE. For the modal analysis the real 3D-geometry has been approximated by a 2D projection with the same radius R_C for the combustor and with scaling the absorber diameters D_A such that the ratio of absorber diameter D_A to combustor perimeter $P_C = 2\pi R_C$ corresponds to the absorber to resonator area ratio of the 3D geometry:

$$\frac{D_A}{P_C} = \frac{A_A}{A_C}$$

where A_A is the cross sectional area of the absorber and A_C the surface of the cylindrical part of the combustor. The modal analysis delivers the resonance frequencies of the eigenmodes and the spatial distribution of the acoustic pressure and velocity fields, $p'(\vec{r})$ and $\vec{v}(\vec{r})$.

B. Absorber admittance

A discussion of the absorber performance with respect to the damping behavior is done based on the acoustic field of the eigenmodes. The objective here is a qualitative evaluation on how the absorber length influences the damping behavior. The approach does not aim to provide a quantitative estimation of damping constants. Searby et al.[7] showed an elegant way how to derive from the numerically obtained acoustic eigenmode a quantitative prediction of acoustic damping. We are currently implementing their method in our numerical tools. As this work is still not finished, here the same procedure is used as for the analysis of the single absorber described in a previous article.[5] It is assumed that the major contribution to the damping processes originates from the absorber inlet region. The velocity field of the modes is evaluated in this inlet region and a non-dimensional parameter γ_C is derived which has the physical characteristics of an acoustic admittance.

IV. Results

A. Eigenfrequencies and Eigenmodes

Eigenspectra of the combustor without and with absorber ring are shown in figure 5. For the combustor without the absorber ring the 1T-, 2T-, 1R-, and 3T-modes have been observed in the spectral range analyzed. The measured resonance frequencies f_{1T}, f_{2T}, f_{1R}, and f_{3T} are in excellent agreement with the prediction for cylindrical resonance volumes.

With the application of the absorber ring with absorbers of specific length the resonance frequencies are found to be strongly dependent on the length of the absorbers. The data shown for the case with absorber ring are obtained for an absorber length of L_A=0.82$\cdot R_C$ where R_C is the radius of the combustor. This length is very near to that of a $\lambda/4$-cavity tuned to the 1T-frequency, where the length would be L_A=0.85$\cdot R_C$. The resonance spectrum shown in figure 5 is thus typical for an absorber ring tuned to damp the 1T-mode. A resonance is seen at the frequency of the 1R-resonance. Two resonances are seen shifted slightly to lower and higher frequencies as compared to f_{2T} and f_{3T} respectively. The most significant effect of the absorber ring is seen in the region of the 1T-frequency. Instead of a single line near to f_{1T} two resonance peaks are observed. The two peaks are significantly shifted, one to a lower, the other to a higher frequency as compared to the 1T-frequency. These two peaks are labeled 1T$^-$ and 1T$^+$. These two resonances will be discussed in more detail below and the justification for the label assignment will be given thereafter.

More insight in the situation is obtained when looking on the eigenfrequencies of the acoustic system as a function of the absorber lengths. The resonance frequencies as function of the absorber length obtained by numerical modal analysis are shown in figure 6. The values for the 64 modes with the smallest eigenvalues are plotted. With increasing absorber length all modes are seen to be detuned to lower frequencies. The resonances of the combustor without absorber ring (L_A/R_C=0) are plotted as colored dash-dotted lines and the frequencies of the $\lambda/4$- and $3\lambda/4$-resonances are shown as black dash-dotted lines in figure 6. Obviously the frequencies of the coupled acoustic system are found preferably near the resonance frequencies of either one of its components.

The black dotted line in figure 6 marks the absorber length for which the experimental spectrum shown in figure 5 for L_A/R_C=0.82 has been obtained. The two predicted modes with the lowest eigenvalues have

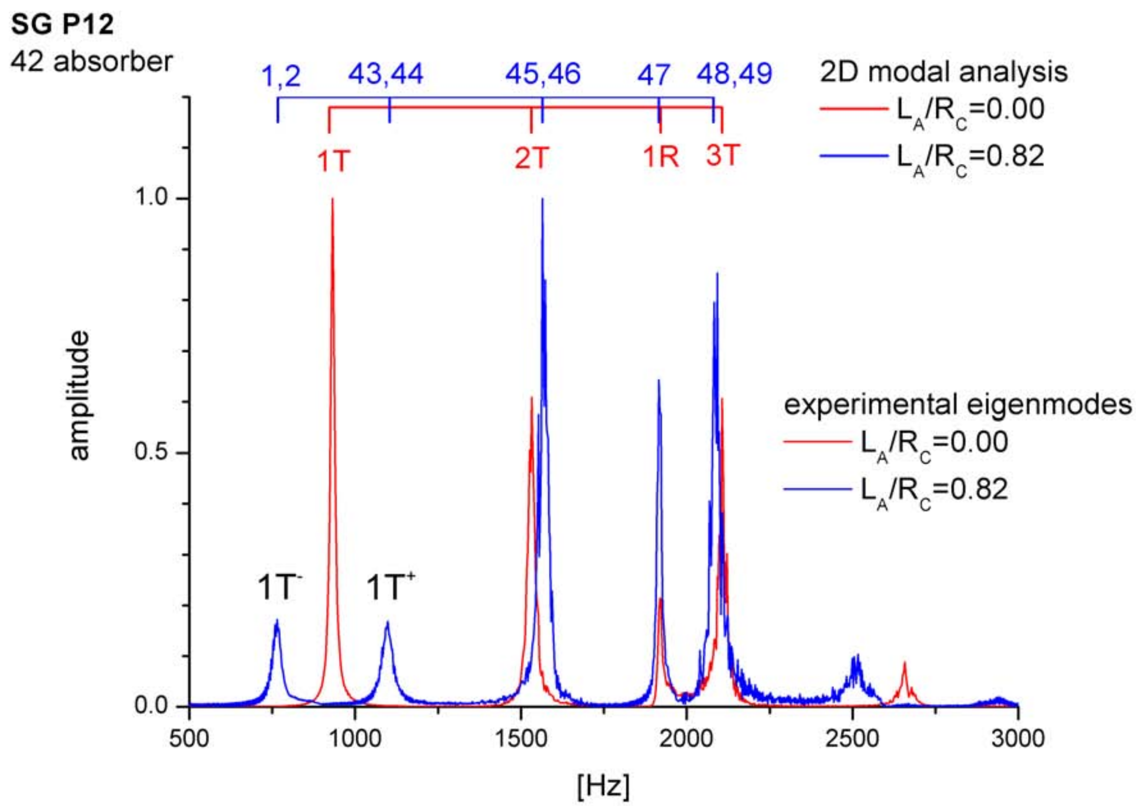

Figure 5. Eigenfrequencies of the SG combustor without (blue) and with (red) absorber ring.

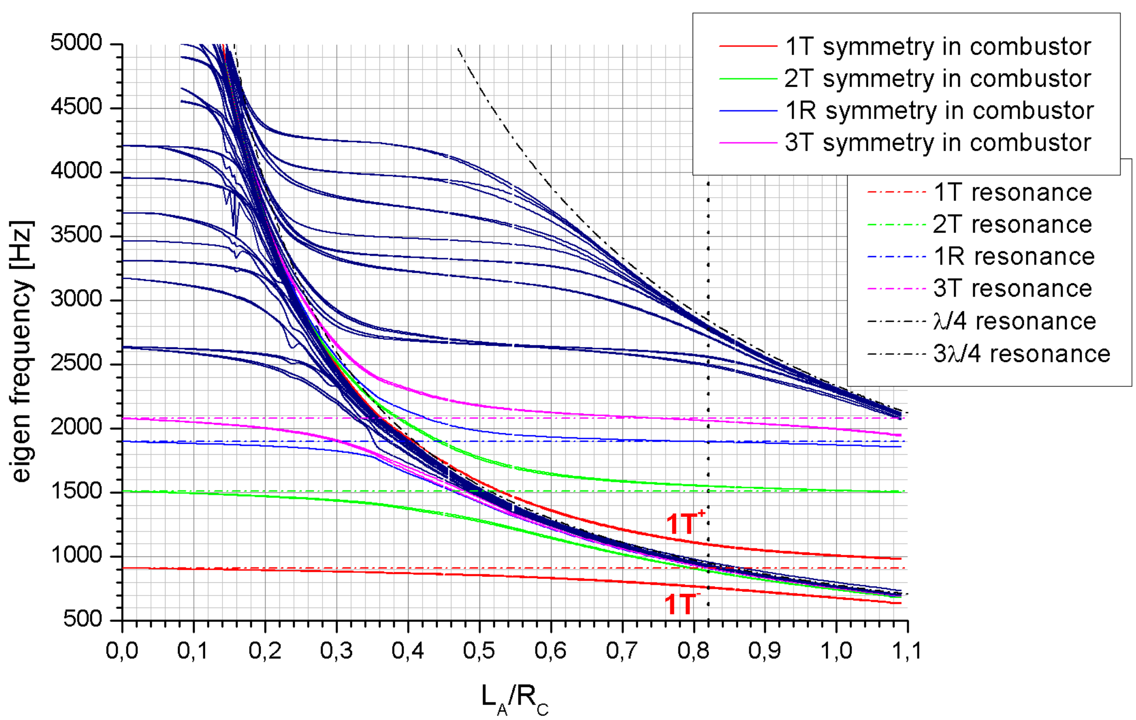

Figure 6. Eigenfrequencies of the modes of a combustor with absorber ring as predicted by FlexPDE

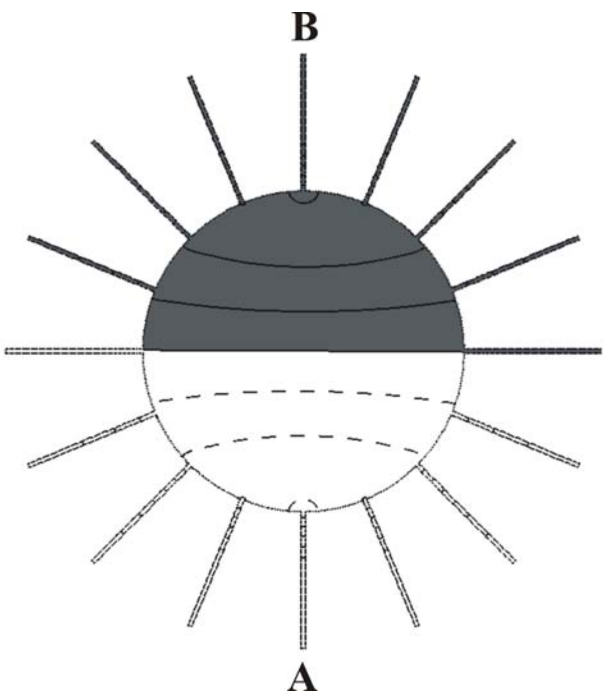

Figure 7. Acoustic pressure field p' for the $1T^{-}$-mode.

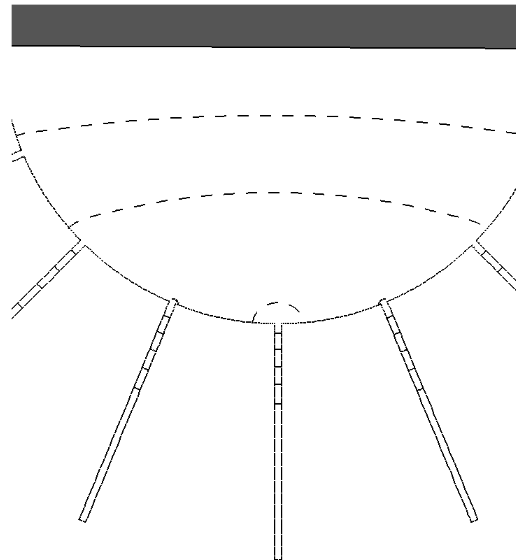

Figure 8. Zoom on the acoustic pressure field p' for the $1T^{-}$-mode in the absorbers.

about the same resonance frequencies, the splitting of which cannot be resolved in figure 5. These frequencies match that of the 1T mode in the limit $L_A \rightarrow 0$. For the combustor without absorber ring there is perfect rotational symmetry and there are two degenerate 1T-modes with their nodal lines perpendicular to each other. The eigenmodes for the case with absorber ring are labeled according the size of their eigenvalue, the lowest lying modes are therefore labeled m=1 and m=2 in figure 5. The pressure distribution for mode m=1 is shown in figure 7 and exhibits the symmetry of a 1T-mode. For that reason the assignment $1T^{-}$ has been chosen to express the symmetry properties of the mode in the combustion chamber and its relative position with respect to the 1T-resonance.

As concluded from the high values of the admittance γ_C derived from the pressure distributions all the modes who's frequencies are clustering near the $\lambda/4$ asymptote are so strongly damped, that they were not visible in the experimental spectrum.

Indeed it is just the mode with m=43 that has a resonance frequency above the $\lambda/4$ asymptotic line. The mode is rather degenerate with mode m=44. Both modes exhibit the symmetry of a 1T-mode in the combustor volume, the acoustic pressure field for mode m=43 is shown in figure 9. To reflect this symmetry the resonance is assigned as the $1T^{+}$-mode. Generally it is observed that all modes who's eigenfrequencies are near to that of a cylinder eigenmode are showing the symmetry of this eigenmode in the combustor domain of the resonance volume, independent what the symmetry of the mode in the limit $L_A \rightarrow 0$ was.

Although the $1T^{-}$- and $1T^{+}$-modes show similar symmetry in the combustor their pressure fields in the absorbers exhibit a systematic difference. For the $1T^{-}$-mode the 1T-symmetry is valid for the complete resonance volume, there is one nodal line on the symmetry axis of the domain as shown in figure 8. A zoom into the absorber area for the $1T^{+}$-mode instead resolves another nodal line in the absorbers near to their inlet as presented in figure 10. Although both modes have a similar acoustic pressure field in the combustor domain their pressure fields in the absorbers is significantly different. Values of the p' and v along the lines $\overline{AB}$ in figure 7 and 9 are shown in figure 11 and 12. These profiles clearly demonstrate the similarity of the acoustic fields in the combustor domain and the systematic difference in the absorber domains. The acoustic field in the absorbers and especially near the absorber inlet is regarded as controlling by a major part their damping performance. One therefore can expect that both modes show different damping characteristics as function of the absorber length. The damping behavior of the two modes will be discussed in section B below.

The systematics how the modes are arranged for a given absorber ring the spectrum of the steam generator

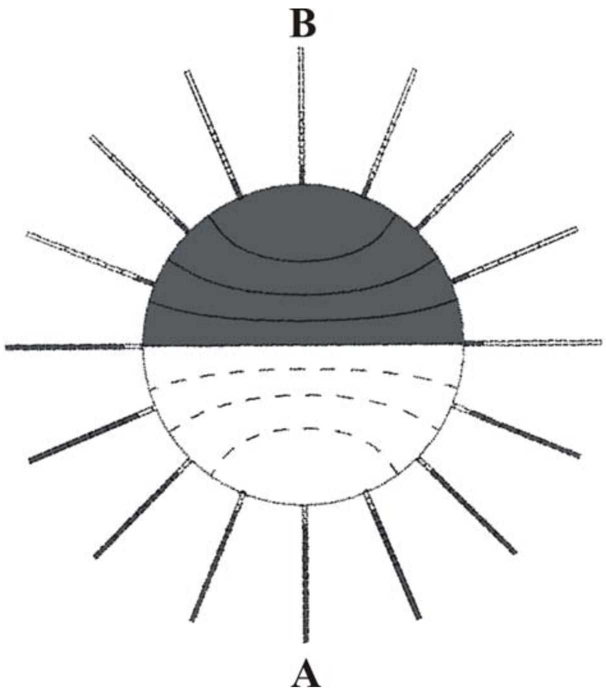

Figure 9. Acoustic pressure field p' for the $1T^{+}$-mode.

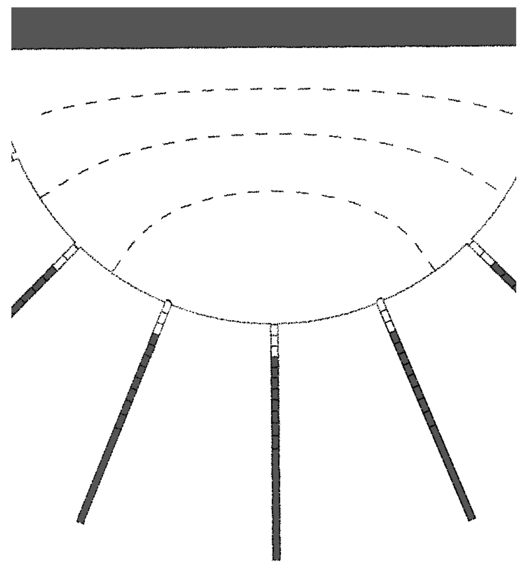

Figure 10. Zoom on the acoustic pressure field p' for the $1T^{+}$-mode in the absorbers.

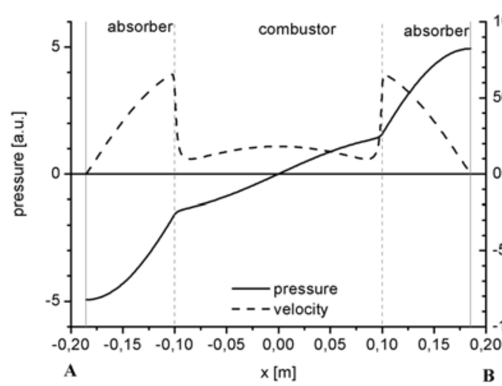

Figure 11. Profiles of p' and v along the line $\overline{AB}$ for the $1T^{-}$-mode (see figure 7).

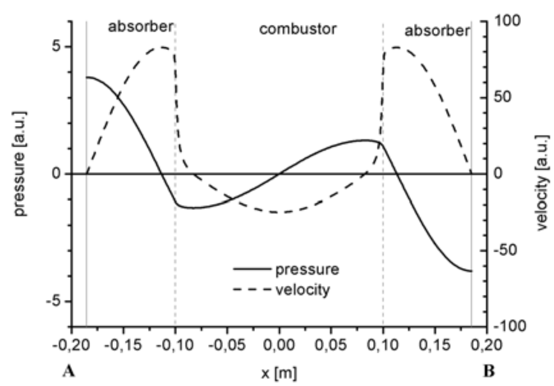

Figure 12. Profiles of p' and v along the line $\overline{AB}$ for the $1T^{+}$-mode (see figure 9).

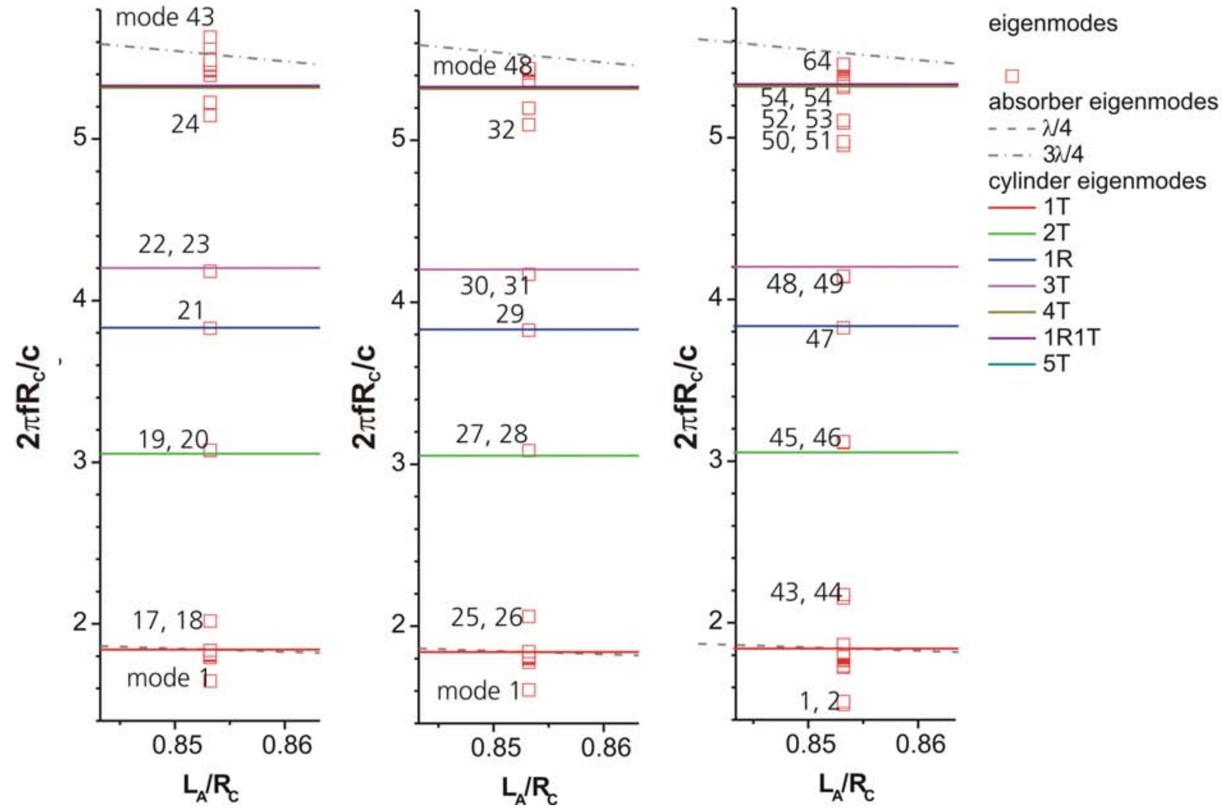

Figure 13. Resonance frequencies for the steam generator with an absorber ring equipped with 16, 24, and 42 absorbers.

with 42 absorbers has been compared to eigenspectra for absorber rings with 16 and 24 absorbers. The results are shown in figure 13 for an absorber length $L_A/R_C = 0.85$ corresponding to absorber cavities tuned to about the $\lambda/4$ resonance. For all three configurations eigenfrequencies are obtained that produce very similar spectra. From these results following general characteristics has been derived for the spectrum when an absorber ring with N absorbers tuned to the $\lambda/4$-resonance of the 1T-frequency is applied:

modes m=1,2:	$f_m < f_{1T}$, 1T-symmetry in the combustor volume (1T$^-$-mode)
modes m=3, ..., N:	$f_m \approx f_{1T}$, strongly damped and not visible in the spectrum
modes m=N+1, N+2:	$f_m > f_{1T}$, 1T-symmetry in the combustor volume (1T$^+$-mode)
modes m=N+3, N+4:	$f_m \approx f_{2T}$, 2T-symmetry in the combustor volume
modes m=N+5:	$f_m \approx f_{1R}$, 1R-symmetry in the combustor volume
modes m=N+6, N+7:	$f_m \approx f_{3T}$, 3T-symmetry in the combsutor volume
modes m=N+8	$f_m \approx 3/4\lambda$-resonance, strongly damped and not visible in the spectrum

Following this analysis it has to be noted that if a modal analysis shall cover the 1T$^+$-resonance at least the first N+2 eigenmodes have to be determined for an absorber ring consisting of N absorbers.

B. Damping of Acoustic Excitations

Apparently the line widths of the 1T$^-$- and 1T$^+$-peaks are larger than that of the 1T-resonance as can be seen in figure 5. As the line width is a measure for the damping rate[5] this proves that the application of the absorber ring results in a stronger damping of the 1T$^-$- and 1T$^+$-resonances as compared to the 1T-resonance for the combustor without absorber ring. The widths of the 1T$^-$- and 1T$^+$ resonances have been determined for absorber lengths ranging from L_A/R_C=0.4 to 1.0 and the measured data are shown in

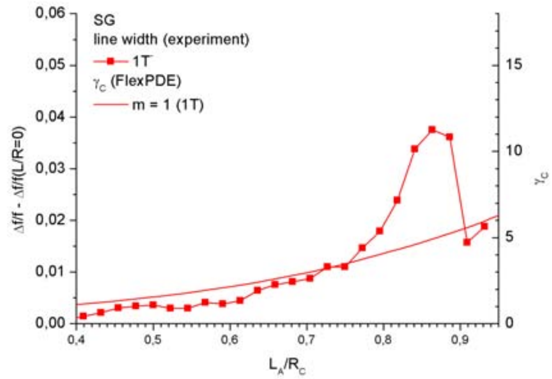

Figure 14. Measured line widths (filled symbols) and admittance γ from modal analysis (open symbols) for the 1T^{-}-mode

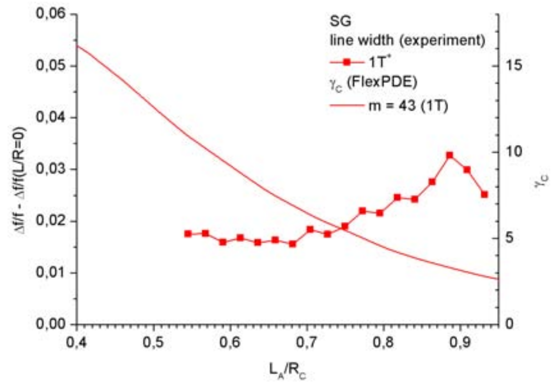

Figure 15. Measured line widths (filled symbols) and admittance γ from modal analysis (open symbols) for the 1T^{+}-mode

figures 14 and 15. In these figures the line widths have been corrected by the value for L_A=0, thus only the contribution of the absorber ring to the overall damping of the acoustic system is shown.

The 1T^{-}-resonance shows increasing damping with increasing absorber length with a maximum damping near to L_A/R_C 0.85. The 1T^{+}-resonance is strongly damped for absorber lengths below L_A/R_C ≈0.5 and the line width could not be measured due to the small resonance intensities. For L_A/R_C >0.5 a increase of the damping is observed with a maximum near to L_A/R_C ≈0.9. For both modes maximum damping is obtained for absorber lengths near to L_A/R_C ≈0.85, the length of a tuned λ/4-cavity.

The values of the admittance parameter γ_C derived from the numerically determined eigenmodes for the steam generator absorber ring are included in figures 14 and 15. For the 1T^{-}-mode the increase of the damping with increasing absorber length is well reproduced by γ_C, however the peak near to L_A/R_C ≈0.85 is not predicted. For the 1T^{+}-mode the admittance parameter γ_C does not show the measured increase of the damping for L_A/R_C >0.5, nor does it exhibit a maximum as seen in the experimental data near to L_A/R_C ≈0.9. The admittance parameter γ_C obviously not does work properly for the prediction of damping behavior for absorber rings, although it had shown good agreement with experiments for the case of an combustor equipped with one absorber.[5]

V. Summary and Conclusions

The application of an absorber ring to a combustion chamber changes the resonance spectrum of the coupled acoustic system significantly as compared to the combustor alone. Especially for absorbers tuned to the 1T-resonance of the cylindrical combustor volume the system exhibits new resonances that were not present in the combustor without absorbers. This finding is of relevance for investigations of rocket combustors equipped with absorber rings. Resonances found in the spectrum of the dynamic pressure near the 1T-frequency cannot be simply identified with the 1T-mode of a cylindrical resonator. Instead two resonances exist in the vicinity of the 1T-frequency. Each resonance belongs to two rather degenerate modes that both exhibit 1T-symmetry in the combustor volume. In the absorber volumes however the acoustic fields of these two resonances show significant differences. When addressing the question of the damping behavior of the absorbers this has to be taken into regard.

Numerical modal analysis has been shown to predict the eigenfrequencies of the coupled acoustic system with excellent agreement to experimental data. From these investigations it is learned that for an absorber ring consistiting of N absorbers at least the first N+2 eigenmodes have to be determined in order to identify all modes with 1T-symmetry in the combustor volume.

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