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SchAve: preliminary test of silencer prototype in a high-pressure test bed with ignited combustor.

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Projects: Silentium, Blue-Sky-AT-TRA, Leiser Antrieb.

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1. Introduction

The acoustic environment in combustor test facilities is relevant for environmental-noise contamination and comfort plus safety for the personnel conducting tests. Environmental noise contamination can occur due to the extremely high levels in the test cell, which are transmitted to the outer environment through the outlet chimney. The control room is normally placed in the vicinity of the test cell; a small fraction of the extremely high-level acoustic field in the test cell can permeate the control room affecting the acoustic environment for people who work and interact there. The possibility of remote sensing of experiments, made with delicate electronic equipment, can also be affected by the extremely loud sound in the test cell, meaning that long information-transmission lines are required, in order to perform experimental measurements.

Model-scale experiments of the noise generation in combustor test beds were conducted at the Engine Acoustics department. These experiments indicated that the operation of the back-pressure valve (BPV) greatly changes the noise emissions: a stream of compressed air was released into a laboratory room through a model-scale BPV (derived by scaling 14 to 1 the geometry of an Isler BPV with 280 mm inlet) which was also used to control the total pressure of the stream. The sound pressure levels (SPL) in the laboratory changed when changing the BPV aperture, with the highest levels measured at high total pressure and reduced mass flow. A large tonal-noise effect was also present at certain aperture conditions. The noise emissions could be greatly reduced by applying a novel silencing technology—the DLR *"**Sch**alldämpfer für **A**uslass**ve**ntile"* or SchAve—which proved to be effective in the reduction of both tonal-dominated and broadband noise, emitted in the laboratory by the BPV model at varying aperture. As part of a DLR Technology Marketing (TM) initiative, the SchAve and its model-scale results were presented to industries and research facilities which could be interested in silencing the operation of high-speed outlet systems. In the framework of the TM initiative, the DLR was invited by Siemens Energy to its Ludwigsfelde facilities, where the SchAve technology, the 3D-printed realization in model scale of both the BPV and the applied SchAve silencer, and the results associated with the model-scale experiments have been presented. The presentation was met by interest and Siemens Energy induced the DLR to prepare a draft project with the objective to realize a full-scale, high-temperature resistant, SchAve prototype to be coupled with the smallest BPV operated in their facilities: an Isler BPV with 160 mm inlet (Isler 160). A project was drafted and discussed by Siemens and DLR, until the COVID pandemic broke in, which caused Siemens to leave the drafted project. A possible research program in the drafted project, where the test of the SchAve prototype was scheduled at the DLR test bed HBK3 in Cologne (operating an Isler 160), was then funded under point 33 of the program "Konjunktur- und Krisenbewältigungspaket" (KoPa 33), issued by the German Federal Government in the summer 2020 in order to counter the economic effect of the corona pandemic. The research program, called Silentium, was used to achieve the following results:

1. A test of a model scale silencer was performed on a hot single stream jet. The jet, issued from a round orifice in subsonic and supersonic conditions, was first let develop in the free space trailing the orifice. A SchAve type silencer was then applied at the orifice, in order to

contain the initial developing region of the jet. The jet was issued both in hot and cold conditions, with and without silencer. A loud tone was measured at low to high subsonic Mach numbers, implying a negative impact of the silencer at these regimes. In supersonic conditions a clear reduction of acoustic noise was observed. No clear acoustic trend was observed when changing the jet from hot to cold conditions.

2. A small-scale experimental simulation test bed was realized at DLR Engine Acoustics. The test bed consists of a plenum connected through a 1-inch valve and pipe system to the compressed-air system at the TU-Berlin Hermann Föttinger Institute. Two outlet systems have been realized for the plenum, which simulate the piping of the combustor test facility, between the test object and the BPV. The outlet systems have 20 mm and 40 mm diameters; this enables verifying the geometrical-scaling effect on the aerodynamics and noise associated with attached models for the BPV and silencer. The test bed has been dimensioned for total pressures up to 10 bar above the ambient pressure.
3. A 1 to 4 reduced-scale model of the Isler 160 was manufactured. The model has the functionality of the valve and can be connected to the 40 mm outlet of the small-scale test bed in point 2. above. Although many elements of the full-scale Isler 160 have been simplified or are not included in the model, the active surface of the Isler 160 (parts in contact with the combustor exhaust flow) is geometrically similar to the one in the model. The trailing part of the reduced-scale model is geometrically similar to the full-scale Isler 160, including the 12 treads carved in the planar surface to which a trailing silencer can be flanged. This allows for testing the kinematic of the connection between the reduced scale model and the interface of a reduced scale silencer.
4. A CAD model for the SchAve technology has been adapted to the Isler 160. The Silencer has been fitted with an adapting interface which allows small geometrical adjustments. As required by the geometrical variability of the Isler 160, due to the coating layer on ist active surface. The model was initially developed to be additively manufactured as a single main part plus adapting-interface components; due to the market availability and the build volume associated with most of the available manufacturers of (selective LASER melting) printed components, the main part had to be divided in 8 components, including an axial cut and two cuts in the longitudinal plane. After finding the final manufacturer trough a best offer procedure, the CAD model had to be reconsidered in order to have a slightly reduced cross section and a single axial cut, which optimized the available build volume. Further modifications have been required by the SLM manufacturer, in order to achieve a set of self-supporting components during the print job. The removal of the longitudinal cuts on the main components, implied the definition of and inspection door, as in the initially envisaged single main part, but with 45-degree sides, allowing self-support during the printing. The model is reported in Figure 1.
5. Small-scale prototypes of the SchAve technology have been produced in 1 to 4 geometric similarity to the models realized in point 4 above. These models could be made in thermo-hardening plastic (photo-sensitive resin) by using high-resolution stereolithography. The

complete geometrical similarity with the commissioned prototype and the similar stratification associated with the additive technique, ensured the verification of the self-supporting characteristics of the models during the print job. The test of the silencer models, connected to the small-scale BPV in point 3. confirmed the aerodynamic, acoustic and structural performance of the various silencer models developed in the project. The structural stability of the silencer models with similarity in material thickness, but realized with less performing material as the planned prototype, and similarity of the aerodynamic-load environment safety margin for the first prototype.

6. A silencer prototype for the HBK3 Isler 160 has been commissioned to be realized in Inconel 718 by using selective LASER melting (SLM). The final model consisted of 2 large components for the main part, 13 smaller components for the BPV interface and a cover part for the inspection hole. A second set was commissioned for the smaller components, in order to reduce the risk in case adaptation works would be necessary when fitting the silencer to the Isler 160. A thermal treatment of the components has also been commissioned, in order to improve the mechanical and thermal performance of the elements.
7. An acoustic measurement of the noise inside the HBK3 test cell at varying BPV aperture was performed in September 2021. For this test he facility was set up with dummy connection between the intake and the BPV. The BPV has been fed with compressed unheated air. The acoustic measurements were taken with a single microphone, by remotely using a Brüel & Kjaer Analyser 2250 light with 1/2-inch microphone. The acquired measurements can be used to verify the acoustic read-trough between the full-scale test bed in HBK3 and model-scale BPV in the test-bed simulator of point 2.
8. A sliding support to hold the silencer on the rail system of the HBK3 test bed has been modelled in standard aluminum profiles. The sliding support is designed to hold the weight of the silencer and to finely adjust the asset of the latter during the connection to the trailing edge of the Isler 160. All the standard components of this structure have been commissioned.

All activities in the Silentium project ceased on 31.12.2021, due to time restrictions on the budget use for KoPa 33 projects. The project management had postponed the desired test of the full-scale SchAve prototype in the HBK3 test bed to 2022, due to unavailability of test time at HBK3 in 2021 and in order to focus on the commissioning activity for the prototype parts, point 6 above. The DLR Institute of Propulsion Technology promoted an internally funded project in 2022, which could be adopted to perform the following activities:

a. Follow the production, geometrically check, and assemble the commissioned silencer-prototype components.
b. Assemble the silencer sliding support and finalize the connection elements to the Isler 160. The connection elements included a non-standard element, which was designed as a 4-sector flange, holding the axial displacement of the silencer by using the existing threaded

holes of the Isler 160 outlet plane as anchor points. The element could be produced in the same steel alloy as the front block of the Isler 160.

c. Connect the prototype to its sliding support and fit it to the HBK3 BPV. Here various non-standard connection elements have been designed and realized at the DLR mechanical workshop of DLR Berlin. These elements secured the connection of the forward connection point of the silencer to the slide and the connection between the rail system at HBK3 to the slide.

The activities in points a. to c. have been closed in July 2022, when the montage test of the SchAve prototype to its Isler 160 was successfully performed in the HBK3 test bed. In the present report we detail the first test of the silencer at the presence of an active combustor in the HBK3 test bed. This test was conducted in November and December 2022.

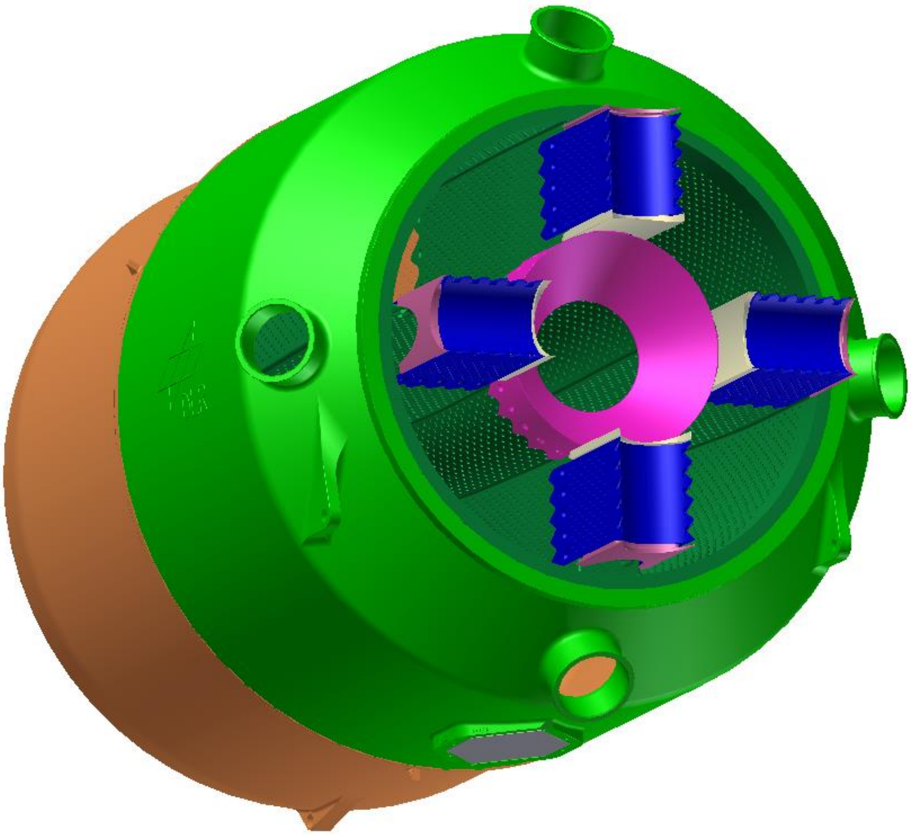


Figure 1: CAD model of the silencer, view from the flow inlet side. This view shows all the components which are assembled to make the SchAve outlet, as adapted for the Isler BPV with 160 mm inlet. Each component is given with an own color. Please note that two tonalities of green are used for a single (the largest) component, with the inner wall and part of the leading ring of the largest component using a darker tone. The largest component includes an inspection port to access the inner cavity of the silencer after assembly. It also includes 4 round ventilation orifices.

2. Montage of the silencer

After the montage test in the summer 2022 the SchAve prototype was stored connected to its support structure with the interface components adjusted to fit the inner surface of the Isler 160, with contact to its struts, inner wall and central body, when the silencer was flanged to the Isler 160 trailing face. A new rail system had been mounted on the test bed, compared to the one present at the time of the design of the sliding support. The original rail-sliding feet of the support had to be removed and the silencer support was fixed on sliding bars available at the test bed.
After adjusting the height and the orientation, the silencer was inserted into the Isler 160 and flanged to its trailing plane. The final assembly is depicted in Figure 2, before the test with pre-heated air. For the final test (with ignited combustor) a 1.5 mm sealing ring was placed between the trailing plane of the Isler 160 and the leading plane of the SchAve, see Figure 3. For the test with ignited combustor, the temperature of the silencer has been monitored: as visible in Figure 3 stripes of temperature-indicating marker (Tempil) at two different melting temperatures have been drawn on the silencer wall.

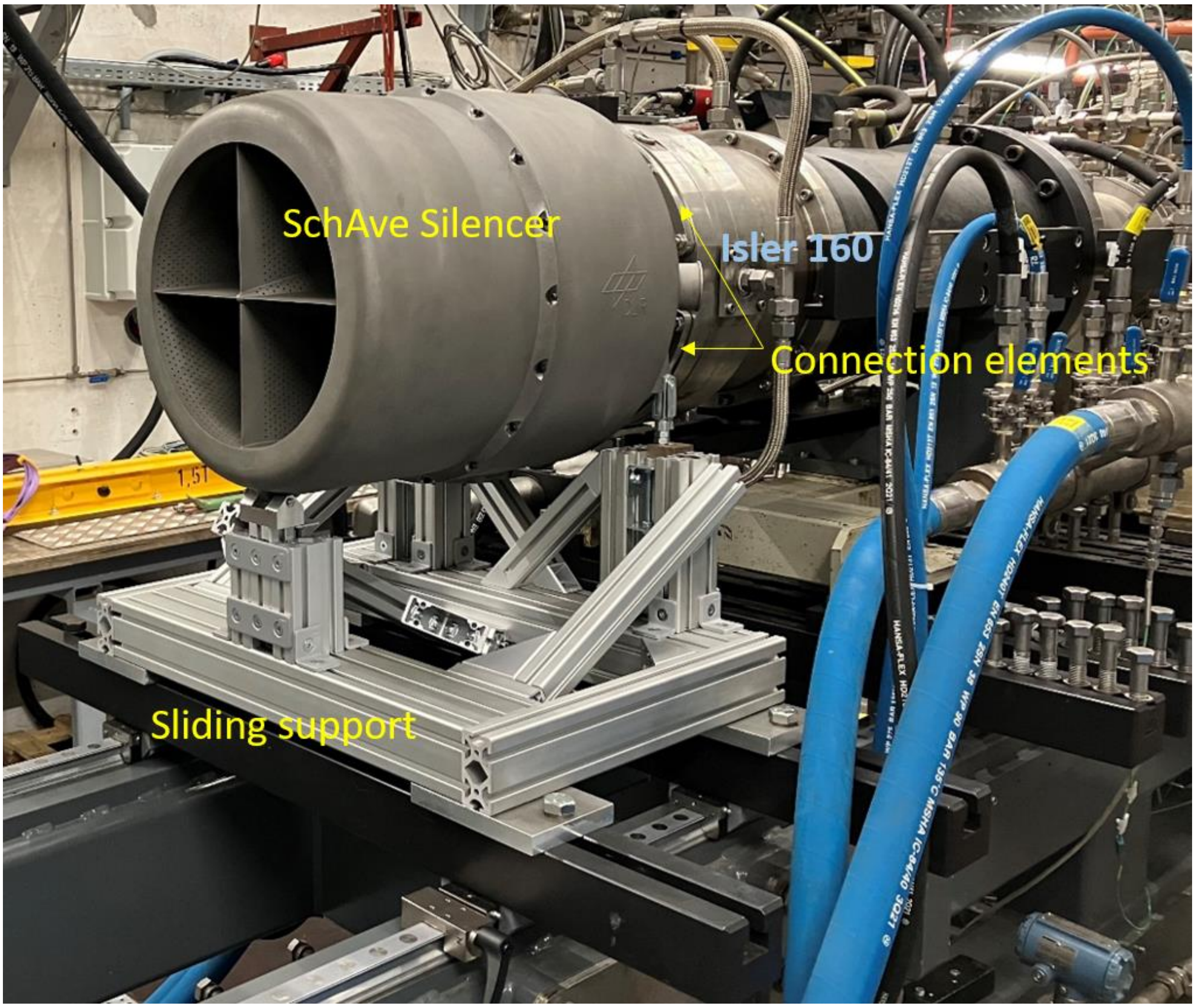


Figure 2: Silencer mounted on the rail system at HBK3 and flanged to the Isler 160 trailing plane. The picture has been made by A. Rudolphi.

A set of thermo-couple sensors was placed on the right side of the silencer, see Figure 4. The type K thermocouples have been connected to the test-bed acquisition system.

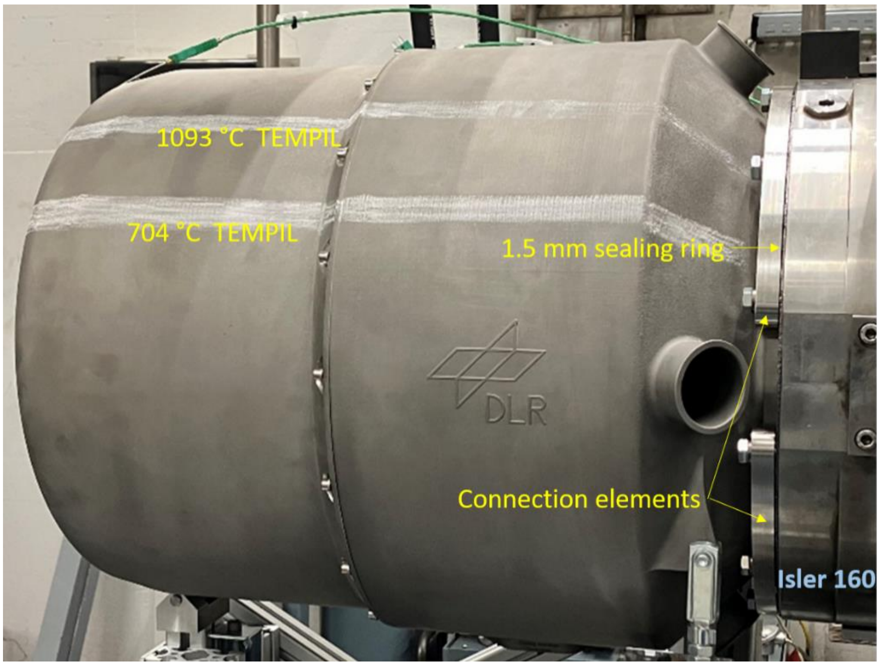


Figure 3: Silencer before test with ignited combustor. A sealing ring has been placed between the Isler 160 trailing face and the leading face of the silencer, which are then pressed together by the action of screws and of the connection elements. Stripes of Tempilstick will melt at the indicated temperature, 704 °C or 1093 °C. Image by A. Rudolphi.

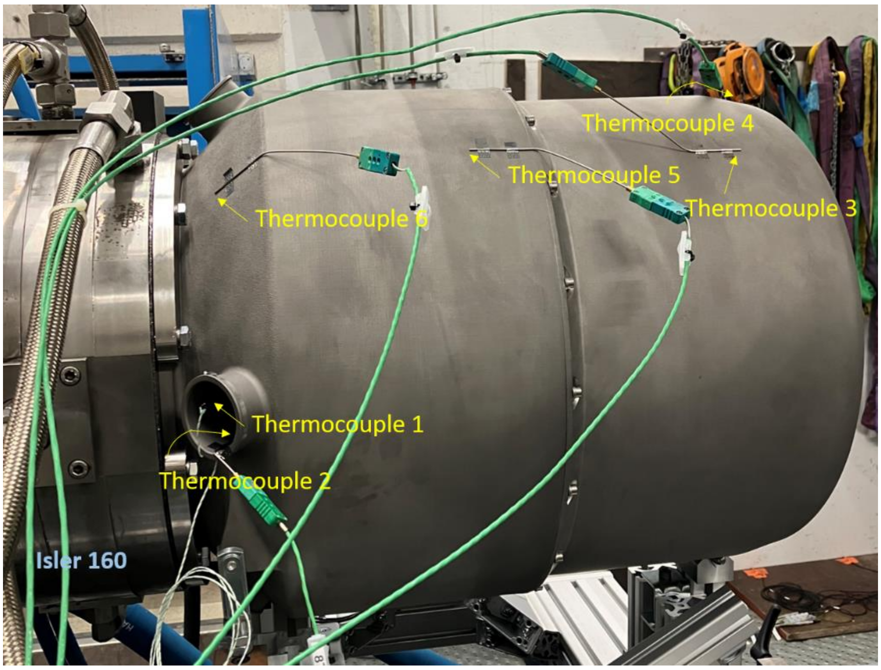


Figure 4: SchAve instrumented with temperature sensors, before test with ignited combustor. Picture by A. Rudolphi.

3. Acoustic test preparation

The acoustic measurement in the HBK3 test bed has been performed by using ¼-inch microphones of type GRAS 46BP-1, which can be used within a frequency range from 4 Hz to 70 kHz and within a sound pressure level (SPL) range from 39 dB to 172 dB (reference pressure 20 μPa). The data acquisition has been realized by using a multiple-channel National Instrument data acquisition system which digitalized the microphone signals with a sample frequency of 65 kHz. Five microphones have been used in the experiment. The microphones have been fixed on a wood plate on the floor of the test bed. The wood plate has been positioned in the downstream corner of the test cell in a way that two of its sides were adjacent to the test-cell walls, see Figure 5. The microphones faced the left wall of the cell, placed at about 9 mm from the wall. This region of the test cell was selected to achieve a good acoustic visibility of the Isler 160, without risking the plate and the measuring equipment being blown off by the high-speed exhaust flow. The vicinity to the wall also reduced the risk of contamination of the acoustic pressure through convective pressure fluctuations.

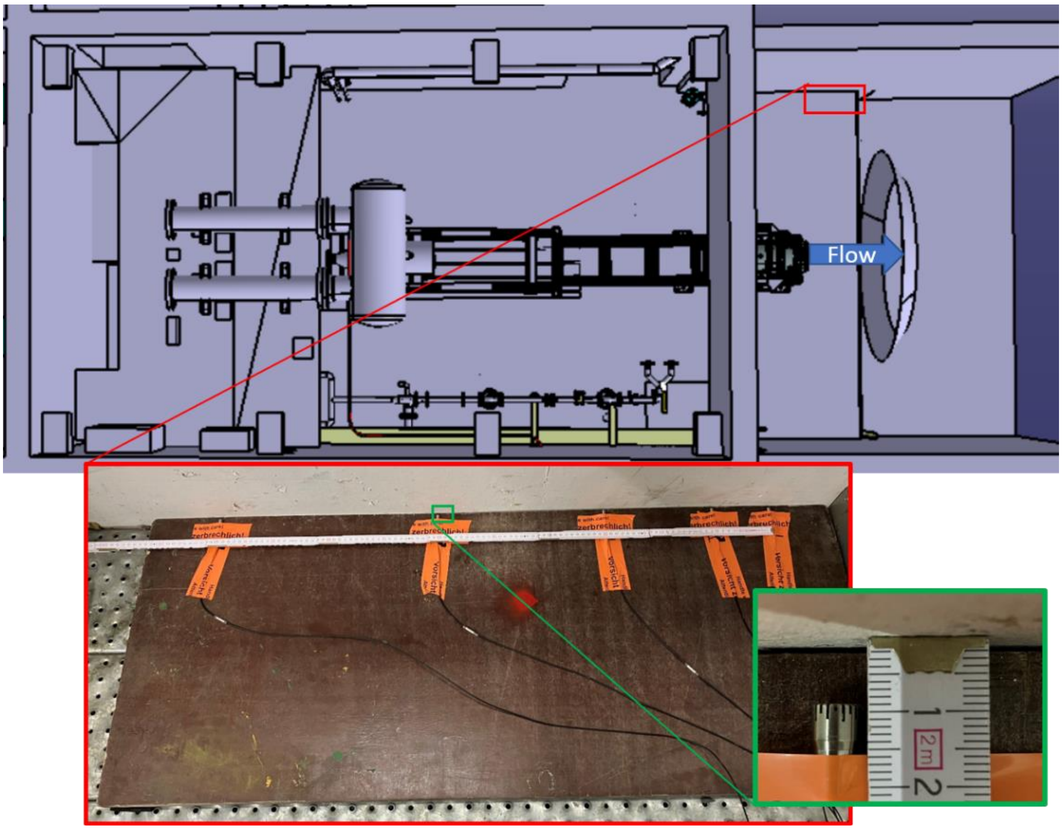


Figure 5: Microphones in the HBK3 test bed. The microphones are attached to a wood plate on the floor of the test cell. The plate is positioned adjacent to the downstream and the left walls of the test cell. The microphones face the left wall, with a distance of about 9 mm between the protection grid and the wall. Pictures by A. Rudolphi, the schematic of HBK3 was provided by R. Widmaier.

4. Test without and with ignition

The test schedule has been adapted in order to be run in parallel with an existing measurement being made at HBK3. This existing measurement uses a combustor in a series of cycles. Each cycle consists of three different flow conditions for the rig, during which the combustion process can be active. The rig parameters associated with the cycles are resumed in Table 1, where the desired air supply values are resumed. It must be noted that the temperature values are only of relevance to the silencer for the cases in which the combustor is not ignited.

Test case Name	Mass [ks/s]	Temperature [°C]	Pressure [bar]
Idle	0.5	490	5.7
Maximum Take Off (MTO)	2.5	477	28
Cruise	1.45	480	16

Table 1:Desired air-suppy conditions for a cycle in the measurement series. Temperatures and pressures are the total, or stagnation, quantities. The pressure value is absolute and not relative to the ambient. For each test point the given desired values will be approximated. The deviations around the given desired value are: in the range 0 to +1.4% for the mass flow, between -8% and +0.8% for the temperature and in the range -2.6% to +2.1% for the pressure.

The test has been performed in three successive steps:

1. The silencer was mounted at the Isler 160 outlet in its standard configuration and a cycle with pre-heated air was made.
2. The silencer has been unmounted and visually checked. With unmounted silencer a cycle with pre-heated air and one cycle with ignited combustor were performed, in order to acquire reference data.
3. The silencer has been instrumented with temperature control sensors and mounted at the outlet, including the 1,5 mm sealing. In this configuration three full cycles have been done, with ignited combustor, see Figure 6 during the MTO test case of the first cycle.

After the test, the silencer has been unmounted and visually inspected. The structure of the silencer resisted the test with no visible damage. The temperature marker on the outer wall indicated increasing temperatures in the direction of the flow, with the 704 °C marking melted on the trailing main element (in orange in Figure 1) of the silencer, see Figure 7 a). The thermocouple 4, see Figure 4, which is the one visible in Figure 6, was detached by the exhaust flow during the first cycle, after the maximum-take-off (MTO) condition. The temperature reading associated with this sensor was 787 °C during the rig operation in MTO condition. It was 258 °C at the idle condition. As shown in Figure 7 b) through the permanent chromatic alteration on the inner-wall material, the cooling effect of the entrained air through the 4 ventilation orifices generated a non-uniform temperature pattern on the inner walls of the silencer. The chromatic alteration suggests that the cooling flow penetrates the central part of the silencer, without getting distributed on the outer part.

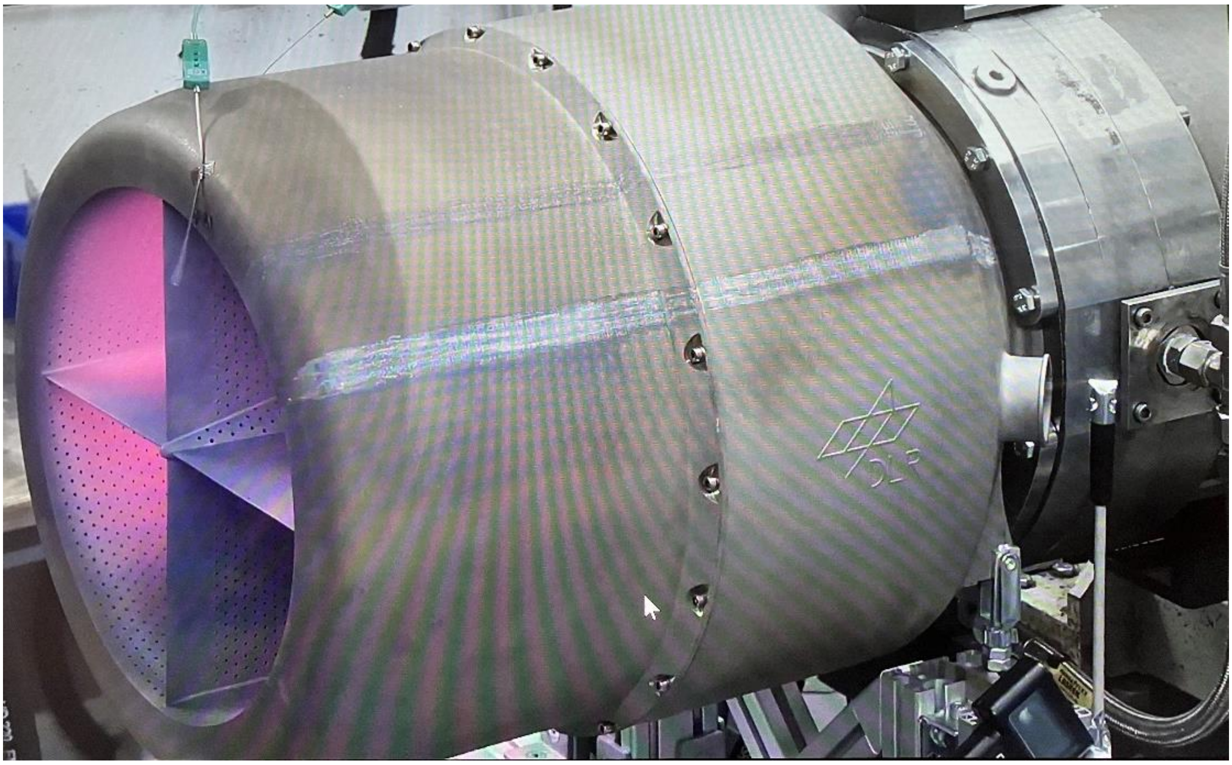
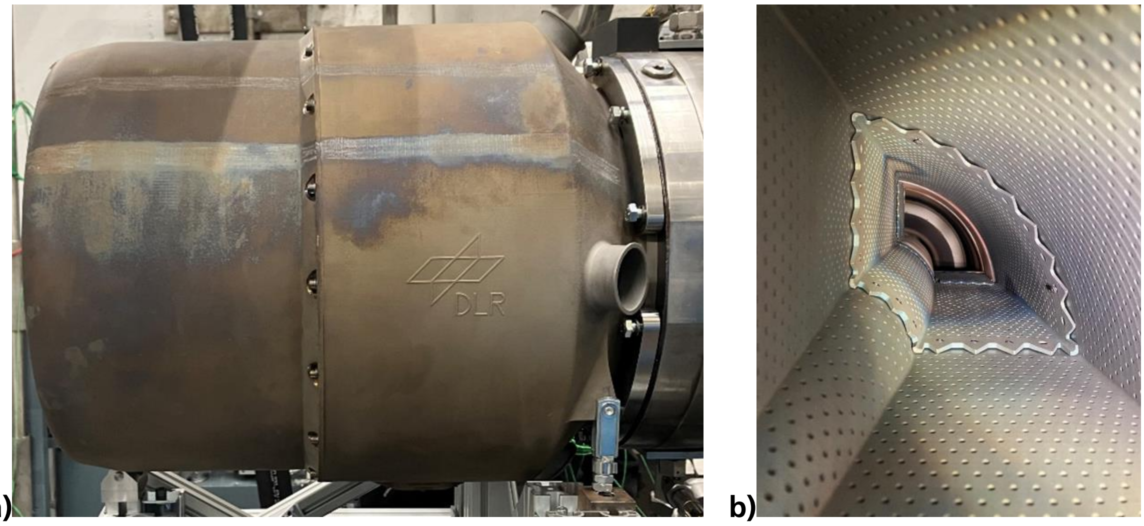


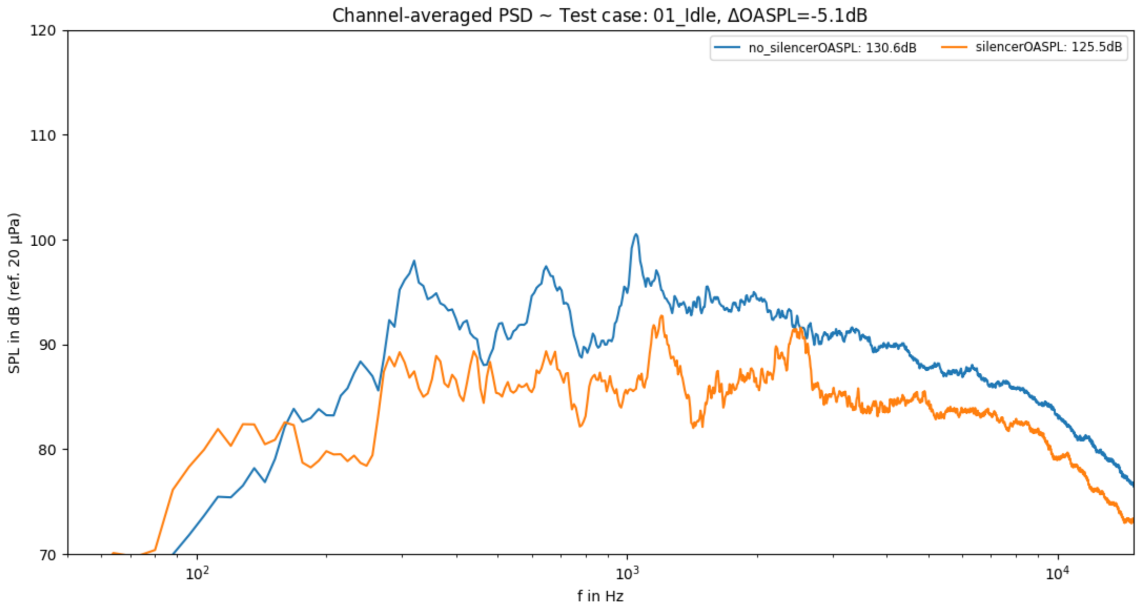
Figure 6: View of the silencer during the first cycle with ignited combustor. The visible thermocouple sensor was detached after reaching the maximum take off condition. The picture portrays the view of the monitor in the control room; it has been taken by A. Rudolphi



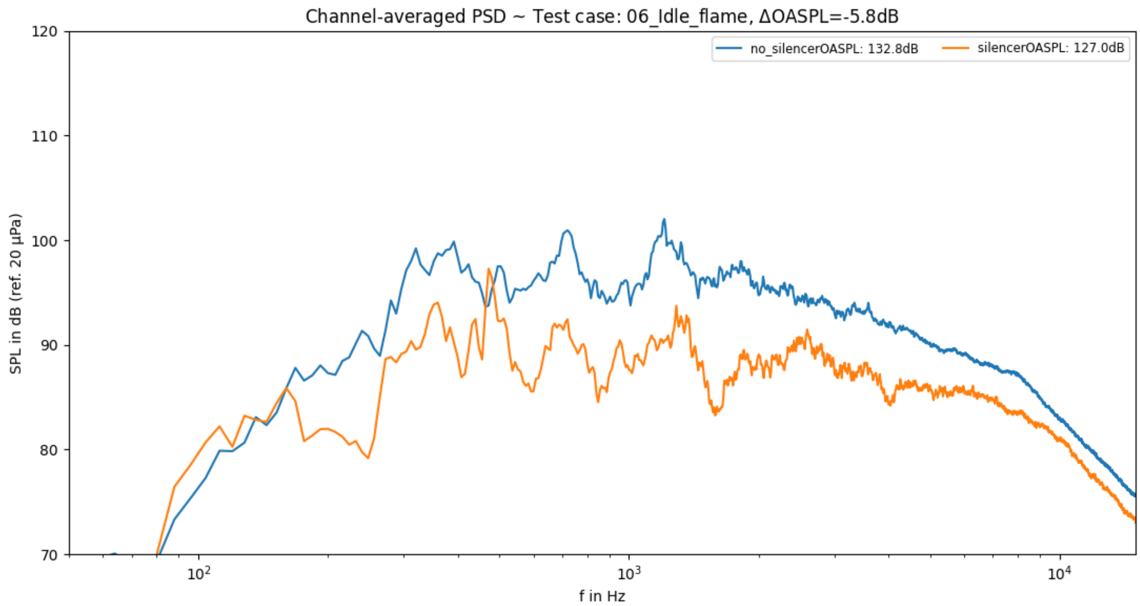
a) b)

Figure 7: Silencer after the test. Due to the high temperature lower marker stripe has been melted, indicating that the trailing-edge part of the silenced reached a temperature above 704 °C. The temperature marker at 1093 °C did not melt. The uneven temperature distribution inside the silencer caused a permanent chromatic alteration of the material, picture b). The chromatic alteration distribution seems to indicate the lower temperature region due to the impact of cool air entrainment, through the ventilation orifices. Pictures by A. Rudolphi.

The acoustic results are reported in Figure 8 to Figure 10 where a comparison of the narrowband (bandwidth 4 Hz) power spectral densities (PSD) of the acquired SPL is reported for each flow condition, in the 4 combinations: with or without silencer and with or without active combustion. The use of the silencer induced an overall noise reduction in all tested flow condition.



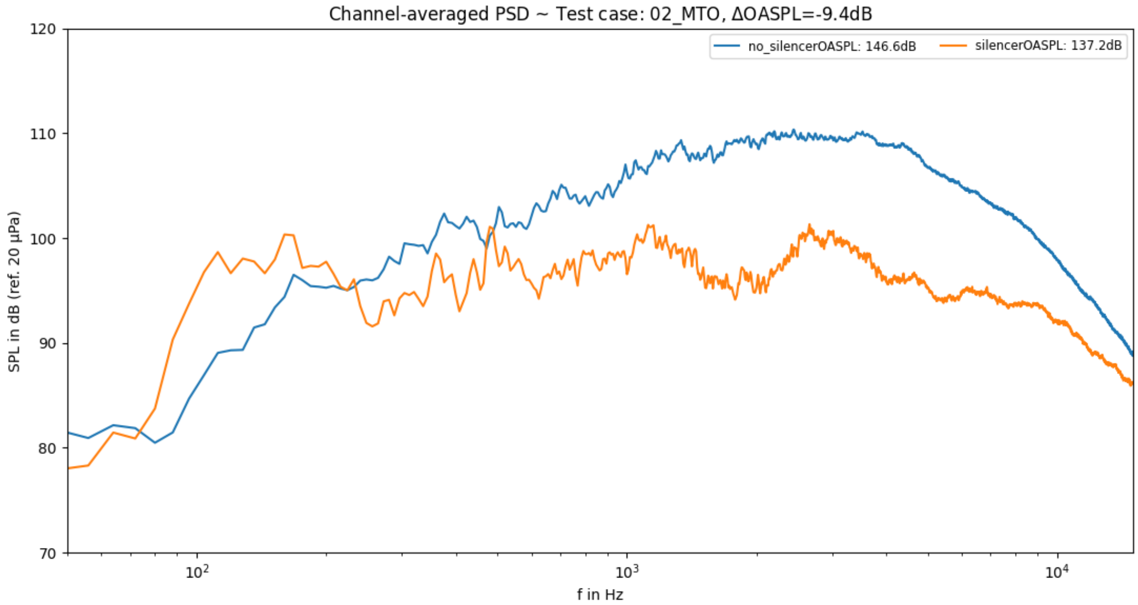
a)



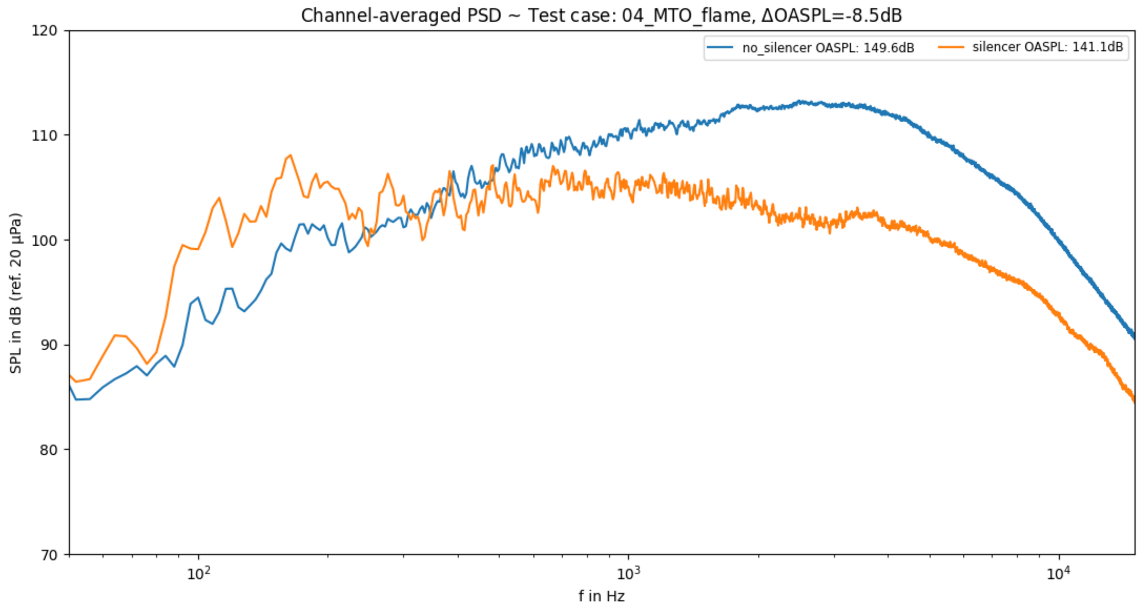
b)

Figure 8: Sound field acquired in idle condition. The labelling reports the overall SPL (OASPL) after averaging the 5 signals from the used microphones. In a) the combustor is not ignited, while in b) the combustion is active. The blue lines indicate the reference measurement without silencer, while the orange lines are the result with the silencer. The symbol ΔOASPL indicates the OASPL difference between the silencer and the reference cases.

The microphone-averaged overall sound pressure level (OASPL) in the test cell (microphone array location as described in section 3) differed between reference and silenced conditions by the following values: 5.1 dB for the idle condition with no flame, 5.8 dB for the idle condition with combustion, 9.4 dB for the MTO case without combustion, 8.5 dB for MTO with flame, 8.3 dB for the cruise case without flame and 7.0 dB for cruise with ignited combustor.



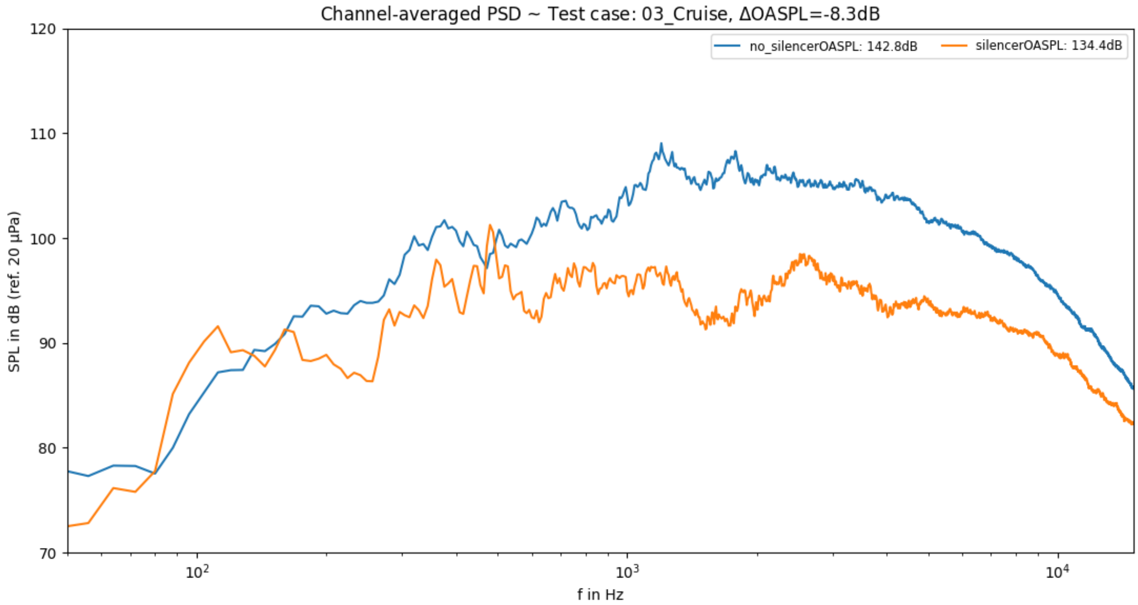
a)



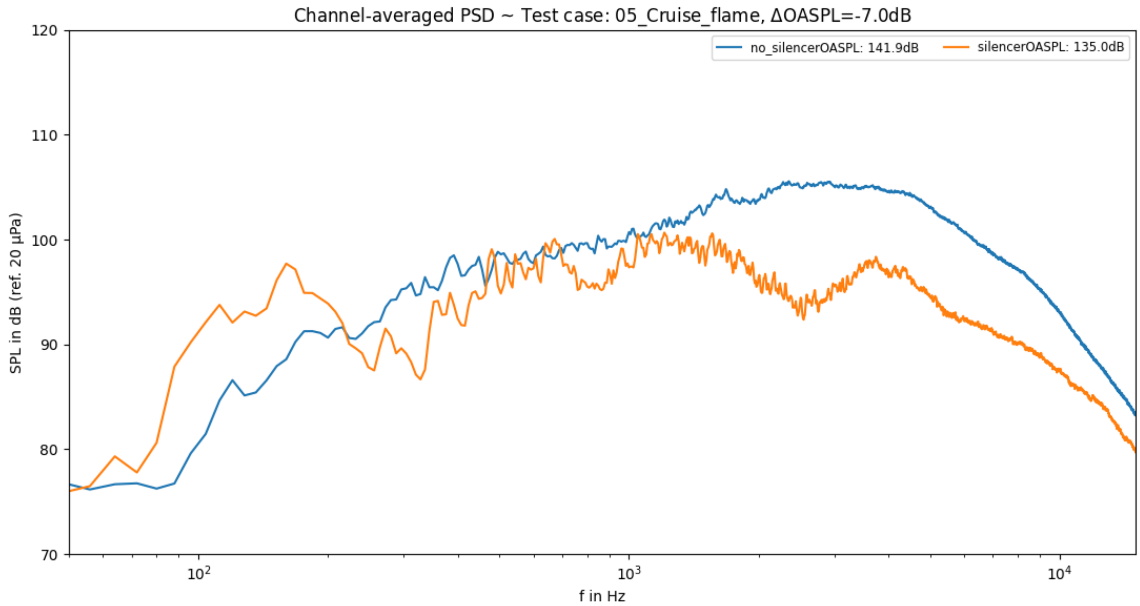
b)

Figure 9: Sound field acquired in maximum-take-off condition. In the labelling we report the overall SPL (OASPL) after averaging the 5 signals from the used microphones. In a) the combustor is not ignited, while in b) the combustion is active. The blue lines indicate the reference measurement without silencer, while the orange lines are the result with the silencer. The symbol ΔOASPL indicates the OASPL difference between the silencer and the reference cases.

The frequency shifting of the sound power through the application of the silencer is clearly visible in both the MTO and the cruise cases. This is possibly a consequence of structural vibration of the silencer. For frequencies below 200 Hz and in MTO condition with ignited combustor, the use of the silencer induced a noise increase although the peak-noise part of the spectrum is greatly attenuated. This noise increase could be of concern, especially regarding acoustic loading of electronic equipment.



a)



b)

Figure 10: Narrowband power spectra of the sound field in cruise condition. In the legend, the overall SPL (OASPL) obtained after averaging the 5 signals from the used microphones is reported. In a) the combustor is not ignited, while in b) the combustion is active. The blue lines indicate the reference measurement without silencer, while the orange lines are the result with the silencer. The symbol ΔOASPL indicates the OASPL difference between the silencer and the reference cases.

5. Conclusions

The silencer prototype for the SchAve technology has been successfully tested at HBK3, connected to its Isler back pressure valve (BPV) with 160 mm inlet. The silencer has been first tested with simple pre-heated air. It has been then tested at the presence of active combustion in the burner. The silencer passed, with no apparent damage, 3 cycles with ignited burner, with a mass flow up to 2.5 kg/s and flow temperature up to 787 °C measured at the silencer outlet.
The condition of the silencer assembly after the test suggests that connection between the various components of the silencer needs improvement:

- The screws exposed to exhaust gas need to be fixed. For the test we used corrosion resistant screws and bolts in stainless steel, which could at best be changed with Inconel 718 ones.
- The interface elements need to be adjusted in order to ensure contact with the trailing edges of the BPV struts and central body, in case sealing material is placed at the flange connection. Alternately, they could be fitted with same sealing material as used for the flange connection, in order to fill their contact points. This should avoid the observed penetration of hot gas in the gaps.
- For longer use a careful analysis of loading of the BPV head is recommended, because in the current configuration the BPV head and the silencer slide on different rail systems. Alignment discrepancies between the two systems result in a load at the interface between silencer and BPV head.

An overall-spectrum acoustic benefit has been observed in the test cell for all studied test cases, when the silencer has been connected to the BPV. The application of the silencer resulted in the following microphone-averaged OASPL deviations, compared to the corresponding reference measurement:

- In idle condition, -5.1 dB without flame and -5.8 dB with ignited combustor.
- For the condition maximum take-off (MTO), -9.4 dB without combustion and -8.5 dB with active combustion.
- For the cruise test case, -8.3 dB without flame -7.0 dB with flame.

The spectral distribution of the SPL indicates a spectral shifting of the sound energy from high to low frequency, which is visible in the MTO and Cruise conditions. The spectral shifting implicates larger sound reduction in the noise-peak region and increased noise at low frequency. The latter is of relevance for the acoustic fatigue in the measurement room. A hypothesis for this low-frequency (0-250 Hz) amplification is the activation of vibration modes of the silencer wall, which could be reduced by improving the connection between the silencer components, by introducing massive elements on the wall or by varying the stiffness and mass distribution of the wall.
The colleagues in the control room noticed an improvement in the acoustic environment, when the silencer was installed, especially at the loudest MTO test condition. Measured noise reductions due to the silencer exceeded 3 dB in various position of the control room.

Acknowledgments

The acoustic measurements have been performed by Angelo Rudolphi. The verification assembly of the silencer prototype to the HBK back-pressure valve has been made by Wolfram Hage and Alessandro Bassetti. The final assembly of the silencer to the HBK3 systems was made by René Berres, Sebastian Kruck and Kilian Ponzel. The work in HBK3 was assisted and coordinated by Thorsten Bäumer. Rolls-Royce kindly accepted to let us perform the silencer test, parallel to their own measurement campaign. The funding through DLR internal programs ("Blue-Sky" and "Leiser Antrieb") is kindly acknowledged. This work had not been possible without the results of the KoPa 33 Program Silentium, stemming from the project-proposal arrangements made with Siemens Energy.