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Experimental aeroacoustic studies of selected three types of helicoidal resonators

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Abstract The paper presents experimental studies of selected three types of helicoidal resonators carried out on an aeroacoustic laboratory stand with the use of pink noise and a duct terminated with a reverberation chamber. The same ratio *s/d* = 1.976 is considered for three numbers of helicoidal turns *n* = 0.671, *n* = 0.695 and *n* = 1.0. The results of the acoustic attenuation performance depending on the air flow velocity were compared in relation to the numerical tests carried out, which resulted in a decrease in resonance frequencies with an increase in the air flow velocity. The measurements were carried out with a high resolution of the FFT spectrum in order to illustrate the changes in the acoustic attenuation performance as accurately as possible. One-third octave bands of flow noise studies were also carried out.

Keywords: aeroacoustics, helicoidal resonators, flow noise, experiment, sound attenuation, duct acoustics.

1. Introduction

Aeroacoustic research has become increasingly vital in addressing the adverse effects of noise pollution across various engineering applications [1, 2]. In this context, helicoidal resonators have garnered significant interest due to their unique geometry and potential for efficient noise control in duct acoustic systems [3-7]. Understanding the behavior of these resonators under varying flow conditions is crucial for optimizing their performance and evaluating their practical suitability in real-world scenarios.

The previous numerical aeroacoustic research [5] of the three types of helicoidal resonators (see Fig. 1), with the same ratio *s/d* = 1,976 with three various numbers of helicoidal turns *n* = 0.671, *n* = 0.695, and *n* = 1.0, demonstrated a noteworthy trend for the investigated helicoidal resonators: as the velocity of air flow increased, the resonance frequencies and transmission loss (TL) levels decreased.

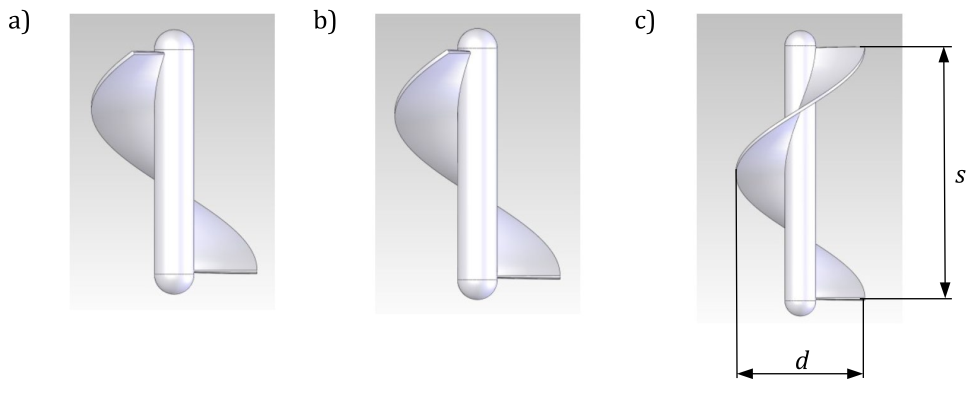

Figure 1. Acoustic helicoidal resonators with ratio *s/d*=1.976 with different numbers of helicoidal turns: *n* = 0.671 (a), *n* = 0.695 (b) and *n* = 1.0 (c) [5].

Notably, the helicoidal resonator with *n* = 1.0 exhibited the most substantial frequency difference between air flow velocities of *v* = 1 m/s and *v* = 20 m/s, amounting to approximately 18 Hz, with a corresponding TL level reduction of about 10 dB. In contrast, the helicoidal resonator with *n* = 0.695

showcased a smaller frequency difference of approximately 4Hz and a comparable TL level reduction of about 5 dB [5].

A more complex behavior was observed for the helicoidal resonator with n = 0.671, where the second resonance frequency displayed a greater change of approximately 7Hz compared to the first resonance frequency, which exhibited only about a 2 Hz difference. Despite this frequency variation, both resonance frequencies experienced a similar TL level reduction of approximately 10 dB. An intriguing observation emerged, revealing that for air flow velocities between v = 1–5 m/s, the lowest TL level between resonance frequencies increased by about 1dB for v = 20 m/s, reaching approximately 21 dB.

Furthermore, a critical global observation from the previous publication [5] highlighted that up to 5 m/s of air flow velocity inside the ducted system, the resonance frequencies remained unaffected. This observation suggests that helicoidal resonators employed in typical ventilation systems, where air flow velocities vary up to 5 m/s, do not require any velocity corrections. However, for industrial applications where higher air flow velocities are prevalent, air velocity corrections should be considered.

The present paper focuses on experimental studies conducted on the same three selected types of helicoidal resonators to investigate their acoustic attenuation performance under varying air flow velocities.

2. Experimental Research Methodology

The experiments were performed in an aeroacoustic laboratory station in accordance with the PN-EN ISO 5135 standard [8] at the Maritime Advanced Research Centre CTO S.A., as presented in Fig. 2.

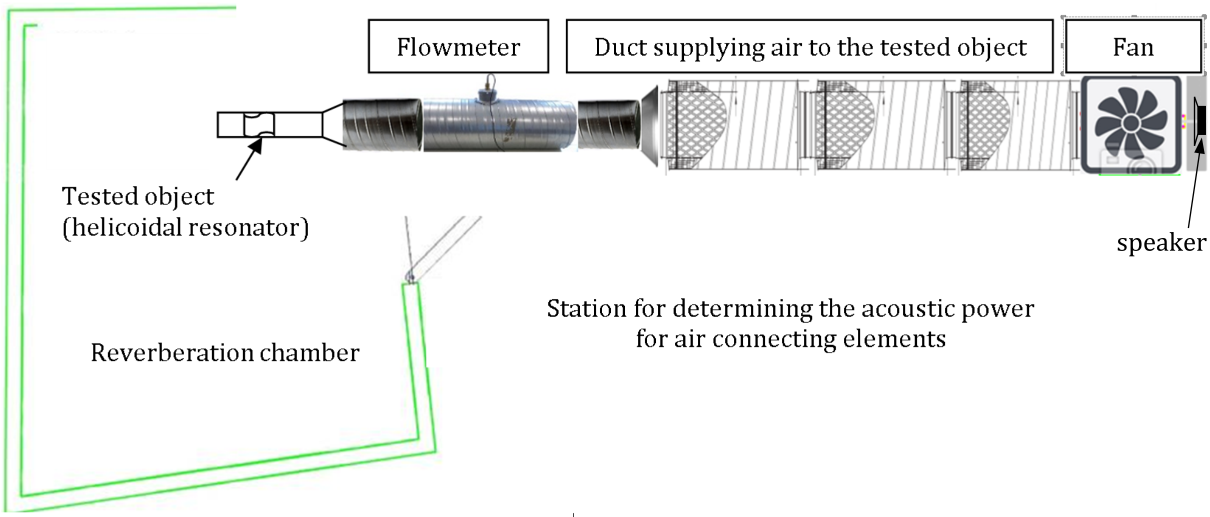

Figure 2. Block diagram of the measuring station in accordance with the PN-EN ISO 5135 standard at the Maritime Advanced Research Centre CTO S.A.

Pink noise was employed as the excitation source (physically was used broadband speaker) and a duct terminated with a reverberation chamber to simulate real-world flow conditions. In Figure 3 are presented the view inside reverberation chamber with example two microphones positions at the outlet of the cylindrical duct (diameter d = 0.125 m, total length l = 1.4 m) with the selected acoustic helicoidal resonators mounted inside the duct at the distance of 0.287 m from the outlet. The measurements were performed with BRÜEL & KJÆR LAN-XI Data Acquisition Hardware Type 3052-A-030 with TYPE 4955, 1/2 "Low-Noise Free Field Microphones. The resonators shared a common ratio of s/d = 1.976, but the number of helicoidal turns was varied, specifically n = 0.671, n = 0.695, and n = 1.0. Test conditions in the reverberation chamber: temperature 22 °C, relative air humidity 45%, atmospheric pressure 1016 hPa. The temperature of the supplied air in the installation ranged from 21°C to 22°C.

To provide detailed insights into the resonators acoustic behavior, high-resolution FFT spectrum measurements were employed. The high-resolution approach allowed for precise visualization and illustration of any changes in the acoustic attenuation performance under different air flow velocities/capacities. Furthermore, one-third octave bands of flow noise studies were carried out to complement the primary analysis and offer a comprehensive evaluation of the resonators performance.

To ensure accurate measurements and analyses, the acoustic attenuation performance was compared to numerical tests [5], which served as a reference for the experimental data. A notable observation from the numerical tests was the decrease in resonance frequencies as the air flow velocity increased, which prompted a thorough examination during the experimental investigations.

a) b)

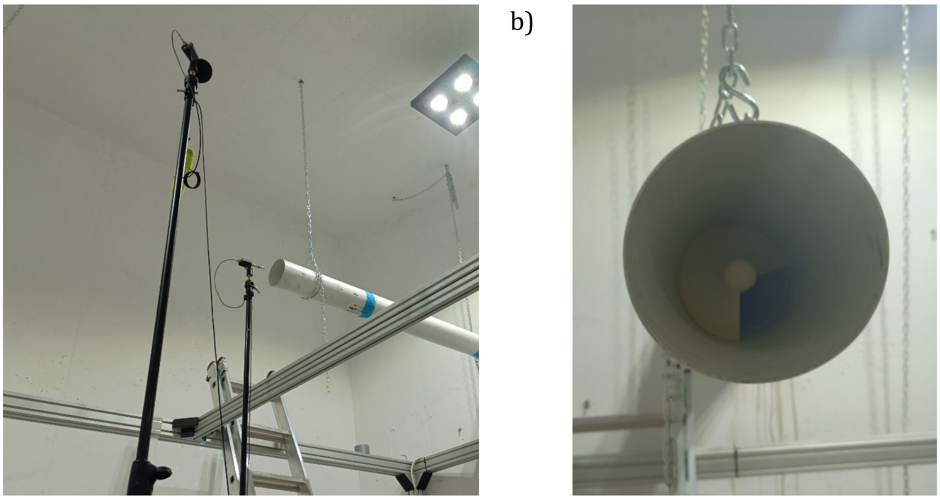

Figure 3. The views inside reverberation chamber: a) with two example microphones positions at the outlet of the cylindrical duct with considered acoustic helicoidal resonators (first microphone position in the distance of 10 cm with aeroacoustic nosecone installed and second microphone position in the distance of 1 m in angle of 45 degrees from central axis with windscreen foam installed), b) way of placing the helicoidal resonator (the helicoidal shape directs the airflow to the side where the microphone at a 45 degree angle is placed).

3. Experimental results

3.1. FFT spectrums and specrograms of flow with pink noise

This chapter presents the experimental results of Fast Fourier Transform (FFT) spectra obtained for three types of helicoidal resonators, each with a fixed ratio s/d = 1.976 and varying numbers of helicoidal turns, namely n = 0.671, n = 0.695, and n = 1.0. The FFT spectra were analyzed as a function of volume flow capacity that has changed in time from 0 m/s to 20 m/s to investigate the acoustic performance of these resonators under different flow conditions. In figure 4 are presented averaged in time FFT spectrums for pink noise with flow (from lowest to highest values). Next are presented FFT spectrograms for pink noise with flow in a distance of 10 cm (see Fig. 5) and in a distance of 1 m (see Fig. 6) from the outlet of cylindrical pipe.

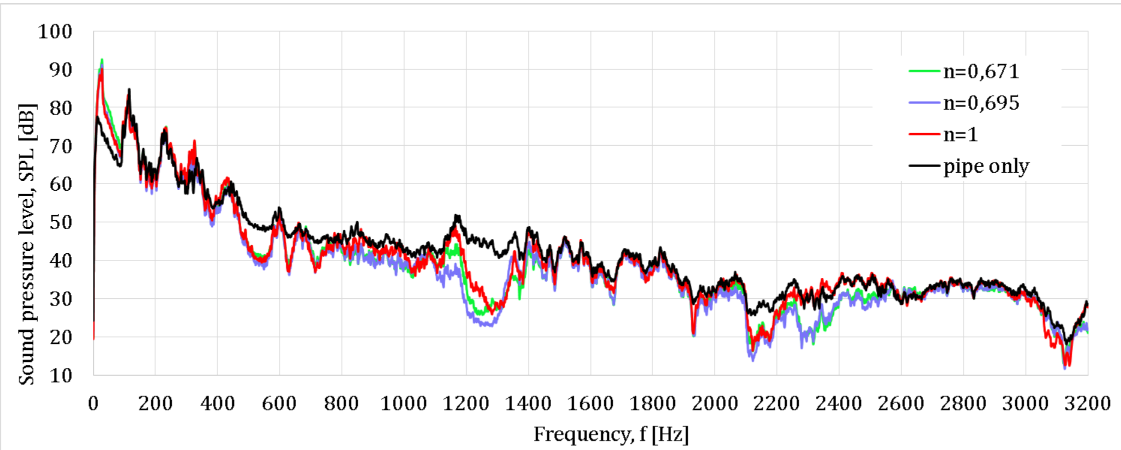

Figure 4. Averaged in time FFT spectrum for pink noise with flow (from lowest to highest values) for three helicoidal resonators with ratio s/d = 1.976 and different numbers of helicoidal turns n, in the distance of 10 cm from the outlet of the pipe with aeroacoustic cone installed at the microphone.

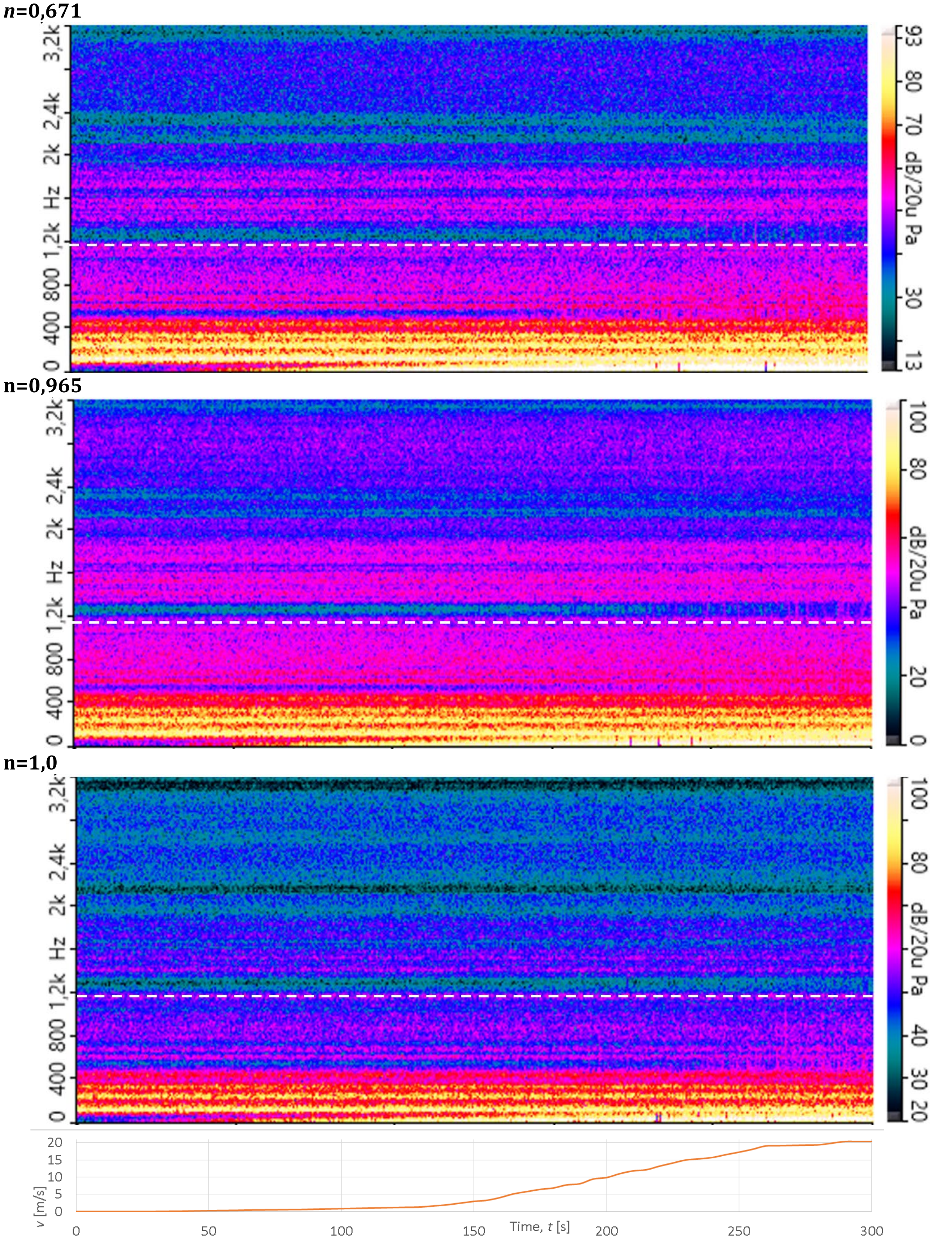

Figure 5. FFT spectrograms for pink noise with flow for three helicoidal resonators with ratio s/d = 1.976 and different numbers of helicoidal turns n, in the distance of 10 cm with aeroacoustic nosecone installed at the microphone. White dashed line is placed below the lowest limiting frequency of sound attenuation range of considered helicoidal resonators. Presented graph of velocity, v [m/s], vs. time, t [s], is valid for all three spectrograms.

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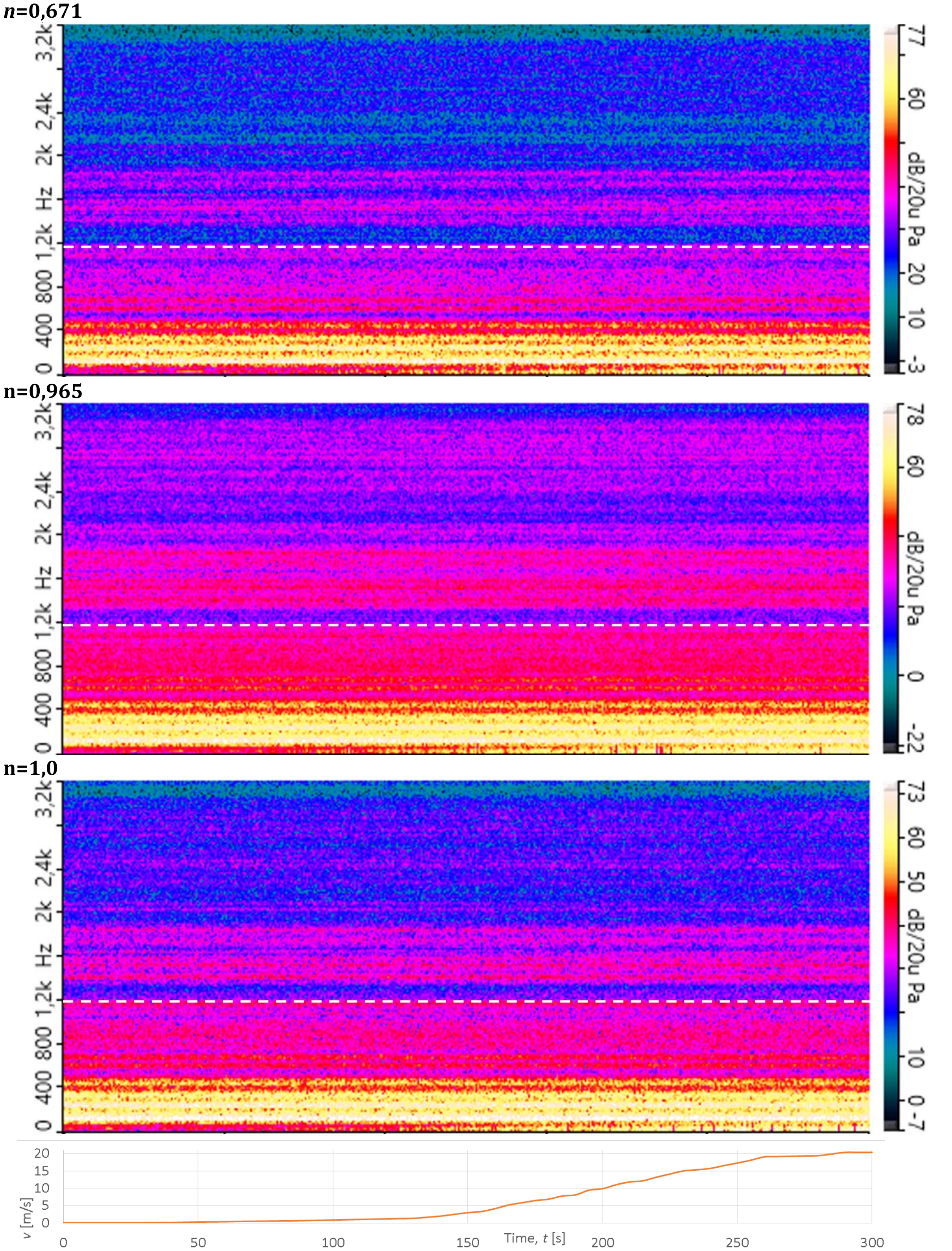

Figure 6. FFT spectrograms for pink noise with flow for three helicoidal resonators with ratio s/d = 1.976 and different numbers of helicoidal turns n, in the distance of 1 m with aeroacoustic cone installed at the microphone. White dashed line is placed below the lowest limiting frequency of sound attenuation range of considered helicoidal resonators. Presented graph of velocity, v [m/s], vs. time, t [s], is valid for all three spectrograms.

The FFT spectrum graphs depict the acoustic behavior of three helicoidal resonators with a fixed ratio s/d=1.976 and varying numbers of helicoidal turns (n) under the influence of air flow and pink noise. The spectrograms were recorded at a distance of 10 cm from the outlet of the pipe, with an aeroacoustic cone installed at the microphone to ensure accurate measurements.

The analysis of the averaged FFT spectrum for each resonator revealed a striking and consistent change in sound pressure levels as the flow velocity increased. Notably, the observed sound attenuation reached approximately 20 dB for all three helicoidal resonators, demonstrating their remarkable acoustic performance under varying flow conditions.

As the flow velocity increased from the lowest (0 m/s) to the highest values (about 20 m/s), the resonators exhibited significant attenuation of sound in clearly visible frequency ranges. This characteristic behavior was a distinguishing feature of the analyzed helicoidal resonators, indicating their effectiveness in mitigating noise across a narrow frequency range.

The prominent sound attenuation observed in the FFT spectrum graphs confirms the potential of these helicoidal resonators as effective noise control devices. The results highlight their ability to suppress sound energy and offer a viable solution for noise reduction in diverse engineering applications.

These findings are crucial for the optimization and practical implementation of helicoidal resonators in real-world scenarios. Understanding the clear change in sound pressure levels and the associated attenuation characteristics provides valuable insights into their performance under varying flow velocities, making them a promising tool in the pursuit of acoustic comfort and noise mitigation.

3.2. Flow noise

The measurements of flow noise were undertaken at two measuring points 1 m away from the pipe outlet. The first measurement point was located in the channel axis, and the microphone was equipped with a nosecone. The second measurement point was located in the same plane as the first but at an angle of 45 degrees, and the microphone was equipped with a windscreen. The positions of measuring point are presented in Figure 7.

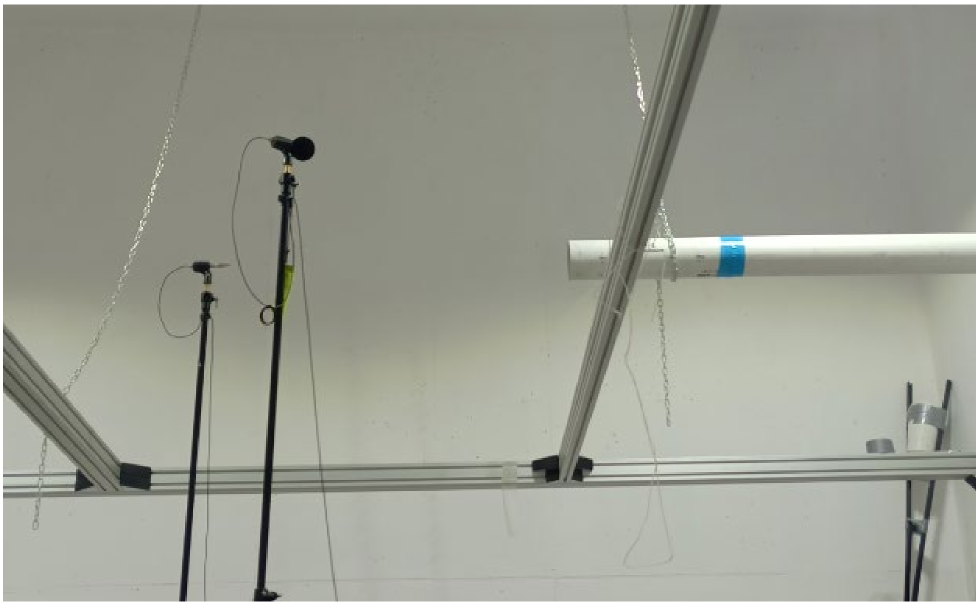

Figure 7. The view inside reverberation chamber with two microphones positions at the outlet of the cylindrical duct in the distance of 1 m with considered three acoustic helicoidal resonators.

The figure 8 shows the time-averaged equivalent sound pressure levels in 1/3 octave bands for three analyzed helicoidal resonators placed in a cylindrical duct with air flow at a speed of 0 to 20 m/s without pink noise for two microphones positions.

a)

b)

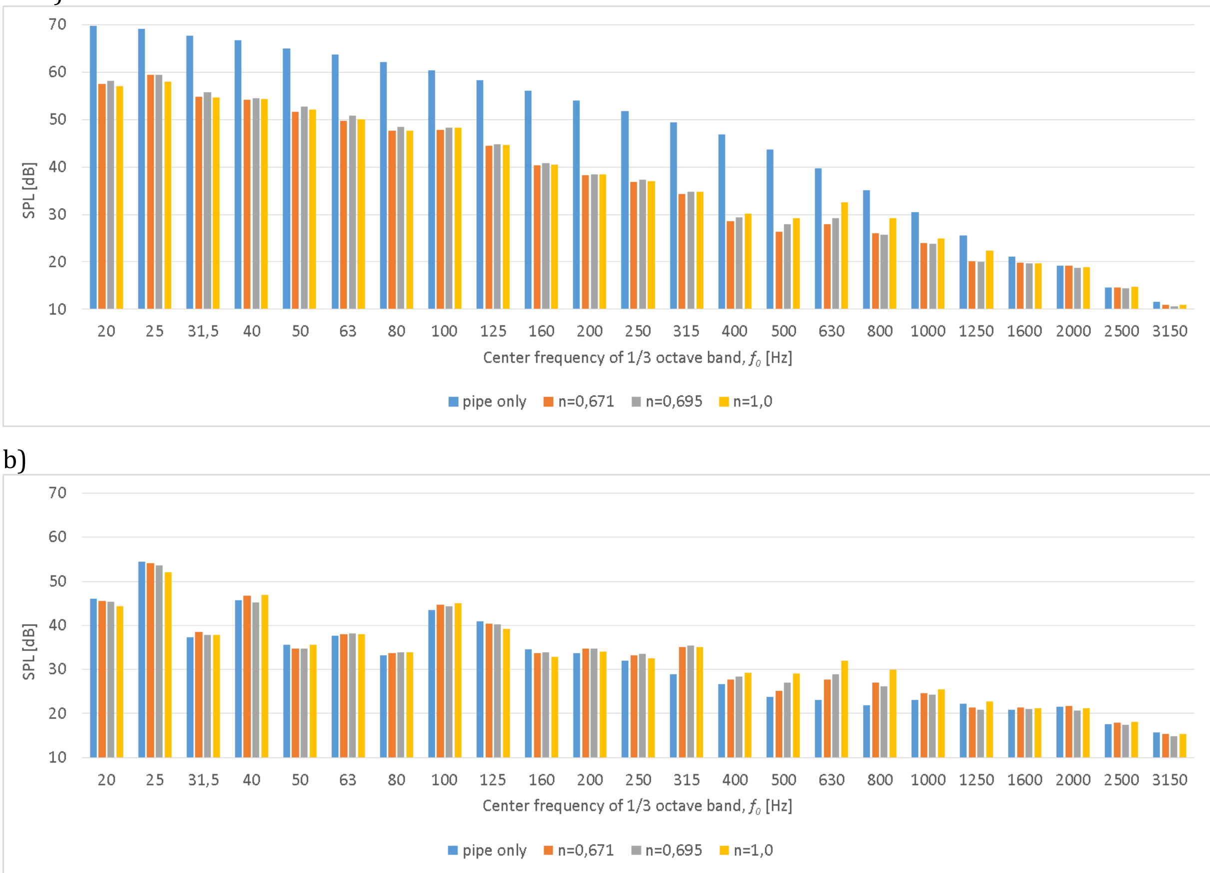

Figure 8. The time-averaged equivalent sound pressure levels, SPL [dB], in 1/3 octave bands for three analyzed helicoidal resonators placed in a cylindrical duct with air flow at a speed of 0 to 20 m/s without pink noise for two microphones positions in the distance of 1 m: a) in the pipe axis, microphone equipped with a nosecone, b) at an angle of 45 degrees, microphone equipped with a windscreen.

On the basis of the flow noise measurements carried out for the three considered helicoidal resonators at two measuring points at a distance of 1 m, the influence of the placement of microphones on the obtained 1/3 octave noise spectrum is clearly visible. Significantly higher sound pressure levels were recorded at the measurement point located in the duct axis. However, it is clear that the noise spectrum recorded in the duct axis for the empty pipe is characterized by the highest levels of flow noise in the center frequency octave bands range from 20 Hz to 1600 Hz. The noise spectra recorded in the duct axis for three helicoidal resonators are characterized by much lower levels in this range of sound frequencies (on average by about 15 dB, in particular in the 1/3 octave band from 20 Hz to 500 Hz). Between the position of the microphone in the axis of the duct and at an angle of 45 degrees, there is also a large difference between the measured sound pressure levels in individual 1/3 octave bands in the center frequency range from 20 Hz to 500 Hz. However, the trend reverses at higher sound frequencies, and in the mid frequency octave bands range from 630 Hz to 3150 Hz, higher sound pressure levels were recorded at the measurement point at an angle of 45 degrees in relation to the duct axis.

4. Conclusions

The numerical tests and experimental investigations of the considered helicoidal resonators have provided valuable insights into their acoustic behavior under varying air flow velocities. A notable finding from the numerical tests was the consistent decrease in resonance frequencies as the air flow velocity increased. This observation prompted further examination during the experimental studies.

The experimental analysis of the averaged FFT spectrum for the three analyzed helicoidal resonators, each with a fixed ratio s/d = 1.976 and different numbers of helicoidal turns (n), has provided compelling evidence of their remarkable acoustic performance under varying flow velocities. The clearly visible change in sound pressure levels, with an approximate 20 dB attenuation of sound, demonstrates the effectiveness of these resonators.

Spectrograms recorded at a distance of 10 cm from the pipe outlet revealed more clearly visible frequency ranges where sound attenuation occurred, characteristic of the considered helicoidal resonators. The difference in sound levels observed in these spectrograms reached approximately 20 dB, demonstrating the significant acoustic performance of the resonators. On the other hand, spectrograms recorded at a distance of 1 m exhibited a difference in sound levels of about 10 dB.

However, it is essential to acknowledge that the experimental studies did not unequivocally confirm a change in the resonant frequency of the helicoidal resonators as the flow velocity increased to about 20 m/s. This lack of clear evidence may be attributed to the interference caused by flow noise and reverberated sounds in the reverberation chamber. The presence of these acoustic interferences might have limited the researchers' ability to accurately record the characteristic frequency range of resonance and the associated sound attenuation.

To obtain more precise and reliable results, it is recommended that further research be conducted in a flow-through anechoic chamber. Such a controlled environment would allow for the isolation of flow noise and reverberation effects, enabling more accurate tests and assessments of the helicoidal resonators' acoustic performance under higher air flow velocities. According to ISO 5135, silencer attenuation should be assessed based on measurements of sound power level in the reverberation field not only by measuring sound pressure levels using 2 microphones placed in a short distance from the end of the resonators. Hence, some conclusions may be incomplete, in particular that large differences in frequency characteristics between microphones placed on-axis and at an angle of 45 degrees from the resonator axis arise as a result of the strong directivity of the radiation from the end of helicoidal resonators.

The numerical and experimental investigations has shed light on the acoustic behavior of the considered helicoidal resonators. While the numerical tests showed a consistent trend of decreasing resonance frequencies with increasing flow velocity, the experimental results were inconclusive due to the presence of acoustic interferences. Future research in a flow-through anechoic chamber holds the promise of providing more accurate and reliable data, advancing our understanding of the resonators' performance and guiding their optimal application in noise control engineering.

The flow noise measurements conducted for the three investigated helicoidal resonators at two distinct measuring points, each positioned at a distance of 1 m, have unveiled significant insights into the influence of microphone placement on the resulting 1/3 octave noise spectrum.

The comparative analysis of sound pressure levels recorded at different microphone positions has revealed distinct trends in the obtained noise spectra. Notably, the measurement point situated along the duct axis exhibited markedly higher sound pressure levels across various frequency bands. Specifically, the noise spectrum captured in the duct axis for the empty pipe exhibited the highest levels of flow noise, primarily within the center frequency 1/3 octave bands spanning from 20 Hz to 1600 Hz.

Importantly, the 1/3 octave band noise spectra recorded in the duct axis for the three helicoidal resonators displayed substantially reduced sound pressure levels within the aforementioned frequency range, with an average attenuation of approximately 15 dB. This attenuation was particularly pronounced within the 1/3 octave band spanning from 20 Hz to 500 Hz, demonstrating the effective noise-reducing capabilities of the helicoidal resonators in mitigating flow noise.

Furthermore, the investigation of microphone placement within the duct revealed notable variations in sound pressure levels across different frequency bands. Between the duct axis and an angular position of 45 degrees, a significant disparity in measured sound pressure levels was evident within the 1/3 octave band central frequency range of 20 Hz to 500 Hz. However, this trend underwent a reversal as sound frequencies increased, with higher sound pressure levels recorded at the measurement point situated at a 45-degree angle in relation to the duct axis within the center frequency 1/3 octave bands ranging from 630 Hz to 3150 Hz.

These findings underscore the intricate relationship between microphone placement, flow noise attenuation, and frequency response. The observed patterns emphasize the potential of helicoidal resonators in effectively attenuating flow-induced noise, particularly within specific frequency ranges. These insights offer valuable guidance for optimizing microphone placement and resonator positioning, enhancing the efficacy of noise control strategies and contributing to the broader field of aeroacoustic engineering.

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Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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