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Research Paper

The Influence of the Surface of Ventilation Duct on Sound Attenuation in the Airflow

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These studies focus on acoustical parameters of steel flat-oval ducts as a function of their roughness. The four types of steel ducts were measured: raw steel, galvanised steel, painted steel, and aluminium as the reference one. The roughness of the duct was measured, and roughness parameters were specified. The sound power level was obtained on the specially constructed stand test with an outlet to the reverberation room. Insertion losses to evaluate the acoustic attenuation performance of the studied steel ducts were obtained. In the present study, an aluminium duct, which is very smooth with minimal airflow friction, was treated as a low-noise object ('silencer'). These studies have shown that for each of the tested steel ducts, the self-noise is higher than for the aluminium duct. The largest differences in this self-noise were observed at a velocity of 12 m/s for the galvanised duct and the raw steel duct compared to the aluminium duct. Insertion losses in straight ducts are consistent with literature and are very low for flat-oval steel ducts. Aluminium duct performs better acoustically than the other ducts studied at lower velocities; however, as airflow velocity increases, the differences in acoustic performance between the materials become less pronounced. This suggests that aerodynamic effects dominate over material surface treatments at higher velocities.

Keywords: steel duct, roughness, insertion loss, HVAC.

Notations

D_i – insertion loss,
L_W – sound power level,
$L_{W\mathrm{I}}$ – sound power level when the test object,
$L_{W\mathrm{II}}$ – sound power level references object,
P – duct perimeter,
R_a – average roughness,
R_q – root mean square (RMS) roughness,
R_z – average maximum height of profile,
S – area ratio,
v – flow velocity,
ΔL_w – differences between single-number values of sound power level.

1. Introduction

Most standards and guidelines for the analysis of sound in ducts are based on the sound power-based description, which has been widely utilised in HVAC systems, for example, ASHRAE (Reynolds, Bledsoe, 1991; American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007), VDI (VDI, 2001), or ISO5136 (International Organization for Standardization, 2003), however, it cannot be applied for frequencies above the cut-off frequency. The sum of the sound power level gains and losses at the component connecting interfaces from the fan to the network's terminal sections can also be used to calculate the sound power level inside a duct network. However, this method ignores any influences caused by wave reflections. This significantly lowers the reliability while simplifying the forecast process. Additionally, the low-frequency range is covered by the plane wave-based description of networks, ducts, and mufflers (Munjal, 1987; Boden, Abom, 1995; Boden, Glav, 2007). However, in HVAC duct networks with their large lateral dimensions the frequency range of plane wave propagation is rather limited. If the duct system is fairly extensive, then existing prediction methods allow the design of HVAC systems that are usually free from noise problems.

The source of the duct break-out in ventilation systems can be calculated thanks to the several prediction algorithms utilised in the ASHRAE scheme. There are several regions where noise is produced, such as diffuser noise, system attenuation from plenum chambers, unlined rectangular ducts and bends, end reflection losses of ducts, breakout from ducts under airflow conditions, and insertion losses of ducts (Reylnods, Bledsoe, 1991). The Allen formula (Allen, 1960) is a well-known technique for forecasting noise levels that emerges from a section of a ductwork. The difference between the areas through which sound enters the duct (i.e., its cross sectional area) and exits the duct (i.e., the duct surface area) is taken into account. It is based on the theory of sound transmission through panels. However, it is widely acknowledged that this approach occasionally produces incredibly erroneous results, especially for low frequencies and lengthy ducts. The approach fails to consider the fact that the sound power within the duct will decrease along its length as a result of breakout from the duct. Negative attenuations may be predicted using the formula, which means that more sound energy is emitted from the duct than enters it. This is due to the fact that using the sound reduction index (or transmission loss) data for duct walls was gathered from sound transmission loss measurements on plane panels rather than in duct tests, presents another challenge. From this time, various analytical and numerical methods have been employed in the modelling of duct wall break-out and break-in (Cummings, 1980; 1983; Cummings *et al.*, 1984; Venkatesham *et al.*, 2011; Herrin, Seybert, 2006). However, because of the various types of noise sources and the various ways that noise spreads, evaluating the noise produced by HVAC systems can be challenging. It takes a lot of programming work to implement any accurate predictive model for duct wall break-out and break-in because the self-noise produced by aerodynamic sources through duct systems depends on the actual system configuration and the effective airflow velocity, although we are also dealing with sound attenuation of various devices and ducts in the whole system. In turns, the attenuation in HVAC systems is a complicated issue.

Sound energy splits at branches, gets rejected at bends and duct terminations, and loses energy due to duct wall vibration, all contributing to the natural attenuation provided by the duct system. The attenuation caused by the duct wall vibration may become significant when the system has extensive ductwork, especially for rectangular ducts. The produced motion of the duct walls reduces the energy of a sound wave as it travels down an unlined duct. The wall mass is mostly responsible for the surface impedance, and the computation of the duct loss is similar to that of the transmission loss. It is significantly harder to excite circular sheet metal ducts than rectangular ones at low frequencies, especially when they are in their first state of vibration, known as the breathing mode. Consequently, unlined rectangular ducts suppress sound significantly more than circular ducts (Cummings, 2001).

Empirical equations for the attenuation was development by Reynolds and Bledsoe (1991) in terms of a duct perimeter (P) to area ratio (S). A large P/S ratio means that the duct is wide in one dimension and narrow in the other. The attenuation of rectangular ducts in the 63 Hz to 250 Hz octave frequency bands can be approximated by using an equation (Reynolds, Bledsoe, 1991):

– for $\frac{P}{S} \geq 3$:

$$D = 17.0 \times \left(\frac{P}{S}\right)^{-0.25} \times f^{-0.85} \times L, \tag{1}$$

– for $\frac{P}{S} < 3$:

$$D = 1.64 \times \left(\frac{P}{S}\right)^{0.73} \times f^{-0.58} \times L. \tag{2}$$

The attenuation of rectangular ducts above 250 Hz octave frequency bands can be approximated by using:

$$D = 0.02 \times \left(\frac{P}{S}\right)^{0.8} \times L. \tag{3}$$

In these formulas, pay attention to the units of measurement: the value of P must be given in feet, the value of A (the area of the duct) in square meters, and the value of L (the length of the duct) in feet. Ductwork in industrial installations can be several dozen or even several hundred meters long. Acoustic losses in the air on the duct walls can dampen the sound transmitted to the duct and its surroundings, which travels great distances. For steel ducts of 200 mm in diameter in ventilation systems, there is a loss of 0.1 dB/m for low frequencies and 0.3 dB/m for high frequencies, as shown by Bessac *et al.* (2018). For lengthy ducts, these tiny values can result in notable attenuations. Experience has shown that design contractors do not pay attention to this loss and frequently overlook this occurrence in their calculations. The AcouReVe project carried out, between 2015–2018, aimed to improve the reliability and quality of acoustic calculations in the ventilation ductwork and provide more reliable input data and insights for acoustical consultants to predict sound levels in rooms more accurately when considering ventilation systems and ductwork. For straight round ducts, it was confirmed that for low frequencies, the measured losses were consistent with literature, showing very low attenuation (~0.1 dB/m). However, for high frequencies (above 1600 Hz), galvanised spiral steel ducts exhibited higher losses than expected, ranging from 0.5 dB/m to 1.5 dB/m, and even up to 3 dB/m in some specific test cases, contradicting the common assumption of minimal losses in circular ducts (Bessac *et al.*, 2018).

The ducts that run to supply registers are frequently built of flexible aluminium or Mylar or sheet metal. Duct surfaces should ideally be maintained dry and clean; however, even brand-new ducts can get dirty from debris from the building's construction and storage before installation. Furthermore, residual oils from the initial machining and construction of new steel ducts have been found to be sources of volatile organic compounds (VOCs) in indoor air (Pasanen *et al.*, 1995). This is connected to the fact that the commercial pipes have different levels of roughness, which affects the behaviour of the fluid flowing through the pipe, particularly the pressure loss caused by friction. There is a strict connection between roughened pipes and the generation of noise. Roughness can influence fluid flow and heat transfer by increasing pressure drop, altering flow regime laminar-turbulent transition, and by inducing secondary flow motions which lead to an enhancement in flow mixing and heat transfer. Also noise radiated from the exhaust of two roughened pipes to the anechoic chamber was studied by Hersh (1983). He claimed that over the whole tested frequency range (down to roughly 3 kHz), totally rough surfaces generated noticeably more sound. The formation of sound can be explained by the scattering on the surface imperfections, which changed turbulent near-field pressure fluctuations (Howe, 1988; 1998). According to Devenport *et al.* (2011), the flow at the rough wall creates quantifiable roughness noise. It was discovered that even hydrodynamically smooth roughness generated noise, which means that the scattering mechanism was a noise source. As the flow speed increases, the wideband roughness noise moves to a higher frequency and rises in level. The roughness noise is also significantly impacted by the roughness size. These changes with the flow speed and roughness size were found to be incompatible with any straightforward scaling. The presence of roughness of pipe wall changes their values in comparison to the smooth design and, as a result, alters the acoustic behaviour. The Monte Carlo method and the finite element solver were used by Yu *et al.* (2024) to analyse the attenuation of acoustic waves in rough cylindrical pipes and to estimate the roughness of the pipes from the measured acoustic wave. However, there is evidence in numerous studies that the research on noise in HVAC systems should be expanded to include a greater variety of noise sources, as well as the interaction between the different components of the duct system and its impact on noise generation and attenuation (Fry, 1988), especially where the roughness is taken into account. This is because the prediction of system attenuation is usually rather conservative, so that predicted sound pressure levels (SPLs) tend to be overestimated, thus in effect incorporating a factor of safety in the design (Henson, 1986).

The purpose of this paper is to clarify the effect of the surface of the steel duct on the aerodynamic sound and also to determine the attenuation of these ducts, which may be essential for engineering design. The experiments were performed on the test stand, meeting the requirements of ISO 7235, which allows to determine the sound power level using the precise method. In these studies, the three steel ducts were used compared to the aluminium one as the base channel. The roughness of the channels was also measured.

2. Test objects

The most important parameters of ducts used in HVAC systems are diameter, shape, and material. In ventilation systems, ducts are most commonly constructed from sheet metal, galvanised steel sheets, stainless steel sheets, aluminium, and PVC pipes. Ducts can also be made of aluminium foil or plastic. The choice of material is usually determined by price and design requirements. Steel ducts, often galvanised, are used in industrial ventilation solutions. These systems utilise rectangular or round ducts and, less frequently, flat-oval ducts.

Flat oval ducts are becoming increasingly popular in HVAC systems, as this configuration can enhance airflow dynamics and reduce material consumption. Botejara-Antúnez *et al.* (2023) emphasized the importance of an efficient duct design in minimizing the embodied carbon of HVAC systems, suggesting that careful consideration of the duct shape can lead to both environmental and economic benefits. Studies on flat-oval ducts underline their effectiveness in optimizing airflow patterns, as illustrated in numerical investigations that demonstrate the impact of duct shape on thermal-flow characteristics (Djeffal *et al.*, 2021; Tahrour *et al.*, 2022). The aerodynamic performance of these ducts can lead to better energy efficiency within HVAC applications, as exemplified by Tahrour *et al.* (2022), which evaluated various tube shapes, including flat-oval, for their performance in heat exchangers.

This study utilised flat-oval ducts with large side dimensions (500 mm by 800 mm), specifically designed for industrial HVAC installations – Fig. 1. The ducts were made of raw sheet metal, galvanised sheet metal, and painted sheet metal with two coats of acrylic paint. Additionally, a drawn aluminium duct was used as the base duct. These ducts are characterised by varying surface roughness. The roughness of steel duct (pipe) refers to an index of surface quality, which is usually used to describe the smoothness of the surface of steel duct after processing. The surface roughness of ducts significantly affects their performance. The excessive surface roughness of ducts will affect the resistance, vortex, and friction of the fluid, reducing the transportation efficiency and the stability of fluid flow. Roughness is usually expressed in R_a value (average roughness), R_q value (root mean square (RMS) roughness) or R_z (average maximum height of profile). In this case, the roughness of the inside pipe wall of all pipes was measured with the surface roughness tester 502.300. The instrument gave as output roughness parameters (R_a, R_q, R_z). The roughness parameters were measured at the bottom of the duct in the axial direction. Each measurement was performed at least three times across three different points of the duct, and the results are presented as the average of these measurements. The uncertainty budget for the R_a, R_q, R_z measurements provides a comprehensive breakdown of the potential errors associated with the surface roughness test. The research took into account uncertainties in type A, derived from statistical repeatability across nine measurements, and type B, which includes the instrument's inherent technical limitations. In this case, the primary source of uncertainty was the instrument error, contributing 5 % uncertainty based on manufacturer specification and a 3 % repeatability factor, which accounted for the surface's spatial variability. By combining these factors geometrically, the combined standard uncertainty is obtained. The coverage factor of $k = 2$ gave the expanded uncertainty, ensuring a 95 % confidence level for the reported value. The dimensions of ducts and parameters R_a, R_q, and R_z with uncertainty are given in Table 1.

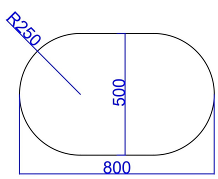

Fig. 1. 2D model of the studied ducts.

The raw steel sheet has a very rough surface with large irregularities. Probably high airflow resistance (turbulent flow) could be observed. Additionally, the surface is poor for sealing or paint adhesion and could trap dust

TABLE 1. Characteristic parameters of the studied ducts.

No.	Duct	Dimension [mm × mm]	Thickness [mm]	Surface condition	R_a [μm]	R_q [μm]	R_z [μm]
1	Raw steel sheet	500 × 800	3	Hot-rolled	12.50 ±0.76	13.75 ±0.84	50.00 ±3.06
2	Galvanised steel sheet	500 × 800	3	Mill finish (as-rolled)	6.30 ±0.39	6.93 ±0.42	25.20 ±1.50
3	Painted steel sheet	500 × 800	3	High-gloss, baked acrylic	1.60 ±0.10	1.76 ±0.11	6.40 ±0.39
4	Drawn aluminium	500 × 800	3	Smooth, seamless	0.80 ±0.05	0.88 ±0.06	2.00 ±0.12

and moisture, which leads to the corrosion risk. The galvanised steel sheet has a moderately rough surface texture; it is better than the raw steel, but still noticeable. The higher airflow resistance than with smooth surfaces could be expected. Suitable for general ducting, but this is not an ideal solution when low drag or ease of cleaning is critical. The painted steel has a smooth surface and low friction in airflow. The surface is mostly smooth, with no sharp defects. But R_z shows some moderate peaks/valleys, but likely not enough to cause airflow turbulence or sealing issues. This duct would be good for cleanrooms or visual/architectural applications. The aluminium duct is very smooth, almost polished, which causes minimal airflow friction. It is excellent for clean environments, lab ducts, or aerospace-grade HVAC. It can be assumed that this channel offers high performance for sealing and corrosion resistance.

3. EXPERIMENT

The experiments were performed on the specific test stand constructed in accordance with two standards PN-EN 3741:2011 'Determination of sound power levels of noise sources using sound pressure – Precision methods for reverberation rooms' and PN-EN 7235:2009 'Acoustics. Laboratory measurement procedures for ducted silencers and air-terminal units. Insertion loss, flow noise and total pressure loss' (see Fig. 2).

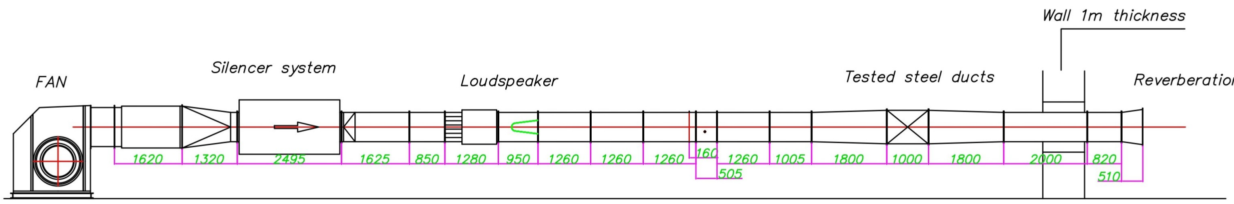

FIG. 2. Test stand with outlet to the reverberation room.

The measurement stand consists of a two-axis fan, a straight duct with a transition to a system of three absorption-resonance silencers, two straight ducts, one of which has an airflow straightener, a straight duct, a loudspeaker chamber, a system of straight ducts (6.5 m), a transition to the test duct, the test duct, transition to the measuring station, and a system of straight ducts with an outlet to the reverberation chamber (3.2 m). The dimensions of the station are shown in Fig. 1. Individual sections of the measuring station have flanges with a glued seal for screw mounting. Thanks to stand test construction, it is possible to determine the sound noise level of devices operating in the flow together with their attenuation effect by the use of precise methods. The reverberation chamber has a volume of 237.0 m^3 and an area of 231.5 m^2, with non-parallel, sound-reflecting walls.

The reverberation chamber has an additional door in the upper part of one of the side walls that opens into a compensation space connected to the laboratory's ventilation system, ensuring free air intake from the chamber and pressure equalisation. Since the outlet of the measuring station is located right next to the wall of the reverberation chamber, the airflow in the chamber space undergoes free expansion due to its dimensions, which causes laminar outflow of excess air from the chamber through an additional door (opening) at the top of the chamber, without affecting the measurement conditions.

During the measurement of self-noise and pressure drop, the tested silencer is connected to a centrifugal fan via three absorption silencers. The fan, noise source, and tested silencer are positioned outside the reverberation chamber, whereas the outlet is situated inside the chamber.

A procedure for determination of the SPL is measurement in points evenly distributed on the circular measurement path of 10 m in circumference by using microphone rotating boom. SPLs are measured in nine discrete microphone positions with an integration time of 30 s for each microphone position and are measured in 1/3 octave bands 100 Hz to 10 000 Hz. The B&K microphone, model no. 4146 was used and data were collected using a two-channels B&K analyser 2144. Microphone was calibrated before commencing the acoustic test. Background noise is recorded for each measurement series with airflow switched off, enabling the calculation of background correction K_1. The reverberation time is measured for four omnidirectional loudspeaker positions with three microphone settings. All sound power level calculations are completed using a dedicated calculation sheet. Due to the high signal-to-noise ratio (the difference between the signal and the background exceeds 15 dB) and excellent spatial uniformity (variance between signals from 12 positions of microphones <0.3 dB), the expanded uncertainty of the sound power level measurement in a reverberation room was estimated at the laboratory as $U = \pm 0.7$ dB. This reflects a high-precision class 1 laboratory measurement where environmental and instrumental errors are effectively minimised.

The flow velocity was determined using the so-called arithmetical calculation method described in the norm PN-ISO 5221:1994 'Distribution and division of air – Measurement procedures for airflow in the duct'. The mean velocity in the channel was determined using the log-Chebyshev method. Acoustic measurements were taken at four flow velocities, $\nu_1 = 3$ m/s, $\nu_2 = 6$ m/s, $\nu_3 = 9$ m/s, and $\nu_4 = 12$ m/s. Ambient pressure was measured by means of the Prandtl probe with a pressure difference converter. While for the duration of the flow noise measurement, the Prandtl probe was removed from the channel measurement space so as not to disturb the measured acoustic signal. Also the static pressure and temperature in the ducts were measured. The use of an automated robotic positioning system in flow measurement significantly reduced the uncertainty associated with probe orientation and spatial sampling. For a velocity of 12 m/s, the expanded uncertainty was estimated at 1.3 %, primarily dominated by the sensitivity of the differential pressure transducer at low dynamic pressures. Whereas, by using a high-precision differential pressure transducer with an absolute error of ±0.1 Pa, the expanded uncertainty at the lower velocity of 3 m/s was 2.86 %. To sum up, the uncertainty of the flow measurements did not exceed 3 %. On a logarithmic scale (decibels), a 3 % error in velocity measurements translates to a measurement uncertainty of approximately ±0.8 dBA. This value is close to the human ear's limit of discrimination (1 dB), meaning that the measurement uncertainty for airflow measurements in the duct under test is at an acceptable level for acoustic engineering.

4. Results

4.1. Flow noise

Table 2 and Table 3 present 1/3 octave band sound power levels and overall sound power level (L_W) values reported for the self-noise of all tested ducts. Table 2 contains results obtained for a single flow velocity, namely 3 m/s and 6 m/s. Table 3 presents the results for flow velocity appropriately 9 m/s and 12 m/s. The penultimate row of each tables contains the single-number values of sound power level (L_w). The last row of tables give the differences between the single-number sound power level studied steel duct and the aluminium duct (ΔL_w).

For each of the tested steel ducts, the self-noise is higher than for the aluminium duct. The lowest single-number sound power level values (L_w) were obtained for the aluminium duct at airflow velocities of 3 m/s, 6 m/s, and 12 m/s; only at 9 m/s was the L_w value, obtained for the aluminium duct, higher than for the tested steel ducts. Considering the estimated uncertainty of the duct's self-noise sound power level measurement of ±0.7 dB, it can also be concluded that at velocities of 3 m/s and 12 m/s, L_w values for the aluminium duct are the lowest compared to the other tested ducts. At velocities of 6 m/s, the difference between the aluminium and galvanised ducts, after taking into account the spread of measurement uncertainty, is 0.6 dB, favouring the galvanised duct. At 9 m/s, the sound power levels of the tested duct are comparable, differing by only 0.1 dB to 0.2 dB.

A positive difference in L_w as a single-number value between the tested steel ducts and the aluminium duct indicates how much higher the acoustic power of this duct is than the base – aluminium duct. The largest differences were observed at velocity of 12 m/s, up to 2.5 dB for the galvanised duct and 2.3 dB for the raw

TABLE 2. Sound power levels of self-noise for all studied duct at 3 m/s and 6 m/s airflow.

f_r [Hz]	Drawn aluminium	Raw steel sheet	Painted steel sheet	Galvanised steel sheet	Drawn aluminium	Raw steel sheet	Painted steel sheet	Galvanised steel sheet
	$\nu_1 = 3$ m/s				$\nu_2 = 6$ m/s			
100	25.2	27.3	27.1	25.9	31.9	32.9	32.8	31.6
125	26.4	28.8	28.9	27.5	33.1	34.5	34.6	33.1
160	28.2	30.6	30.1	28.6	34.9	36.3	35.8	34.3
200	28.3	30.4	30.2	30.0	35.1	36.0	35.9	35.6
250	31.6	36.7	34.5	32.3	38.3	42.4	40.2	37.9
315	34.0	35.0	34.6	33.6	40.7	40.7	40.3	39.3
400	33.6	35.4	35.2	34.5	40.3	41.1	40.9	40.2
500	32.7	34.1	33.7	33.1	39.4	39.8	39.4	38.8
630	32.7	34.1	33.5	32.9	39.4	39.8	39.2	38.6
800	30.5	32.0	31.9	30.8	37.2	37.7	37.5	36.5
1000	27.4	28.6	28.2	27.5	34.1	34.3	33.9	33.1
1250	25.3	26.8	26.5	25.6	32.1	32.5	32.2	31.3
1600	21.2	22.8	22.3	21.3	27.9	28.5	28.0	27.0
2000	18.2	19.7	19.5	18.4	24.9	25.4	25.2	24.1
2500	14.5	16.2	16.0	15.1	21.3	21.9	21.7	20.8
3150	13.0	15.1	14.6	14.4	19.7	20.7	20.2	20.1
4000	12.5	15.8	16.3	15.9	19.3	21.5	22.0	21.5
5000	13.0	15.9	16.1	15.5	19.7	21.5	21.7	21.2
6300	15.1	16.8	17.0	16.9	21.8	22.5	22.7	22.6
8000	10.0	11.5	11.5	11.6	16.7	17.2	17.2	17.3
10 000	8.7	11.2	10.9	10.9	15.4	16.9	16.5	16.6
$\boldsymbol{L_w}$	**41.6**	**43.7**	**43.0**	**42.0**	**48.3**	**49.4**	**48.7**	**47.7**
$\boldsymbol{\Delta L_w}$	–	**2.1**	**1.5**	**0.5**	–	**1.1**	**0.4**	–0.6

TABLE 3. Sound power levels of self-noise for all studied duct at 9 m/s and 12 m/s airflow.

f_r [Hz]	Drawn aluminium	Raw steel sheet	Painted steel sheet	Galvanised steel sheet	Drawn aluminium	Raw steel sheet	Painted steel sheet	Galvanised steel sheet
	$\nu_3 = 9$ m/s				$\nu_4 = 12$ m/s			
100	41.8	42.3	41.7	41.9	45.6	48.6	47.4	49.3
125	43.5	44.2	45.7	43.9	47.4	50.5	50.2	50.5
160	44.2	45.1	44.6	43.9	49.8	52.5	51.1	51.8
200	44.7	45.4	44.9	45.8	49.8	52.6	51.5	53.2
250	47.0	46.7	47.9	47.2	52.8	53.6	53.8	54.4
315	51.2	50.1	49.9	50.0	56.8	58.2	57.0	57.9
400	50.9	51.0	50.9	50.9	56.3	59.0	58.1	59.3
500	50.3	50.1	49.7	49.9	55.7	58.1	57.1	58.2
630	50.5	50.4	49.7	49.9	56.1	58.4	57.1	58.5
800	49.3	49.2	48.9	49.0	54.7	57.4	56.3	57.7
1000	47.0	46.4	45.9	46.2	52.5	54.5	53.3	54.7
1250	46.5	46.1	45.7	46.0	52.6	54.8	53.7	54.9
1600	43.5	43.2	42.6	42.9	50.5	53.1	51.8	53.3
2000	41.3	41.0	40.6	40.9	48.4	51.5	50.2	51.9
2500	38.2	37.9	37.6	37.9	45.6	48.8	47.6	49.2
3150	34.7	34.4	34.1	34.5	42.4	45.8	44.7	46.3
4000	32.4	32.3	32.2	32.5	40.0	43.8	42.8	44.3
5000	28.5	28.6	28.9	29.0	35.0	39.4	38.5	39.7
6300	27.6	28.1	27.9	28.9	32.5	36.5	35.8	36.9
8000	21.1	21.9	22.2	22.9	28.3	32.4	31.7	32.8
10 000	18.4	19.6	20.2	21.2	25.1	29.1	27.9	29.4
$\boldsymbol{L_w}$	**59.3**	**59.1**	**58.9**	**58.9**	**64.8**	**67.2**	**66.1**	**67.3**
$\boldsymbol{\Delta L_w}$	–	–0.2	–0.4	–0.3	–	**2.3**	**1.3**	**2.5**

steel duct. A 2.1 dB difference was also observed for the raw steel duct at a velocity of 3 m/s. The raw steel duct has the highest roughness among the tested ducts, which translates into L_w values. It can therefore be concluded that this type of duct tends to increase the sound power level in the flow. The influence of the roughness of the used duct on the generated noise is significant for ventilation systems, where the surface is a factor, due to higher flow velocities than for liquids and lower fluid viscosity. For the tested ducts, the range of the R_a parameter is from 0.80 µm to 12.50 µm (over a 15-fold difference). In ventilation technology, a duct with R_a = 0.80 µm behaves like a 'hydraulically smooth' duct, while a duct with R_a = 12.50 µm (raw sheet metal) enters the region of turbulent flow, where roughness directly increases the resistance coefficient λ. The 6 % uncertainty in the R_a measurement associated with the roughness measurement is negligible compared to the 1500 % difference between the sheet metal variants. Higher roughness increases the thickness of the boundary layer, which physically 'narrows' the duct lumen for core flow (Keli *et al.*, 2023). The wall roughness is therefore a source of so-called generated noise, because air 'catches' surface irregularities, creating vortices that are the source of sound. The uncertainty of the profilometer measurement does not change the fact that a duct with a high R_a will generate higher self-noise. In the case of galvanised duct, the galvanising method (hot-dip galvanisation, electroplating, or spraying) is important. In this study, galvanised sheet metal with a mill finish (as-rolled) was used, which refers to being hot-dipped in zinc after being hot-rolled and potentially pickled (the hot-dip method). This galvanising and finishing method results in a higher roughness suitable for spraying or painting as the next step of the metal process (Tatarek *et al.*, 2009). For the painted duct, which has lower roughness, the difference ΔL_w does not exceed 1.5 dB.

A velocity measurement uncertainty of 3 % translates to the SPL uncertainty of approximately ±0.8 dB, considering that acoustic power typically scales with v^6 (sound power is proportional to the sixth power of flow velocity). This uncertainty is within acceptable limits for most industrial acoustic assessments. Take into account the measurement uncertainty of surface roughness, the observed variations in sound parameters from flow characteristics across the ducts stem from genuine differences in a surface finish rather than instrumental error. The measurement uncertainty may marginally reduce the resolution of the comparison, but it does not undermine the fundamental findings of the study. The higher parameters of surface roughness had a more dominant effect on the sound power levels due to the increased turbulence intensity in the boundary layer. Literary studies suggested that roughness elements can amplify certain frequencies of sound due to the interaction between the turbulent boundary layer and the acoustic waves or lower them (Raposo *et al.*, 2021). The sound characteristics in ducts with uneven surfaces could lead to increased noise levels due to flow-induced vibrations, and the type and severity of roughness directly correlate with noise pollution within duct systems (Mori, Ishihara, 2020). The conclusion is that the roughness of ventilation system elements could alter sound radiation patterns and influence the overall acoustic performance of ducted systems. However, airflow within ducts must be understood to prevent undesirable sound generation and maintain efficiency. The study by Choy and Huang (2005) demonstrated that under certain conditions, airflow does not significantly alter acoustic performance up to a defined turbulence intensity, like in this case where the similar values of L_w are observed for studied ducts at 9 m/s. The conclusion idea is that the ventilation duct design should carefully balance aerodynamic and acoustic considerations.

4.2. Insertion loss

The insertion loss (IL or D) is often used to evaluate the acoustic attenuation performance of the object working in airflow conditions. The tested duct's acoustic performance is measured using insertion loss. The insertion loss D_i is defined as the reduction in sound power level measured downstream of the studied aluminium duct and after replacing it with the studied steel ducts. In the present study, a drawn aluminium duct, as a very smooth with minimal airflow friction was treated as a low-noise object ('silencer'). The insertion loss is calculated according to:

$$D_i = L_{W\text{II}} - L_{W\text{I}}, \tag{4}$$

where $L_{W\text{I}}$ is the the sound power level in the considered frequency band, measured for aluminium duct ('silencer'), and $L_{W\text{II}}$ is the sound power level in the same frequency band, measured for studied steel ducts.

This approach enables the evaluation of the acoustic effectiveness associated with the use of steel ducts of varying surface roughness. For the tested duct, the correlation between insertion loss and duct surface roughness was determined for fully turbulent flow. Each of the tested velocities results in fully turbulent flow, i.e., the Reynolds number for 3 m/s is 60 200, for 6 m/s – 120 397, for 9 m/s – 180 595, and for 12 m/s – 240 794. Table 4 and Table 5 present the calculated insertion loss values in 1/3 octave bands for the studied steel ducts. The insertion loss spectra in 1/3 octave bands for tested ducts are shown in Fig. 3. The cut-off frequency (f_{cutoff}), the lowest frequency at which a particular wave mode can propagate through the duct, was marked in Fig. 3. The vertical pink line indicates the cut-off frequency (f_{cutoff} = 214 Hz), meaning that below it frequency, in a 500 mm × 800 mm duct, waves propagate flat, while above it, transverse modes begin to occur.

Due to the use of the aluminium duct as a reference ('silent'), the following assumptions should be made when interpreting the insertion loss of the tested ducts:

– if the insertion loss represents positive values, then the aluminium channel is quieter than the tested steel channel which acts as a 'muffler,'

– if the insertion loss assumes negative values, then the tested steel ducts are quieter than the reference aluminium duct which acts as an 'anti-muffler.'

Insertion loss allows us to draw key conclusions regarding the influence of the physical structure of the channel walls on aeroacoustic phenomena. Generally, from Table 3 and Table 4 and Fig. 3, we can conclude that at low frequencies (<500 Hz), large fluctuations and high attenuation values (up to 3 dB) are visible. This is the region where channel geometry and eigenmode resonances have the greatest impact on acoustics. At medium and high frequencies (500 Hz to 5000 Hz), the graphs stabilise and oscillate around 0 dB to 1 dB. This indicates that the type of sheet material has less influence on sound level changes. At very high frequencies (above 5000 Hz) and at higher velocities (9 m/s and 12 m/s), a further increase in attenuation is observed (especially for painted sheet metal), which may be due to the absorption characteristics of the material or changes in the boundary layer structure at higher flow rates.

TABLE 4. Insertion loss values in 1/3 octave bands the studied steel duct (reference duct – aluminium duct) at 3 m/s and 6 m/s flow velocity.

f_r [Hz]	Raw steel sheet	Painted steel sheet	Galvanised steel sheet	Raw steel sheet	Painted steel sheet	Galvanised steel sheet
	ν_1 = 3 m/s			ν_2 = 6 m/s		
100	3.4	2.8	2.9	2.4	1.8	1.9
125	1.0	1.6	1.5	–0.1	0.6	0.5
160	2.0	0.7	0.7	1.0	–0.3	–0.4
200	1.7	1.7	1.7	0.7	0.6	0.7
250	1.1	1.7	1.4	0.0	0.7	0.3
315	1.5	1.5	2.5	0.4	0.5	1.4
400	2.0	0.9	1.1	0.9	–0.1	0.1
500	0.7	0.7	0.8	–0.4	–0.3	–0.2
630	0.8	0.5	1.1	–0.3	–0.5	0.1
800	0.6	0.7	0.5	–0.5	–0.4	–0.5
1000	1.0	0.5	0.5	–0.1	–0.6	–0.5
1250	1.3	0.6	1.3	0.3	–0.4	0.3
1600	1.9	1.1	1.3	0.8	0.1	0.2
2000	0.8	1.3	1.2	–0.2	0.3	0.2
2500	1.6	0.9	1.6	0.6	–0.2	0.6
3150	0.7	1.2	0.9	–0.3	0.1	–0.1
4000	0.2	1.2	0.7	–0.8	0.1	–0.4
5000	1.0	1.2	1.1	–0.1	0.1	0.1
6300	0.8	1.4	1.1	–0.2	0.4	0.1
8000	0.6	1.7	1.4	–0.5	0.7	0.4
10 000	–0.3	1.3	0.5	–1.3	0.3	–0.6

TABLE 5. Insertion loss values in 1/3 octave bands the studied steel duct (reference duct – aluminium duct) at 9 m/s and 12 m/s flow velocity.

f_r [Hz]	Raw steel sheet	Painted steel sheet	Galvanised steel sheet	Raw steel sheet	Painted steel sheet	Galvanised steel sheet
		ν_3 = 9 m/s			ν_4 = 12 m/s	
100	2.2	1.8	2.2	2.3	1.5	3.0
125	0.4	0.8	1.0	0.6	1.4	0.6
160	0.7	–0.6	0.0	–0.3	–1.4	–1.2
200	0.8	0.5	1.3	0.1	–0.1	0.6
250	0.4	0.9	1.2	–0.2	0.1	0.1
315	0.5	0.4	1.8	–0.4	–0.3	0.6
400	1.1	0.2	0.7	0.5	–0.4	–0.1
500	–0.2	–0.2	0.2	–0.2	–0.3	–0.5
630	–0.2	–0.4	0.6	–0.3	–0.6	–0.2
800	–0.2	–0.3	0.1	–0.4	–0.5	0.0
1000	0.1	–0.5	0.1	0.6	0.0	0.2
1250	0.4	–0.3	0.8	0.1	–0.6	0.3
1600	0.9	0.1	0.7	–0.1	–1.0	–0.2
2000	0.0	0.3	0.5	0.4	0.7	0.6
2500	0.8	–0.1	1.1	0.4	–0.2	0.5
3150	0.1	0.4	0.8	0.4	0.6	0.7
4000	–0.5	0.2	0.2	0.2	0.7	0.5
5000	–0.1	0.1	0.4	0.2	0.2	0.4
6300	–0.2	0.4	0.6	0.9	1.3	1.3
8000	–0.4	0.5	0.5	1.2	2.1	1.6
10 000	–1.1	0.5	0.0	1.1	2.6	1.8

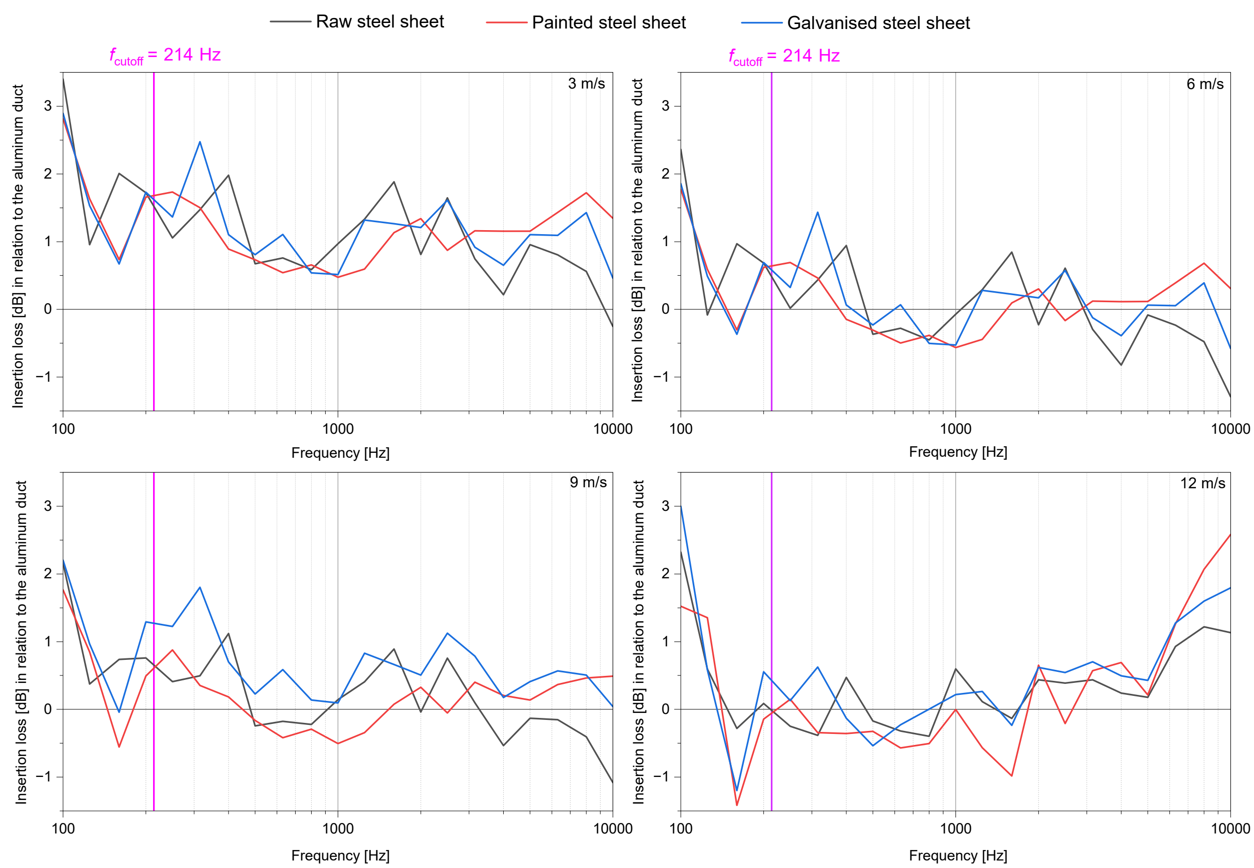

FIG. 3. Insertion loss spectra in 1/3-octave bands for studied steel ducts (aluminium duct as references) depending on the airflow velocity.

The effect of flow velocity on the differences in insertion loss between sheet metal types is noticeable but not dominant, particularly at flow velocities of 3 m/s and 6 m/s. Positive insertion loss values at 3 m/s indicate that the aluminium duct is an effective attenuator ('muffler') compared to the other tested ducts. For example, the highest insertion loss is 2 dB at 400 Hz compared to the raw duct, but compared to the galvanised duct, the highest insertion loss is 2.5 dB at 315 Hz. At 6 m/s, the aluminium duct attenuates sound in the ranges of 250 Hz to 500 Hz, 1000 Hz to 3000 Hz, and above 6000 Hz (only painted and galvanised duct). But, at 9 m/s, only the galvanised duct exhibits positive insertion loss, not exceeding the maximum value of 2 dB at 315 Hz. These results may indicate that the aluminium duct attenuates sound better than the galvanised duct at this airflow speed. At the highest velocity, deep minima (drops below 0 dB) are visible, suggesting that at this velocity, the airflow generates its own noise (self-noise), which may exceed the attenuation, or that surface resonances in the sheet metal are excited.

Figure 3 also shows that painted sheet metal often exhibits different minima than unpainted sheet metal. The paint layer changes the material's internal damping (damping), which shifts the resonance points. It is worth noting that, the painted channel has lower insertion loss values than the other two channels up to approximately 5000 Hz. It may mean that the painted duct will be comparable to the aluminium duct in terms of acoustic efficiency. It could also be connected with the similar roughness of these ducts. However, the insertion loss value increases above 5000 Hz for this duct, which means that the aluminium duct is acoustically better above this frequency than the painted one. A distinct resonance peak observed at 315 Hz for the galvanised steel sheet, which remains stationary across all flow velocities (3 m/s to 12 m/s), indicates a structural or geometric resonance rather than an aerodynamic phenomenon. This is likely caused by the specific panel resonance of the galvanised duct walls or the inherent damping properties of the zinc coating, which coincides with the excitation of the first transverse acoustic modes above the 214 Hz cut-off frequency.

In summary, it can be concluded that aluminium duct is acoustically more advantageous for use at lower airflow speed. However, at higher flow velocity, it may not be. This observation can be useful for designers because of the higher cost of aluminium ducts than steel ones. From single-number values of L_w studied, ducts can be observed that the roughness of the ducts affects their insertion loss. As airflow velocity increases, the differences between the materials become less pronounced, suggesting that aerodynamic effects dominate over material surface treatments at higher velocities.

4.3. Correlation between geometric surface properties and acoustic parameters

In this study, the Pearson linear correlation coefficient was applied to assess the strength and direction of the relationship between the channel surface roughness and the sound power level. The choice of this method is motivated by the continuous nature of the variables considered and by the assumption that, within the investigated range of operating conditions, the relationship between roughness and acoustic power can be approximated as linear. Moreover, the use of sound power level expressed in decibels contributes to the linearisation of the relationship and to variance stabilisation, which further supports the application of a linear correlation measure. Prior to the use of the Pearson correlation, the data were examined with respect to linearity, approximate normality of distributions, and the presence of outliers. These preliminary analyses indicated that the assumptions of the Pearson correlation were sufficiently satisfied for the considered dataset. Therefore, the Pearson coefficient was deemed an appropriate tool for quantifying the correlation between the geometric parameter (channel roughness) and the acoustic parameter (sound power level), providing an objective measure of the strength and direction of their linear relationship.

Table 6 summarises data on the roughness of the tested ducts and single-number values (and also in octave bands) of the sound power level depending on velocity. The last row of the table illustrates the Pearson coefficient.

The strongest relationship was observed at a flow velocity of 12 m/s (r = 0.91), where the correlation is almost perfectly linear. This indicates that, at this velocity, surface roughness becomes the dominant factor in noise generation: the boundary layer is sufficiently thin for roughness elements of about R_z = 50 µm to directly interact with the core flow, producing strong turbulence and regenerated noise. The difference between

Table 6. Pearson coefficient for studied ducts from the dependency between R_a and L_w (for single-number values and for octave band values) at different airflow speeds.

Air-flow speed [m/s]	Sound power level [dB]							
	L_w	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
12	0.91	0.90	0.81	0.84	0.86	0.86	0.82	0.85
9	−0.15	0.44	−0.69	−0.26	−0.48	−0.38	−0.29	0.55
6	0.32	0.39	0.59	0.46	0.38	0.44	0.81	0.55
3	0.78	0.38	0.39	0.38	0.36	0.37	0.36	0.36

aluminium (64.8 dB) and raw sheet metal (67.2 dB) is 2.4 dB, which is statistically highly significant. At 3 m/s (r = 0.78), the correlation is still high, suggesting that even at low flow rates, differences in surface structure are detectable by the measurement system, although absolute sound levels are much lower (around 42 dB). At 9 m/s, an almost zero correlation (r = −0.15) was obtained. Sound power levels are nearly identical for all materials (≈59 dB), which suggests that geometry-induced noise dominates and wall roughness temporarily loses its significance at this operating point. Parameters R_a and R_z are perfectly correlated in the dataset, but R_z = 50 µm is the physically meaningful factor, as it represents the actual height of obstacles interacting with the airflow. Considering the number of acoustical measurements (n = 12), low standard deviation, and very high correlation at 12 m/s, it may be concluded that the effect of roughness on acoustic power is statistically significant and not accidental.

Designers of ventilation systems often require sound power parameters in octave bands, because such data are directly necessary for designing installations in accordance with engineering practice and standard requirements. In connection with this, it is important to find the correlation between octave band results and surface roughness across the frequency spectrum. Table 6 shows also Pearson correlation coefficients for the octave bands of the tested ducts depending on their surface roughness at different air-flow speed. The octave band analysis at 12 m/s reveals a consistently high Pearson correlation (r > 0.81) across the entire frequency spectrum (125 Hz to 8000 Hz). The strongest correlation (r = 0.90) was observed at 125 Hz, indicating that surface roughness significantly enhances low-frequency turbulent pressure fluctuations and favours the formation of large-scale turbulent structures that generate low-frequency noise. It confirms that surface finish is a critical factor in flow-induced noise generation for this duct geometry. The spectral correlation analysis at 9 m/s demonstrates a significant shift in aeroacoustic behavior compared to higher velocities. While the 12 m/s data showed a dominant link between roughness and noise, at 9 m/s the Pearson coefficients fluctuate between weak positive and moderate negative values across most octave bands. This suggests that at this flow regime, surface-induced noise is no longer the primary sound source, and the small measured variations of L_w (often <0.3 dB) fall within the margin of experimental uncertainty. At this speed, the noise level generated by the wall roughness itself is so low that it is 'covered' by other sound sources, such as general turbulence in the channel or noise generated by the edges of the measuring holes. Consequently, the impact of surface morphology on the acoustic profile is effectively masked by broader flow turbulence at this specific velocity.

Spectral correlation analysis at 6 m/s reveals a consistent positive relationship (r > 0 across all bands) between the surface roughness (R_a) and sound power levels (L_w). Notably, a strong correlation (r = 0.81) is observed in the 4000 Hz octave band, indicating that at lower flow velocities, high-frequency noise components are the most sensitive to surface morphology. This suggests that roughness primarily generates high-frequency noise before becoming dominant across the spectrum at higher speeds. At the lowest tested velocity of 3 m/s, the spectral correlation analysis shows a consistent but weak positive relationship (r ≈ 0.37) across all octave bands. The results are influenced by non-linearities, particularly a localised noise increase observed for the R_a = 1.6 µm variant, which suggests that at very low flow regimes, factors other than pure surface roughness – such as panel vibration or specific material damping – may play a more significant role.

The experimental data confirm that the influence of surface roughness on the sound power level (L_w) is non-linear and strictly dependent on the flow regime. At 12 m/s, a very strong linear correlation (r = 0.79) exists between roughness and noise. The thin boundary layer allows surface asperities to act as primary sources of broadband noise, scaling with the sixth power of velocity. At 9 m/s, a 'dead zone' was identified where the correlation collapses (r = −0.12). In this state, general duct turbulence and geometric effects mask the acoustic signature of the surface texture. At the low-velocity regime (3 m/s to 6 m/s), roughness impacts the spectrum selectively, beginning with high-frequency bands (4000 Hz to 8000 Hz). At the lowest speeds, structural damping and resonances of the specific materials (e.g., the 315 Hz peak in galvanised steel) outweigh the influence of the R_a profile. The application of the Pearson correlation analysis across octave bands proved to be superior to single-number evaluations. It successfully pinpointed the exact frequency ranges where surface-induced noise is generated, providing a localised understanding of the aeroacoustic phenomena. This methodology could support a more precise approach to selecting insulation and attenuation components tailored to the specific roughness-induced noise profile of the ductwork.

5. Conclusions

This study investigates how the surface roughness of flat-oval ventilation ducts affects acoustic parameters, specifically focusing on self-noise and insertion loss. The three types of steel ducts – raw, galvanised, and painted – against a smooth-drawn aluminium duct used as a reference were compared. The experiments demonstrated that all tested steel ducts generated higher levels of self-noise than the smoother aluminium duct, with the most significant differences observed at the highest airflow velocity of 12 m/s, where the galvanised duct's noise level reached up to 2.5 dB higher. Painted steel ducts exhibited acoustic performance and self-noise levels very similar to the aluminium duct due to their comparably low surface roughness. A strong linear correlation was found between surface roughness and sound power level at 12 m/s, indicating that roughness becomes a dominant noise generator at high speeds. Conversely, at a medium velocity of 9 m/s, this correlation disappeared, suggesting that general turbulence masks the acoustic effects of surface texture at this specific speed.

The study confirmed that insertion loss in straight flat-oval steel ducts is generally very low, which is consistent with existing literature. At lower airflow velocities, such as 3 m/s and 6 m/s, the aluminium duct functioned as a more effective silencer than the steel ducts. However, as the airflow velocity increased, the differences in acoustic performance between the various materials became much less pronounced. This convergence indicates that at higher velocities, aerodynamic effects and turbulence dominate over the influence of the duct's material surface treatment. The spectral analysis further revealed that surface roughness impacts noise generation selectively, primarily affecting high frequencies between 4000 Hz and 8000 Hz at lower flow speeds.

A distinct structural resonance peak was observed in the galvanised steel duct at 315 Hz, which remained constant regardless of the airflow velocity. From a design perspective, while aluminium ducts are acoustically superior at low speeds, their higher cost may not be justified at high flow rates where aerodynamic noise prevails. Ultimately, predicting noise in HVAC systems remains difficult because the interaction between turbulent flow and surface roughness is non-linear and varies significantly across different flow regimes.

The main conclusion of this review study is that a comprehensive knowledge of turbulent flows over rough surfaces is still a long way off, even though there has been substantial development in this area. The main reason is that turbulent flows are erratic and unexpected, which makes accurate forecasting practically impossible. The large variety of roughness types, which significantly affect the flow dynamics in roughness sublayers, and the lack of comprehensive studies on the structure of turbulent flow are further problems.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contribution

Joanna Maria Kopania conceptualized the study and contributed to the analysis and interpretation of the data, and wrote the original draft. Kamil Wójciak performed the measurements, analysed, and interpreted the data. Patryk Gaj performed the measurements and contributed to the analysis. Grzegorz Bogusławski performed the measurements. All authors reviewed and approved the final manuscript.

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