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LINEAR SOURCES WITH NON-LINEAR DISTRIBUTION OF SOUND ENERGY

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Abstract

In practical circumstances we often meet sources the structures of which approach those of current HVAC ducts but with dimensions and mode of radiation completely different. Typical are light stacks of factories, refuse incinerating plants, etc.
The core of the problem is that a stack must be considered as a linear source where sound power is radiated in two parts. The first is the top of the stack (point source) and the second, considerably greater, is the outer surface of the stack (linear source). Sound power, however, is radiated by the outer surface of the stack in a non-linear mode and drops from the flue gas inlet to the top of the stack. In projects it is therefore very difficult to predict how a stack radiates sound energy, in order to avoid exceeding hygienically permissible limits. This paper deals with ducts with walls made of relatively thin sheets.

1. INTRODUCTION

Difficulties with noise in HVAC systems have a number of reasons. One of them is noise generated from surfaces of ducts in which the high sound pressure level is caused mainly by the sound power of fans, another one can be noise generated by combustion of gases in combustion systems.
Data on noise emission from HVAC ducts can be found in paper [1] published in 1960. The sound power level transmitted through the walls of ducts into the ambient environment is estimated by relation

$$L_{W2} = L_{W1} - R + 10 \log \frac{S_2}{S} \tag{1}$$

where L_{W1} [dB] sound power level transmitted in the duct by air,
L_{W2} [dB] sound power level transmitted from the duct into the ambient environment,

S_2 [m^2] outer surface of duct,
S [m^2] cross-section of duct,
R [dB] air transmission loss of duct.

At first sight the solution of this problem is similar to that of transmission of noise from a live to a protected room. However there are a few differences. The air transmission loss of buildings is characterized by gradual increase of noise insulating properties of walls with increasing frequency. In HVAC ducts this is true only for ducts with flat walls. In circular cross-section ducts the situation is absolutely opposite. And this type of duct is used most often.
According to [2] for emission of noise from a circular cross-section duct (see diagram in Figure 1) reduction of noise can be determined in the form

$$R = 10 \log \left(\frac{W_1}{W_2} \frac{S_2}{S} \right) \tag{2}$$

where W_1 [W] sound power emitted into the duct at its front end,
W_2 [W] sound power emitted from the duct into the ambient environment,
R_t [dB] air transmission loss.

2. TRANSMISSION LOSS OF DUCT

The procedure of assessment of the transmission loss of the wall of a circular cross-section duct is according to [2] based on an approximation of the sound insulating property for individual octave bands by a broken line which can be seen in Figure 2. It must be emphasized that circular cross-section ducts exhibit different transmission losses for the emission of sound from the duct into the ambient environment and that for the opposite case of emission from the ambient environment into the duct. This paper deals mainly with the most current case of emission of noise from the duct into the ambient environment.
In lower frequency bands the transmission loss of a circular cross-section duct does not exceed 50 dB as can be seen from the diagram in Figure 2. In medium frequency bands the transmission loss of a circular cross-section duct is given by equations for $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$**.** The resulting transmission loss is then given by the higher value of both.

$$R_1 = 17{,}6 \log(m") - 55{,}3 \log(D) - 49{,}8 \log(f_m) + 130{,}07 \tag{3}$$

$$R_2 = 17{,}6 \log(m") - 36{,}9 \log(D) - 6{,}6 \log(f_m) + 26{,}4 \tag{4}$$

where $m“$ [kg/m^2] specific mass of duct
d [m] diameter of duct
f_m [Hz] medium frequency in the octave.

The above relations can be used for ducts up to a diameter of 630 mm. For ducts with larger diameters the transmission loss in the 4000 octave is determined by the following equation:

$$R_3 = 17{,}6 \log(m") - 36{,}9 \log(D) + 19{,}62 \tag{5}$$

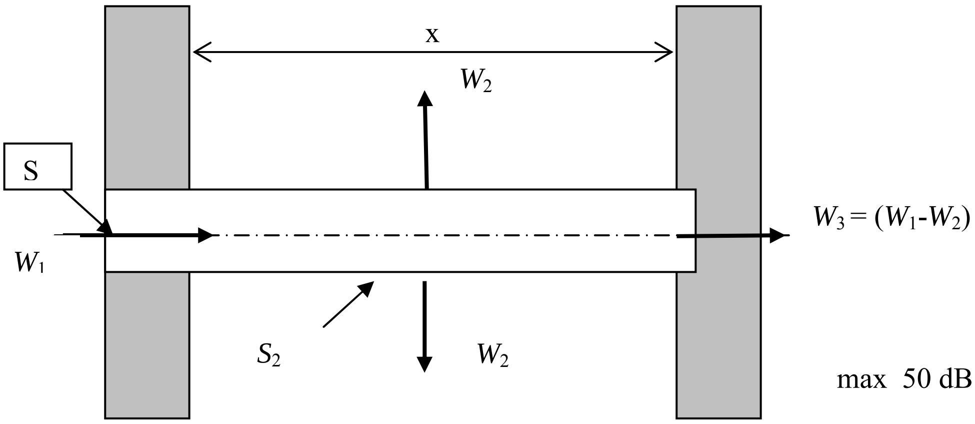

Figure 1 Diagram of noise emission from duct

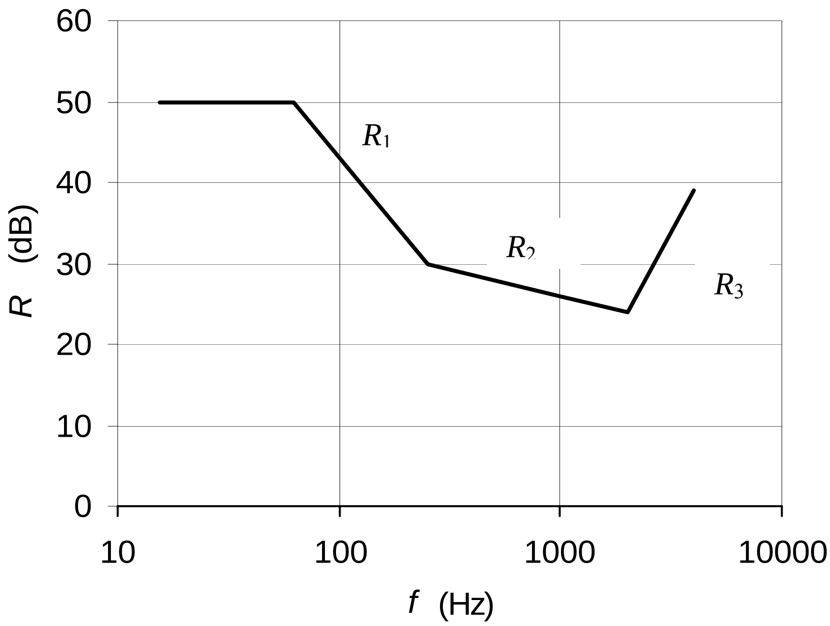

Figure 2 Spectrum of air transmission loss of a circular cross-section duct

3. EMITTED SOUND POWER FROM DUCT

The sound power emitted from a duct expressed by the sound power level in an octave band is given by Eq. (1). From the energy conservation law follows that from a duct ***x*** (m) long the sound power emitted into further sections of the duct is reduced by the value of the sound power emitted into the ambient environment, which is expressed by equation:

$$L_{W3} = L_{W1} + 10\log\left(1 - \frac{S_2}{S}10^{-0,1R}\right) \tag{6}$$

where L_{W1} (dB) sound power level at entry into duct,
L_{W3} (dB) sound power level emitted into further sections of duct.

The surface of the shell of a duct $\boldsymbol{S_2}$ can be expressed by formula

$$S_2 = \pi D x \tag{7}$$

The area of the cross-section of a duct can be determined from relation

$$S = \frac{\pi D^2}{4} \tag{8}$$

Equation (6) after substitution can be arranged in the form

$$L_{W3} = L_{W1} + 10 \log \left(1 - \frac{4x}{D} 10^{-0,1R} \right) \tag{9}$$

A more detailed analysis of the topic dealt with shows that the recommended calculation procedure according to [2] is limited namely by the length of the duct. For relatively short ducts this calculation can be applied without significant errors. In long ducts, however, propagation of noise into the ambient environment and by the duct itself must be calculated using equations which take into account gradual reduction of the sound power level in the duct. The corresponding differential equation for propagation of sound power in a duct with an elementary length dx will be set up with respect to the diagram in Figure 3.

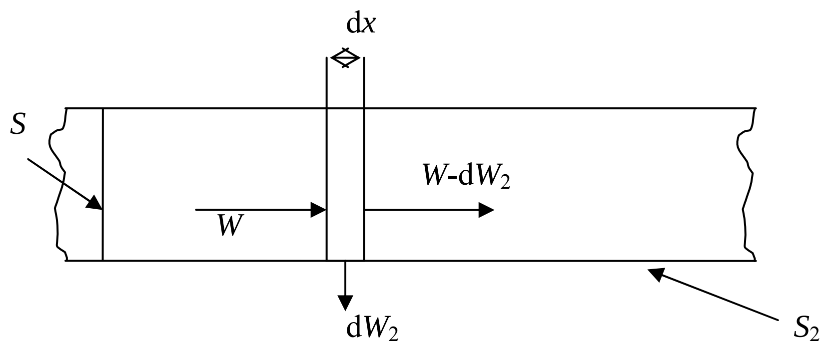

Figure 3 Diagram of sound propagation in a duct without transmission losses

Sound power

$$W = \frac{p^2}{\rho c} S \tag{10}$$

enters the checking element, where p (Pa) is sound pressure.

Elementary sound power

$$dW_2 = 10^{-0,1R} \frac{W dS_2}{S} \tag{11}$$

is emitted into the neighbourhood of the element.

Sound power reduced by

$$-dW = \frac{d}{dp}\left(\frac{p^2}{\rho c}S\right)dp = \frac{p^2}{\rho c}\pi D\, 10^{-0,1R}\, dx$$

is emitted from the checking element in the direction of the x-axis.

By solving this equation we obtain

$$\int_{p_1}^{p}\frac{1}{p}dp = -\frac{\pi D}{2S}10^{-0,1R}\int_0^x dx \tag{12}$$

which relation leads to a solution giving the behaviour of sound power in a duct as a function of the distance

$$\ln\left(\frac{p}{p_1}\right) = -\frac{2}{D}10^{-0,1R}x = -g(x) \tag{13}$$

In simplified form

$$p = p_1\, e^{-g(x)}$$

In shortened notation the behaviour of the intensity of sound along the duct is expressed in the form

$$I = \frac{p^2}{\rho c} = \frac{p_1^2}{\rho c}e^{-2g(x)} \tag{14}$$

Sound emitted by a duct with general dimensions into the ambient environment depends on the reduction of sound power per duct length ***x***.
At the front end of the duct the level of noise in the duct is given by the value of sound power $\boldsymbol{W_1}$**,** which is expressed by relation

$$W_1 = \frac{p_1^2}{\rho c}S \tag{15}$$

At the end of the monitored section the sound power transmitted by the duct will be $\boldsymbol{W_3}$

$$W_3 = \frac{p_1^2}{\rho c}e^{-2g(x)}S \tag{16}$$

The difference between these two values gives the total emitted sound power from the duct $\boldsymbol{W_2}$

$$W_2 = W_1\left(1 - e^{-2g(x)}\right) \tag{17}$$

The derived relations can be converted into a logarithmic scale by substituting into expressions for sound power level

$$L_{W_3} = L_{W_1} - 17{,}372\,.10^{-0{,}1R}\,\frac{x}{D} \tag{18}$$

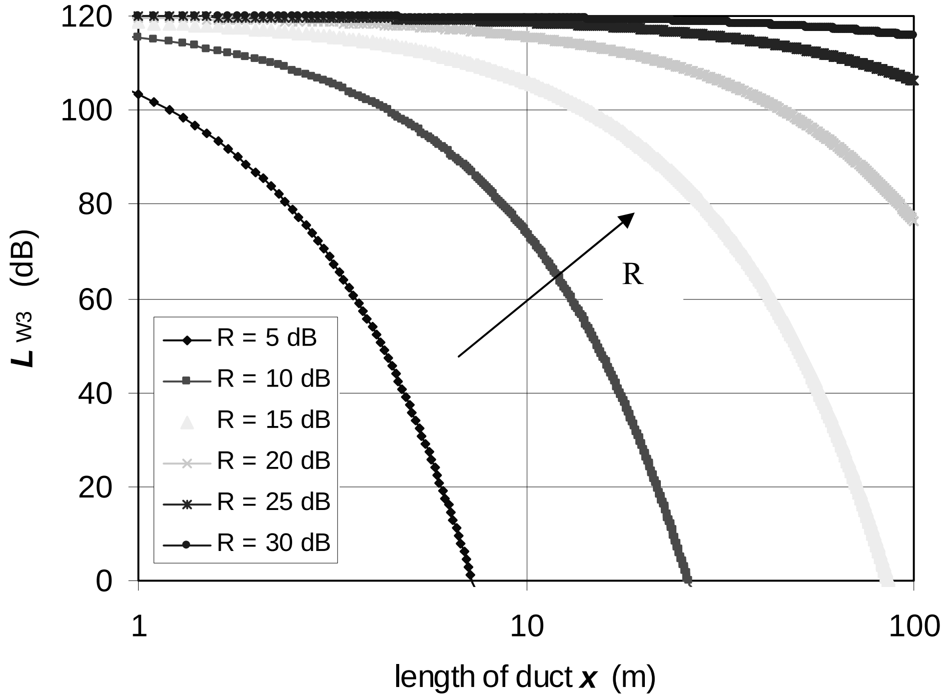

Figure 4 Diagram of sound emission from smoke stack (L_{W1} = 120dB, D = 400 mm)

The following relation will hold for the sound level emitted from the surface of the duct

$$L_{W_2} = L_{W_1} + 10\,\log\left(1 - e^{-2g(x)}\right) \tag{19}$$

4. SECTION OF DUCT AS LINEAR EMITTER

HVAC ducts or combustion equipment flues generate undesirable noise into the ambient environment. Experienced project engineers differentiate in acoustic calculations between point and linear emitters of sound energy. In calculations of sound fields of e.g. smoke stacks made of light ducts, generation of noise from the surface of the stack is usually neglected and only generation of noise from the top of the stack is taken into account. Due to the above the sound field in the neighbourhood of the smoke stack should be calculated on the basis of the interference of noise generated at the top of the stack and that from its surface, as shown in Figure 5.

From the top of the smoke stack only noise on the sound power level $\boldsymbol{L_{W3}}$ will be emitted. Noise generated from the surface of the smoke stack will not be distributed uniformly along the stack but its intensity will be exponentially reduced.

If a project engineer would like to know the distribution of the sound intensity on the outer surface of a duct he could use relation:

$$I_2 = I_1.e^{-2.g(x)}.10^{-0{,}1.R} \tag{20}$$

Sound power level $\boldsymbol{L_{w21}}$ emitted into the environment corresponding to 1m of the length of the smoke stack will then be given by expression:

$$L_{W21} = L_{W1} + 10 \log (e^{-2.g(x)}) - R + 10 \log (\frac{\pi.D}{S}) \tag{21}$$

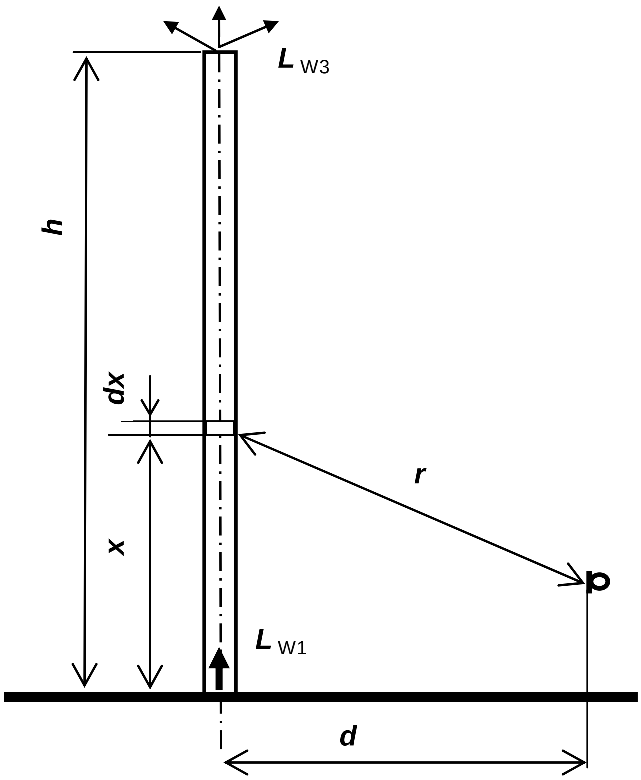

Figure 5 Distribution of sound from smoke stack

Noise generated in the check point by sound energy from the surface of the duct can be expressed by an equation for sound intensity in the check point

$$I = \frac{W_1}{\pi D} \int_o^h \frac{e^{-2g(x)}}{\left(x^2 + d^2\right)} dx \tag{22}$$

By substituting Eq. (22) into the relation defining the sound pressure level, we obtain a practically utilizable expression which gives information on the effect of emission of noise from the surface of a smoke stack on the noise in the check point

$$L_{p2} = L_{W1} + 10 \log \left(\frac{1}{\pi D} \int_o^h \frac{e^{-2g(x)}}{\left(x^2 + d^2\right)} dx \right) \tag{23}$$

where L_{w1} (dB) sound pressure level at entry into smoke stack.

The check point also receives sound power from the top of the smoke stack, as given by expression (18). The corresponding sound pressure level will be given by expression:

$$L_{p3} = L_{W3} + 10\log\left(\frac{Q}{4\pi(h^2 + d^2)}\right) \tag{24}$$

where h (m) height of the smoke stack.

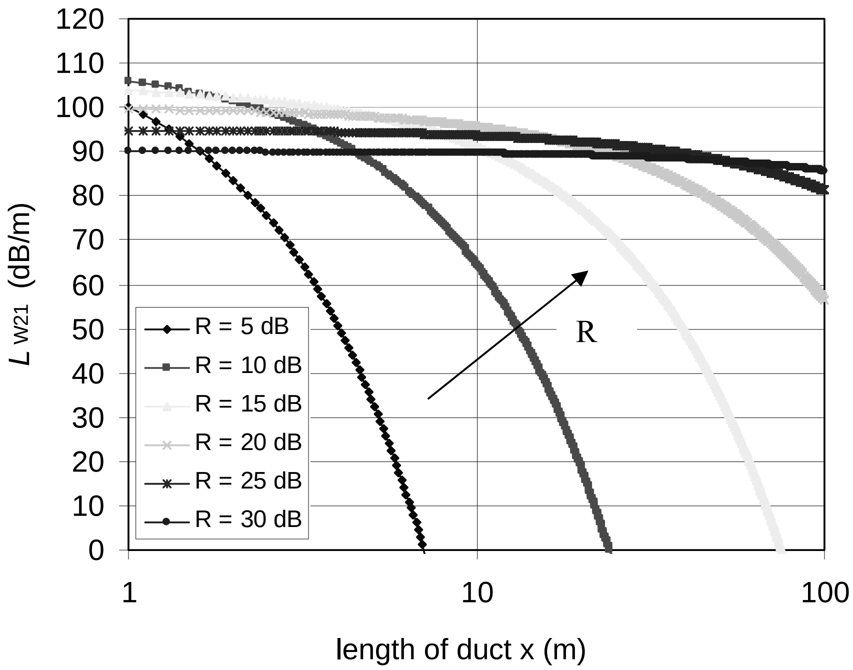

Figure 6 Distribution of sound power level $\boldsymbol{L_{W21}}$ along duct (related to sound power level at the beginning of the duct $\boldsymbol{L_{W1}}$ = 120 dB, D = 400 mm)

From the above relations it follows that for a high smoke stack noise emitted by the shell of the smoke stack will be decisive for the resultant noise in the check point (high transmission loss of the shell and high smoke stack). On the contrary for a short smoke stack decisive will be the top of the smoke stack (low transmission loss of smoke stack, short smoke stack).

5. CONCLUSIONS

The above relations enable reliable determination of noise generated by a duct in a check point and ensure already on a project level compliance with hygienic noise limits. They will be namely useful in concepts of light flues and light smoke stacks of higher-power boiler rooms.

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