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Flow-Generated Noise in Ventilation Systems

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Contributed Report 02

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1. Introduction

When an obstruction is present in a ventilation ductwork, the noise level may be considerably higher than the level measured without the obstruction. This excess noise is due to the interaction of the flow with the element and it is called flow-generated noise in the element. Numerous examples may be found in the literature where this mechanism occurs, such as flow noise generated in duct elbows, dampers, grilles, louvers, duct discontinuities. It reduces the attenuation performance of dissipative silencers and is responsible of the well-known aeolian tones of wires and rods.

The bandwidth of the flow-generated noise spectrum is more or less important according to the type of component and flow characteristics and the maximum level is observed at a frequency f such as the Strouhal number $St = \frac{fd}{U}$ (where d and U are typical obstruction dimension and mean flow velocity) is constant, the constant depending on the component geometry. Some of these phenomena may generate very narrow bands or even tones, especially when aeroacoustic or vibroacoustic resonances occur.

Numerous studies have been carried out for a better understanding and prediction of flow-generated noise in ventilation systems. Most of this research rests on empirical approach, which allows to make predictions whose limit of validity depends on the model and the considered application. More recent attempts have been made to predict flow-generated noise levels in obstructions such as orifice plates by an entirely numerical approach, but these attempts remain marginal in industrial applications.

The objective of this paper is to make a non-exhaustive review of this research, considering that the obstructions are rigid, i.e. they do not radiate noise because of mechanical excitations by the airflow. Otherwise, a coupling between the flow and the vibrating element should be considered. Such a coupling is not very efficient in air, unlike in water, and may be avoided by stiffening the element.

Duct elements that are dealt with here are dampers, grids, orifice plates, elbows, takeoffs, duct discontinuities, more or less streamlined spoilers. To simplify the presentation the different references used for this review will be successively considered.

2. Analysis of the different references

2.1. Noise of HVAC equipment [1]

This practical guidebook in French[1] deals with noise radiated by HVAC equipment and is therefore concerned by flow-generated noise in ventilation ducts. The results that are presented in this book are partly taken from ASHRAE and EUROVENT publications [2], [3].

2.1.1. Flow-generated noise in elbows

Flow-generated noise in an elbow is, like in many components, almost proportional to the pressure loss of the elbow. The sound level is therefore higher in a sharp elbow than

[1] The title in French is "Bruit des équipements"

in a smooth or segmented elbow. The quietest configuration is the smooth elbow with turning vanes (figure 1). Measurements show that doubling the induct flow velocity induces a sound level increase of up to 20 dB. A prediction method of the noise level generated in elbows with or without turning vanes is presented in [2]. According to [1] this method appears more accurate than those proposed up to now.

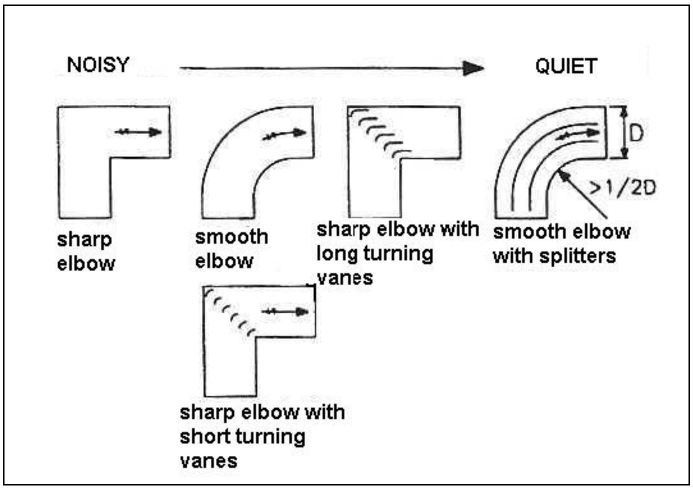

Figure 1 Guidelines for minimising flow-generated noise in duct bends [1]

2.1.2. Flow-generated noise at duct discontinuities

An abrupt change in duct section generates much more flow noise than a gradual transition. A cone of 10° half-angle or less (figure 2) induces a sound level similar to that of a duct of constant diameter.

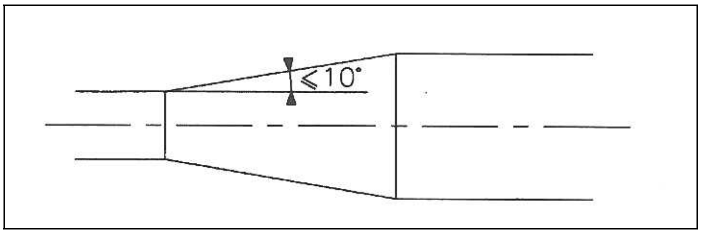

Figure 2 Gradual transition for limiting flow-generated noise in a duct discontinuity [1]

A grid or a perforated plate in the downstream duct section may reduce the flow-generated noise produced by an abrupt discontinuity.

2.1.3. Flow-generated noise in dampers

A wide-open butterfly damper generates a noise spectrum similar to that of a flat plate in an airflow with no incidence. Two noise sources prevail in this case: trailing edge noise, inducing a broadband spectrum, and vortex shedding noise, which is of narrowband type with a hump centred on a frequency f such as the Strouhal number $St = \frac{fd}{U}$, where d is the wake thickness of the valve and U is the duct flow velocity, is close to 0.3 [3]. Figure 3 shows the evolution of the sound power spectrum as a function of flow velocity of an open butterfly damper in a 600 x 600 mm square duct.

When the damper is progressively closed the sound level considerably increases due to the raising of the flow velocity in the restriction and to the flow separation on the downstream side (figure 4).

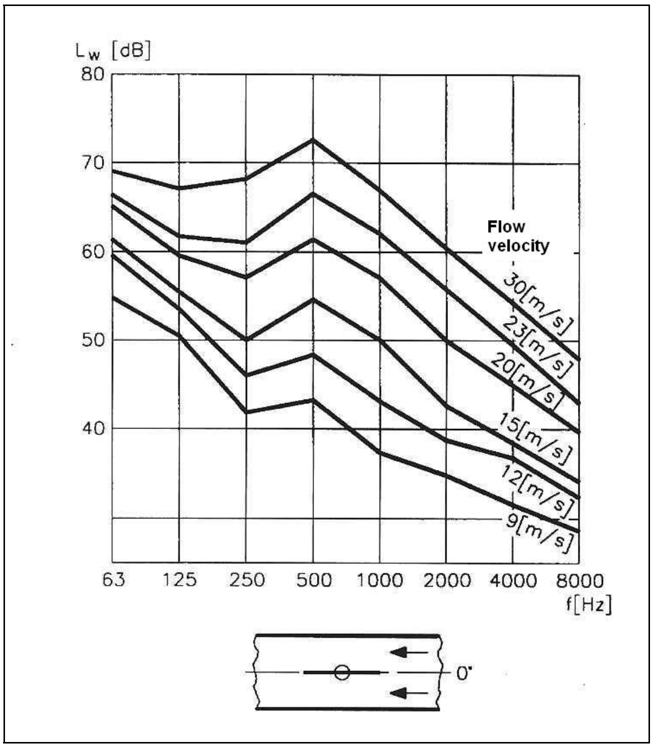

Figure 3 Flow-generated noise spectra of a wide-open damper [1]

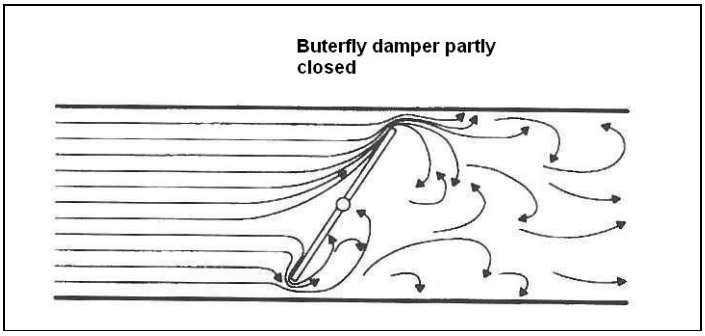

Figure 4 Flow around a partly closed damper [1]

Figure 5 shows the sound power spectra of the damper 3 for a 45° opening angle.

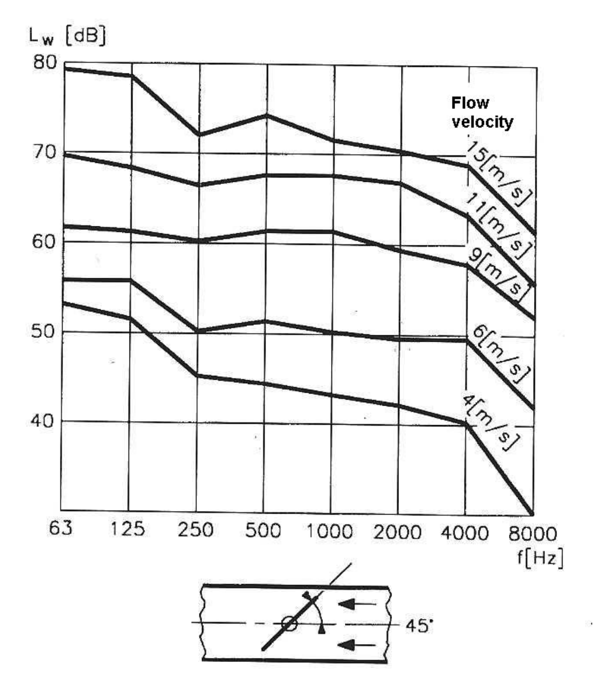

Figure 5 Flow-generated noise spectra of a damper opened at 45° [1]

The evolution of the sound power level of the damper with the opening angle has a direct link with its pressure drop:

$$\Delta L_W = k \log \frac{\Delta p_\theta}{\Delta p_0}$$

where Δp_θ and Δp_0 are the damper pressure losses at the opening angle θ and at θ = 0° respectively, and k is a constant depending on the damper shape.

2.1.4. Flow-generated noise through air inlet or outlet

Flow noise generated through air inlet or outlet in a ventilation system depends on:

- the volume flow
- the air passage area
- the geometry of the opening and its pressure drop.

The overall sound power level of the noise generated through an opening may be estimated by the following formula [2]:

$$L_W = 10 \log S + 30 \log \xi + 60 \log V + 10$$

where:

- L_W: overall sound power level (dB)
- S: air passage area (m^2)
- ξ: pressure drop coefficient of the inlet or outlet ($\xi = \frac{2\Delta p}{\rho V^2}$)
- V: mean flow velocity in the air passage (m/s).

An estimation of the sound spectrum is given in [1] for different geometries of outlets.

2.2. Mechanics of flow-induced sound and vibration [4]

This reference book from W.K. BLAKE presents, among many other subjects, the various mechanisms of aerodynamic noise generated by obstacles in an airflow and the models implemented for their noise prediction. For instance, an estimation of the sound spectrum generated by a diffuser terminated with a grid is given by:

$$L_W(f) = F\left(\frac{fd}{U_D\sqrt{\xi+1}}\right) + 60\log\left(\frac{U_D}{U_0}\right) + 10\log A + 20\log\xi$$

where:

- L_W (f): flow-generated sound power spectrum (dB)
- d: characteristic dimension of the obstruction (for a grid d is the mesh thickness, see figure 6) (m)
- U_D: induct flow velocity (m/s)
- U_0 = 10 m/s (reference flow velocity)
- A: obstruction area of the grid (m^2)
- ξ: pressure drop coefficient of the grating
- F(): function depending on the diffuser shape.

Figure 6 shows function $F\left(\frac{fd}{U_D\sqrt{\xi+1}}\right)$ for three geometries of gratings. This function F, which does not vary much with the grid shape, applies for U_D = 5 to 30 m/s.

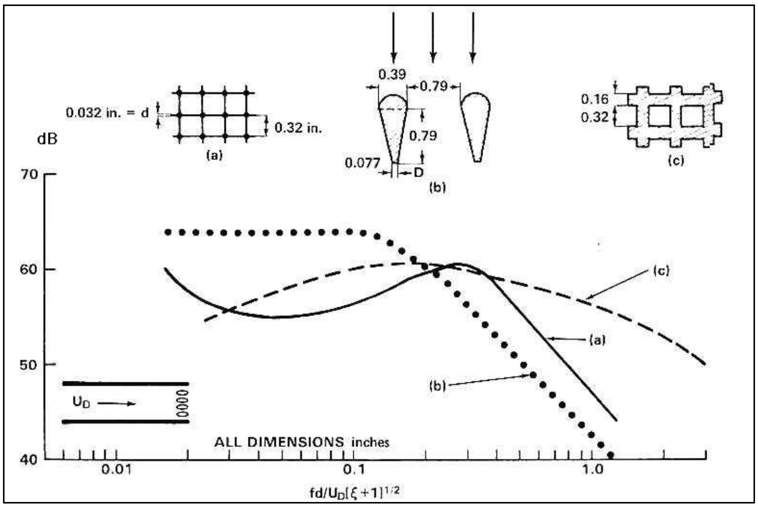

Figure 6 Function F for three geometries of gratings [4]

Reference [4] also shows experimental results on flow-induced noise by dampers and orifice plates at high duct flow velocity ($U_D \geq 50$ m/s), as well as results on the noise levels generated by different types of obstacles in an airflow.

2.3. *Various papers on the prediction of flow-generated noise by obstacles*

2.3.1. Introduction

Much work has been made since 30 years to try to predict flow-induced noise levels by duct obstructions using empirical similarity laws. For establishing these laws it is necessary to understand the noise mechanisms in order to choose the relevant similarity parameters. One of these parameters is, as mentioned before, the obstacle pressure drop. The main findings in this field are now presented.

2.3.2. Gordon [5]

This author studies noise generated by obstacles of various shapes (figure 7) placed at the end of a duct of 47 mm in diameter. Induct flow velocities are quite high (60 to 300 m/s) since the author is mainly interested by aeronautic applications, but Gordon's work has inspired other researchers who were concerned by lower velocities, such as those encountered in ventilation systems.

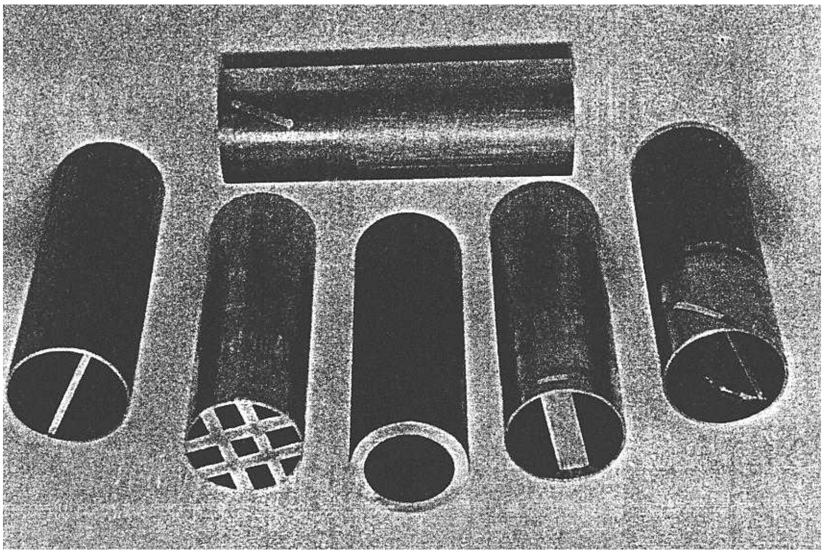

Figure 7 Duct terminations tested [5]

Gordon relates the sound power level measured outside the duct to the following parameters:

- flowrate
- obstacle pressure drop
- ratio of the obstructed area to the total duct area

The external noise spectrum is of broadband type with a maximum level at frequency f such as $St = \frac{f\delta}{U_c} \cong 0.2$, where δ is the wake thickness of the obstacle and U_C is the mean flow velocity in the restriction

2.3.3. Nelson and Morfey [6]

The work of these authors is important and comprehensive. They develop a prediction model based on similarity laws relating the flow-generated noise to parameters typical of the obstacles and of the flow. This model, similar in its principle to that of Gordon, has been extended by other authors since then.

The duct considered in this study is of 300 x 300 mm square section. Obstructions are plates normal to the flow, of constant thickness 3 mm and various width. These strip spoilers are centred or put sideways in the duct as shown in figure 8. Unlike Gordon's experiment, obstacles are not at the end but in the middle of the duct. The flow velocity ranges from 10 to 50 m/s.

centred plate side plates

Figure 8 Shape of the obstructions in the duct section [6]

The prediction model rests on the assumption that the sound power is proportional to the drag fluctuations of the obstacle, which are themselves proportional to the mean drag. The authors provide two formula for the radiated noise spectrum, one valid for frequencies higher than the duct cut-off frequency and the other for frequencies below this frequency.

The cut-off frequency of a square duct is $f_c = \frac{c_0}{2a}$, where c_0 is the sound speed (≈ 340 m/s) and a is the square side. For a rectangular duct: $f_c = \frac{c_0}{2b}$ where b is the largest side of the rectangular cross-section.

The 1/3 octave power spectrum of the noise generated by the obstruction is then, according to whether the central frequency is lower or higher than f_C:

($f < f_C$) $$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 A\left(\sigma^2(1-\sigma)\right)^2 C_D^2 U_c^4 / 16c_0\right] + 120 \qquad (1)$$

($f > f_C$) $$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 \pi A^2 (St)^2 \left(\sigma^2(1-\sigma)\right)^2 C_D^2 U_c^6 / 24c_0^3 d^2\right] + 10\log[1 + \frac{3c_0}{8f}\frac{(a+b)}{A}] + 120 \qquad (2)$$

where:

- K(St): ratio of the root-mean-square fluctuating force over the mean force exerted by the flow on the obstacle
- $St = fd/U_C$ Strouhal number
- d: characteristic dimension of the obstacle (plate width in this case)
- U_C: average flow velocity in the restriction
- A: area of the duct cross-section
- $\sigma = A_c / A$, where A_C is the air passage area
- c_0: speed of sound in air
- a and b: height and width of the rectangular duct section

- C_D: drag coefficient of the obstruction, which is deduced from the static pressure drop Δp_s by: $C_D = \dfrac{\Delta p_s}{\frac{1}{2}\rho_0 U_c^2 \sigma^2 (1-\sigma)}$.

The unknown quantity in equations (1) and (2) is K(St). This function can be obtained from testing for different flow velocities and obstacle shapes. Experimental results show that the curves 20log K(St) + 120 of the different obstacles tested in this research collapse fairly well (figure 9).

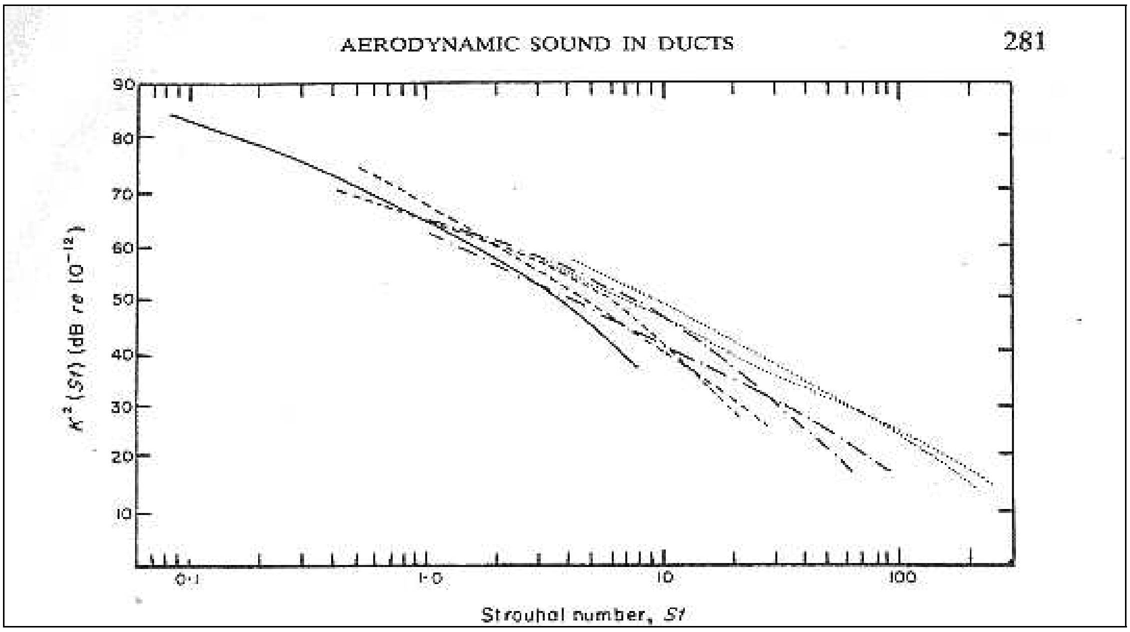

Figure 9 Function 20 log K(St) + 120 for strip spoilers [6]

Equations (1) and (2) provide a flow-induced noise sound spectrum prediction if K(St) is replaced by an average curve deduced from the curves of figure 9. This prediction only applies to obstacles of the same type as those tested here. This research has been pursued by other authors in order to get a prediction on other obstruction shapes.

Finally, it can be noticed that the evolution of the noise level with flow velocity is different according as the frequency is below or above the duct cut-off frequency. Below f_c the sound level varies as 40 log U, while above f_c the level varies as 60 log U.

2.3.4. Oldham et Ukpoho [7]

These authors have extended the work of Nelson and Morfey [6] to study the noise generated by spoilers more representative of those encountered in ventilation systems than simple plates in a duct section. In their case obstructions are butterfly dampers and orifice plates in circular ducts, but by extension this prediction may also apply to elements such as elbows and abrupt duct discontinuities.

For circular ducts, equations (1) and (2) may be rewritten as:

($f < f_c$) $$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 A \sigma^4 C_L^2 U_c^4 / 16 c_0\right] + 120 \qquad (3)$$

(f > f_c)

$$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 \pi A^2 (St)^2 \sigma^4 C_L^2 U_c^6 / 24 c_0^3 d^2\right] +$$
$$+10\log\left(1 + 3c_0 / 8rf\right) + 120 \qquad (4)$$

where:

- $L_W(f)$: in-duct 1/3 octave sound power spectrum of the noise generated by the obstacle
- $f_c = 100/r$ cut-off frequency of a circular duct of radius r
- $St = \dfrac{f\pi r(1-\sigma)}{2U_c}$
- σ: open area ratio (ratio of the air passage area over the duct cross-section area). According to [7] σ is given by: $\sigma = (C_L^{1/2} - 1)/(C_L - 1)$
- $C_L = \Delta p / \frac{1}{2}(\rho_0 U^2)$, where Δp is the static pressure drop of the spoiler and U is the induct mean flow velocity
- $U_c = U/\sigma$ flow velocity in the air passage
- $A = \pi r^2$ duct cross-section area
- c_0: speed of sound in air
- $d = \pi r(1-\sigma)/2$ characteristic dimension of the spoiler.

The results of Oldham and Ukpoho, obtained on a 300-mm duct for flow velocities between 10 and 25 m/s, show that the curve 20 log K(St) + 120 is nearly constant for obstacles such as butterfly dampers at different openings or orifice plates of different diameters (figure 10).
From equations (3) and (4) and the trend line of figure 10, one-third octave sound power spectra of obstacles of similar shape may be predicted.

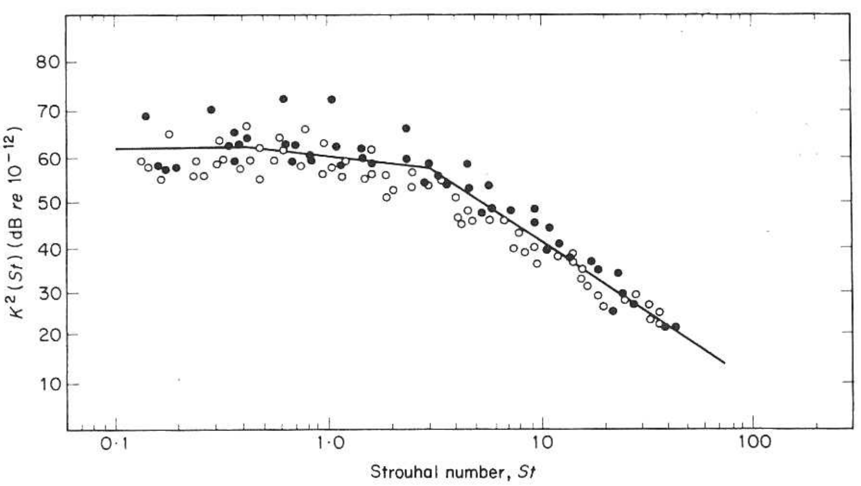

Figure 9. Collapse of all data: ●, damper; ○, orifice plate; ——, trend line.

Figure 10 Function 20 log K(St) + 120 for dampers and orifice plates [7]

The authors indicate that their results may be extended to other obstructions like elbows, grilles or diffusers provided that the two major parameters of the prediction, i.e. the open area ratio σ and the characteristic dimension d of the obstacle, are known.

2.3.5. Oldham and Waddington [8]

This recent work deals with the prediction of airflow generated noise in ducts for components such as bends and branch takeoffs. The prediction technique, which is very similar to the one presented in 2.3.4., applies to ducts of rectangular cross-section.
Equations (3) and (4) become in this case:

($f < f_c$) $$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 A\sigma^4 C_L^2 U_c^4 / 16c_0\right] + 120 \qquad (5)$$

($f > f_c$)
$$L_W(f) = 20\log K(St) + 10\log\left[\rho_0 \pi A^2 (St)^2 \sigma^4 C_L^2 U_c^6 / 24c_0^3 d^2\right] + $$
$$+10\log\left[1 + \frac{3c_0}{8f}\frac{(a+b)}{A}\right] + 120 \qquad (6)$$

where:
A = a.b
a: height of the duct cross-section
b: width of the duct cross-section

$f_c = \dfrac{c_0}{2b}$ cut-off frequency of the rectangular duct

$St = \dfrac{fd}{U_c}$

$d = \dfrac{A(1-\sigma)}{b}$ characteristic dimension of the obstruction.

The other notations are identical to those listed below equations (3) and (4).
Figure 11, plotted from [8], shows average curves 20logK(St) + 120 for different geometries of elbows and branch takeoffs.

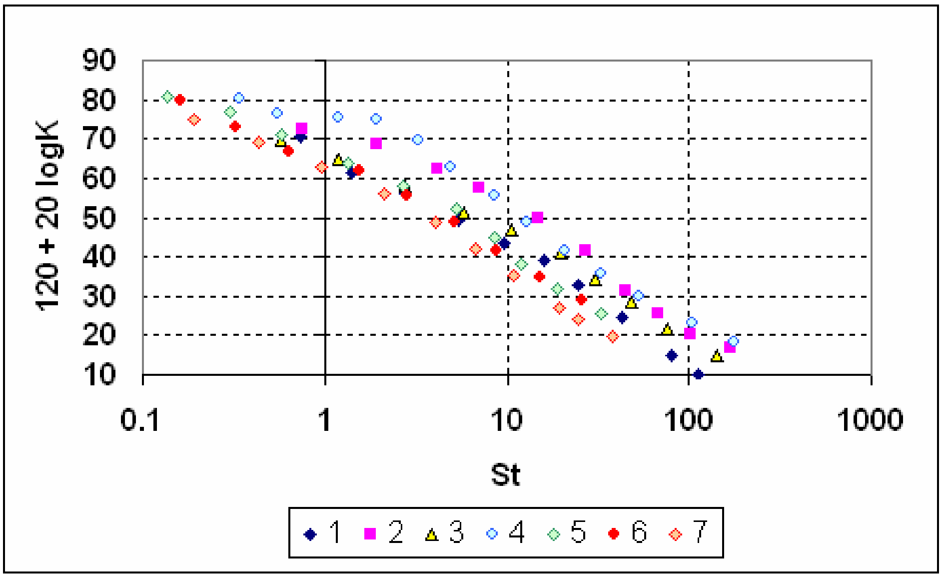

Figure 11 Function 20 log K(St) + 120 for elbows and branch takeoffs

1: mitred elbow, **2**: mitred elbow with vanes, **3**: circular elbow, **4**: circular elbow with splitters, **5**: 90° abrupt takeoff, **6**: 45° takeoff, **7**: radius takeoff (deduced from [8])

When plotting some results of figure 11 together with average curves of figures 9 and 10, we obtain figure 12 that shows a very good collapse of the data (except for the data in figure 9 when St < 1). This indicates that a prediction of the sound power spectrum of airflow generated noise by substantially different spoilers is possible using equations (3) and (4) for circular ducts or (5) and (6) for rectangular ducts, in which the values of 20log K(St) +120 are taken from figure 11 or 12.

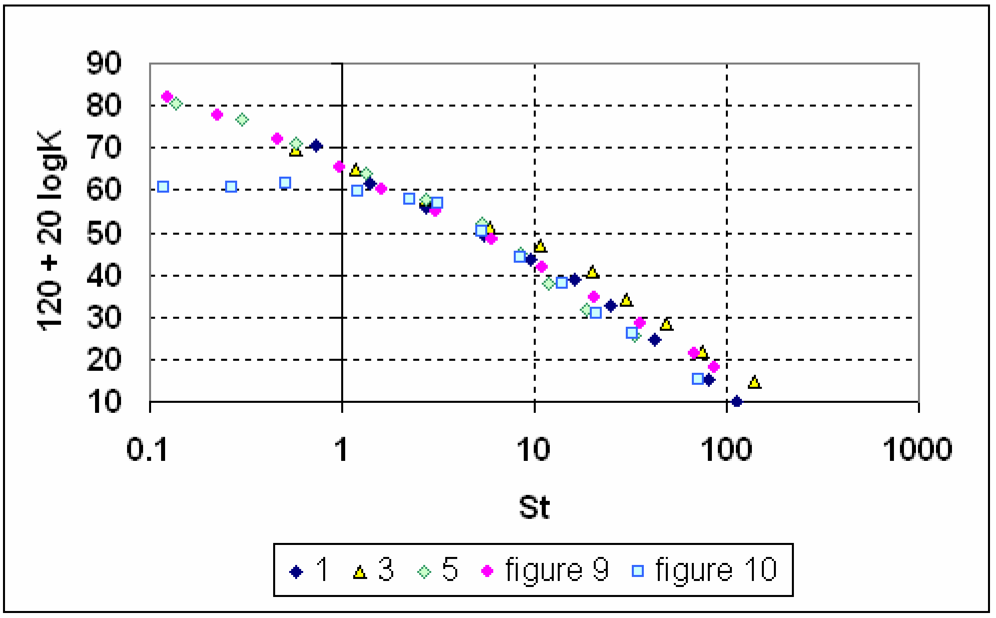

Figure 12 Function 20 log K(St) + 120 for different geometries of spoilers
1: mitred elbow, **3**: circular elbow, **5**: 90° abrupt takeoff, **figure 9**: strip spoilers, **figure 10**: dampers and orifice plates (deduced from [6] to [8])

3. Conclusions

The objective of this paper was to present prediction methods for the noise generated by singularities and obstructions in ventilation ductworks. This review is of course non exhaustive because of the large amount of work that has been carried out in this domain.
Two types of papers have been found while making this review: the first series of papers presents experimental results on given obstructions with a minimum of analysis. These results may be extrapolated to other flow velocities or to other component sizes, but the obstacles have to be geometrically similar. This approach has been applied for instance for establishing ASHRAE database.

Conversely, some authors have tried to implement prediction methods using similarity laws based on relevant parameters such as pressure drop or typical dimension of the obstacle. This approach, which has been used first by Nelson and Morfey and pursued by several researchers, is of wider purpose since the prediction applies to obstacles and singularities of quite different shapes. A kind of "universal law" seems to apply, at least to all the components that have been tested by the authors who have implemented this method.

Other more sophisticated methods, not mentioned in the present paper, are based on CFD (computational fluid dynamics) calculation and aeroacoustic models to predict flow-generated noise of simple spoilers like orifice plates. Due to its complexity this kind of approach cannot still be used on industrial components.

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