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RECENT WORK ON THE PREDICTION OF FLOW GENERATED NOISE IN DUCTS

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1 INTRODUCTION

At long distances from the primary noise source (the fan) of a ventilation system regenerated noise from duct fittings can become the major noise problem. There exists only a limited amount of measured data on regenerated noise produced by some in-duct elements such as bends and transition pieces. This lack of data reflects the difficulty in obtaining such information from conventional measurement techniques. As an alternative to large scale data collection, attempts have been made to develop pressure-based techniques for predicting the regenerated noise in a flow duct. In this paper it is shown that the work of a number of investigators over a long period of time has resulted in the development of techniques for the accurate prediction of flow generated noise due to duct components.

The larger the flow discontinuity caused by a duct component then the greater is the pressure drop cross it and the greater is the sound power generated. This simple idea of a correlation between the pressure loss across a duct discontinuity and the acoustic power generated has attracted many researchers to investigate the possibility of the existence of a simple predictive technique for regenerated noise based upon pressure loss characteristics[1]. In this paper we review the attempts that have been made to devise such techniques and suggest that current work, which has built upon the earlier efforts, may mean that a practical technique is close at hand.

2. AERODYNAMIC NOISE

It has long been known that turbulent motion produces noise and that the noise must be directly related to the fluctuating pressure distribution. New impetus to research on aerodynamic noise was provid ed by the theory of Lighthill [2,3] which predicts the sound intensity produced by fluid motion. It became the classical theory of aerodynamic-noise generation and describes the mechanism whereby the free turbulence in the mixing region of a jet exhaust radiates sound. He demonstrated that the sound field is produced by a static distribution of acoustic quadrupoles and that the noise generated increases in intensity according to the eighth power of the exhaust velocity. The basis of his approach was that the equations governing the fluctuations of density in the real fluid are compared with those which are appropriate to a uniform acoustic medium at rest. The difference between the two sets of equations is considered as if it were the effect of a fluctuating external force field (external applied fluctuating stresses) acting on the uniform acoustic medium at rest and hence radiating sound according to the laws of acoustics.

In 1955, Curle [4] extended Lighthill's general theory of aerodynamic sound by incorporating the effect of solid boundaries upon the sound field. These effects include reflection and diffraction of the sound waves at the solid boundaries and a resultant dipole field at the solid boundaries which are the limits of Lighthill's quadrupole distribution. It was shown that these effects are exactly equivalent to a distribution of dipoles.

In 1967, Davies and Ffowcs Williams [5] dealt with the problem of estimating the sound field generated by a limited region of turbulence in an infinitely long, straight, hard-walled pipe. The acoustic power in the pipe is considered and calculated for two types of turbulent motion. In the first, the eddies are so large that the motion is completely correlated across the pipe and all the sound is in the form of a plane wave propagating in the axial direction. The second type of motion is a statistically slowly varying flow with an eddy correlation length small compared with the cross-sectional pipe dimension.

3. PRESSURE BASED TECHNIQUES

The effect of a discontinuity in a duct carrying airflow is to generate turbulence, some of which is converted into sound energy. The power required to generate the turbulence in the vicinity of the discontinuity is supplied by the system fan and the work done by the fan is manifested as a drop in static pressure across the discontinuity. The larger the discontinuity then the greater is the pressure drop cross it and the greater is the sound power radiated. This simple idea of a correlation between the pressure loss across a duct discontinuity and the acoustic power radiated has attracted many researchers to investigate the possibility of the existence of a simple predictive technique for regenerated noise due to any duct component based upon pressure loss characteristics which are usually expressed in terms of a pressure loss coefficient given by:

$$C_L = P/0.5\rho V^2 \tag{1}$$

In this section we review this work and highlight current developments.

3.1 The Work of Iudin

The concept of pressure-based scheme for predicting the sound generated by the interaction of flow with a surface was first proposed by Iudin [6]. He started with the assumption that the acoustic power of flow-generated noise, and its distribution over the frequency spectrum, were determined by the geometric shape of the duct, its dimensions, flow parameters and the acoustic properties of the volume in which the sound was generated. He further made the assumption that the flow parameters in an air duct of specified geometric shape are determined by the static pressure differential ΔP across it, the physical properties of the medium (density ρ and the sound velocity c) and by the dimensionless constants (Reynolds no., Re and Mach no., M):

$$Re = \frac{Vd}{\nu} \tag{2}$$

$$M = \frac{V}{c} \tag{3}$$

Where
V = the time-averaged flow velocity at a characteristic point in the air duct
d = the determining geometric dimension (representative dimension)
ν = the kinematic viscosity of the medium

The acoustic properties of the volume according to Iudin, were determined by the dimensionless impedances Z of the boundaries and by the relationship between a sound wavelength and the dimensions of the volume λ/d. The frequency of the aerodynamic sound is determined by the Strouhal number St,

$$St = fd/V = Q_1(\text{the geometric shape}, Re, M) \tag{4}$$

Since the frequency is f = c/λ, then λ/d = 1/MSt and therefore λ/d which is a constant under the condition Z = constant, is not a determining criterion.
Based on the assumptions, the acoustic power of an air duct was expressed as follows:

$$W = Q_2(\Delta p_s, \rho, c, d, Re, M, Z, \frac{\lambda}{d}) \tag{5}$$

By using dimensional analysis of the source mechanism, he obtained a simple formula from his assumptions:

$$\frac{W}{\rho c^3 d^2}(\frac{\Delta p_s}{\rho c^2})^{\alpha} = Q_3(\text{shape}, Re, M, Z) \tag{6}$$

This derived equation was the working similarity formula for his experiments.

He studied the noise of various metal air duct elements including low- and high-pressure ejectors, layers of powdery granular material and aerodynamic velocity pipes. The investigations were performed both in acoustic and untreated rooms, and in the open air. By combining the results of his studies with dimensional analysis of the source mechanism, he concluded that the acoustic power was proportional to the cube of the excess pressure and the square of the geometric dimension.

3.2 The Work of Gordon

Iudin's work has been rather neglected and more interest has been aroused by the work of Gordon. Initially, Gordon and Maidanik [7] studied the sound-generating capabilities of a flow spoiler within the environment of a pipe on a scale model. Their investigation of the effect of upstream flow discontinuities on the acoustic power radiated by an air jet was then expanded by Gordon [,8,9,10]. The analysis of Gordon was based on an assumption that the magnitude of the fluctuating forces associated with an aerodynamic source was proportional to the steady-state drag forces. He investigated the sound power generated by a variety of spoilers close to the end of a pipe carrying high-velocity air flow. He first obtained the following empirical formula for predicting the total acoustic power gene rated by a spoiler in a duct[7]:

$$W = \frac{K(p_o - p_a)^3 D^2}{\rho_a^2 c_a^3} \tag{7}$$

W = acoustic power
p_o = the total stagnation pressure on the upstream side of the spoiler (as measured with a pitot static tube)
p_a = the atmospheric pressure
ρ_a = the atmospheric density
c_a = velocity of sound
D = duct diameter
K = constant having an experimentally determined value of 2.5×10^{-4}

The geometry of the spoiler did not enter directly into equation but was implicit in the pressure drop $(p_o - p_a)$ across the flow spoiler.

Gordon attempted to obtained a normalised spectrum by collapsing the data from a series of experiments on different spoiler configurations against a Strouhal Number given by $St = f_c d/U_{local}$ Where f_c was the octave band centre frequency, d was a representative dimension (the wake thickness of the flow spoiler) and U_{local} was the velocity of airflow in vicinity of the spoiler (constriction velocity).

Although the data collapsed onto a single curve for low Strouhal Numbers there was considerable divergence at high Strouhal Numbers.

Gordon introduced an empirical modification to equation (7) to obtain the following:

$$W = \frac{K(p_o - p_a)^3 D^2}{\rho_a^2 C_a^3}[1+(\frac{f_c}{f_o})^2] \qquad (8)$$

Where

f_o = some constant frequency related to the dimension of the duct spoiler system

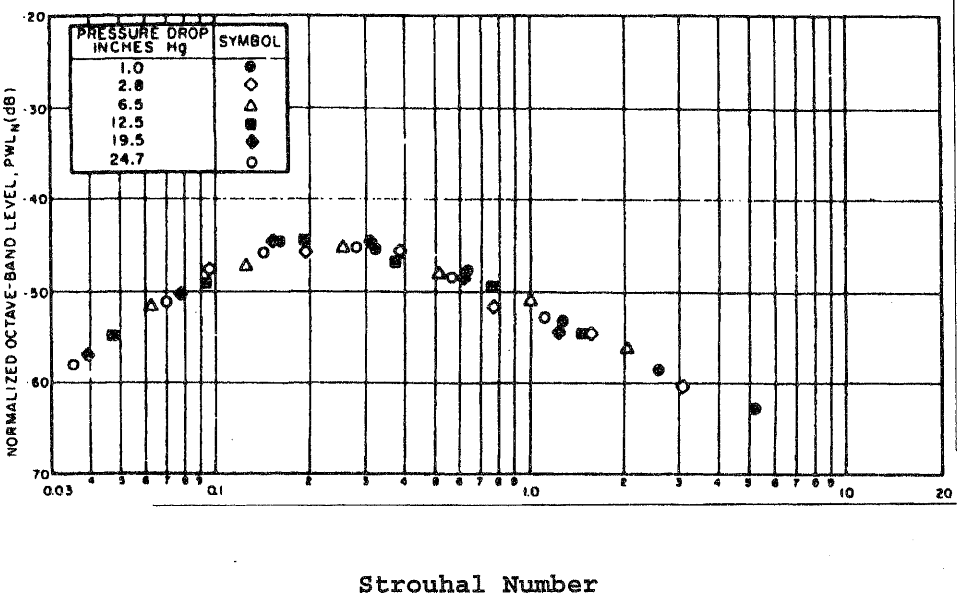

Figure 1 **Normalised octave band sound power levels versus Strouhal Number for strip spoiler. (After Gordon [9])**

Fig.1 shows the collapse of his data based on this correction. Gordon observed that f_o tended to lie close to cross-mode onset frequency and in a later publication [10] he took f_o as being equal to the cut on frequency.

Gordon's experiment was aimed at developing a better understanding of the noise generation mechanisms in jet engines and for this reason he positioned his flow spoiler close to the end of the duct. The pressure difference to which he related his sound power generated was not the static pressure drop across an in-duct element but the difference between the upstream stagnation pressure at the spoiler and the ambient air pressure outside the duct. He also worked at air velocities and with pressure drops across spoilers well in excess of those encountered in ventilation systems. For these reasons his work cannot be applied directly to the prediction of regenerated noise in ventilation systems. However, his work, along with that of Iudin, does lend support to the idea that a pressure-based prediction technique might be applicable to conditions encountered in ventilation systems and his work represents a significant milestone in the development of pressure based prediction techniques.

3.3 The Work of Heller and Widnal

In 1970, Heller and Widnall [11] presented their results of a theoretical and experimental study of the correlation of fluctuating forces on rigid flow spoilers with the resulting sound radiation. In an extension of the experimental work of Gordon and Maidanik [12], they measured directly the fluctuating drag and lift forces on flow spoilers. They then demonstrated a direct correlation between fluctuating forces and the radiated sound under both free-field and confined-environment conditions.

Their data correlated well when they plotted [$20\log10(F_{drag}/F_o) - 40\log10(U/U_o)$] and [$20\log10(P/P_o) - 60\log10(U/U_o)$] against the Strouhal number $St = f_c d/U$ [35,36].

F_{drag} is the measured fluctuating drag force in Newtons, F_o is the reference force which is equal to 1×10^{-5} Newtons, U is either the jet exhaust velocity or the in-pipe flow velocity in m/s, U_o is a reference velocity equal to 1 m/s, f_c is the 1/3 octave band centre frequency, d is the a length dimension related to a typical dimension of the spoiler, P is the sound pressure and P_o is the reference pressure.

A theory that considered the effect of the enclosure upon the sources and the effect of pipe-end reflection was developed to predict the sound power radiated to the free field from pipe-immersed flow spoilers. In this theory, the efficiency of the sound-power radiation from dipole sources within a hard-walled pipe (confined environment) increases by a frequency-squared term that changes the sound-power/flow-velocity dependence to that of a quadrupole dependence, i.e. to an eight-power-law dependence. However, the effect of end reflection introduces an inverse frequency-squared term that restores the original sixth power of velocity dependence of the dipole-source power radiation. In addition, a net increase of the radiated sound power from dipole sources within a confined environment by a factor of 3 was predicted and observed in their experiments.

3.5 The Work of Nelson and Morfey

Nelson and Morfey [13] investigated aerodynamic sound production in low speed flow ducts. In developing their theory, they again took into account the effect of the duct environment on the generation of noise. The basis of the Nelson and Morfey theory is that the sound power radiated by an in-duct spoiler is related to the total fluctuating drag force acting on spoiler which is a function of the turbulence intensity in the region of spoiler. In order to arrive at a predictive technique, since they were unable to determine the actual spectrum of the turbulence intensity in the vicinity of the spoiler, they further made the assumption that the fluctuating drag force is in direct proportion to the steady drag force. (This assumption was also made by Gordon [8] in devising his theory and its validity has been confirmed by the experiments of Heller and Widnall [11].)

The collapse of the experimental data into a generalised spectrum (Fig.2) to form the basis of the predictive technique was achieved by the empirical evaluation of the constant of proportionality between the fluctuating and steady drag forces as a function of Strouhal number.

Nelson-Morfey derived the folowing two equations for determining the sound power generated by an in-duct spoiler corresponding to frequencies below duct cut on and frequencies above:

For $f_c<f_o$

$$120+20\log_{10}K(St)=SWL_D-10\log_{10}[\rho_0 A\{\sigma^2(1-\sigma)\}^2 C_D^2 U_c^4/16\,c_0] \tag{9}$$

For $f_c>f_o$

$$\begin{aligned}120+20\log_{10}K(St)=SWL_D\\ -10\log_{10}\{\rho_0\pi A^2(St)^2[\sigma^2(1-\sigma)]^2 C_D^2 U_c^6/24\,c_0^3 d^2\}\\ -10\log_{10}\{1+(3\pi c_0/4\,\omega_c)(a+b)/A\}\end{aligned} \tag{10}$$

Where

SWL_D	= in-duct sound power level
K(St)	= single Strouhal number dependent constant
ρ	= density of air
A	= cross-section area of the duct
σ	= A_c/A = duct unobstructed area/duct area = open area ratio
St	= Strouhal number = $f_c d/U_c$
U_c	= q/A_c = volume flow rate/duct unobstructed area = velocity in the restriction
c_o	= ambient speed of sound
d	= characteristic dimension of the spoiler
ω_c	= angular centre frequency of the band of frequencies under consideration
a	= duct width
b	= duct height
C_D	= drag coefficient = $F_3/(½\rho U^2 A(1-\sigma))$

where F_3 = the steady state force on the spoiler

The normalised spectra are capable of being used "in reverse" to predict the level of airflow generated noise for similar configurations using Equations 17 and 18. All terms in these equations are constants or measurable variables plus a single Strouhal number dependent constant. With the value of the Strouhal number dependent constant established, it is possible in principle to employ the Nelson -Morfey theory for predictive purposes. However, their curves have been obtained from measurements made on simple strip spoilers for which the necessary parameters of representative dimension and open area ratio can be easily established. It is not obvious how these parameters can be obtained for more realistic duct components such as bends.

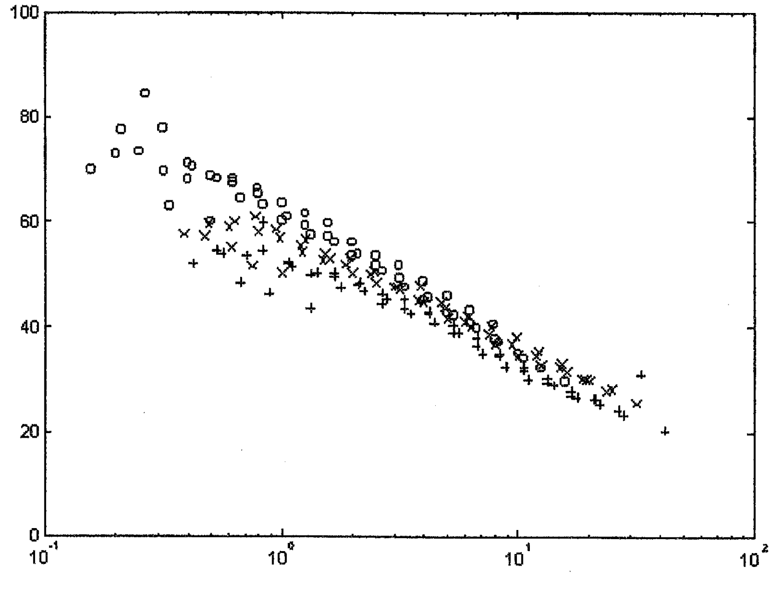

Figure 2 Normalised Nelson & Morfey strip spoiler in-duct sound power levels. Cd=2.3, 15.5 & 21.1 for 0.1, 0.15 & 0.2m strips (recalculated for 0.2m strip)

3.6 The Work of Oldham and Ukpoho

In order to apply the theory of Nelson and Morfey to other duct obstructions, however, it necessary to be able to determine the appropriate values of this parameter. For obstructions other than flat plate spoilers in a squared duct or for any obstruction in a circular duct, the values of this parameter cannot be determined simply from an inspection of the geometry of the situation.

Oldham and Ukpoho [14] have employed a technique for calculating the blockage factor found in standard texts to extended the work of Nelson and Morfey to the case of circular ductwork and more complex flow spoilers. They rewrote the Nelson-Morfey equations by determining the appropriate values of the open area ratio and the characteristic dimension in order that Nelson and Morfey's work can be applied to more complex flow spoilers in circular or square ducts.

The modified Nelson-Morfey equations by Oldham and Ukpoho for determining the sound power generated by an in-duct spoiler are:

For $f_c<f_o$

$$120+20\log_{10}K(St)=SWL_D-10\log_{10}[\rho_0 A\sigma^4 C_L^2 U_c^4/16\, c_0] \tag{11}$$

For $f_c > f_o$

$$120 + 20\log_{10} K(St) = SWL_D - 10\log_{10}[\rho_0 \pi A^2 (St)^2 \sigma^4 C_L^2 U_c^6 / 24 c_0^3 d^2] - 10\log_{10}[1 + 3c_0/8rf_c] \quad (12)$$

Where,

$$d = \pi r(1-\sigma)/2 \quad (13)$$

and

$$St = f_c \pi r(1-\sigma)/2U_c \quad (14)$$

Oldham and Ukpoho carried out experiments on dampers and orifice plates in a circular duct to produce a generalised spectrum (Fig.5) by the collapse of experimental data on the basis of the modified Nelson-Morfey equations. The spectra obtained using dampers and orifice plates as spoilers was similar to the observed by Nelson and Morfey with simple strip spoilers.

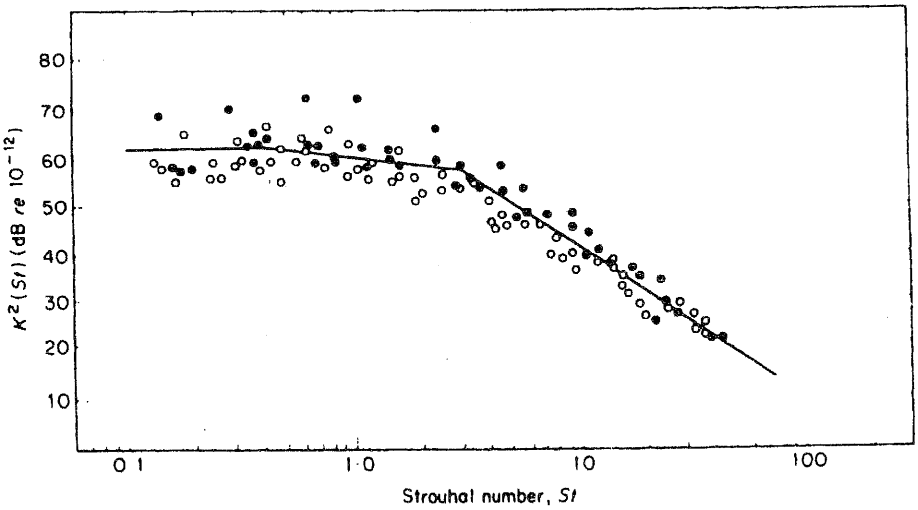

Figure 3. Collapse of data for dampers and orifice plates in circular duct on the basis of the Oldham and Ukpoho method.

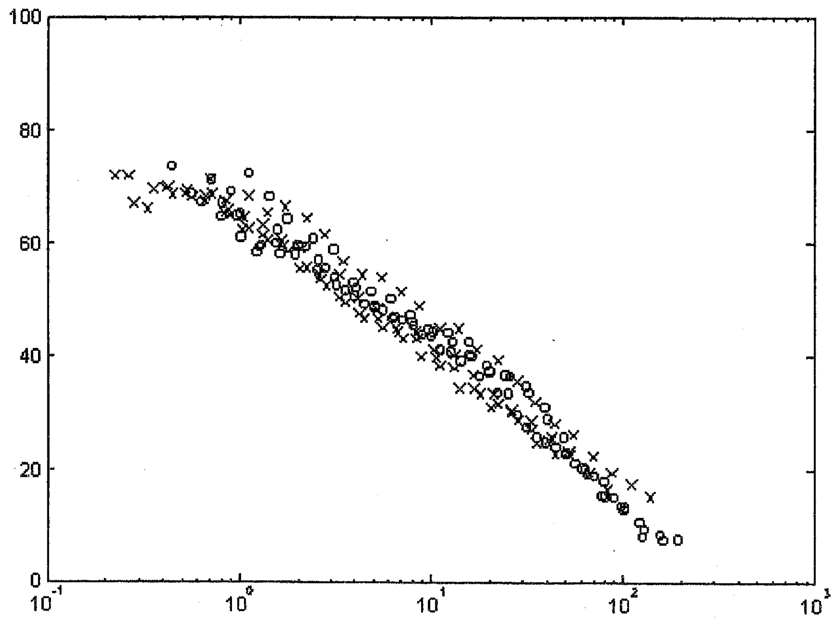

Figure 4 **Normalised in-duct sound power levels for mitred bends without turning vanes: 0.6 x 0.6m bend (O), 0.4 x 0.4m bend (X)**

3.7 The Work of Waddington and Oldham

Although the results of Oldham and Ukpoho lend further support to the concept of a generalised prediction method based upon pressure loss, their experiments carried out using ductwork of similar size to that of Nelson and Morfey and using a limited number of duct components. As an extension of the work of Oldham and Ukpoho [15] Waddington and Oldham have applied Equations 20, 21, 22 and 23 to measured data on mitred bend in square section ductwork. They used data supplied by Atkins Noise and Vibration of Epsom, UK which was obtained from a comprehensive series of measurements of a the airflow noise generated by a number of duct components.

Figure 7 shows the collapse of data obtained for a range of air velocities for mitred bends in ductwork by application of the Oldham and Ukpoho equations. It can be seen that the individual spectra collapse onto one single spectra which could form the basis of a predictive design curve for this type and size of component.

6 CONCLUSIONS

As an alternative to large scale data collection, attempts have been made to develop pressure-based techniques for predicting the regenerated noise in a flow duct. In this paper it has been shown that the work of a number of investigators over a long period of time has culminated in the development of techniques for the accurate prediction of flow generated noise due to duct components from knowledge of the component pressure loss coefficient. Work is now in progress on applying the technique of Oldham and Ukpoho to a range of induct components using measured data supplied by Atkins Noise and Vibration with the objective of producing a definitive design methodology.

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REFERENCES:

[1] C M MAK, D C WADDINGTON and D J OLDHAM, 1998 *Building Acoustics* **4**, p.275-294, The prediction of airflow generated noise in ventilation systems.

[2] M.J. LIGHTHILL, 1952 *Proc. Roy. Soc. (London)* **A 211**, p.546-587, On sound generated aerodynamically: I, General theory.

[3] M.J. LIGHTHILL, 1953 *Proc. Roy. Soc. (London)*, p.1-32 , On sound generated aerodynamically: II, Turbulence as a source of sound.

[4] N. CURLE, 1955 *Proc. Roy. Soc. (London)* **A 231**, p.505-514, The influence of solid boundaries upon aerodynamic sound.

[5] H.G. DAVIES and J.E. FFOWCS-WILLIAMS, 1968 *Journal of Fluid Mechanics* **32**, p.765-778, Aerodynamic sound generation in a pipe.

[6] E.Y. YUDIN, 1955 *Soviet Phys.-Acoust.* **1**, p.383, The acoustic power of the noise created by air-duct elements.

[7] C.G. GORDON and G. MAIDANIK, 1966 *Bolt, Beranek and Newman Inc. Report* **No.1426**, Influence of upstream flow discontinuities on the acoustic power radiated by a model air jet.

[8] C.G. GORDON, 1968 *The Journal of the Acoustical Society of America* **43**, p.1041, Spoiler generated noise : I experiment.

[9] C.G. GORDON, 1969 *The Journal of the Acoustical Society of America* **45**, P.214, Spoiler generated flow noise II, The results.

[10] C.G. GORDON, 1968 *A.S.H.R.A.E. Semi-Annual meeting*, The problem of duct generated noise and its prediction.

[11] H.H. HELLER and S.E. WIDNALL, 1970 *The Journal of the Acoustical Society of America* **47**, p.924-936, Sound radiation from rigid flow spoilers correlated with fluctuating forces.

[12] H.H. HELLER, S.E. WIDNALL and C.G. GORDON, 1968 *Bolt, Beranek and Newman Inc. Report* **No.1734** Correlation of fluctuating forces with the sound radiation from rigid flow spoilers.

[13] P.A. NELSON and C.L. MORFEY, 1981 *Journal of Sound and Vibration* **79**, p.263-289, Aerodynamic sound production in low speed flow ducts.

[14] D.J. OLDHAM and A.U. UKPOHO, 1990 *Journal of Sound and Vibration* **140**, p.259-272, A pressure-based technique for predicting regenerated noise levels in ventilation systems.

[15] D C WADDINGTON and D J OLDHAM, 1998 *Journal of Sound and Vibration* **222**, p.163-169, Generalised flow noise prediction curves for air duct elements.