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Technical Note

# Generalized flow-generated noise prediction method for multiple elements in air ducts

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**Abstract**

Unavoidable discontinuities due to in-duct elements in a ventilation ductwork system result in the generation of localized turbulence. Some of the turbulence energy is converted into noise. The flow-generated noise problem caused by in-duct elements is due to the complicated acoustic and turbulent interactions of multiple in-duct flow noise sources. Prediction of the flow-generated noise at the design stage is important in engineering, since it is almost impossible to solve the problem after the installation of a ventilation ductwork system. The measurement and computational fluid dynamics simulation can provide an accurate prediction but are expensive in terms of resources. There is an urgent need for developing a practical prediction method for the flow-generated noise in air ducts. Current design guides only provide a prediction method for aerodynamic sound produced by a single in-duct element in the ventilation system, which is usually not in accord with actual systems. An interaction factor $\beta_m$ is therefore proposed to take account of the interaction effects of multiple in-duct elements. Experimental measurements were conducted to verify the proposed prediction results. The predicted results show an acceptable agreement with the measurements. The proposed method provides engineers a practical generalized technique for predicting noise produced by multiple in-duct elements.

***Keywords***: Flow-generated noise; multiple in-duct elements; prediction; air ducts

## 1. Introduction

Ventilation ductwork system is the essential component in modern buildings to maintain good indoor environment quality. Some unavoidable in-duct elements, such as dampers, sensors, bends, transition pieces, duct corners, branch points or even attenuators will make the air duct become discontinuities. The discontinuities in the air duct will influence the airflow and result in the generation of localized turbulent as the ventilation system begins to operate [1-3]. The interaction between the turbulent airflow and the discontinuities in air duct will lead to the generation of noise, which causes many problems to engineers since it is almost impossible to solve the problem after the installation of the ventilation system [4,5]. It is therefore that the prediction of the flow-generated noise at the design stage is significant in engineering. Accurate determination of the flow-generated noise in the ventilation system can be obtained by measurement. However, some specially combined acoustic and aerodynamic experimental facilities are needed in the measurement [6]. An alternative to the measurement is using computational fluid dynamics (CFD) software packages. CFD is a powerful design tool that could provide an accurate prediction of the fluid flow regimes in the ventilation system [7-9]. However, complex simulation conditions should be taken into consideration in the application of the CFD simulation, which are still a challenge for engineering applications. Besides, time-consuming is an anther obvious drawback of both the measurement and CFD simulation. A simple, rapid and convenient method to obtain an approximate level of the flow-generated noise in ventilation ductwork system is desired in engineers' daily practical cases.

One of the fundamental work with respect to the flow-generated noise prediction was proposed by Nelson and Morfey [10]. Oldham and Ukpoho [11] developed the Nelson and

Morfey equations in terms of more commonly used parameters in ventilation system design. Later, Waddington and Oldham [12] suggested a technical prediction method based upon the pressure loss characteristics of real duct components, which was adopted in the CIBSE Guide. Kårekull et al. [6] presented a general prediction method for in-duct orifice geometries of high pressure loss by assuming a momentum flux of the dipole force. However, these works only provide the prediction methods for aerodynamic sound produced by an isolated in-duct element in the ventilation ductwork system. It is only applicable to an isolated component, which is different from practical systems consisted of multiple components. It is therefore that Mak and his co-investigators established a prediction method of the flow-generated noise produced by multiple in-duct elements based on the theory of Nelson and Morfey [13-16]. The interaction effects of the flow-noise sources in the ventilation ductwork were taken into considerations in their method. However, their method seems to be more theoretical rather than practical and has not yet become a practical method in engineering applications.

Current design guides, the CIBSE Guide and the ASHRAE Handbook, only provide a prediction method for the flow-generated noise produced by a single in-duct element in a ventilation system [17,18]. The CIBSE Guide is the current design guide adopted in UK and Hong Kong. It is therefore that this paper proposes a practical generalized prediction method for the flow-generated noise produced by multiple in-duct elements based on the CIBSE Guide as well as the works of Mak and his co-investigators. An interaction factor $\beta_m$ is introduced to the prediction equations of CIBSE Guide to take account of the interaction effects of multiple in-duct elements. To verify the results predicted by the proposed prediction method, the experimental measurements were conducted. The prediction results show an acceptable agreement with the measurements. The proposed method provides a practical generalized technique for predicting noise produced by multiple in-duct elements and it is a significant improvement to the current design guides for the design of a ventilation system.

## 2. Generalized prediction method for flow-generated noise

### *2.1 CIBSE Guide for a single in-duct element*

For the sake of completeness, a brief description of the prediction method in the CIBSE Guide B4 is presented here. Two prediction equations for the flow-generated noise produced by a single in-duct spoiler are given in the CIBSE Guide B4 to determine the sound power level $L_W$ in respect of different frequency ranges (below and above the "cut-on" frequency $f_c$ of the duct). The cut-on frequency $f_c$, which is only decided by the geometries of the duct as $f_c = c/2l$ for rectangular ductwork or $f_c = 1.841c/2\pi r$ for circular ductwork (where $c$ is the velocity of sound, $l$ is the longest sectional dimension of the rectangular ductwork and $r$ is the radius of the circular one), determines the wave propagation modes through the duct. According to the CIBSE Guide B4, the equations for the sound power level $L_W$ are given as [17]:

For $f_0 < f_c$ (below the cut-on frequency)

$$L_W = -37 + 20\lg(K(St)) + 20\lg\zeta + 10\lg A + 40\lg u \qquad (1)$$

and for $f_0 > f_c$ (above the cut-on frequency)

$$L_W = -84 + 20\lg(K(St)) + 20\lg(St) + 10\lg\zeta - 40\lg\sigma + 10\lg A + 60\lg u \qquad (2)$$

where $f_0$ represents the octave band center frequency, $A$ is the cross-sectional area of the duct, $u$ is the air velocity in the duct, $\zeta$ is the pressure loss factor, $\sigma = (\zeta^{1/2} - 1)/(\zeta - 1)$

is the clear area ratio, and $K(St)$ is an experimentally determined factor related to the Strouhal number $St = af_c\sigma(1-\sigma)/u$ ($a$ represents duct height or duct diameter). Fig. 1 illustrates the determination of term $20\lg(K(St))$ from Strouhal number. The $20\lg(K(St))$ can be obtained once the Strouhal number is derived. It should be noted that pressure loss factor $\zeta$ could be gained according to the CIBSE Guide C for a particular element [19] or the expression of $\zeta = \Delta P/0.5\rho u^2$ ($\Delta P$ is the static pressure drop due to the component, $\rho$ is the density of air) [20].

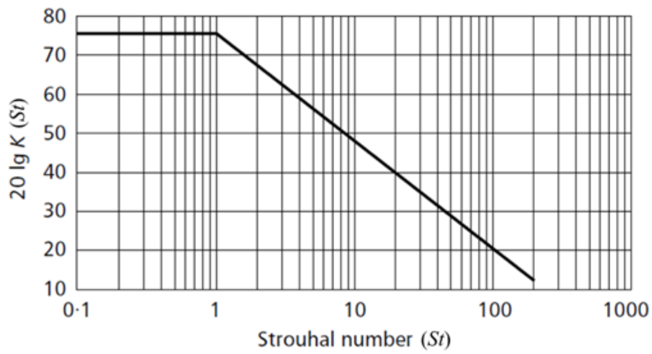


Fig. 1 Determination of term $20\lg(K(St))$ from Strouhal number [17]

*2.2 Generic formulae for multiple in-duct elements*

The flow-generated noise problem caused by in-duct elements is due to the complicated acoustic and turbulent interactions of multiple in-duct flow noise sources. The interaction effects of flow-noise sources in the ventilation ductwork are taken into consideration by introducing an interaction factor $\beta_m$ to the prediction equations given in the CIBSE Guide B4. The sound power generated by a single in-duct element could be obtained according to Eq. (1) (for $f_0 < f_c$) and Eq.(2) (for $f_0 > f_c$) in respect of different frequency ranges. For the sound power generated by multiple in-duct element, a simple relationship between the sound power level due to multiple elements and that due to a single element is then obtained as follows:

$$L_{Wm} = L_W + 10\lg \beta_m \tag{3}$$

where $L_{Wm}$ represents the sound power level due to multiple elements, $L_W$ represents the sound power level due to a single element (obtained from Eq. (1) and Eq. (2) ), $\beta_m$ is the interaction factor. It should be noted that the $L_W$ chosen here is the element with the largest pressure loss factor $\zeta$ . Based on the works of Mak and his co-investigators in regard to the interaction factor, the simplified equations of the interaction factor are expressed as:

For $f_0 < f_c$ (below the cut-on frequency)

$$\beta_m = m + m\cos kL\cos(kL - kL\frac{u}{c}) \tag{4}$$

and for $f_0 > f_c$ (above the cut-on frequency)

$$\beta_m = \begin{cases} m + m\dfrac{8kA + \pi(a+b)}{2kA + \pi(a+b)}, & \text{for a rectangular duct} \\ m + m\dfrac{4kA + \pi r}{kA + \pi r}, & \text{for a circular duct} \end{cases} \tag{5}$$

where $m \geq 2$ is the number of in-duct elements, $k = 2\pi / f_0$ is the wave number, $L$ is the shortest distance between two elements, $a$ and $b$ are the duct cross-sectional dimensions respectively, and $r$ is the radius of the circular duct.

The interaction factor $\beta_m$ is mainly a function of frequency, distance between the various duct elements, and geometries of the ventilation ductwork system. It can observe from Eq. (3) that the $L_{Wm}$ increases when the interaction factor $\beta_m > 1$ and decreases when the interaction $0 < \beta_m < 1$. However, Eq. (5) only provide the cases for $\beta_m > 1$ by removing the product-term $\cos(kL - kLu/c)$ of the second term on the right-hand side of Eq. (5). The purpose of such simplification is to avoid underestimations at high frequencies. The values of the interaction factor could be obtained straightforward at the design stage once the geometries of the ventilation ductwork system have been determined. Although the proposed interaction factor $\beta_m$ only represents an approximated added sound pressure level and may overestimate it, the simple and convenient prediction formulae meet the requirement of engineers in their daily practical cases and could be a significant improvement to the current design guides.

## 3. Experimental measurements

An experiment was conducted to verify the results predicted by the proposed generic formulae, as demonstrated in Fig. 2 [16]. The schematic diagram of the experimental test rig is illustrated in Fig. 3. A three-phase variable speed centrifugal flow fan, which was isolation of vibration by four springs and was enclosed in a lined acoustic enclosure, was used to provide airflow. Silencers and acoustically lined elbows were installed to attenuate both the upstream and downstream sides. In order to reduce breakout noise from the air duct, 25-mm-thick absorbing material lining was assembled through each side of the long steely test duct of 0.1 m$\times$0.1 m. Hence, a quiet and fully developed flow at the first test piece counted from the inlet of airflow could be obtained, which was located at approximately 1.75 m away from the duct entrance section. The second and third spoilers were situated 1 m and 3 m downstream from the first spoiler respectively. The total length of the duct was 5.45m, which included the extended part in the reverberation chamber. This chamber had an outlet cone of 0.16 m$\times$0.16 m and a length of 0.3 m for acoustic measurement. The chamber was also provided with lined outlet ducts that enabled air to escape without the penetration for outside noise. The entire experimental test rig was located in another reverberation chamber to ensure the level of sound measured in the system was always well above the background noise level in the laboratory.


Fig. 2 Experimental test rig photography

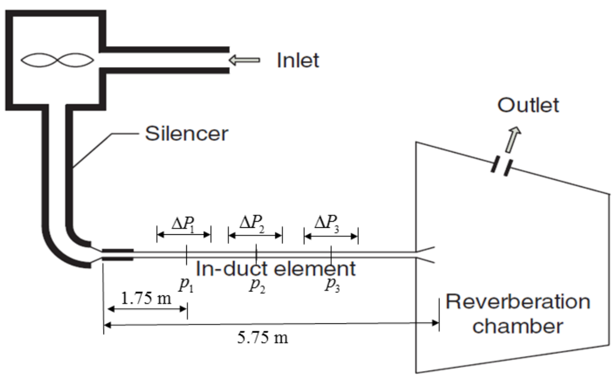


Fig. 3 Schematic diagram of the experimental test rig ( $\Delta P$ with subscript represents the static pressure drop across the in-duct element)

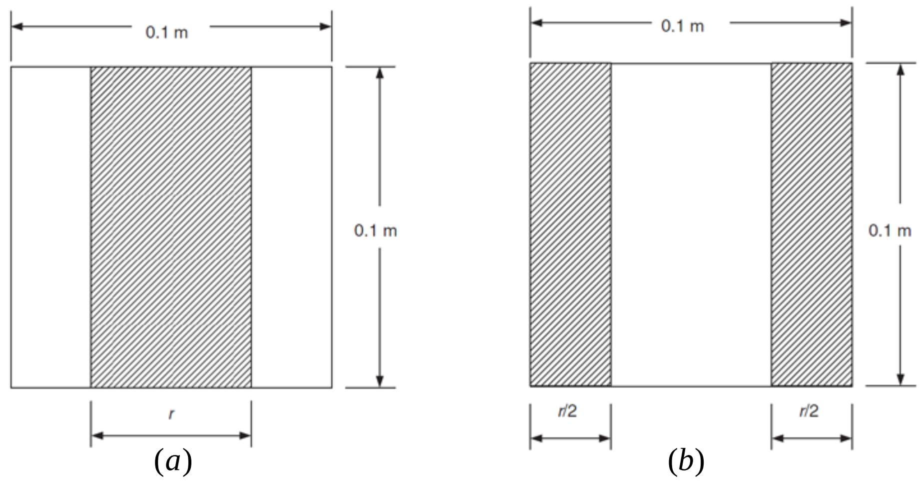


Fig. 4 Cross-section of the duct with two main types of spoilers used (a) centrally placed strip spoiler (b) two strip plates placed symmetrically at both sides of the duct, leaving a central vertical strip of the duct open.

The spoilers used in the experimental were made from 1-mm thick steel plate in order to provide a nearly rigid obstruction without significant vibration in the air stream. The spoiler plates were fixed by springs and force transducers between the flanges of two adjoining sections of the test duct. Compressed foam rubber was used to seal the gaps. Fig. 4 shows the cross-section of the duct with two main types of spoilers used in the experiment: centrally placed strip spoiler and two strip plates placed symmetrically at both sides of the duct by leaving a vertical opening at the center of the duct. Their height is that of the test duct of 0.1 m, and various widths of spoilers used in the experiments are exhibited in Fig. 5. Seven different configurations of spoilers under seven different mean flow velocities were chosen to validate the generalization of the proposed formulae, as illustrated in Fig. 5. The first five experiments (case 1, 2,3,4 and 5) only included two spoilers, while the last two experiments (case 6 and 7) contained three spoilers.

| Case | Different spoilers used in the experiments | Mean flow velocities |
|---|---|---|
| 1 | $r$=0.025m at p1 $r$=0.025m at p2 | 20 |
| 2 | $r$=0.025m at p1 $r$=0.05m at p2 | 22 |
| 3 | $r$=0.05m at p1 $r$=0.05m at p2 | 10 |
| 4 | $r$=0.075m at p1 $r$=0.075m at p2 | 11 |
| 5 | $r$=0.025m at p1 $r$=0.025m at p2 | 18 |
| 6 | $r$=0.025m at p1 $r$=0.025m at p2 $r$=0.025m at | 19 |
| 7 | $r$=0.05m at p1 $r$=0.05m at p2 $r$=0.05m at p3 | 12 |

Fig. 5 Different experimental configurations of spoilers under different mean flow velocities (m/s)

## 4. Results and discussion

The proposed generic formulae for the flow-generated noise produced by multiple in-duct elements are used to predict the sound power levels of aforementioned cases. The configurations of spoilers adopted in this paper are random rather than specific for the sake of clarifying the generalization of the proposed method. In light of the low speed flow of interest in the ventilation system, especially the mean flow velocities between 10 m/s and 20 m/s, the minimum and maximum mean flow velocities chosen in the experiment are 10 m/s and 22 m/s respectively.

The sound power levels predicted by the proposed generic formulae and the CIBSE Guide B4 are compared with the experimental measurements, as demonstrated in Fig. 6

(two in-duct elements cases) and Fig. 7 (three in-duct elements cases). The solid lines with dotted circles, dashed lines with dotted circles and dashed lines with dotted crosses represent the predictions of the proposed method, the predictions of the CIBSE Guide B4 and the measurement results respectively. Although some relatively large discrepancies between the predicted results of the proposed method and the measurement results could be observed in Fig. 6, the predicted results show an acceptable agreement with the measurements in all these two in-duct elements cases. For three in-duct elements cases, the prediction results of the proposed method fit well with the measurements results, as illustrated in Fig. 7.

Fig. 6 shows that the CIBSE Guide B4 could also provide approximate predictions around the measurement result, which seems to be better than the predictions of the proposed methods. However, the predictions of the CIBSE Guide B4 underrate the sound power levels due to neglecting the interaction effects of the multiple noise sources. It will be a serious issue since it is almost impossible to remedy the problem after the installation of the ventilation system. More serious underestimations of the sound pressure level predicted by the CIBSED Guide B4 could be observed in the three in-duct elements cases, as illustrated in Fig. 7. Almost every predicted sound pressure levels of the CIBSE Guide B4 are lower than the measurement results through the one-third octave center frequency domain. A relatively large discrepancy between the predictions of the CIBSE Guide B4 and measurement results exits in case 6. Whereas a good agreement between the prediction results of the proposed method and measurement results could be seen in Fig. 7.

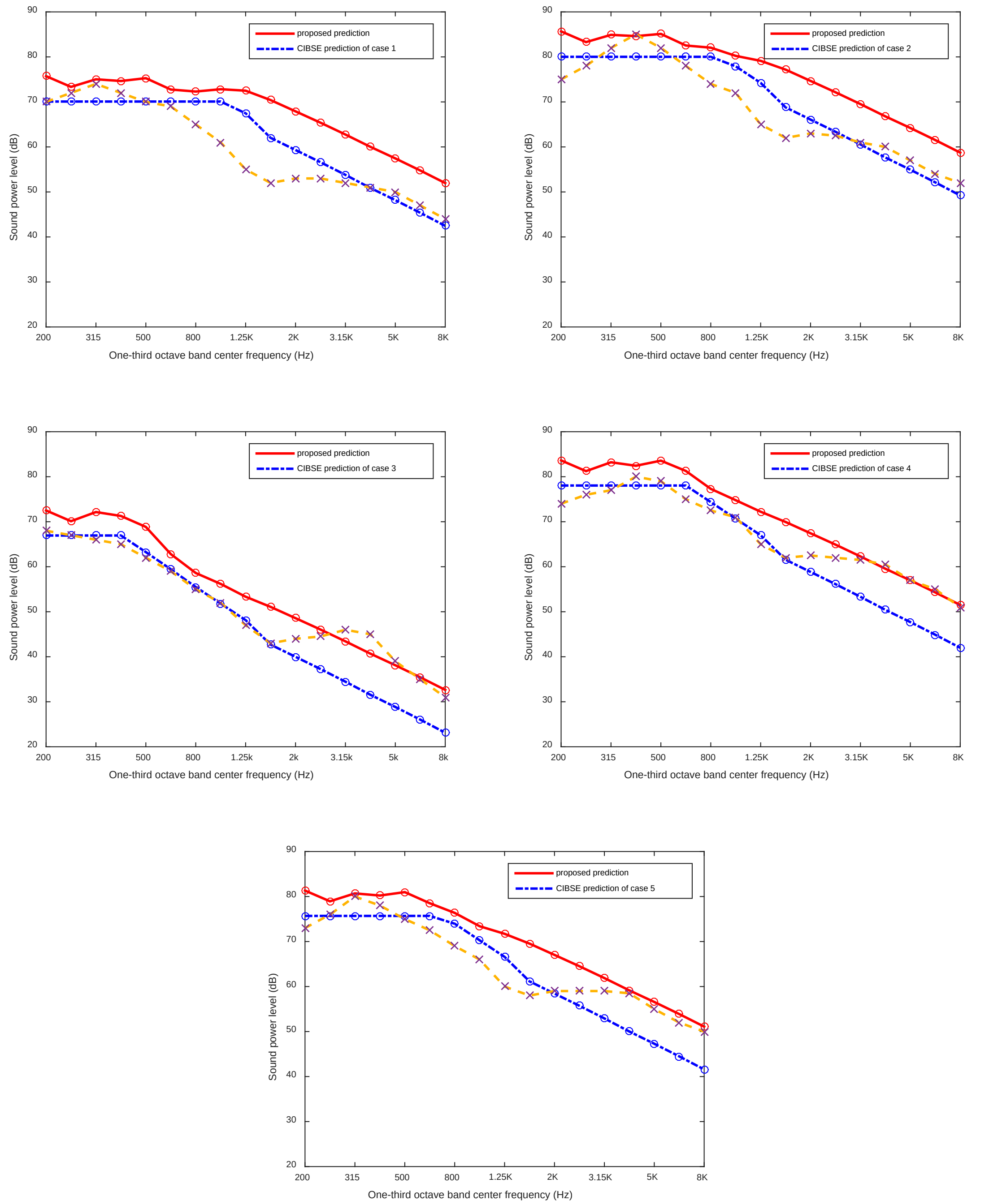


Fig. 6 Comparison of the predicted sound power levels and measurement results with respect to two in-duct elements cases (solid lines with dotted circles, dashed lines with dotted circles and dashed lines with dotted crosses represent the predictions of the

proposed method, the predictions of the CIBSE Guide B4 and the measurement results respectively)

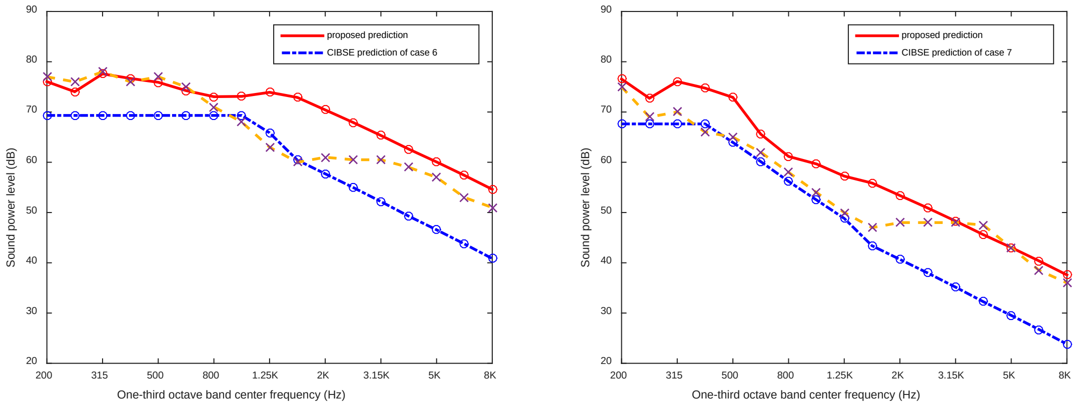


Fig. 7 Comparison of the predicted sound power levels and measurement results with respect to three in-duct elements cases (solid lines with dotted circles, dashed lines with dotted circles and dashed lines with dotted crosses represent the predictions of the proposed method, the predictions of the CIBSE Guide B4 and the measurement results respectively)

The results indicate that the proposed method occasionally overestimates the interaction effects of multiple in-duct flow noise sources. By neglecting the interaction effects of multiple in-duct elements in CIBSE Guide B4 results in the underestimated sound power levels. The underrated sound pressure level is inappropriate for the design of a ventilation ductwork system. It is better to overestimate the sound power level than to underestimate it due to the impossibility to solve the noise problem after the installation of a ventilation ductwork system. The proposed generalized formulae provide a practical technique for the prediction of the flow-generated noise generated by multiple elements in air ducts. It is a significant improvement to the current design guides for the design of a ventilation system.

## 5. Conclusion

The flow-generated noise problem caused by unavoidable in-duct elements is related to the complicated acoustic and turbulent interactions of multiple in-duct flow noise sources. However, current design guides only provide the prediction method for a single in-duct element. Based on the works of Mak and his co-investigators, a generalized practical prediction method for the flow-generated noise produced by multiple in-duct elements is therefore proposed in this paper. An interaction factor $\beta_m$ is introduced as a result of a simple relationship between the sound power due to the interaction of multiple in-duct elements and that due to a single in-duct element. Experiments were conducted to verify the proposed generic formulae in this paper. The predictions of the proposed method show an acceptable agreement with the measurement results, especially for the three in-duct elements cases. It should be noted that the proposed interaction factor $\beta_m$ considered as the interaction effects of multiple in-duct elements only represents an approximated added sound pressure level and may overestimate it occasionally. However, overestimations of the sound pressure level are better than the undervalued predictions of the CIBSED Guide B4 without regard to the interaction effects. It is because of the impossibility to solve the flow-generated noise problem after the installation of a ventilation ductwork system. The generalized prediction method can provide a practical technique for engineers to predict flow-generated noise produced by multiple in-duct elements in air ducts. Future work is necessary to carry out different generic formulae with respect to different numbers of in-duct elements or different types of spoilers for the sake of accuracy, and the present work should be extended to realistic ventilation system components in the future as well.

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**Figure captions**

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