Flow-induced Noise Prediction for 90° Bend Pipe by LES and FW-H Hybrid Method

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This paper focuses on an aerodynamic noise study of outlet elbow of Continuous Positive Airway Pressure (CPAP) machine by analyzing the wall pressure fluctuations and predicting the far field sound generated by turbulent flow. A hybrid approach combing the Larger-Eddy Simulation (LES) and Ffowcs Williams-Hawkings (FW-H) acoustic analogy was used to simulate the flow distribution as well as calculate the flow-induced noise for a three-dimensional elbow pipe. Then, a different elbow structure was designed to form the appropriate structure for the air outlet via considering the sound pressure level of each model. As a result, elbow with guiding plate was demonstrated to be an effective method to reduce the aerodynamic noise strength since this design could weaken the wall pressure fluctuation and vortex magnitude. Furthermore, the decreased magnitude could reach more than 1dB when velocity increased from 5m/s to 9m/s. The results of simulation were a little higher than experimental results since the background noise, elbow vibration and the defect of FW-H equation which couldn’t be eliminated thoroughly.

Key words: Exhaust elbow, aerodynamic noise, Large-Eddy simulation, guiding plate, FW-H Acoustic Analogy

INTRODUCTION

Clinical practice has shown that Continuous Positive Airway Pressure (CPAP) is a far more effective therapy for Obstructive Sleep Apnea Syndrome (OSAS) than traditional surgery. Since the devices used in CPAP therapy inevitably creates noise, evaluating the impact of noise on sleeping was given a fair amount of attention in the past decades (Mcdaid et al., 2009; Katrien and Bauters, 2010). It is known from previous research that major sources of noise from a ventilator are vibration, the

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Author(s) agree that this article remain permanently open access under the terms of the Creative Commons Attribution License 4.0 International License.
In recent years, the Large-Eddy Simulation (LES) has been widely applied on flow filed analysis of elbow because it resolves large scales of the flow field solution allowing better fidelity than Reynolds-averaged Navier–Stokes (RANS) methods, as well as models the small scales of the solution with low cost of computing resources than direct numerical simulation (DNS). Later, Rütten et al. (2005) studied the oscillation caused by vortex shedding at the inner side of the bend and shear layer instability based on LES. Research work showed that the cause of the measurable low frequency oscillation was the shedding of dean vortices and that the oscillation and its effect on the flow field varied in strength over time. Liu et al. (2010) used k-ε and Large-Eddy Simulation (LES) model to calculate the flow field of the transition zone at specific Reynolds numbers, respectively. The simulation results indicated that the LES model was more effective than the k-ε model. Eguchi et al. (2011) proved that flow separation played an important role in determining pressure fluctuation by simulating flow pressure distributions of a short elbow pipe which was critical in Sodium-cooled Fast Reactor (JSFR) with a Large-Eddy Simulation for a high Reynolds number flow. Tan et al. (2014) applied a hybrid numerical method of LES combing with characteristic-based split scheme (CBS) to analyze the flow filed and vortex shedding phenomenon. However, these research works mainly focused on the study of flow distribution. Limitation information on has been reported aerodynamic noise generated by flow.

When it comes to aerodynamic noise simulation, many researchers have done tremendous work on the theory and numerical simulation algorithms. Lighthill (1951) was the first to develop the aerodynamic theory by reformulating the Navier-Stokes equation into an exact, inhomogeneous wave equation. Later, Curle (1955) developed the acoustic equation for the flow field with boundary based on the work of Lighthill. In the case of stationary walls, Curle demonstrated that pressure fluctuations on walls could also become a significant noise source which was regarded as dipole source. Furthermore, Williams and Hawking (1969) extended the circumstance to moving walls by taking moving effect into consideration. If only stationary walls existed, the FW-H equation degenerated into Curle equation.

Entering new century, many researchers started to focus on the aerodynamics noise generated by flow as the development of the computational ability.

Lafon et al. (2003) shed light on the mechanism of the flow acoustic coupling in the cavity and in the duct through an aeroacoustical analysis and also proposed the way of energy transfer from the fluid to the main pipe through a vibro-acoustical analysis. Adam et al. (2008) used low dissipative Lattice Boltzmann theory to calculate the aeroacoustic sources that could generate turbulent fluctuations. They also depicted sound propagation as well as flow field with CFD software PowerFLOW.

Ji and Wang (2010) used LES simulation and Lighthill's theory to analyze the aeroacoustics of low-Mach-number flow over backward steps by comparing the calculated pressure fluctuations with experimental results. Moon et al (2010) proposed a hybrid method to predict the low-subsonic, turbulent noise. LES was employed to compute the noise source in the near wall or in the wake, while the characteristics of wall pressure fluctuations also were analyzed further to quantify the sizes of the noise sources.

Later, Zhang et al. (2010) simulated the wall pressure fluctuations by large eddy simulation and the flow induced noises calculated by FW-H acoustic analogy were compared to experimental data. For the similar case, Wang et al. (2011) investigated the hydrodynamic noise induced by mechanic cavities with different shapes with a hybrid method in which LES was used to simulate the noise source in near wall turbulences or in the wake and FW-H acoustic analogy was adopted to calculate the propagation. Zhu et al. (2013) investigated the transient flow field in the aerostatic bearing based on LES, and relationship between pressure fluctuations and bearing vibration was studied as well.

Zhang et al. (2014) linked the LES with the Lighthill's acoustic theory to simulate the flow-induced noise for a three-dimensional pipeline. They mainly focused on the hydrodynamic noise (dipole source) of flow through the pipe with different types of trash racks which was used to determine the best form of trash rack. In summary, pressure fluctuations which were obtained by numerical and experimental in previous studies were used to be an evaluating index in sound source.

From the above overview of literatures, it is apparent that past researches were mainly focused on the sound propagation in an elbow or how pressure fluctuations played a critical role in determine the sound source in other models. However, how pressure fluctuation affects the acoustic in the elbow has yet to be fully investigated. This paper employed the LES model to present the detailed flow field analysis and wall pressure fluctuations of an elbow with a guiding plate, which could be used as the exhaust onSleep Portable Ventilators and other portable air exhausting devices. Velocity distribution, wall pressure fluctuations as well as sound pressure level (SPL) was computed based on the LES and FW-H hybrid method which regards wall pressure fluctuations as a noise source. Finally, experiments were also carried out to investigate how the guiding plate reduces the pressure difference and overall (SPL).

THEORY AND EXPERIMENTAL PROCEDURES

Large-Eddy simulation

For incompressible air, Navier-Stokes equations in the Cartesian coordinates can be described as the following when gravity is
\[
\frac{\partial \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \tau + \rho \vec{f} \quad \text{with \ the \ motion \ of \ the \ frames \ of \ reference \ and \ in \ this \ paper, \ } P_i=0 \quad \text{(Tan et al., 2014)}.
\]

where, \( \vec{r}_i \) (i=1,2,3) is the grid scale velocity component in the x, y, and z directions. \( \bar{p} \) is the grid-scale static pressure. \( \rho \) is air density, \( \vec{v} \) is the kinematic viscosity. And \( P_i \) is the inertial force associated with the motion of the frames of reference and in this paper. 

The model constant \( C_d \) is computed is a local and instantaneous quantity and thus can vary widely in time and space. As a result, to avoid numerical instability resulting from negative values of \( C_d \), the numerator and denominator are averaged in the homogeneous directions. The constant \( C_d \) is manually set to be zero for the few instances when it is still negative. Therefore, this paper adopts the dynamic Smagorinsky-Lilly (DSL) to avoid the instability as mentioned above (Wang et al., 2011; Zhang et al. 2010).

### FW-H analogy theory

This paper focused on flow analysis when normal air flows through elbow at low Mach number as well as the noise level generated by the air flow. As aforementioned, Lighthill was the first to use the acoustic analogy method to separate the acoustic equation from the Navier-Stokes equations (Lighthill, 1952) and the equations are the following:

\[
\frac{\partial^2 p'}{\partial t^2} - c_0^2 \nabla^2 p' = \frac{\partial^2 T_{ij}}{\partial y_i \partial y_j} + \rho \vec{u}_j \vec{u}_j - e_{ij} \nabla \left[ (p - p_0) - c_0^2 (\rho - \rho_0) \right]
\]

where, \( T_{ij} \) is Lighthill stress tensor, \( e_{ij} \) is viscous stress tensor, \( \rho' = \rho - \rho_0 \) is the density fluctuation defined with respect to a reference density \( \rho_0 \). \( c_0 \) is sound speed in the air, and \( \rho, \rho_0 \) are the air pressure and density before and after perturbation, respectively.

If the right side of the first equation is seen as a sound source term, it can be regarded as a typical acoustic wave equation, which can be solved by the classical acoustic approach. Lighthill stress tensor can be obtained by experiments or other methods according to the literatures. Curle took the wall boundary into consideration. However, our work focused on problems involving solid surfaces and FW-H equation is more suitable for stationary surfaces (Wang et al., 2012). For the FW-H equation below, pressure fluctuation is substituted into the sound source term to compute SPL (Zhang et al., 2014).

\[
1 - \frac{c_0^2}{\rho_0} \frac{\partial^2 p'}{\partial t^2} \nabla^2 p' = L_M + L_D + L_Q
\]

\[
L_M = -\frac{\partial}{\partial x_i} \left[ (\rho_0 - \rho) v_n + \rho u_n \right] \delta(f)
\]

\[
L_D = -\frac{\partial}{\partial x_i} \left[ P_{nj} u_n + \rho u_i (u_n - v_n) \right] \delta(f)
\]

\[
L_Q = \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right]
\]

where, \( u_i, u_n, v, v_n \) are the tangential and normal velocity of flow and solid wall, respectively. \( \delta(f) \) is Dirac Delta function, \( H(f) \) is Heaviside function. \( L_M, L_D, L_Q \) are monopole, dipole, quadrupole sound source, respectively. Flow field must be obtained in order to apply the FW-H equation. According to the acoustic analogy theory, there are two major steps in the analysis of hydrodynamic noise.
Firstly, the sound source region is computed by unsteady flow in the elbow pipe. Secondly, sound propagation is calculated by the FW-H equation in the fluid medium (Zhang et al., 2014).

MODEL SETUP AND MESHING

Figure 1 showed the schematic of a stainless steel elbow and computational mesh of two different models. The pipe diameter $D$ was 22 mm, the straight part of the inlet and the outlet measured 50 mm each, inner and outer diameters of the bend part to the pipe diameter ratio ($R/D$) was 1.5. A guiding plate was located at the center of the bend part of the pipe. Besides, the plate had the same curvature radius with the bend pipe. After completing the model design, ICEM mesh software was used to mesh the model. Special attention was paid to the wall mesh processing. According to reported literatures, all three approaches used logarithmic law of the wall based functions to solve a separate set of equations in the near-wall region, and simulate this region in Reynolds-averaged sense. Cavar and Meyer (2011) demonstrated that the computational mesh chosen for modeling of subgrid scale stresses in the conducted LES simulation was of high importance, and they pointed out that LES seem to be fully capable of explain the fundamental properties of the complex no-equilibrium boundary layer flow over a surface with discontinuity. Since the near-wall mesh resolution was of critical importance in LES, the thickness of the first layer of cells near a wall must satisfy the requirement $y^+ \approx 1$ (Cavar and Meyer 2011). Pressure implicit with splitting of operator (PISO) method was employed to solve the pressure-velocity coupling equation for both steady and unsteady cases, while Pressure Staggering Option (PRESTO) method was adopted to discretize the continuity equation and the spatial discretization for momentum was Bounded Central Differencing. In addition, steady simulation was first processed in order to accelerate the convergence. The inlet velocities were chosen from 5 to 7 m/s according to the CPAP application. The wall of elbow and guiding plate were regarded as stationary and non-rough ones. The outlet was set as pressure-outlet and pressure was the same as atmosphere pressure. As sound boundary condition of acoustic simulation, the same mesh was used and we assumed that sound can penetrate the pipe wall and propagated in the free-space. In order to capture the wall pressure fluctuation, the step time was selected as $\Delta t=10^{-4}$ s. Moreover, we adopted proper CFL number (CFL was set as 0.2 by considering the max velocity, cell size and time step size) to ensure the convergence of our cases. In the paper, we presumed that flow-induced sound can penetrate the pipe wall without attenuation as well as sound can propagate in an infinite free space (Kim et al., 2002; Jung and Chung, 2012).

Experimental procedures

Figure 2 showed the schematic of the noise test setup. The
background sound pressure of anechoic chamber on the right hand of the figure was 19±1 dB. The air generated by a centrifugal fan which was controlled by the computer flowed into the inlet and then it passed the long straight pipe and developed fully before it reached the elbow. In addition, there were two flow sensors (160PC serials: provided by Honeywell company) to monitoring the flow rate to determine the inlet flow rate and the outlet velocity flow rate. The flow rates monitored by two flow sensors were the same value and it indicated that there was no air leakage at the joints between elbow and flow sensors. The elbow was manufactured in stainless materials so that sound can penetrate the pipe wall without substantial attenuation. Furthermore, the guide plate should be as thin as possible so that the vortex shedding’s effect can be avoided on sound calculation. The thickness and radius were 0.9 and 33 mm, respectively. The elbow was fixed on a platform to avoid it vibrating. A multifunctional sound level meter provided by Hangzhou Aihua Instruments Co. Ltd. was used to monitored the SPL whose microphone was 1/2" Prepolarized Condenser Mic. Model AWA14425. Then, the sound level meter was located at the center of the plate in z=0 plane. All data was recorded by the data record and processed by a computer.

RESULTS

Figure 3 showed the pressure distributions of the elbow pipe of two different models. The circle displayed the pressure distribution of θ (45º) cross section of the elbow. Obviously, we can tell that pressure of the outer wall (the red area) was larger than the inner wall (the blue area). Figure 4 showed the velocity on the three probe lines I–III which were shown in Figure 1 in the curved section of
two models on the symmetric plane (z=0). In the cases without plate, the flow pattern was symmetric in the straight part before flow reached the bend part. However, this pattern was disrupted when air flow passes through the elbow part as Figure 4-A1 and 4-B1 (Tan et al., 2014). Then, velocity at the outside region decreased, the majority of the flow trended to the inner side as Figure 4-A2 and 4-B2 at the $\theta=45^\circ$ (Adam et al., 2008). At rear half of curved section of the elbow, the velocity happened to deflect to the outside. Therefore, the curved section of elbow can affect the flow distribution to a great degree. The velocity on the probe line happened to deflect to the outside greatly and has a trough nearly at the non-dimensional radius -0.2 as Figure 4-A3 as well as at -0.1 as Figure 4-B3. Another conclusion was that the velocity curves nearly are symmetric to the zero at $\theta=45^\circ$ and $60^\circ$ except last one as Figure B1 and B2. It also can be found that when a plate was inserted in elbow, the trough of the curve at $\theta=90^\circ$ was not that clear as Figure 5.

The wall pressure fluctuation at eight observation points of two models was presented in Figure 6 in which pressure fluctuations were average values (twenty time steps) between 0.07 and 0.08 s, respectively. In addition, these computations were used to verify the performance of the LES in predicting the unsteady features of turbulent flow and all the eight figures demonstrated that the LES was stable to simulate the turbulent flow in elbow pipes as the fluctuations were stable in time domain. According to the figures of cases without guiding plate, it can be observed that pressure fluctuation amplitudes at all points were periodic in nature and their cycles were the same. Similarly, fluctuation curves in cases with plate were periodic except delayed a little comparing to the other model.

The vorticity distribution shown in the figure indicated that, when a guiding plate inserted into the elbow pipe, the magnitude of the vorticity on both the pipe wall and cross section decreased obviously according to the vorticity contour.

Figure 8 presented the calculated SPL spectrum of two models. It can be observed that the overall trend was similar and both curves decreased as frequency increased. Moreover, both curves had a peak at ~800 Hz and another peak at ~1500 kHz. However, the peak of SPL spectrum of model with guiding plate appeared a little earlier than that without plate.

Figure 9 was A-weighted sound pressure level of the monitoring point recorded by the data receiver. According to the figure, for the cases with the guiding plate or not, both the simulation and experimental results increased as inlet velocity increased from 5 to 9 m/s, respectively. It can be observed that, the calculated result was 2 dB smaller than the experimental result when inlet velocity was 5 m/s for both two models. However, the difference between the experiment and simulation values decreased to 1 dB when velocity is 9 m/s.

**DISCUSSION**

The pressure difference between inner and outer wall results from a contraction effect on the concave side of the elbow and the increasing flow velocity (Tan et al., 2014). When the air has just passed by the bend part, the centrifugal effect, though not material, still has an effect on the straight pipe. Then, fluid velocity and pressure field become uniformly distributed gradually. By comparing the two pictures of Figure 3, we see a more
Figure 6. Pressure fluctuations in time domain at eight observation points at inlet velocity 7 m/s of two models (Solid line for without plate and dot line for with plate).
Figure 7. Vorticity distributions on the pipe wall and cross section wall of two models at 7 m/s (Unit: s⁻¹); A: without plate; B: with plate; C and D: $\theta=45^\circ$; E and F: $\theta=90^\circ$
even pressure distribution between the inner and outer wall when a guiding plate was inserted in the middle of elbow. Evidently, this design reduced the pressure difference between the inner and outer walls. By comparing the two models, the velocity tendency on three probe lines is similar if we regard the elbow with guiding plate as two elbows without plate whose radius is half length of the big one. Speaking of difference, the most obvious one is that the velocity at the guiding plate is zero as figure series B. Furthermore, the differences of velocity profile in two models are mainly caused by curved section since centrifugal force exerted on the flow (Adam et al., 2008).

The wall pressure fluctuations are important characteristics of turbulence and also play an important role to assess the aerodynamic sound source in calculating the far field sound pressure level (Zhang et al., 2010). Due to the low Mach number, the contribution of quadrupole sources is so slight that it can be ignored. Therefore, most of the sound is generated on wall surfaces (dipole and monopole sources). As the numerical simulation method makes it possible to compute the unsteady pressure fluctuations of the model, it is flexible to evaluate the aerodynamic noise by regarding the pressure fluctuations as sound source. Evidently, pressure fluctuation values of cases without guiding plate are much larger than cases with plate and the difference varies from 1.2 to 9 Pa. It is because the flow disturbance can be decreased when a guiding plate is inserted in the elbow. Speaking of amplitudes of the waves, all pressure fluctuation amplitudes of models with guiding plate are smaller than that without plate to some extent and pressure fluctuation waveform at each point is similar according to the figures (Zhu et al., 2013). Actually, all fluctuation amplitudes approximate to each other as seen in Table 1. This is because that all pressure fluctuations vary synchronously as guiding plate is inserted into the elbow. In summary, the results of simulation demonstrate that predominant component of the pressure fluctuation as flow passes through the elbow is correlated with flow separation characteristics (Tan et al., 2014). From analysis of above figures, pressure fluctuations are mainly generated by oscillation of the vortices excited by the flow separation and it is unsteady according to the curves (Eguchi et al., 2011). Simultaneously, magnitude of vorticity decreases when a guide plate is inserted into elbow since both the velocity and amplitude decrease to some degree. This also can demonstrate that intensity of sound source weakens slightly as rapid changes of vortexes which are adjacent to walls in the flow are the primary sources to generate sound (Zhang et al., 2010; Wang et al., 2011). To mention the sound spectrum, the reason why peaks of SPL spectrum of model with guiding plate appears a little earlier is that, we speculate, the pressure fluctuations have prolonged when a plate is inserted in the elbow based on the analysis of pressure fluctuation figures as mentioned above (Zhang et al., 2010; Shi et al., 2012). In addition, the spectrum of model with plate has another peak at frequency ~4.7 kHz and this may be induced by vortex frequency change.

The reason why SPL of simulation is smaller than experimental results is that this work didn’t take pipe vibration into consideration since we haven’t found an effective way to quantify the vibration noise yet, and background noise is another possible factor for the variation (Lin and Tsai, 2012). Since FW-H equation is applicable only in predicting the propagation of sound toward the free space according to the reported literatures. It doesn’t take into account wave reflection or
scattering due to any existing solid surface between the sound flow-field source and the observer. In aggregation, these factors translate into a lower SPL computed by simulation than SPL from experiments (Martínez-Lera et al., 2015).

Furthermore, the results obtained by experiment are approximately linear, while the calculated results deviate slightly from linearity. When the cases with and without the guiding plate are compared, large consistent differences could be easily observed. The experiments show that the sound pressure level values of cases with a flow guiding plate is approximate 1 dB less than cases without a plate, regardless of the inlet velocity. This is because the wall pressure fluctuation attenuated as well as vorticity magnitude decreased when guiding plate is inserted into the pipe as mentioned in previous part, and the intensity of sound source diminishes to some extent so that SPL at the receiver decreases accordingly (Zhang et al., 2010; Shi et al., 2012). In summary, results of simulation agree well with experimental data and it proves that the hybrid combing LES and FW-H theory is flexible to evaluate the aerodynamic noise generated by flow.

**Conclusion**

Firstly, this paper adopted large-eddy simulation which has been widely used on engineering application to simulate the flow distribution of a creative elbow structure with a guiding plate inserted in the pipe. Compared to other turbulent models, LES is more advantageous for its flexible to evaluate the aerodynamic noise generated by flow. As elbow vibration, background noise and the defect of the FW-H equation. The results show that, SPL decreased significantly when inserted a plate in the elbow as wall pressure fluctuations weakened when a guiding plate existed and the biggest difference could reach 1 dB. These results provide a theoretical explanation and a simple method to reduce aerodynamic noise as outlet in airflow devices. Therefore, this paper promises wide applications in industrial fields, such as some medical device design, air exhaust setup and so forth.

**Conflict of Interests**

The authors declared that they have no conflicts of interest to this work.

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**REFERENCES**


**Table 1.** Pressure Fluctuation amplitude at each observation point (Unit: Pa).

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<th>Pressure fluctuation amplitude</th>
<th>11</th>
<th>12</th>
<th>21</th>
<th>22</th>
<th>31</th>
<th>32</th>
<th>41</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Plate</td>
<td>1.3776</td>
<td>1.3777</td>
<td>1.3761</td>
<td>1.3765</td>
<td>1.3729</td>
<td>1.3720</td>
<td>1.3696</td>
<td>1.3690</td>
</tr>
<tr>
<td>With Plate</td>
<td>0.2734</td>
<td>0.2709</td>
<td>0.2753</td>
<td>0.2701</td>
<td>0.2734</td>
<td>0.2713</td>
<td>0.2697</td>
<td>0.2731</td>
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