Investigation of noise characteristics of periodic jet impinging on a flat plate

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Abstract: Noise characteristics of periodic jet impinging on a flat plate are investigated. The numerical model is established by large eddy simulation and FW-H acoustic analogy method. Compared with experimental data obtained by noise measurement experiment, the effects of acoustic integral surface and different subgrid-scale models on noise simulation results are studied. The accuracy of the optimized numerical model is also validated by verification experiment. Further, the present numerical model is applied to numerical prediction of noise directivity and spectrum distribution with different waveforms and periodic frequency. Compared with the steady impinging jet, noise characteristic of periodic jet impinging on a flat plate are presented and the mechanism of acoustic source is analyzed. The present work provides a reference value for the analysis and control of noise of periodic jet impinging on a flat plate.

Keywords: Periodic impinging jet; Noise characteristic; Waveform; Periodic frequency

1. Introduction
Impinging jet is widely used in many practical problems and industrial fields[1], such as drying of process products, cooling of gas turbine components and electronic equipment, landing of aerospace vehicles[2,3]. The research on impinging jet mostly concentrates on two fields. One is the aerospace field, the other is the heat transfer and cooling field. In the aerospace field, impinging jet noise may lead to fatigue damage of aircraft structure and reduce the safety performance and service life of aircraft. Therefore, noise characteristics and acoustic source mechanism of high-speed impinging jet are the center of various studies. Dhamanekar[4] studied the acoustic and flow variations in jets impinging on inclined plates by experiment. He found that the noise of subsonic impinging jet is equal for all inclinations, however, the noise of supersonic impinging jet increases as the inclination increases because of the presence of impinging tones. Sinibaldi[5] carried out an experiment study on effects of the impinging surface on screech tones of impinging jets. The results validates the coupling between acoustic discrete tones and fluctuating flow velocities. Akamine[6,7] studied the influence of the distance between the flat plate and the jet nozzle on the difference of acoustic field when the supersonic jet impinges on the inclined plate. The experimental results show that the radiation intensity of the sound source of impinging jet mainly depends on the location of the acoustic monitoring point and the pressure ratio at the nozzle outlet. Balakrishnan[8] experimentally investigated the noise spectra and directivity of circular and non-circular impinging jets on flat plate at various nozzle pressure ratios and emission angles. The results reveal that the structure and symmetry of shock cell structures are destroyed for the non-circular jets compared with the circular jet.

In recent decades, the numerical methods has been widely used due to the development of computing technology[9-11]. Romain[12,13] studied the noise characteristics of a supersonic jet impinging on a flat plate using large eddy simulation. The results show that the impinging tones and
standing waves are caused by the acoustic feedback loop between the nozzle and the plate. Yao et al.[14] presented the interaction between shock wave and vortex structure when supersonic jet impinges on a flat plate by large eddy simulation. Christoph[15], Lyrintzis[16] and Nonomura[17] numerically investigated the noise characteristics and acoustic source mechanism of supersonic jet impinging on the inclined plate. The effects of inclination on the overall sound pressure level, spectrum and noise directivity are analyzed.

As for the heat transfer and cooling field, numerous researches mainly focus on the heat transfer characteristics of low-speed impinging jet[18-20]. In addition to changing the impinging distance, nozzle parameters and the shape of impinging surface, researchers gradually turn their attention to periodic impinging jets with unsteady velocity to improve heat transfer performance[21,22]. However, there is a paucity of literature on noise generation by periodic impinging jets and most researchers have ignored the accompanying noise problem. In actual industrial applications, noise emission not only affects the work efficiency of the staff, but also hurts the physical and mental health of the staff. Therefore, it is of great significance and innovative value to investigate the noise characteristics of periodic impinging jet.

In this paper, a numerical model for predicting noise generation of impinging jet is established in Section 2. Effects of acoustic integral surface and subgrid-scale models on simulation results are studied and the numerical model is validated by noise measurement experiment in Section 3. The validated numerical model is applied to investigation on noise characteristics and acoustic source mechanism of periodic jet impinging on a flat plate with different waveforms and periodic frequency in Section 4. The present work provides a reference value for the analysis and control of noise of periodic jet impinging on a flat plate.

2. Numerical method

2.1. Numerical model

Fig 1 shows the three-dimensional numerical model of periodic jet impinging on a flat plate. The diameter of the jet nozzle (D) is 10 mm, and the length of the jet nozzle is 25 mm. The average impinging velocity is 30m/s. The size of the flat plate is 800mm×800mm. The distance between nozzle outlet and flat plate (X) is the impinging distance. The computational domain is a hexahedral region with a size of 200mm×200mm×200mm. The size of the acoustic integral surface is defined as L×L×H. Noise monitoring points are arranged on a semicircle with R=1m as shown in Fig 2. Axis is the center line of the nozzle. $\theta$ is the angle between axis and the straight line from a monitoring point to the plate center. There are 11 monitoring points in the range of 15° to 165°. 90° direction is perpendicular to the impinging jet.

![Fig 1. Numerical model of periodic jet impinging on a flat plate](image1)

![Fig 2. Distribution of Noise Monitoring Points](image2)

2.2. Governing equations

The numerical method used in the study of acoustic characteristics is based on large eddy simulation (LES) and Ffowcs Williams-Hawkings (FW-H) acoustic analogy. Firstly, time-accurate solutions of the
flow-field variables can be obtained by LES. For incompressible fluids, governing equations of LES are defined as[23]:

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0
\]  

(1)

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial }{\partial x_j} (\bar{u}_i \bar{u}_j) = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \nabla^2 \bar{u}_i - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{F_i}{\rho}
\]  

(2)

\[
\tau_{ij} = (\bar{u}_i \bar{u}_j - u_i u_j)
\]  

(3)

where \(\tau_{ij}\) is the subgrid-scale (SGS) stress.

The SGS stress has great influence on LES method and can be solved by SGS models. In order to study the effect of the SGS model on the simulation results, different SGS models are constructed such as Smagorinsky-Lilly (SL) model, Wall-Adapting Local Eddy-Viscosity (WALE) model, Wall-Modeled Large Eddy Simulation (WMLES) model and Kinetic-Energy Transport (KET) model. Secondly, the acoustic field are obtained by solving the FW-H acoustic analogy equation. The method adopts the most general form of Lighthill’s acoustic analogy, and is capable of predicting noise generated by equivalent acoustic sources. The FW-H formulation can be written as the following equation[24]:

\[
\frac{1}{c^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial}{\partial t} \left[ (\rho_0 U) \delta (f) \right] - \frac{\partial}{\partial x_j} \left[ L \delta (f) \right] + \frac{\partial^2}{\partial x_j \partial x_j} \left[ T_{ij} H (f) \right]
\]  

(4)

\[
U_i = v_i + \frac{\rho}{\rho_0} (u_i - v_i)
\]  

(5)

\[
L_i = P_i \delta (f) + \rho u_i (u_i - v_i)
\]  

(6)

\[
T_{ij} = \rho \delta (f) - c^2 (\rho - \rho_0) \delta_{ij}
\]  

(7)

\(p'\) is the sound pressure at far field, \(c\) is the sound velocity, \(u\) is the fluid velocity, \(v\) is the body surface velocity, \(n\) is the normal vector pointing into the fluid, \(\delta (f)\) is Heaviside function, \(H (f)\) is Dirac delta function, \(T_{ij}\) is the Lighthill stress tensor.

The acoustic integral surface has great influence on FW-H acoustic analogy method. In order to study the effect of acoustic integral surface on the simulation results, the size of acoustic integral surface is \(100 \text{mm} \leqslant L \leqslant 170 \text{m}\) and \(95 \text{mm} \leqslant H \leqslant 170 \text{mm}\).

2.3. Mesh strategy

Structured mesh is applied to mesh generation. The computational domain is divided into several parts as shown in Fig 3. Part 1 and Part 2 needs to be encrypted to ensure the simulation accuracy. Then from Part 3 to Part 4, the grid density decreases gradually. The detail view of computational mesh in the cross section of the model can be seen in Fig 4.

![Fig 3. Schematic diagram of model partition](image1)

![Fig 4. The detail view of computational mesh of the model](image2)
Verification of grid independence is carried out. The numerical model is meshed with the mesh number of $2.44 \times 10^6$, $3.14 \times 10^6$, $3.69 \times 10^6$, $4.11 \times 10^6$, $4.66 \times 10^6$ and $5.26 \times 10^6$ respectively when $X=5D$. As the important parameter of impinging jet, the velocity changes of monitoring points are taken as references to validate the grid independence as shown in Fig 5. Monitoring point A is located on the central axis of the nozzle, and the distance to the center of the nozzle outlet is defined as X1; Monitoring point B is located parallel to the plane, the distance to the plate is 2mm, and the distance to the central axis is defined as X2; Various values are taken for X1 and X2 respectively. The results of independent verification of grids are displayed in Fig 6. One can observe that velocity distribution no longer changes when the mesh number increases to $4.66 \times 10^6$. Therefore, $4.66 \times 10^6$ grids are employed to discretize the computational domain.

Fig 5. Distribution of velocity monitoring points

![Fig 5. Distribution of velocity monitoring points](image)

(a) Velocity monitoring point A  (b) Velocity monitoring point B

Fig 6. Results of independent verification of grids

![Fig 6. Results of independent verification of grids](image)

2.4. Boundary conditions and solving method

Noise characteristics of periodic impinging jet are compared to that of steady impinging jet with constant velocity. For the steady impinging jet, the boundary condition for the nozzle inlet is velocity-inlet. The left boundary of the computational domain is pressure-inlet. The other boundaries of the computational domain are pressure-outlet. The surface of nozzle and flat plate is provided with non-slip wall boundary conditions. For the periodic impinging jet, most boundary conditions are the same as those of steady case. However, the difference lies in the use of UDF program to achieve the output of periodic velocity signal for the nozzle inlet. Figure 7 shows four typical waveforms of periodic velocity signals used in the paper. The average velocity ($\bar{u}$) is 30m/s. The periodic frequency (1/T) varies from 5Hz to 40Hz. Due to the different instantaneous noise of different periodic impinging jets, equivalent continuous sound pressure level is introduced as an evaluation index of periodic impinging jet noise, as follows.

$$L_{eq} = 10 \log \left( \frac{1}{T} \int_0^T 10^{0.1L_{PA}} dt \right)$$  (8)

where $L_{PA}$ is the instantaneous sound pressure level at a certain time $t$, and $T$ is the specified measurement time. Then the noise source of periodic impinging jet can be equivalent to that of steady impinging jet.
Steady flow field is obtained by standard k-ω model as the initial field of LES. The transient flow field accurately near the noise source is obtained by LES. The PISO scheme is used in pressure-velocity coupling. The PRESTO! is applied to spatial discretization pressure equation and second-order upwind format is applied to momentum equation. Acoustic fields of steady and periodic impinging jets are calculated by FW-H model. Time step size is $2.5 \times 10^{-5}$ s according to the noise frequency range recognized by the human ear. From the noise source to the receiver, the noise propagation is obtained by solving the acoustic wave equation.

![Waveform of the periodic impinging jet](image)

**Fig 7. Waveform of the periodic impinging jet**

### 3. Experimental verification

Taking the steady impinging jet case as an example, numerical results are compared with experimental data to investigate the effects of acoustic integral surface and SGS model on noise simulation results. The accuracy of numerical model can also be verified based on the comparison results.

#### 3.1. Experimental system

The noise measurement system used for experimental verification is shown as Fig 8. It includes nozzle jet device, control room and anechoic room of size $3.5 \times 3.5 \times 3$ m (wedge tip-to tip). In order to reduce the effect of nozzle jet device on experimental results, the gas tank, the control system, gas tank and air compressor of the nozzle jet device are arranged in the control room, while the nozzle is arranged in the anechoic chamber. The impinging velocity is $30$ m/s. The diameter of the jet nozzle, impinging distance and the size of the flat plate are consistent with the numerical model. The location of the microphone sensor is the same as shown in Fig 8. The microphone sensor is PCB 377B11 with PCB 426E01. Data acquisitions are carried out with NI PXI-1042Q, PXI-4472 and PXI-8106 control system, which has a band width from 20Hz to 20 kHz. The background sound pressure level is 19.9dB. The noise distribution of jet impinging on the flat plate is measured through the above system.

![Schematic diagram of experimental system](image)

1-Gas tank 2-Compressor 3-PID controller 4-Differential pressure sensor 5-Diffuser section 6-Rectification section 7-Jet nozzle 8-Flat plate 9-Cone support 10-Microphone sensor

(a) Schematic diagram of experimental system
3.2. Effects of acoustic integral surface

The influence of size of the acoustic integral surface ($L \times L \times H$) on the calculation results of the acoustic field of impinging jet is studied. Firstly, the KET model is initially selected as the SGS model and the length of acoustic integral surface parallel to the jet direction remains unchanged ($H=140\text{mm}$). The length of acoustic integral surface parallel to jet direction varies from $100\text{mm}$ to $170\text{mm}$ ($10 \leq L/D \leq 17$). Fig 9 shows the variation of overall sound pressure level (OASPL) with $L$ under different noise monitoring points. It can be observed that the impinging jet noise decreases as $L$ increases. When $L$ increases from $100\text{mm}$ to $130\text{mm}$, the maximum difference between the simulation results of impinging jet noise is 2.0dB. When $L$ increases from $130\text{mm}$ to $170\text{mm}$, the maximum difference between the simulation results of impinging jet noise is 0.2dB. Acoustic integral surface has little influence on the simulation results when $L \geq 130\text{mm}$.

In theory, the acoustic integral surface already contains the main acoustic source region. The size of acoustic integration surface should have no effect on the simulation results. However, in the actual simulation progress, the jet impinges on a flat plate and flows through the acoustic integral surface, thus producing a non-physical virtual sound source[25]. The greater the velocity is when flowing through the acoustic integral surface, the greater the influence of the virtual sound source has on the simulation results. Based on this, the variation of velocity through the acoustic integral surface with $L$ is displayed in Fig 10. It can be seen that the attenuation trend of velocity is flat gradually when $L \geq 130\text{mm}$. The velocity decreases to around 3m/s and the simulation results of the impinging jet noise are less affected by the virtual sound sources. The total mesh number will increase as $L$ increases. Considering the
computational efficiency and accuracy of the numerical method, the value of $L$ is chosen to be 130mm ($L/D=13$).

Secondly, the value of $L$ remain unchanged ($L/D=13$), the length of acoustic integral surface perpendicular to jet direction varies from 95mm to 170mm ($9.5\leq H/D\leq 17$). Fig 11 shows the variation of OASPL with $H$ under different noise monitoring points. It can be seen that the impinging jet noise increases as $H$ increases. When $H$ increases from 95 mm to 130 mm, the maximum difference between the simulation results of impinging jet noise is 0.1dB. When $H$ increases from 130 mm to 170 mm, the maximum difference between the simulation results of impinging jet noise is 0.4dB. Acoustic integral surface has little influence on the simulation results when $H\geq 130$mm. Since Part 1 and Part 2 should be inside the acoustic integral surface, the value of $L$ is chosen to be 130mm ($H/D=13$).

![Fig 11. Variation of OASPL with H under different noise monitoring points](image)

### 3.3. Effects of SGS model

Fig 12 shows the effects of different SGS model on the simulation results of impinging jet noise when the size of the acoustic integral surface is chosen as $130\text{mm}\times 130\text{mm}\times 130\text{mm}$. Compared with the experimental data, the results of WALE model are smaller and the results of the other three SGS models are larger. The comparison result is quantitatively analyzed. Table 1 shows the noise computation errors for different SGS models. One can observe that the computational errors of SL model and WMLES model are relatively large and the simulation result of KET model is in the best agreement with the experimental data. Therefore, the SGS model of LES is selected as KET model.

### 3.4. Validation of numerical model

The above selected numerical model is applied in the simulation for noise distribution under different impinging distances ($3D\leq X\leq 9D$) and monitoring positions ($15^o\leq \theta \leq 90^o$). Compared with the experimental data, the noise calculation errors is shown in Table 2. The maximum calculation error is
1.3dB and the maximum relative error is 2.8%. The numerical results are all in good agreement with the experimental data which validates the accuracy of the numerical model.

![Experimental and simulated results comparison](image)

**Fig 12.** Effects of different SGS models on the simulation results of impinging jet noise

| Model     | Maximum difference (dB) | Average difference (dB) | Average relative error (%) |
|-----------|-------------------------|-------------------------|---------------------------|
| SL model  | 4.8                     | 4.3                     | 9.3                       |
| WALE model| -1.5                    | -1.3                    | 2.8                       |
| WMLES model| 5.3                     | 4.8                     | 10.3                      |
| KET model | 1.1                     | 0.8                     | 1.8                       |

**Table 1. Noise computation errors for different SGS models**

| Maximum difference (dB) | Maximum relative error (%) |
|-------------------------|----------------------------|
| X=3D                    | 1.1                        | 2.4                       |
| X=5D                    | 1.1                        | 2.4                       |
| X=7D                    | 1.2                        | 2.6                       |
| X=9D                    | 1.3                        | 2.8                       |

**Table 2. Noise computation errors under various impinging distances and monitoring positions**

4. **Noise characteristics analysis**

The validated numerical model is applied to investigation on noise characteristics of periodic jet impinging on a flat plate with different waveform and periodic frequency.

4.1. **Effects of waveform**

The noise directivity distribution of periodic impinging jet with different waveform is compared to that of steady impinging jet as shown in Fig 13. Generally speaking, the noise of periodic impinging jet is much larger than that of steady impinging jet and the noise of rectangular case is larger than that of the other cases. The average difference of noise between steady case and rectangular case is 24dB. As for the other three waveforms, the average difference is about 14dB. The noise distribution of rectangular waveform fluctuates greatly in the range of 60° to 120° whereas the noise distribution of the other three waveforms is more uniform.

Specifically, the effect of waveform on noise spectrum is studied as shown in Fig 14. The periodic frequency is 40Hz and the monitoring angle is 90°. For the steady impinging jet, the noise decreases as the frequency increases. As for the periodic impinging jet, the noise decreases first and then increases with the increase of frequency. Compared with the noise spectrum of steady impinging jet, the waveform has a greater influence on high-frequency noise. Especially for the rectangular waveform, the spectrum is of obvious high-frequency characteristic.
Acoustic sources of impinging jets mainly contains two factors: one is the quadrupole source caused by the internal stress of fluid in the free jet section, the other is the dipole source caused by the reaction force between fluid and flat plate. Based on our previous conclusions[26], the dipole source leads to the broadband characteristics in medium and high frequency bands and the spectrum of free jet is of low-frequency characteristic. So the quadrupole source plays a more important role on the acoustic source of the steady jet impinging on the flat plate. However, for the periodic impinging jet, another acoustic source is the unstable fluctuation of fluid pressure at nozzle outlet caused by the unsteady velocity. Then the noise of periodic impinging jet is larger than that of steady impinging jet. According to the noise spectrum of the periodic impinging jet, the fluid pressure fluctuation has a greater influence on high-frequency noise. For the rectangular waveform, the fluid pressure fluctuation of impulse type leads to a great increase of noise in high-frequency band. The direction of the acoustic source caused by the fluid pressure fluctuation of impulse type is perpendicular to the jet. So the maximum noise is in the 90° direction. For the other three waveform, the change of velocity is gentle.
The strength of fluid pressure pulsation at nozzle outlet is relatively small. Therefore, the noise distribution is different from that of the rectangular case and the noise is also smaller.

When the periodic variation frequency is 40Hz and the velocity is 30m/s and the impact distance is 5D, the instantaneous velocity distribution nephogram of the periodic jet flow field of flat plate impact in one cycle (T) is shown in Fig 15 and the end time of one cycle is also the starting time of the next cycle. It also can be seen from the figure that the velocity attenuation rate of rectangular waveform is faster than that of other waveforms, which is also the reason why rectangular waveform has greater impact on high frequency noise.

4.2. Effects of periodic frequency
Fig 16 shows the effects of periodic frequency on noise directivity of periodic impinging jet. The noise of periodic impinging jet increases as the periodic frequency increases. Specifically, when the periodic frequency increases from 5Hz to 40Hz, the average noise increases by 7–9dB.

For the sinusoidal waveform and sawtooth waveform, noise distribution is relatively uniform. But the noise increase of sawtooth waveform is very small when the periodic frequency is greater than 20Hz. For the triangular waveform, noise in the perpendicular direction to the jet is smaller than that in the parallel direction to the jet. As for the rectangular waveform, noise in the perpendicular direction to the jet is larger than that in the parallel direction to the jet.

Fig 17 shows the effects of periodic frequency on noise spectrum of periodic impinging jet (θ=90°). It can be observed that for the rectangular waveform, the rise of periodic frequency only increases the noise value, but has little influence on the spectrum distribution. As for the other three waveforms, the periodic frequency has a relatively small effect on noise in the frequency band from 1000 Hz to 6000 Hz, and the noise in other frequency bands increases with the increase of periodic frequency.

For the rectangular waveform, the main acoustic source is the fluid pressure pulsation at nozzle outlet and the periodic frequency has a greater influence on this factor. As the periodic frequency increases, the strength of the fluid pressure pulsation increases. This is why the periodic frequency only changes the noise value but has relatively small influence on the spectrum characteristics. For the other three waveforms, the main acoustic source is the fluid pressure pulsation and the quadrupole source.
The increase of periodic frequency has a greater influence on the fluid pressure. Therefore, the noise in high frequency band is enhanced more, especially when the periodic frequency increases from 20 Hz to 40 Hz.

Fig 16. Effect of periodic frequency on noise directivity of periodic impinging jet

Fig 17. Effect of periodic frequency on noise spectrum of periodic impinging jet
5. Conclusions
In this paper, based on LES and FW-H acoustic analogy, a numerical model for predicting the noise of impinging jet is established and the noise measurement experiment is carried out to validate the numerical model. The comparison between experimental data and numerical results shows that when the size of the acoustic integral surface is chosen as 130mm×130mm×130mm and the SGS model of LES is KET model, the maximum calculation error is 1.3dB and the maximum relative error is 2.8%, which validates the accuracy of the numerical model.

Then the present numerical model is applied to the investigation on noise characteristics of periodic jet impinging on a flat plate. Compared with the steady impinging jet, noise directivity and spectrum distribution of periodic impinging jet are analyzed with different waveforms and periodic frequency. The results show that the average noise of periodic impinging jet is more than 14 dB larger than that of steady impinging jet and the noise of rectangular waveform is the largest. As the periodic frequency increases from 5Hz to 40Hz, the average noise increases by 7~9dB. The differences of noise characteristic between periodic impinging jet and steady impinging jet mainly depend on the unstable fluctuation of fluid pressure at nozzle outlet caused by the unsteady velocity. The drastic change of velocity (such as rectangular waveform) and the increase of periodic frequency lead to the increase of strength of the fluid pressure fluctuation. The fluid pressure fluctuation has a greater influence on high-frequency noise.

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