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Numerical Analysis on Instability of Supersonic Impinging Jet using LES

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1. Introduction

The US-NRC requires the assessment of unsteady jet impinging load in high energy pipe break caused by the potential feedback mechanism[1]. Potential feedback mechanism refers to a phenomenon in which acoustic wave generated by jet impingement on a structure surface amplifies vortex and jet instability in the jet shear layer. In this study, the evaluation methodology of unsteady jet impinging load using CFD(Computational Fluid Dynamics) analysis technique was established. And by using this, a preliminary analysis was carried out to simulate the flow and acoustic fields of the impinging jet. The pressure filed are also described by computing sound pressure level and using Fourier decomposition. And its spectral and hydrodynamic properties are studied and compared to the experiment result.

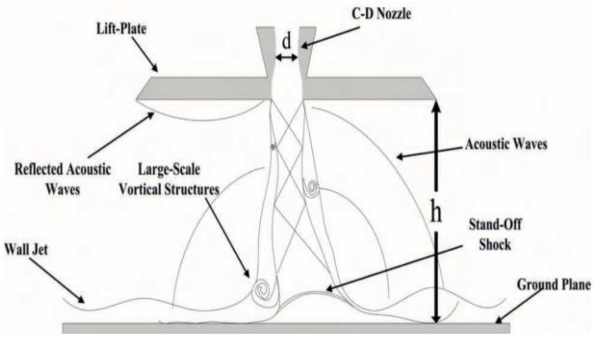


Fig. 1. A schematic of potential feedback mechanism

2. Evaluation Methodology of Jet Instability

The evaluation of the dynamic behavior of steam jet using CFD analysis technique can be divided into four stages. In the first step, a three-dimensional CAD model of the piping and target structure is made and a grid system for the flow region is constructed. In case of applying the LES(Large Eddy Simulation) turbulence model, it is important to construct a grid system having proper size and quality. In the second step, steady state analysis is performed using the RANS(Reynolds Averaged Navier-Stokes) turbulence model to obtain the initial solution of LES. Since the amount of computation of LES is very large, the time and resources required for the analysis can be saved by performing the pre-analysis using the RANS model. In the third step, CFD analysis using the LES model is performed. In this step, the dynamic behavior of the steam jet is evaluated. In the final step, the characteristics of the hydrodynamic acoustic wave and dynamic jet impinging load are analyzed by using Fourier decomposition.

3. Numerical Analysis

A preliminary analysis was carried out to estimate the applicability of evaluation method for unsteady jet impinging load based on CFD analysis technique. In the preliminary analysis, the dynamic behavior of the jet and impinging load were evaluated according to the distance between the jet injection nozzle and the target structure. And the vibration characteristics of the unsteady jet were evaluated by frequency analysis.

3.1 Thurow's Jet Impingement Experiment

The preliminary analysis of the dynamic jet behavior was performed for the same analysis condition as Thurow's jet impingement experiment[2]. In the Thurow's experiment, the behavior of the reflected pressure wave caused by impingement of supersonic (Ma=1.28) planar jet was evaluated. A jet ejected from a rectangular nozzle tip having a width (w) of 38.1 mm and a height (h) of 12.7 mm impinge on a flat plate in the experiment chamber. Distance between the nozzle tip and the flat plate can be set in the range of 0 mm to 356 mm. Experiments were performed for a total of 28 jet length conditions. In this study, numerical analysis is performed for the condition that the distance between the nozzle tip and the plate is L=8.27h, which is comparable with experiment result. And further analysis is performed for the condition of L=3.94h.

3.2 Calculation Conditions

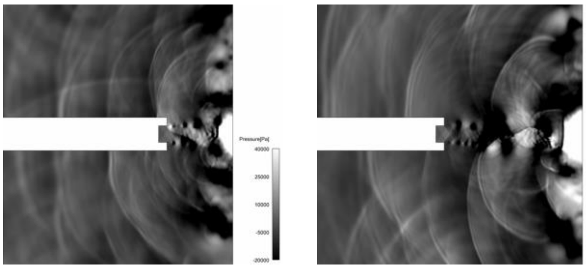
CFD analysis of unsteady jet behavior using LES model was performed for the above experimental conditions. A rectangular jet nozzle was considered, and the distances between nozzle tip and plate were L=3.94h and L=8.27h, respectively. The Reynolds number at the nozzle exit was set at about 50,000 and the Mach number was set at 1.28. An acoustic signal receiver was installed at the point x=0, y=1.5h on the top of the nozzle tip to quantitatively evaluate the behavior of the acoustic wave generated by jet impingement. The time interval used in the analysis was set to $dt=h/300U_e$, and the total analysis time was set to $t_{total}=100U_e/h$.

4. Analysis Results

Fig. 2 shows the analysis results of pressure distribution near the jet. As the jets ejected from the nozzle impinge on the plate, reflected pressure waves are generated. When the distance between the nozzle tip and the target surface is close(L/h=3.94), the gap between the pressure waves is relatively narrow. On the other hands, When the ejection distance of jet is long (L/h=8.2), pressure waves of long period are formed. Pressure waves generated alternately at the upper and lower portions of the jet. Fig. 3 shows the fluid density distribution near the jet. It can be seen that the acoustic waves are formed in the same shape as the pressure distribution. And the periodic vortex patterns are formed in the jet by the pressure waves generated alternately in the upper and lower portion of the jet.

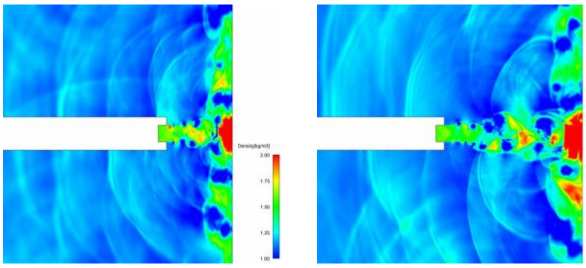
Fig. 4 shows the variation of acoustic pressure at the installation position of acoustic signal receiver. As result of frequency analysis for the variation data of sound pressure, evaluation results of sound pressure level and power spectral density are shown in Fig. 5 and Fig. 6, respectively. Based on the evaluation results of the power spectral density, the dominant frequency bands of the unsteady jet behavior can be estimated. When the distance between the nozzle tip and the target is short(L/h=3.94), the short-period vibration and long-period vibration appear in combination. On the other hand, when the jet distance is long(L/h=8.27), the long-period vibration characteristics become predominant. And the sound pressure level in the dominant frequency band is estimated to be about 120 dB.

Fig. 7 shows Thurow's experimental results(Sound Pressure Level vs. Strouhal Number) for the condition that the distance between the nozzle tip and the plate is L/h=8.27. The main dominant frequencies(Strouhal Number) of the jet oscillation are about 0.19, 0.35, 0.41 and 0.63, and the sound pressure levels at the corresponding frequencies are about 107 dB, 100 dB, 101 dB, and 97 dB, respectively. On the other hand, in the numerical analysis results under the same conditions, the main dominant frequencies(Strouhal number) of the jet oscillation are about about 0.16, 0.30, 0.44 and 0.61, and the sound pressure levels at the corresponding frequencies were evaluated as 125 dB, 119 dB, 118 dB and 115dB respectively. The results of the numerical analysis for the unsteady jet behavior were evaluated to be within 20% relative error compared to the experiment results(Table Ⅰ and Table Ⅱ).



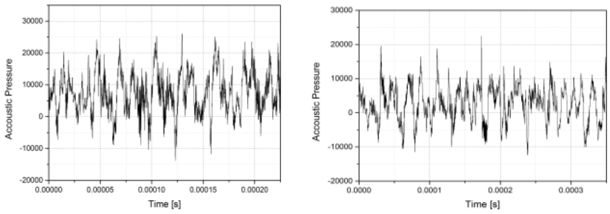
(a) L/h=3.94 (b) L/h=8.27

Fig. 2. Pressure distribution



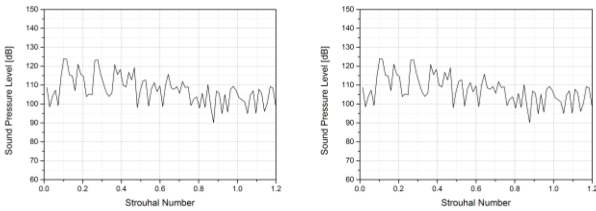
(a) L/h=3.94 (b) L/h=8.27

Fig. 3. Fluid density distribution



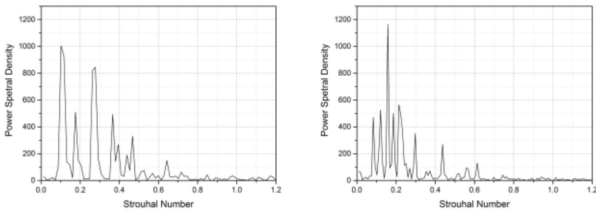
(a) L/h=3.94 (b) L/h=8.27

Fig. 4. Variation of the acoustic pressure at x=0 and y=1.5h



(a) L/h=3.94 (b) L/h=8.27

Fig. 5. Sound Pressure Level at x=0 and y=1.5h as a function of Strouhal Number



(a) L/h=3.94 (b) L/h=8.27

Fig. 6. Power spectral density at x=0 & y=1.5h as a function of Strouhal Number

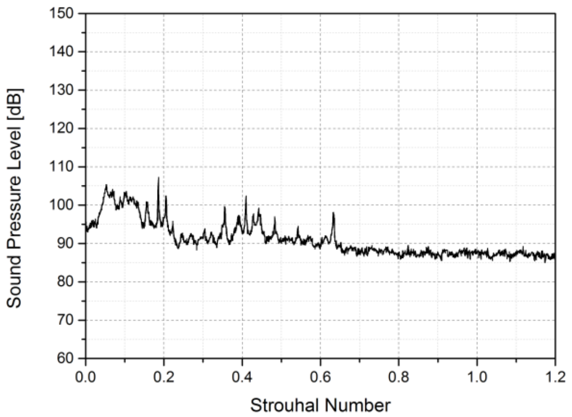


Fig. 7 Jet Impingement Experiment(Thurow, 2002) Result (L/h=8.27)

Table Ⅰ: Comparison between Exp. & CFD on dominant frequency of the jet oscillation

	Strouhal Number (Experiment)	Strouhal Number (CFD)	Relative Error
1st Peak	0.19	0.16	15.3%
2nd Peak	0.35	0.30	15.8%
3rd Peak	0.41	0.44	6.6%
4th Peak	0.63	0.61	2.6%

Table Ⅱ: Comparison between Exp. & CFD on Sound Pressure Level

	SPL [dB] (Experiment)	SPL [dB] (CFD)	Relative Error
1st Peak	107	125	16.5%
2nd Peak	100	119	19.4%
3rd Peak	101	118	17.1%
4th Peak	97	115	18.7%

5. Conclusions

A preliminary analysis was carried out to estimate the applicability of evaluation method for unsteady jet impinging load based on CFD analysis technique. The preliminary analysis was performed for the same conditions as Thurow's jet impingement experiment. And the dynamic behavior of the jet and the acoustic wave generated by jet impingement were evaluated. The potential feedback mechanism caused by the disturbance of the jet shear layer due to the reflected pressure wave is clearly shown in the numerical analysis results. When the distance between the nozzle tip and the target is relatively short, the short-period vibration and long-period vibration appear in combination. On the other hand, when the jet distance is long, the long-period vibration characteristics become predominant. The results(dominant frequency and sound pressure level) of the numerical analysis for the unsteady jet behavior were evaluated to be within 20% relative error compared to the experiment results.

ACKNOWLEDGMENTS

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