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A study on the vibration and noise characteristics of a Delft Twist11 hydrofoil according to cavitation number

Hong-Sik Hwang [1], Kwang-Jun Paik [1]*, Soon-Hyun Lee [1] and Gisu Song [2]

1 Department of Naval Architecture and Ocean Engineering, Inha University, Incheon 22212, Republic of Korea
2 Division of Ocean and Ship Engineering, National Korea Maritime & Ocean University, Busan 49112, Republic of Korea
* Correspondence: kwangjun.paik@inha.ac.kr; Tel.: +82-32-860-7331

Abstract: Underwater radiated noise (URN) is greatly increasing due to increase in commercial shipping, sonar activities, and climate change. As a result, marine life is having difficulty communicating, and marine ecosystem disturbances are occurring. The noise from the cavitation of propellers is affecting URN. Cavitation is a phenomenon in which rapid changes of pressure in a liquid lead to the formation of small vapor-filled cavities in places where the pressure is relatively low. This phenomenon results in poor efficiency of the propeller or turbine of a ship and noise, vibration, and erosion. For these reasons, this study examines the URN of sheet and cloud cavitation. A numerical analysis was done using a Delft Twist11 hydrofoil. The URN resulting from cloud cavitation and sheet cavitation was compared with the numerical results of previous studies. The results showed that URN normally increases due to pressure fluctuations when cavitation occurs. URN increased more significantly in conditions of cloud cavitation than cavitation inception. It is also shown that a frequency begins to occur after the occurrence of the cloud cavitation, and the frequency grew as the cavitation fully developed.

Keywords: Delft Twist11 hydrofoil; URN (Underwater Radiated Noise); Sheet cavitation; Cloud cavitation

1. Introduction

Cavitation is a phenomenon in which a rapid pressure changes in a liquid condition results in the formation of a small vapor cavity where the pressure is relatively low. The cavitation caused by a propeller rotating causes erosion of the propeller, vibration, and noise. This reduces the efficiency of the propeller and turbine, and the noise produced by the cavitation greatly affects the communication of marine life.

This study analyzed the noise and vibration characteristics based on the cavitation characteristics of a Delft Twist11 hydrofoil. The noise characteristics produced by cavitation were predicted using the Schnerr-Sauer model by analyzing the cavitation features and frequency. RANS, DES, and LES models were used as turbulence models, and simulations were performed with three time steps to obtain accurate results. A study was conducted to predict the sound pressure level (SPL) from cavitation using a direct method. In addition, SPLs were compared according to the cavitation number to identify the correlation between the noise and cavitation.

2. Materials and Methods

2.1 Materials

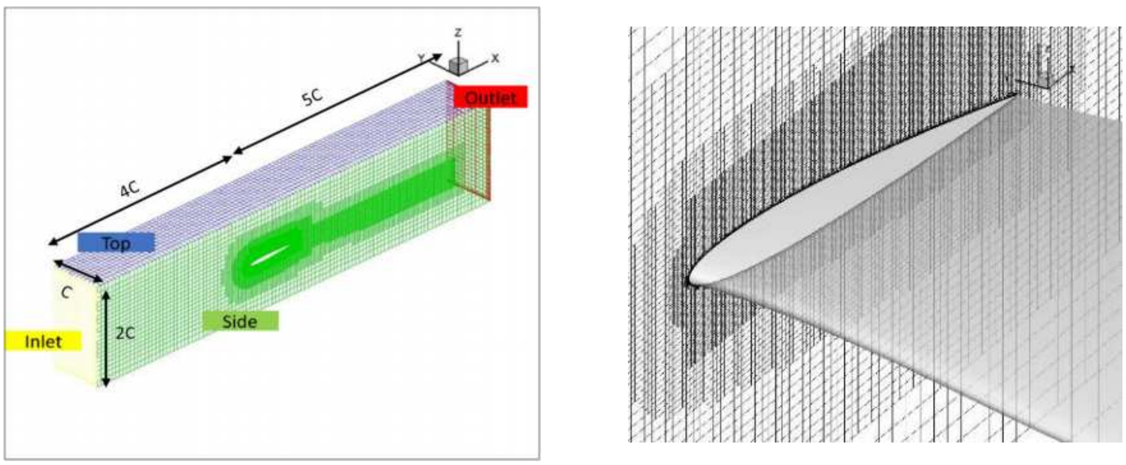
The shape of the hydrofoil used in the cavitation simulation has a NACA0009 profile with a chord length C of 150 mm and span length S of 300 mm. The hydrofoil's angle of attack at both ends is -2°, the angle of attack at the mid span is 9°, and it has a symmetrical shape. The domain used for the numerical simulation is 9C in the streamwise direction. The distances from the inlet to the leading edge of the foil and

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

from the trailing edge to the outlet are each 4C. The centerline is symmetrical in the direction of the span, and there is a distance of C up and down in the Z direction. For the boundary conditions of the domain, the top, bottom, and sides are set as walls. The velocity is 6.97 m/s, and the cavitation number is 1.07 from the experimental paper by Foeth [5]. The Reynolds number of the simulation condition is 1.2×10^6

The commercial CFD software Star-CCM+ 13.06 was used. The governing equation and turbulence model were RANS (SST k-ω), DES (SST k-ω), and LES models. The Eulerian Multiphase model was used to simulate the formation of cavitation due to the pressure drop in the fluid. Also, the cavitation model was the Schnerr-Sauer model. To measure URN, a direct method was used to directly predict the measured pressure at a point.

The number of grids was about 3.9 million (all isotropic elements) with y+≤1 at the walls. A fixed pressure of 29 kPa was applied to generate cavitation, and the simulation was calculated in wetted flow conditions until the simulation showed convergence. A numerical discretization technique of second-order accuracy was applied for time and space, and simulations were performed with time intervals of 2.5×10^{-5}.



(a) (b)

Figure 1. Domain of cavitation tunnel (a) and geometry of Delft Twist11 hydrofoil (b)

3. Results

3.1. Wetted flow

The simulation results of the wetted flow according to the time step are shown for the time step verification. The simulation results are shown in Table 2, and the three turbulence models could be seen to increase their accuracy with a lower time step. Also, the lower the time step, the greater the accuracy of the LES model was, and the accuracy was increased in the order of LES, RANS, and DES models.

Table 2. Time-averaged lift coefficient at wetted flow according to the time steps and turbulence models (RANS, DES, LES)

Wetted flow		RANS		DES		LES	
Time step	EXP	C_L	Error rate [%]	C_L	Error rate [%]	C_L	Error rate [%]
2.5×10^{-4}		0.4424	2.98	0.4321	5.24	0.4425	2.96
5.0×10^{-5}	0.456	0.4428	2.89	0.4329	5.06	0.4434	2.76
2.5×10^{-5}		0.4428	2.89	0.4336	4.91	0.4463	2.12

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

3.2. Cavitating flow

3.2.1. Lift coefficient

In the case of cavitation flow, the lift coefficient is shown according to time step in Table 3 for each turbulence model, and Figure 3 shows the lift coefficient over time for each turbulence model. In the case of the RANS model, there was a tendency to converge and not to fluctuate periodically after the occurrence of the cavitation, indicating that the lift coefficient also resulted in a large error. For the DES model, the results were more accurate than the RANS model, and it was also noted that the lift coefficient fluctuated periodically over time. For LES models, the accuracy was the highest compared to other models.

When comparing the lift coefficient for each model according to the time step, we could see that the smaller the time step, the lower the lift coefficient was compared to the experimental results, and the error was larger. However, the smaller the time step, the more constant the lift coefficient values are, so this cannot be regarded as similar to the experimental value when the time step is large, nor is the simulation result incorrect. By analyzing the frequency shown in the section 3.2.2., the reliability of the analytical results could be obtained.

Table 3. Time-averaged lift coefficient in cavitating flow according to the time steps and turbulence models (RANS, DES, LES)

Cavitating flow		**RANS**		**DES**		**LES**	
Time step	**EXP**	**C_L**	**Error rate [%]**	**C_L**	**Error rate [%]**	**C_L**	**Error rate [%]**
2.5×10^{-4}		0.4095	19.71	0.4535	11.08	0.4737	7.12
5.0×10^{-5}	0.510	0.4093	19.75	0.4370	14.31	0.4427	13.20
2.5×10^{-5}		0.4079	20.02	0.4366	14.39	0.4410	13.53

3.2.2. Shedding frequency

Table 4 shows that the smaller the time step in the DES and LES models is, the greater the accuracy of the shedding frequency. In the case of the RANS model, the cavitation developed stably, and not only near the wall. Thus, it was difficult to identify the frequency, and only a representative value could be put in Table 4. In the case of the DES and LES models, the frequency increased due to lower time steps, and similar results were obtained.

In addition, Table 4 shows four numerical papers announced at the SMP workshop [7]. Frequencies were compared, and the results were higher than the results of the experiment. This is thought to be similar to how the LES model in this study has a frequency that is slightly higher at 33.32.

Table 4. Shedding frequency according to the time steps and turbulence models (RANS, DES, LES) and another numerical study

Cavitating flow	**Frequency [Hz]**							
Time step	**EXP**	**Present**			**Bensow (LES)**	**LR (DES)**	**TUHH (RANS)**	**MARIN (RANS_corr)**
		RANS	**DES**	**LES**				
2.5×10^{-4}	32.55	15.81	24.37	24.78				
5.0×10^{-5}			29.24	30.00	34	35	38.79	38

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

2.5×10^{-5}	32.00	33.32

Table 5 shows Strouhal number [St] according to experiment and turbulence models. Also, DES and LES model show high accuracy at lowest time step. The LES model shows slightly higher results, but it is difficult to see due to errors in the analysis results.

Table 5. Comparison of Strouhal number according to experiment and turbulence model.

Cavitating flow	**Strouhal number [St]**			
Time step	**EXP**	**RANS**	**DES**	**LES**
2.5×10^{-4}			0.52	0.53
5.0×10^{-5}	0.70	0.34	0.63	0.65
2.5×10^{-5}			0.69	0.72

3.2.3. Cavitation features

For comparison of the results of Foeth [5], cavitation features are presented in Figure 5 in a time sequence. From the left, the results of the experiment are RANS, DES, and LES model. The time sequence is shown from top to bottom, and after sheet cavitation, cloud cavitation and contraction are repeated. First of all, the results of the RANS model show that sheet cavitation is created, but there is no cloud cavitation. Also, as mentioned in Section 3.2.2 earlier, cavitation developed stably, so periodicity was not visible, and it could not simulate the characteristics of cavitation that developed periodically.

Secondly, we can see that the cavitation shape of the DES model is similar to the results of the experiment. Periodic development and contraction of sheet cavitation and cloud cavitation were identified. However, the Q-criterion confirmed that it did not appear on the surface of the hydrofoil, which showed stable flow near the wall due to the characteristics of the DES model, which was interpreted as a RANS model near the wall.

Finally, the LES model showed a cavity shape similar to the experimental results. The development and contraction of periodic cavitation, like in the DES model, could be seen. Also, we were able to check the free movement of sheet cavitation compared to the DES model. This can be seen as a result of the model's characteristic of performing eddy simulation in the entire domain, whereas the DES model uses the RANS (SST k-w) model near the wall to generate stable sheet cavitation.

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

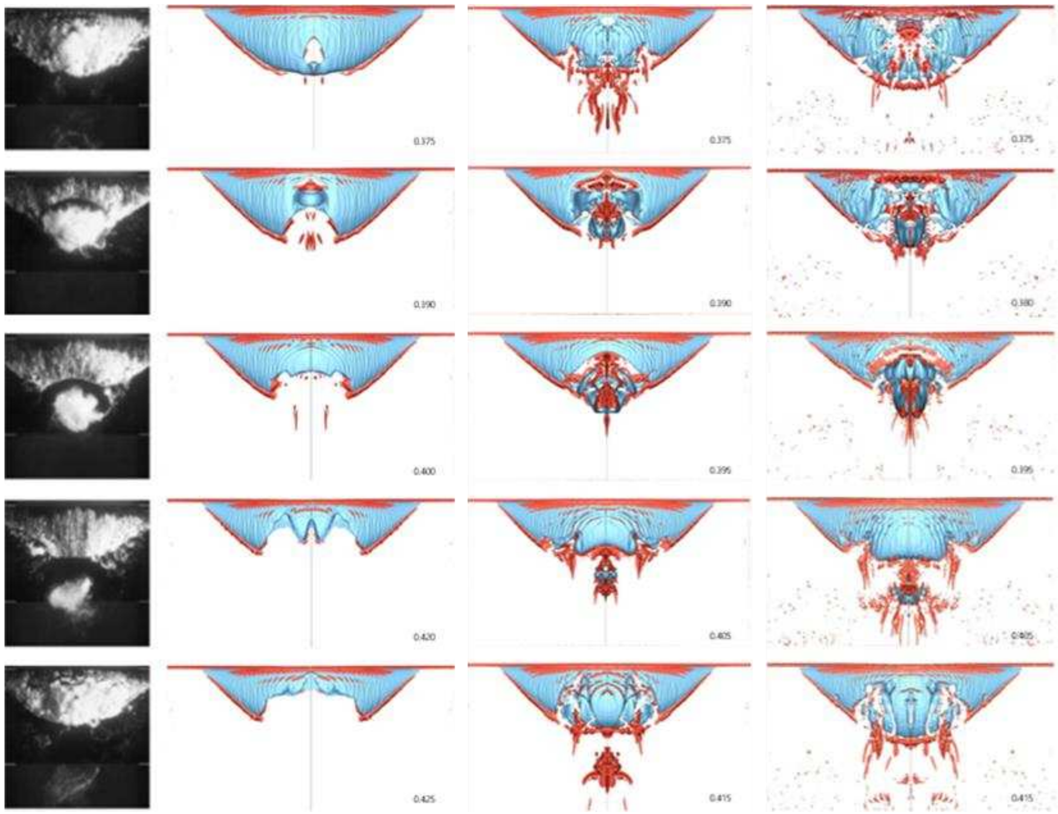


Figure 5. Comparison of RANS (left), DES (middle) and LES (right); iso-surfaces show the volume fraction α=0.5 and Q-criterion

3.2.4. SPL

SPL was measured using the frequency and PSD. The point at which the pressure was measured is indicated by coordinates in Table 5 as LE/c. First, the measured sound pressure at the points was expressed as SPL_1, which was expressed as the reference SPL on a 1-m distance basis. The expression for SPL is shown below.

$$SPL_1 = 20\log_{10}(\frac{p}{p_0}) \quad (1)$$

$$SPL = SPL_1 + 20\log_{10}(r) \quad (2)$$

p is the measured pressure at each point, p_0 is the reference pressure, and r is the distance to the measured position from leading edge of hydrofoil.

SPL according to the distance is shown in Table 5. The results were compared with Lidtke's numerical analysis paper [2], and the numerical method was confirmed to have used RANS. The results of the reference paper can be seen to be similar to those of the RANS model in this study, thereby verifying the results of this study. For DES and LES models, the results are more than 10 dB higher than the RANS model's SPL. Considering the accuracy of the DES and LES model's results, it was determined that the SPL

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

of the DES and LES models was correct. In addition, in distance generally indicates a decrease in SPL, but the difference in distance was not significant.

Table 5. The results of SPL of wall pressure

SPL [dB]	LE/c	Lidtke (RANS)	RANS	DES	LES
Probe 1	1.25	152.30	155.07	164.46	167.02
Probe 2	1.12	153.00	155.30	165.03	167.63
Probe 3	1.08	153.20	155.41	165.19	167.81
Probe 4	1.05	153.38	155.54	165.23	167.81
Probe 5	1.02	153.43	155.62	165.24	167.85
Probe 6	1.00	153.50	155.66	165.23	168.28

3.2.5. SPL according to cavitation number

Finally, the SPL was predicted and compared according to the cavitation number. The cavitation number conditions for the simulation were carried out with a total of six conditions, including atmospheric pressure conditions, experimental conditions, cavitation inception, and cavitation development conditions. The cavitation numbers of 3.1 and 3.0 are cavitation inception conditions, and the cavitation numbers of 2.5 and 2.0 are set for the cavitation development conditions.

The results are shown in Table 6. Overall, SPL increases when the cavitation number is smaller, the cavitation inception section increases by about 6 to 10 dB compared to the wetted flow, and the frequency cannot be shown. When the cavitation number is 2.5, the SPL is approximately 4 dB higher than the cavitation inception condition, and high frequency is created. From the cavitation number of 2.5, we were able to check the fluctuation of cavitation. Subsequently, when the cavitation number was 2.0, the SPL increased significantly, similar to the experimental condition when the cavitation number is 1.07. The frequency was also confirmed to be constant at about 120 Hz.

Table 6. SPL_1, SPL, and cavitation volume according to cavitation number

	Cavitation number σ	SPL_1 [dB]	SPL [dB]	Cavitation volume (m^3)
LES	4.17	142.97	126.49	0.00
	3.1	148.57	132.09	1.11E-10
	3.0	152.75	136.27	7.37E-10
	2.5	156.76	140.28	1.30E-8
	2.0	184.39	167.91	1.99E-7
	1.07	184.76	168.28	9.36E-6

4. Conclusions

In this study, cavitation simulation was performed using a Delft Twist11 hydrofoil. Several numerical studies have been carried out using Foeth's [5-6] experimental results. This study was conducted according to various turbulence models and time steps to analyze the correlation between cavitation and noise. The accuracy of the results was best in the order of LES, DES, and RANS models, and the lower the time step overall, the more similar the experimental results were. In the case of the RANS models, the periodic movement of the cavitation was not predicted, and accordingly, the noise produced by the cavitation was

* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr

not predicted. Cavitation was created once after the pressure drop, but the cavitation no longer developed after shrinkage, as in Figure 5. Thus, the accuracy of the frequency was reduced, and the result was that the SPL was low without the creation of the cloud cavitation. Lidtke et al [2]. predicted SPL using the RANS model, and using the RANS model of this study, we could see that it was similar to the predicted SPL.

In the case of the DES model, the accuracy in predicting cavitation and noise was high, and for sheet cavitation near the wall, stable cavitation features were confirmed like in the RANS model. However, away from the wall, periodic cloud cavitation was formed, like in the experiment results and the LES model. This is due to the use of the RANS (k-w) model on the wall and the other parts following the characteristics of the LES model, which is a characteristic of the DES model. Therefore, SPL was similar to the RANS model in stable wetted flow where no cavitation occurred. In cavitating flow, where pressure fluctuation occurred due to periodic cavitation. In addition, the SPL was similar to the LES model because of the occurrence of a cloud cavitation that affected noise.

For LES models, cavitation features were similar to DES models. The development and contraction of cavitation were well illustrated, and the Q-criterion, which indicates the degree of turbulence, was also well shown along the cavitation features. In addition, a similar frequency was obtained from Foeth's [5] experiment results. The SPL appeared similar to the DES model with similar cavitation geometry and frequency. However, the SPL results in the wetted flow state were different from the DES model.

Using the above results, we were able to obtain the correlation between cavitation and SPL by simulating it according to the cavitation number. We could see that noise increased as cavitation occurred, especially with the occurrence of cloud cavitation, which resulted in a significant increase in SPL.

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* Corresponding Author: Kwang-Jun Paik, kwangjun.paik@inha.ac.kr