Numerical Study on the Vibration and Noise Characteristics of a Delft Twist11 Hydrofoil

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Abstract: Underwater radiated noise (URN) is greatly increasing due to an 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 in 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; RANS; DES; LES; vibration; FW-H; Shenrr-Sauer model

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. Various organizations and committees, including IMO, MEPC, MSFD, and NORSOK, are making efforts to resolve problems related to Underwater Radiated Noise (URN). In addition, guidelines have been developed to regulate URN emitted by ships in the North Sea (SONIC, 2012), and the European Union have established ‘quietMED’ to address noise problems in the Mediterranean region.

The effects of noise from the propellers of ships are considerable. Therefore, studies on cavitation occurring from the propulsion of ships are needed. Foeth et al. [1,2] did an experimental study on the cavitation features and frequency of hydrofoils. The experiment was conducted at the cavitation tunnel of Delft University of Technology, and detailed research was conducted on cavitation features over time using Particle Image Velocimetry (PIV) according to the flow rate and cavitation number. Hoekstra et al. [3] compared and analyzed the results simulated by various institutions based on the results of the experiment by Foeth et al. [2]. A variety of turbulence models and mass transfer models were used.
Bensow [4] conducted a numerical study on the cavitation features and frequency of a Delft Twist11 hydrofoil and compared the results for different turbulence models. RANS (Reynolds-Averaged Navier–Stokes equations), DES (Detached Eddy Simulation), and LES (Large Eddy Simulation) models were used as turbulence models, and the LES models obtained the results most similar to those of the experiments. Asnaghi [5] carried out a cavitation analysis using the LES model. Two-dimensional (2D) and three-dimensional (3D) hydrofoils and a cavitating propeller were used, and the cavitation was examined. Vaz et al. [6] conducted a cavitation analysis with RANS, RANS including an eddy-viscosity “Reboud” correction, and DDES (Delayed Detached Eddy Simulation) Scale-Resolving-Simulation models.

Lidtke et al. [7] compared the results of frequency and noise from the cavitation of a Delft Twist11 hydrofoil using different cavitation models. The turbulence model was the DDES model, and the cavitation model was compared with the results obtained using the Schnerr–Sauer model and a hybrid Lagrangian–Eulerian cavitation model based on the Schnerr–Sauer model.

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 had 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 was -2°, the angle of attack at the mid span was 9°, and it had a symmetrical shape. Figure 1 shows the domain of cavitation tunnel and the geometry of the Delft Twist11 hydrofoil. The domain used for the numerical simulation was 9C in the streamwise direction. The distances from the inlet to the leading edge of the foil and from the trailing edge to the outlet were each 4C. The centerline was symmetrical in the direction of the span, and there was 1C up and down in the Z direction. For the boundary conditions of the domain, the top, bottom, and sides were set as walls. The velocity was 6.97 m/s and the cavitation number was 1.07 from the experimental paper by Foeth [2].

![Figure 1. Domain of cavitation tunnel (left) and geometry of the Delft Twist11 hydrofoil (right).](image)

The commercial CFD (Computational Fluid Dynamics) 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. Additionally, 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 $y^+ \leq 1$ 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 $2.5 \times 10^{-5}$.

2.2. Governing Equation

2.2.1. RANS

The Reynolds Averaged Navier–Stokes model is based on the average of the Navier–Stokes equation. RANS models are available in unsteady flow, but not in most turbulence models. However, this model has been used often because it works reasonably well in unsteady flows and it has the advantage of shorter simulation times than DES and LES models. The equations are expressed in the form of integral equations:

\begin{align}
\frac{d}{dt} \int_{\Omega} \rho d\Omega + \int_{\partial\Omega} \rho u_n dS &= 0 \\
\frac{d}{dt} \int_{\Omega} \rho d\Omega + \int_{\partial\Omega} \rho u_n dS &= \int_{\partial\Omega} \tau_{ij} n_j - pn dS + \int_{\partial\Omega} \rho b_d d\Omega \\
(\mu + \mu \tau_{ij}) &= \mu \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j} \right)
\end{align}

where $\rho$ and $p$ are the density and pressure, respectively, $u_i$ is a velocity tensor, $b_i$ is a volume tensor, and $\tau_{ij}$ is the effective stress caused by viscosity and turbulence, as shown in Equation (3).

2.2.2. DES

A Detached Eddy Simulation (DES) is a mixed method of using a RANS model near walls and LES in areas with active vortex flows such as separation flows. In other words, it is a mixture of the SST model, which is a RANS model, and the LES model. DES was initially formulated for the Spalart–Allmaras model, but the length scale associated with the RANS model can be adjusted accordingly to be implemented in other RANS models. It can also be transformed into Delayed Detached Eddy Simulation (DDES) and Improved Delayed Detached Eddy Simulation (IDDES). DDES incorporates delay factors that enhance the functionality of models that address the grid ambiguity of LES and RANS. The IDDES model was introduced to provide several Wall-Modeled LES (WMLES) features in the DES expression.

In the case of IDDES, the wall thickness allows RANS to be used in areas near walls that are much thinner than the boundary layer thickness. The RANS model uses the nearest distance, $d$, from the wall as the length scale. However, in DES, it is replaced by the minimum between the distance to the wall and the length of the grid spacing, which is shown by Equation (4).

$$d_{\text{DES}} = \min \left( d, C_{\text{des}} \Delta \right)$$

$C_{\text{DES}}$ is 0.65 and constant according to other studies and $\Delta$ is the grid spacing. For structured grids, this is the maximum grid spacing for all three orientations; otherwise, it is generally considered the maximum length of the distance from the center of the cell to the edge.
2.2.3. LES

The Large Eddy Simulation model is a method of directly simulating a large scale of turbulence at all locations in the flow area and modeling small motion. Kolmogorov (1941) said that large eddies of flux depend on the shapes, while small scales are universal. This characteristic allows for explicit resolution of large eddies and the use of a sub-grid scale (SGS) model to explain small eddies. In contrast to the RANS model for solving the mean flow, it interprets a natural, sustained, and small flow structure. In other words, unlike RANS, which is obtained by an averaging process, equations are obtained by spatial filtering.

Mathematically, it can be thought of as separating the sub-grid part from the disassembled part of the speed field. The disassembled part is represented by large eddies, and the sub-grid part of the speed range is shown in small size. Filtering is expressed in Equation (5) as a function of filtering tunnel G.

$$\overline{u_i}(\overline{x}) = \int G(\overline{x} - \overline{\xi}) u_i(\overline{\xi}) d\overline{\xi}$$  

As a result,

$$u_i = \overline{u_i} + u'_i$$

In Equation (6), $\overline{u_i}$ is the disassembled part and $u'_i$ is the sub-grid part. The filtered equation comes from the Navier–Stokes equation and is equal to Equation (7).

$$\frac{\partial \overline{u_i}}{\partial t} + u_j \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial \overline{u_i}}{\partial x_j} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} \right)$$

However, this filtering and differentiation process results in errors, which has led to the development of new filters that work with differentiation, as shown in Equations (8) and (9).

$$\overline{u_j \frac{\partial \overline{u_i}}{\partial x_j}} \neq \overline{u_j \frac{\partial u_i}{\partial x_j}}$$

$$\tau_{ij} = \overline{u_i u_j - u_j u_i}$$

Similar equations can be derived in sub-grid parts, where turbulence models usually adopt the Boussinesq hypothesis to calculate SGS stress.

$$\tau_{ij} - \frac{1}{3} \tau_{ik} \delta_{ij} = -2 \mu_s S_{ij}$$

$S$ is defined by a strain tensor in Equation (11).

$$\overline{S_{ij}} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right)$$

$v_t$ is the turbulent viscosity of the sub-grid and is replaced by a filtered Navier–Stokes equation, as shown in Equation (12).
3. Simulation Results

3.1. Wetted Flow

Table 1 and Figure 2 show the results of the experiment and the simulation results for each turbulence model according to the number of grids in a wetted flow where cavitation does not occur. The time step was $2.5 \times 10^{-4}$. The RANS model, DES model, and LES model were simulated, and the RANS model showed a 3% lift force error rate, regardless of the number of grids. The result of the number of grids was not changed, and it is thought that the reason for this is that sufficient grids had been added to check the lift coefficient ($C_l$). The reliability for performing the simulation in the cavitating flow was verified.

In the case of the DES model, the error rate increased as the number of grids increased, but it was determined that there was no problem in terms of the Grid Convergence Index (GCI) because it showed convergence as the number of grids increased. The LES model also showed a tendency for the lift coefficient to converge as the number of grids increased, and the error rate converged to around 3.5%. Because all three models converged in the medium grid condition, the analysis was carried out under the medium grid condition in the subsequent analysis. When comparing by turbulence models, the RANS, LES, and DES models in the wetted flow state showed high accuracy in that order.

Table 1. Time-averaged lift coefficient in wetted flow according to the number of grids and turbulence models (RANS, DES, LES).

| Grid           | Wetted Flow | RANS        | DES        | LES        |
|----------------|-------------|-------------|------------|------------|
| Coarse (1.9M) | 0.4440      | 0.4440      | 0.4328     | 0.4328     |
| Medium (4.0M) | 0.4424      | 0.4321      | 0.4320     | 0.4425     |
| Fine (5.5M)   | 0.4423      | 0.4320      | 0.4425     | 0.4425     |

Figure 2. Lift coefficient according to the number of grids.

In addition, 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. Additionally, the lower the time step, the greater was the accuracy of the LES model, and the accuracy was increased in the order of LES, RANS, and DES models.

Finally, the GCI was identified based on the above results. The GCI represents the grid convergence of a solution and was proposed by Roache. The GCI is a measurement
of the percentage that a computed value is different from an asymptotic numerical value. It indicates how much the solution would change with further refinement of the grid.

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   | Experiment | 
|             | Ct. | Error Rate [%] | Ct. | Error Rate [%] | Ct. | Error Rate [%] |
| $2.5 \times 10^{-4}$ | 0.4424 | 2.98 | 0.4321 | 5.24 | 0.4425 | 2.96 |
| $5.0 \times 10^{-5}$ | 0.456 | 2.89 | 0.4329 | 5.06 | 0.4434 | 2.76 |
| $2.5 \times 10^{-5}$ | 0.4428 | 2.89 | 0.4336 | 4.91 | 0.4463 | 2.12 |

The GCI on the fine grid is defined as:

$$GCI_{fine} = \frac{F_s |\delta|}{(r_p - 1)}$$

(13)

where $F_s$ is a safety factor. The safety factor is recommended to be 1.25 for comparisons over three or more grids. When a design or analysis activity involves many CFD simulations, one may want to use a coarser grid. The GCI for a coarser grid is defined as:

$$GCI_{coarse} = \frac{F_s |\delta| r_p}{(r_p - 1)}$$

(14)

It is important for each grid level to yield solutions that are in the asymptotic range of convergence for the computed solution. This can be checked by observing two GCI values computed over three grids:

$$GCI_{23} = r_p GCI_{12}$$

(15)

It has been confirmed that a GCI value of 20% or less is reliable, and the results in this study show a total of 1% or less, as shown in Table 3. Therefore, the reliability of the simulation could be determined once again.

Table 3. Grid Convergence Index (GCI) of lift coefficient according to turbulence models and time steps.

| Variables | RANS | DES | LES |
|-----------|------|-----|-----|
| Time Step | Experiment | Ct. | GCI (%) | Ct. | GCI (%) | Ct. | GCI (%) |
| $2.5 \times 10^{-4}$ | 0.4424 | 0.4321 | 0.4425 |
| $5.0 \times 10^{-5}$ | 0.456 | 0.4329 | 0.4344 | 0.000 |
| $2.5 \times 10^{-5}$ | 0.4428 | 0.4336 | 0.4463 | 0.000 |
| Grid Number of Grid | 1,906,833 | 0.4440 | 0.4440 | 0.4328 |
| Medium | 3,957,019 | 0.4424 | 0.4321 | 0.4425 | 0.000 |
| Fine | 5,477,206 | 0.4423 | 0.4320 | 0.4425 | 0.000 |

3.2. Cavitation Flow

3.2.1. Lift Coefficient

In the case of cavitation flow, the lift coefficient is shown according to time step in Table 4 for each turbulence model, and Figure 3 shows the lift coefficient over time for
each turbulence model. For stability in the process of simulation, a pressure drop was carried out after convergence in the wetted flow state and simulation of the cavitating flow. 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.

Table 4. Time-averaged lift coefficient in cavitating flow according to the time steps and turbulence models (RANS, DES, LES).

| Cavitating Flow | Time Step | Experiment | RANS | Error Rate [%] | DES | Error Rate [%] | LES | Error Rate [%] |
|-----------------|-----------|------------|------|---------------|-----|---------------|-----|---------------|
|                 | 2.5 × 10⁻⁴ | 0.510      | 0.4095 | 19.71         | 0.4535 | 11.08         | 0.4737 | 7.12          |
|                 | 5.0 × 10⁻⁵ | 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         |

Figure 3. Lift coefficient according to turbulence model with a narrow time interval.

When comparing the lift coefficient for each model according to the time step, the smaller the time step, the lower the lift coefficient and the greater the error compared to the experimental results. However, the smaller the time step, the more constant the lift coefficient values, so it cannot be considered similar to the experimental value when the time step is large, and the simulation results are neither inaccurate. By analyzing the frequency shown in Section 3.2.2., the reliability of the analytical results could be obtained.

3.2.2. Shedding Frequency

Table 5 shows that the smaller the time step in the DES and LES models is, the greater the accuracy of the shedding frequency. Based on the results in Table 3, the simulation was done with the time step of 2.5 × 10⁻⁵. 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 5. 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 5 shows four numerical papers announced at the Second International Symposium on Marine Propulsors [3]. 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. The Strouhal numbers of the experimental and numerical results are compared at Table 6. The Strouhal numbers of DES and LES are closer to the experimental result with smaller time steps, while that of RANS is constant at different time steps. The Power Spectral Density (PSD) of $C_l$ was also compared to each model and to the time step. Figure 4a shows that the DES and LES models present a larger PSD of $C_l$ than the RANS models, and Figure 4b confirms again that the lower the time step, the more similar the frequency value is to the experimental results.

Table 5. Shedding frequency according to the time steps and turbulence models (RANS, DES, LES) and another numerical study.

| Cavitating Flow | Frequency [Hz] |
|-----------------|----------------|
| Time Step       | Experiment    | Present | Bensow | LR | TUHH (RANS) | MARIN (RANS_Corr) |
| 2.5 $\times$ 10^{-4} | 24.37 | 24.78 |
| 5.0 $\times$ 10^{-5} | 29.24 | 30.00 | 34 | 35 | 38.79 | 38 |
| 2.5 $\times$ 10^{-5} | 32.00 | 33.32 |

Table 6. Comparison of Strouhal number according to experiment and turbulence model.

| Cavitating Flow | Strouhal Number [St] |
|-----------------|----------------------|
| Time Step       | Experiment | RANS | DES | LES |
| 2.5 $\times$ 10^{-4} | 0.70 | 0.52 | 0.53 |
| 5.0 $\times$ 10^{-5} | 0.70 | 0.34 | 0.63 | 0.65 |
| 2.5 $\times$ 10^{-5} | 0.69 | 0.72 |

Figure 4. Power spectral density of lift coefficient (PSD of $C_l$) according to turbulence model (a) and time step (b).

3.2.3. Cavitation Features

For comparison of the results of Foeth [2], cavitation features are presented in Figure 5 in a time sequence. From the left, the results of the experiment are RANS, DES, and LES. 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. Additionally, 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, as in the DES model, could be seen. Additionally, 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.

![Figure 5. Comparison of RANS (left), DES (middle), and LES (right); iso-surfaces show the volume fraction $\alpha = 0.5$ and Q-criterion.](image)

3.2.4. Pressure Coefficient

Next, the $-C_p$ curve of the mean time in the cavitating flow was compared according to the span direction section, and the results are shown in Figure 6. From the top, $y/S = 0.3, 0.4,$ and $0.5$ are shown. The black symbol shows the experiment results; red is RANS, blue is DES, and green is LES. Figure 7 shows the mean time value of the volume fraction at $y/S = 0.5$.

First of all, Figures 6 and 7 show that sheet cavitation is developed in the case of the RANS model, but it is created less in the direction of code length compared to other models. Additionally, errors occur compared experiment results as it progresses in the direction of code. In the case of the DES model, Figure 7 shows the development of sheet cavitation and cloud cavitation. It can also be seen that sheet cavitation is strongly developed. Thus, similar results were obtained to those in Figure 6.
The model of LES was also able to show the development of cavitation and the results of Figure 7. The DES model showed that sheet cavitation was smaller than those of Figure 7. As mentioned in Section 3.2.3, this is a result of the characteristics of the DES model, and it is judged that the LES model is also a model that interprets large eddies directly.

\[ C_P = \frac{p - p_v}{0.5 \rho U^2} \]  

(16)

Figure 6. Mean Cp curve of cavitating flow at y/S = 0.3 (a), 0.4 (b), and 0.5 (e) according to turbulence models and mean volume of fraction (VOF) at y/S = 0.5 using RANS (d), DES (e), and LES (f).

Figure 7. Variation of lift coefficient (left) and distribution of pressure coefficient (right) of LES model according to time series (a is at t=2.040, b is at t=2.050, c is at t=2.065, d is at t=2.075, e is at t=2.087).

3.2.5. Pressure Coefficient

Next, we checked the relationship between the shedding frequency, cavitation features, and pressure distribution. The results resulted in the most accurate LES model. The left of Figure 7 shows the lift coefficient according to the time series, and the right of Figure 7 shows the Cp curve in the order of numbers in order of red (a), orange (b), pink (c), green (d), and blue (e). Figure 8 shows the cavitation features according to the time series of Figure 7 and the Cp in the central span section starting from the left.
Figure 8. Cavitation features and pressure coefficient of the LES model at \( y/S = 0.5 \) according to the time series (a) is at \( t = 2.040 \), (b) is at \( t = 2.050 \), (c) is at \( t = 2.065 \), (d) is at \( t = 2.075 \), (e) is at \( t = 2.087 \).

Condition (a) is when the lift coefficient is low. The \( C_p \) curve shows that it appears low near to \( X/C = 0.2 \) and can be checked through the cavitation geometry in Figure 7. Sheet cavitation is developing into cloud cavitation. In condition (b), the lift coefficient is high, and the \( C_p \) curve has a low \( C_p \) near \( X/C = 0.4 \), indicating that the cloud cavitation has almost disappeared as sheet cavitation has developed. In the case of condition (c), the \( C_p \) curve is a flat graph at the end of the high lift coefficient range. The cavitation feature also shows that sheet cavitation is developed. Condition (d) is like condition (a), and cloud cavitation has developed to produce a similar \( C_p \) curve and cavitation features. Condition (e) also shows the development of sheet cavitation, as in condition (c).

3.2.6. SPL

SPL was measured using the frequency and PSD, as mentioned in Section 3.2.2. The point at which the pressure was measured is indicated by coordinates in Table 7 and in Figure 9. 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:

\[
SPL = 20 \log_{10} \left( \frac{p}{p_0} \right)
\]

\[
SPL = SPL_1 + 20 \log_{10}(r)
\]

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

| Probe | LE/c | X [m] | Y [m] | Z [m] |
|-------|------|-------|-------|-------|
| 1     | 1.25 | 0.038 | 0.150 | 0.150 |
| 2     | 1.12 | 0.001 | 0.150 | 0.150 |
| 3     | 1.08 | −0.013| 0.150 | 0.150 |
| 4     | 1.05 | −0.028| 0.150 | 0.150 |
| 5     | 1.02 | −0.043| 0.150 | 0.150 |
| 6     | 1.00 | −0.066| 0.150 | 0.150 |
Figure 9. Geometry of Delft Twist11 hydrofoil and location of probes 1 to 6.

SPL according to the distance is shown in Table 8 and Figure 10. LE/c is the distance from the center of the leading edge of the hydrofoil to each point. The results were compared with the numerical analysis by Lidtke et al. [7], 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 models’ results, it was determined that the SPL of the DES and LES models was correct. In addition, the SPL generally decreases as the distance increases, but the difference in distance was not significant.

Figure 10. Sound pressure level (SPL) of wall pressure with LE/c according to turbulence model.
Table 8. The results of SPL of wall pressure.

| SPL [dB] | LE/c | Liddke et al. (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 |

In addition, the above results are presented in Figures 11 and 12 and Table 9 according to the time step and the turbulence model. The results were from Probe 6, which was closest to the leading edge, and the results from the time step were compared with the LES model. As mentioned earlier, the results for each model were highest in the order of the LES, DES, and RANS models. Frequency also shows that the LES and DES models are most similar to the experimental paper by Foeth [2]. As mentioned in Section 3.2.2 for the results of other LES models in the time step, the lower the time step, the more similar the frequency is to the experimental results. SPL increases when the time step is lower.

Figure 11. SPL of wall pressure according to turbulence model.

Table 9. SPL\textsubscript{1} and SPL of wall pressure using LES model according to time steps and turbulence model at probe 6.

| Time Step | SPL\textsubscript{1} [dB] | SPL [dB] |
|-----------|--------------------------|----------|
| LES       | 2.5 × 10\textsuperscript{-4} | 171.74  | 155.26 |
|           | 5.0 × 10\textsuperscript{-5} | 179.10  | 162.62 |
|           | 2.5 × 10\textsuperscript{-5} | 184.76  | 168.28 |
| RANS      | 2.5 × 10\textsuperscript{-5} | 172.14  | 155.66 |
| DES       | 2.5 × 10\textsuperscript{-5} | 181.71  | 165.23 |
| LES       | 184.76                  | 168.28  |
Next, SPL with or without cavitation is shown in Figure 13 and Table 10 for each model. The conditions of wetted flow are atmospheric pressure conditions, and the cavitating flow is the same as the experimental conditions. Results from the cavitating flow indicate that the LES model's result was the highest, as mentioned earlier, the DES model had similar results to the LES, and the RANS model result was 10 dB below the other two models.

In the case of wetted flow, the LES model was also the largest. However, the DES model was significantly smaller than the LES model and was similar to the RANS model, unlike the results for the cavitating flow. This is because of the RANS and DES models’ characteristics. Unlike LES models that use eddy simulation, as mentioned in Section 3.2.2, these models use the RANS (SST k-ω) model near the wall to achieve more stable results. Therefore, the SPL of the RANS model is lower with or without cavitation, and the DES model obtains stable results near the wall.

Table 10. Comparison difference of SPL1 and SPL according to cavitating flow and wetted flow.

| Probe 1 | Flow       | SPL1 [dB] | SPL [dB] |
|---------|------------|-----------|----------|
| LES     | Cavitating | 184.76    | 168.28   |
|         | Wetted     | 142.97    | 126.49   |
| DES     | Cavitating | 181.71    | 165.23   |
|         | Wetted     | 100.8     | 84.32    |
| RANS    | Cavitating | 172.14    | 155.66   |
|         | Wetted     | 100.9     | 84.42    |
3.3. 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 conditions are shown in Figure 14 and Table 11. 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 11 and on the right side of Figure 14. 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 a high frequency is created. In addition, the cavity volume was expressed according to the time series to confirm the frequency occurrence, which is shown in Figure 15. 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. The fluctuation of the overall cavity volume shows that the frequency decreases as the cavitation number decreases, and the cavity volume can be seen to increase as the cavitation number decreases.

Table 11. SPL₁, SPL, and cavitation volume according to cavitation number.

| Cavitation Number | SPL₁ [dB]   | SPL [dB]   | Cavitation Volume (m³) |
|-------------------|-------------|------------|------------------------|
| LES               | 4.17        | 142.97     | 126.49                 | 0.00                        |
| 3.1               | 148.57      | 132.09     | 1.11 × 10⁻¹⁰          |
| 3.0               | 152.75      | 136.27     | 7.37 × 10⁻¹⁰          |
| 2.5               | 156.76      | 140.28     | 1.30 × 10⁻⁸           |
| 2.0               | 184.39      | 167.91     | 1.99 × 10⁻⁷           |
| 1.07              | 164.76      | 168.28     | 9.36 × 10⁻⁶           |

Finally, by comparing the cavitation features according to the cavitation number, the relationship between cavitation and noise was identified. The shape according to cavitation number is shown in Figure 16, and the Cp curve is shown in Figure 15. When the cavitation number is 4.17, cavitation does not occur, and when the cavitation number is 3.0 and 3.1, which are the cavitation inception conditions, there is very small cavitation in the leading edge. When the cavitation number is 2.5, we were able to see cavitation at the leading edge, and we confirmed that it was vibrating finely. The cavitation number of 2.0 indicates that cloud cavitation occurs and, as we have seen in Table 11, the SPL increases significantly in these conditions. Therefore, the reason for the significant increase in SPL is related to the development of cloud cavitation. The cavitation number of 1.07 confirmed that cavitation is fully developed.
4. Discussion

In this study, cavitation simulation was performed using a Delft Twist11 hydrofoil. Several numerical studies have been carried out using Foeth’s [2] 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 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. [7] 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 as in the RANS model. However, away from the wall, periodic cloud cavitation was formed, as 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, it was similar to the RANS model near the wall and similar to the LES model in other areas of cloud 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 the 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 ad-
dition, a similar frequency was obtained from Foeth’s [2] 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.

Future research will simulate the noise generated by the Tip Vortex Cavitation (TVC) using a NACA16-020 because TVC occupies a large amount of noise generated by cavitation. After conducting a study on the correlation of noise according to the case of cavitation, we will conduct a study to predict noise from propellers of ships by simulating propellers.

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References

1. Foeth, E.J.; van Terwisga, T. The structure of unsteady cavitation. Part I: Observation of an attached cavity on a three-dimensional hydrofoil. In Proceedings of the 6th International Symposium on Cavitation, Wageningen, The Netherlands, 11-15 September 2006.
2. Foeth, E.J. The structure of three-dimensional sheet cavitation. Ph.D. Thesis, Technische Universiteit Delft, Wageningen, The Netherlands, 2008.
3. Hoekstra, M.; van Terwisga, T.; Foeth, E.J. smp’11 Workshop—Case 1: DelftFoil. In Proceedings of the Second International Symposium on Marine Propulsors, Hamburg, Germany, 15-17 June 2011.
4. Bensow, R.E. Simulation of the unsteady cavitation on the Delft Twist11 foil using RANS, DES and LES. In Proceedings of the Second International Symposium on Marine Propulsors, Hamburg, Germany, 15-17 June 2011
5. Asnaghi, A. Developing Computational Methods for Detailed Assessment of Cavitation on Marine Propellers. Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden, 2015.
6. Vaz, G.; Lloyd, T.P.; Gnanasundaram, A.K. Improved Modeling of sheet cavitation dynamics on Delft Twist11 Hydrofoil. In Proceedings of the 7th International Conference on Computational Methods in Marine Engineering, Nates, France, 15-17 May 2017.
7. Lidtke, A.K.; Turnock, S.R.; Humphrey, V.F. Multi-Scale Modeling of Cavitation-Induced Pressure Around the Delft Twist11 Hydrofoil. In Proceedings of the 31st Symposium on Naval Hydrodynamics, Monterey, CA, USA, 11-16 September 2016.