Calculation of pressure fluctuations induced by the marine propeller with a boundary element method

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Abstract

In this work the application of a tridimensional boundary element method to the computation of pressure fluctuations induced by the propeller is studied. The method is applied to a case study which consists in the determination of pressure fluctuation amplitudes and phases induced by a marine propeller on a flat plate aligned with the undisturbed flow. The propellers DTMB 4118 and DTMB 4119 are considered in the calculations and the influence of the advance coefficient and distance between propeller tip and plate in the numerical solution is studied. The code PROTRAN which implements a low order panel method is used to compute the flow velocity. The velocity is then used to determine pressure values with Bernoulli equation and an harmonic analysis is carried to compute the fluctuation amplitudes and phases. The convergence of the solution with discretization level is studied and the numerical results are presented for open water diagrams, pressure fluctuation amplitudes and phases on a flat plate. Numerical results are compared with experimental values and results from other methods presented in the literature.

Keywords: Pressure fluctuation, Marine propeller, Boundary Element Method, Potential flow, Ship vibration.

1. Introduction

With the increasing demand for larger and faster ships, the topic of structural vibration affecting this kind of structures becomes more important on their design process [1]. Vibration on ships may cause discomfort to passengers and crew, it may impair machine performance, increasing its maintenance costs, and in the most critical cases may even lead to fatigue failure of main structural components jeopardizing the safety of the structure and the people on board [2]. There are three main sources of vibration on a ship: sea waves, ship’s main engine and propeller generated forces. The latter excites the ship’s structure either through the shaft or in the form of pressure fluctuations induced on the hull. The fluctuating forces transmitted through the propeller shaft correspond to fluctuating thrust and moments caused by the non-uniform flow in which the propeller operates. The pressure fluctuations induced on the hull are caused by the rotating pressure field generated and carried by the propeller and it can represent up to 90% of the excitation forces originated in the propulsion system if cavitation occurs [3]. The objective of this work is to study the application of a panel method to the calculation of such pressure fluctuations induced by the propeller. To achieve that goal a case study is analysed which consists in determining the amplitudes and phases of pressure fluctuations induced on a flat plate near the propeller. No cavitation effects are considered in this study.

2. Mathematical Formulation

Consider a propeller of radius $R$ with $K$ blades symmetrically placed around an axisymmetric hub, rotating with constant angular velocity $\Omega$ in a flow of incompressible ideal fluid. A Cartesian coordinate system $(x_0, y_0, z_0)$ fixed in the domain and a Cartesian coordinate system $(x, y, z)$ rotating with the propeller are used to describe the problem. The $x$ and $x_0$ axes coincide with the propeller rotation axis and point towards the downstream direction of the undisturbed flow. The $y_0$ and $y$ axes coincide with the propeller rotation axis and point towards the downstream direction of the undisturbed flow. The $z_0$ and $z$ axes are contained in the plane of the propeller with $y_0$ pointing upwards and $z_0$ completing the right-hand system. The $y$ axis is coincident with the reference line of one of the blades and $z$ completes the system by the right-hand system. The cylindrical coordinate systems $(x_0, r_0, \theta_0)$ and $(x, r, \theta)$ are related to the Cartesian systems by

\[
y_0 = r_0 \cos \theta_0, \quad z_0 = r_0 \sin \theta_0, \quad (1)
y = r \cos \theta, \quad z = r \sin \theta. \quad (2)
\]
The relation between the two reference frames is

\[ x_0 = x, \quad r_0 = r, \quad \theta_0 = \theta - \Omega t, \]

where \( t \) is the time variable. The undisturbed flow on the fixed reference frame is steady but not necessarily uniform and is called \( \bar{U}_c(x_0, y_0, z_0) \). In the rotating coordinate system the undisturbed flow velocity is time dependent and given by

\[ \bar{U}_\infty(x, r, \theta, t) = \bar{U}_c(x, r, \theta - \Omega t) - \bar{\Omega} \times \bar{x}, \]

with \( \bar{x} = (x, y, z) \).

### 2.1. Potential flow

The flow velocity in any field point may be seen as the sum of the undisturbed flow velocity with a perturbation velocity \( \bar{v}(x, y, z, t) \) and if the flow is irrotational then this perturbation velocity may be written as the gradient of a scalar perturbation potential,

\[ \bar{v}(x, y, z, t) = \nabla \phi(x, y, z, t), \]

which satisfies Laplace equation

\[ \nabla^2 \phi(x, y, z, t) = 0. \]

The perturbation potential must verify the boundary condition at infinity

\[ \nabla \phi \rightarrow 0, \quad \text{if } |\vec{r}| \rightarrow \infty \]

and the impermeability condition on the solid boundaries of the domain, which consist of the propeller blades surfaces \( S_B \) and hub surface \( S_H \),

\[ \frac{\partial \phi}{\partial n} \equiv \vec{n} \cdot \nabla \phi = -\vec{n} \cdot \bar{U}_\infty \quad \text{on } S_B \cup S_H, \]

where \( \partial/\partial n \) represents differentiation along the normal to the surface and \( \vec{n} \) is the unit vector normal to the surface pointing to the exterior of the body. The existence of circulation around the blades requires a vortex sheet to be shed from the blade trailing edge forming a wake surface \( S_W \). On this surface two boundary conditions must be verified: that the flow velocity on the surface is continuous and equal to the surface velocity

\[ \bar{V}^+ \cdot \vec{n} = \bar{V}^- \cdot \vec{n} = \bar{V}_w \cdot \vec{n} \quad \text{on } S_W, \]

and the pressure is continuous across the surface

\[ p^+ = p^- \quad \text{on } S_W, \]

where \( \bar{V} \) is the flow velocity, \( \bar{V}_w \) is the wake surface velocity, \( p \) is the pressure and the superscripts \( ^+ \) and \( - \) represent values on each side of the wake surface.

In order to uniquely define the problem it is necessary to enforce a Kutta condition which bounds the velocity on the blade’s sharp trailing edge to finite values.

### 2.2. Wake model

Representing the wake surface by \( S_w(x, t) = 0 \), equation (9) implies that

\[ \frac{\partial S_w}{\partial t} + \bar{V}^+ \cdot \nabla S_w = \frac{\partial S_w}{\partial t} + \bar{V}^- \cdot \nabla S_w = 0. \]  

(11)

Pressure values in the flow field are computed by Bernoulli equation

\[ \rho \frac{\partial P}{\partial t} + \frac{1}{2} |\bar{V}|^2 + \frac{\partial \phi}{\partial t} = \rho_{\infty} \left[ \frac{1}{2} |\bar{U}_\infty|^2 \right], \]

(12)

where \( P \) is the pressure in the undisturbed flow and \( \rho \) is the fluid’s density. Applying Bernoulli equation to each side of the wake surface and subtracting, we obtain

\[ \frac{\Delta P}{\rho} = -\frac{\partial (\Delta \phi)}{\partial t} - \frac{1}{2} \left( |\bar{V}^+|^2 - |\bar{V}^-|^2 \right), \]

(13)

where \( \Delta P = p^+ - p^- \) and \( \Delta \phi = \phi^+ - \phi^- \) are the pressure jump and the potential jump across the surface, respectively. Boundary equation (10) forces the pressure jump across the surface to be zero, resulting

\[ \frac{\partial (\Delta \phi)}{\partial t} + \bar{V}_m \cdot \nabla \bar{V} = 0, \]

(14)

where \( \bar{V}_m = \frac{1}{2}(\bar{V}^+ + \bar{V}^-) \) is the mean flow velocity on the wake surface.

Solving the velocity field requires the simultaneous solution of the vortex sheet location, given by (11), and the intensity of the vortices shed, given by (14), which is generally difficult to achieve. One way to simplify the problem is to assume that the mean flow velocity in the wake surface is equal to the circumferential average of the undisturbed flow velocity \( \bar{U}_c \). The solution of the wake surface location is of the form

\[ S_w = x - x_{TE} - \frac{U_c}{\Omega} (\theta - \theta_{TE}) = 0, \]

(15)

corresponding to a helicoidal surface and the shed vortices intensities are determined by

\[ \Delta \phi(r, \theta, t) = \Delta \phi \left[ r, t - \frac{\theta - \theta_{TE}}{\Omega} \right], \]

(16)

with the boundary condition on the blade trailing edge,

\[ \Delta \phi(r, \theta_{TE}(r), t) = \phi_{TE}(r, t), \]

(17)

and the initial condition,

\[ \Delta \phi(r, \theta, 0) = \phi_{TE}(r, 0). \]

(18)

### 2.3. Integral equation

Applying Green’s second identity and defining \( \phi = 0 \) in the interior of the propeller bodies, the
perturbation potential in a point $P$ on the surface is determined by

$$2\pi \phi(P, t) - \int_{S_B \cup S_H} \phi(Q, t) \frac{\partial}{\partial n_Q} \left( \frac{1}{R(P, Q)} \right) ds =$$

$$= \int_{S_W} \Delta \phi(Q', t) \frac{\partial}{\partial n_{Q'}} \left( \frac{1}{R(P, Q')} \right) ds +$$

$$+ \int_{S_B \cup S_H} \left( \vec{n} \cdot \vec{U}_\infty(Q, t) \right) \frac{1}{R(P, Q)} dS,$$

(19)

where $R(P, Q)$ is the distance between the point $P$ and a point $Q$ on the surface.

2.4. Velocity, pressure and forces

The differentiation of the potential on the surface of the propeller yields the velocity field on that surface. Pressure values are computed by Bernoulli equation and presented in the form of pressure coefficient

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho U_\infty^2} = 1 - \frac{|\vec{V}|^2}{|U_\infty|^2} - \frac{2}{|U_\infty|^2} \frac{\partial \phi}{\partial t}$$

(20)

The propeller thrust force and torque are computed through the integration of the pressure values on the surface and are presented in the form of thrust coefficient and torque coefficient, respectively,

$$K_T = \frac{T}{\rho N^2 D^4}, \quad K_Q = \frac{Q}{\rho N^2 D^5},$$

(21)

where $N$ is the propeller revolution rate and $D$ is the propeller diameter.

3. Results

Pressure fluctuation amplitudes and phases induced on a flat plate were calculated for propellers DTMB 4118 and DTMB 4119. Three advance conditions were considered corresponding to the design advance condition, a heavy loaded advance condition and the zero-thrust advance condition. In order to assess the influence of propeller tip clearance, the flat plate aligned with the undisturbed flow was studied in two different positions: the first one giving a distance between the plate and propeller tip of 10% of propeller radius and the second one giving a distance of 30% of propeller radius. The calculations were made for several points along a longitudinal line belonging to the surface of the plate with coordinates:

$$-1.5 \leq x_0/R \leq 1.5, \quad y_0/R = 0, \quad z_0/R = -1.10,$$

(22)

and

$$-1.5 \leq x_0/R \leq 1.5, \quad y_0/R = 0, \quad z_0/R = -1.30,$$

(23)

Calculated results are compared with experimental values and the results from other methods presented in [4].

3.1. Open Water Diagrams

First, results of the open water performance diagrams calculations are presented. Figure 1 shows thrust coefficient and torque coefficient calculated for several advance conditions ranged form $J = 0$ to $J = 1.160$ for propeller DTMB 4118 and the respective experimental results. The same results for propeller 4119 are presented in figure 2.

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peller DTMB 4119 where a small discrepancy between calculated and experimental values is seen. This discrepancy is minimal near the design advance condition $J = 0.833$ and may be explained by the fact that no viscous corrections were considered in this model.

3.2. Design advance condition - $J = 0.833$

Results from amplitude and phase of pressure fluctuations calculated with propeller DTMB 4118 for design advance condition, $J = 0.833$, with a propeller tip clearance of 10% are shown in figures 3 and 4, respectively. Results calculated for a tip clearance of 30% are shown in figures 5 and 6.

Calculated amplitudes overpredict the experimental ones in both cases. In the region downstream of the propeller plane, fluctuation amplitudes fail to diminish, contradicting the experimental results. This effect is more intense in the 10% tip clearance situation. Phase values behaviour agrees with experimental values behaviour along the axial direction for the 10% tip clearance but not in the 30% tip clearance case.
3.3. Heavy loaded advanced condition

Figures 11 to 14 present values calculated with an advance coefficient $J = 0.600$, corresponding to an increase in propeller loading compared with the design condition.

Similar conclusions may be drawn from these results about the overprediction of amplitude values and the fact that they fail to approach zero in the downstream region, noting that this propeller with thicker blades gives rise to larger amplitude fluctuations compared to the previous one. Again, phase results follow the evolution of experimental values in the $z_0/R = -1.10$ location but not on the $z_0/R = -1.30$.
An increase in propeller loading is seen to lead to larger fluctuation amplitudes both in the maximum value and in the region of downstream flow. Predicted values overestimate experimental ones for both tip clearances. Results for propeller DTMB 4119 are presented in figures 15, 16, 17 and 18.

3.4. Zero-thrust advance condition

Results presented in figures 19 to 22 show the amplitudes and phases calculated with an advance coefficient $J = 1.160$ corresponding to the zero-thrust advance condition for both propellers.
The results calculated with this advance coefficient still overestimate the experimental values but succeed in the representation of the diminishing pressure fluctuations on the downstream region of the plate. Computed phase values evolution along the plate agree well with experimental values for both plate positions. Figures 23 trough 26 present results for propeller DTMB 4119 operating at zero-thrust condition. The same behaviour as in propeller DTMB 4118 values may be seen in these results for both amplitudes and phases.
3.5. Wake surface contraction

Here wake contraction is considered. Four different wake surface geometries are used to compute pressure fluctuation amplitudes and phases for the propeller DTMB 4118, with the three advance conditions and two plate positions. Each wake geometry has a different exterior radius \( r_u \) on the downstream region but all have the same radius on the blade trailing edge \( R_{te} = 0.98 \). Results are presented in figures 27 to 30 for the design advance condition, figures 31 to 34 for the heavy loaded condition and figures 35 to 38 for the zero-thrust condition.
Figure 31: Pressure fluctuation amplitude with wake contraction. Propeller DTMB 4118, $J = 0.600, z_0/R = -1.10$.

Figure 32: Pressure fluctuation phase with wake contraction. Propeller DTMB 4118, $J = 0.600, z_0/R = -1.10$.

Figure 33: Pressure fluctuation amplitude with wake contraction. Propeller DTMB 4118, $J = 0.600, z_0/R = -1.30$.

Figure 34: Pressure fluctuation phase with wake contraction. Propeller DTMB 4118, $J = 0.600, z_0/R = -1.30$.

Figure 35: Pressure fluctuation amplitude with wake contraction. Propeller DTMB 4118, $J = 1.160, z_0/R = -1.10$.

Figure 36: Pressure fluctuation phase with wake contraction. Propeller DTMB 4118, $J = 1.160, z_0/R = -1.10$. 
Results show that wake contraction leads to smaller fluctuation amplitudes downstream of the propeller plane with greater differences in the heavy loaded condition and no influence in the zero-thrust condition. Phase values seem to be almost insensitive to wake contraction in the 10% tip clearance position, being only affected in the near propeller downstream region for the cases with 30% tip clearance.

4. Conclusions
Pressure fluctuations induced on a flat plate were calculated with a panel method. It was seen that thicker blades, heavier propeller loads and smaller tip clearances all lead to larger fluctuation amplitudes and that the computed values react well to these parameters. Fluctuation amplitude results overestimated experimental values in every condition studied. Phase values calculated agree well with the evolution of experimental values along the plate for a tip clearance of 10% of propeller radius. In the region downstream of the propeller plane, calculated results fail to predict the decay of fluctuation amplitudes with axial distance seen in the experimental values. This effect was seen to be proportional to propeller loading and is attenuated with contraction of the wake surface.

References

