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Bilge keel loads and hull pressures created by bilge keels fitted to a rotating cylinder

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ABSTRACT

This paper presents bilge keel loads and hull pressure measurements carried out on a rotating cylinder in a free surface water basin. A flat plate bilge keel and one more complex shaped bilge keel were studied to investigate the geometry effect. The draft of the cylinder was varied to study the effect of the vicinity of the free surface on the bilge keel loads and hull pressures. The rotation axis of the cylinder was fixed to define a pure roll experiment (one degree of freedom).

The cylinder was subject to forced oscillations of varying amplitude leading to a KC range of 0.3–16. Using Fourier analysis the first three harmonic coefficients representing the normal bilge keel load were derived. The first harmonic drag and inertia coefficients are in good agreement to existing experimental data obtained for wall bounded flat plates fitted in a U-shaped water tunnel as reported by Sarpkaya and O'Keefe (1996). New insight is gained by the fact that the addition of higher harmonic contributions is essential to capture the time varying bilge keel normal force.

The pressure measurements next to the bilge keel are compared to measurements reported by Ikeda et al. (1979). Similar findings are obtained, showing that the pressure on the hull in front of the moving bilge keel is KC independent while the vortex system in the wake of the bilge keel leads to KC dependent hull pressure distributions. The hull pressure jump over the bilge keel correlates well to the force coefficient on the bilge keel. The complex nature of the vortex induced hull pressures is manifested. The empirically derived hull pressure distribution by Ikeda et al. (1979) for the time instant of maximum velocity is shown to correlate reasonably well to the measured data with some conservatism in the absolute value.

Although a cylinder is very different from a ship-shaped section, the experiments provide essential insight into the physics associated with roll damping and into the factors that should be included in a roll damping prediction method.

1. Introduction

To date, bilge keels are fitted to almost all sea going vessels since it is by far the most economical solution to reduce vessel roll motions. Despite its wide application, an accurate numerical prediction of the roll damping contribution from bilge keels remains difficult due to complex physics associated with flow separation at the bilge keel tip.

The most extensive research on roll damping has been performed about 35 years ago and reported in for example Ikeda et al. [4], Ikeda et al. [5] and Himeno [2]. The resulting empirical method is widely used in the industry since it is a practical method leading to reasonable results in many situations. It is referred to as the ITH-method in this paper, after the main authors. In more recent years the method has been adopted for special ship types or conditions, see e.g. Ikeda et al. [3], but the fundamental breakdown of the roll damping in different contributions remained the same. Due to its success the ITH roll damping method has become the ITTC recommended roll damping prediction method (ITTC [7]). A short description of the essential components at zero speed is provided.

The present research is motivated by the fact that Veer et al. [16] shows that the prediction of the bilge keel loads can be improved utilizing 3D potential flow when accurate load coefficients – including higher harmonics – are applied. However, additional research was deemed necessary to better quantify the coefficients and to understand the influence of different parameters on these coefficients.

As such, this paper presents experimental results that detail the induced hull pressures and in particular the load coefficients

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including higher harmonics. These can be utilized in a zero speed roll damping method which is to be further developed.

1.1. ITH roll damping method

In the ITH roll damping method (Himeno [2]) the bilge keel damping at zero forward speed is attributed to mainly two contributions: the damping due to the normal force acting on the bilge keel plates $B_{bk,N}$ and the damping due to the hull pressures caused by the separating bilge keel vortices $B_{bk,H}$.

For the normal force, leading to $B_{bk,N}$, the Morison equation is used with a KC dependent drag coefficient. The drag coefficient is derived from the work of Keulegan and Carpenter [10] for flat plates and fitted by Ikeda to the equation $C_D = 22.5/KC + 2.4$, where the KC number is defined by $KC = fU_AT/(2h)$ where h is the bilge keel height, U_A the amplitude of the harmonic motion, T the oscillation period and f an empirical velocity correction factor. The bilge keel normal force over a bilge keel length L is given by $F_{bk,N}(t) = C_D(1/2)\rho(hL)\nu(t)|\nu(t)|$ in which the velocity $\nu(t)$ in the ITH-method is obtained from the roll motion and corrected by the empirical velocity factor f. Equivalent linearization is applied to obtain the linearized roll damping moment $B_{bk,N}$ that can be used in the motion equation.

The roll damping component $B_{bk,H}$ due to the hull surface pressure is derived in the ITH-method in analogy to the normal drag force. The pressure component is given by $p(t) = C_p(1/2)\rho\nu_\phi(t)|\nu_\phi(t)|$ where $\nu_\phi(t)$ is the instantaneous relative velocity at the bilge radius calculated from the roll motion velocity. The pressure coefficients and its distribution is derived from measurements and somewhat simplified. In front of the moving bilge keel the positive pressure coefficient C_p^+ is linearly decreasing to zero. The maximum positive pressure coefficient is set to 1.2 and found to be independent from the KC number. Behind the bilge keel the negative pressure coefficient C_p^- is set constant over a length $S/2$ that depends on the bilge keel height before it linearly decreases to zero at the distance S from the bilge keel. The pressure jump over the bilge keel depends on the KC number - since the eddy shedding occurs in the wake behind the moving bilge keel - and the relationship $C_D = C_p^+ - C_p^-$ holds (Ikeda et al. [5]). The length of negative pressure region is for a cylindrical hull shape defined as $S/h = 0.4(U_AT/2h) + 2.6$.

1.2. Further development of an ITH inspired roll damping method

It has been shown in Veer et al. [16] that the bilge keel loads on the weather and leeward side of a vessel in beam seas are very different. This effect is obtained when the roll-motion induced velocity $\nu(t)$ in the bilge keel load force equation is replaced by a local fluid velocity from potential flow calculations which include the contributions from all wave components (incident wave, diffracted wave, and radiated waves). Further improvements are obtained when an inertia contribution is added and when higher harmonic components are included. It remains of interest to investigate the influence of factors not considered in the ITH-approach like the free surface and the effect of the bilge keel geometry.

In the ITH method the pressure distribution is given at the moment of maximum global roll motion velocity, and no further details are presented. Verification of the ITH-approach under different conditions is of interest and hence detailed pressure measurements for different bilge keel geometries oscillating in a free surface bounded fluid are executed. Application of computational fluid dynamics (CFD) to quantify the pressure distribution and it's related roll damping moment (for ship shaped sections) is as well a possibility and to validate CFD application, detailed measurements are required. The present research is intended for that purpose as well.

1.3. Present experiments

The present experiments are conducted with a cylindrical hull since such geometry will not generate hull radiation waves under pure rotation. For an unappended cylinder, the local relative velocity at the intended bilge keel location is determined solely by the rotational velocity of the cylinder and hence the KC number is well defined.

A test matrix was defined to determine the influence in the load coefficients and pressure distribution due to the presence of the free-surface, the bilge keel geometry and the oscillation frequency. Both irregular and harmonic oscillations were applied to study a possible flow memory effect, which were observed in previous research reported by Ikeda et al. [6] for flat plates and by Veer et al. [15] in roll decay experiments with an FPSO hull. The contribution of the higher harmonics in the bilge keel normal force are presented in the same manner as in the work by Keulegan and Carpenter [10] for free plates.

A detailed description of the experiments is given in Section 2. The data analysis is presented in Section 3. The normal bilge keel force coefficients are discussed in Section 4 and the pressure results are discussed in Section 6. Section 5 discusses the measured loads in irregular motion. The conclusions are drawn in Section 7.

2. Description of experiments

2.1. Test set-up

An experiment was designed with the objective to measure the bilge keel normal force and the hull pressures induced by the separating vortex system from the bilge keel (denoted as hull-vortex-pressure). For this purpose a cylindrical hull was constructed with an interchangeable bilge keel and two rows of ten pressure sensors each.

Forced oscillations were applied with regular (sinusoidal) and irregular rotation around the axis of the "2D" cylindrical hull.

The experiments were conducted in the No. 1 Towing Tank of the Laboratory of Ship Hydromechanics at the Delft University of Technology. Fig. 1 shows the model in the free surface (a) and the bilge keel set-up from under water (b).

The test basin is 142 m long, 4.22 m wide and 2.5 m deep. On one side there is a beach to reduce wave reflection, on the other side there is a wave maker. The wave maker was positioned under an angle to minimize wave reflections since it is not used in the experiment. Essentially, the duration of the experiments was such that reflected wave energy could not disturb the measurements.

A Hexamove was used to generate the roll motions. It consists of two platforms connected via six hydraulic drives. One platform was firmly anchored to the carriage while the other was connected to the model and was subject to controlled motions. The rotation axis, being at the origin of the circle-cylindrical hull shape, was positioned at three different heights with respect to the calm water level thereby simulating three different draft conditions of the cylinder. In the most shallow condition the bilge keel operates very close to the free surface. The global motions were recorded by an infrared Krypton measuring system which has an accuracy of about 0.10 mm. The roll motions were generated with great accuracy. The standard deviation of the translations of the center of rotation recorded during the experiments was on average 0.15 mm and at most 0.34 mm for the largest roll angle. The standard deviation of the rotations other than roll were on average 0.025 deg and at most 0.06 deg.