THE FORCES ON AN OSCILLATING FOIL MOVING NEAR A FREE SURFACE

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It has in recent time been considerable interest in exploiting the energy from free surface waves to produce forward thrust of ships (Jakobsen 1981, Isshiki et al. 1984). The idea is to fix one or two hydrofoils to the ship. When the ship is heaving and pitching in incoming waves, also the hydrofoils will perform a heaving motion. Since the ship (and thereby the foil) is moving forward, the heaving of the foil will create a forward thrust on the foil and the foil will act as a propeller. Applying this principle the angle of attack must not be too large to escape stall. It is therefore favourable that the foil also performs a pitch motion. Thereby it may be possible, by for example an arrangement of springs, to obtain that the maximum angle of attack is small enough to escape stall, but large enough to obtain an important thrust. Model experiments and experiments in full scale show that the foil propeller is rather effective.

We shall here study mathematically the thrust acting on a moving, oscillating foil. This problem has been studied quite in detail by Wu (1961, 1971a, 1971b) in a series of papers on the hydrodynamics of swimming propulsion. In the present problem the foil may be sited close to the free surface. Therefore it is important that the free surface is taken into account when modelling the problem, which is not done in the papers by Wu. Besides there may be incoming waves which further complicate the problem. Incoming waves on an oscillating foil are discussed by Wu (1972) and by Isshiki et al. (1984). The effect of the free surface is, however, neglected in these papers and their results are only valid when the foil is relatively deeply submerged.

It is assumed that the problem is two-dimensional. The foil is moving with a velocity U and performing a heaving motion and a pitching motion with arbitrary phase difference. The foil is assumed to be thin and is replaced by a flat plate, making a small angle with the horizontal plane. The equations are linearized, but otherwise the effect of the free surface is taken into account. One complicating factor is that the problem is depending on as many as seven independent non-dimensional quantities. Therefore only some few values of each of the parameters are considered.

We consider first an oscillating foil with no incoming waves. The energy is taken from a motor or the like. The energy equation reads

$$P = TU + E \tag{1}$$

where P is the power, T the thrust and E wasted energy. We are interested in a large thrust, but also a large efficiency. Since the theory for an oscillating foil in an unbounded fluid has been studied quite extensively by Wu, we are here emphasizing on the effect of the free surface. Generally speaking, the free surface is important in two respects. Firstly, it generates surface waves which increase the value of E, but they also lead to a momentum flux which may be positive or negative. Secondly, the free surface has an impact on the vortex wake which is build up behind the foil. The generated waves are especially important for relatively small values of $U\sigma/g$ (σ the frequency of encounter, g the acceleration of gravity). In this case four different waves are generated. Three of them (k_1-, k_2-, k_3-waves) have phase velocities in the same direction as the foil is moving, whereas one of them (k_4-wave) has phase velocity in the opposite direction. The three first mentioned waves therefore have a momentum transport leading to a smaller thrust while the k_4-wave leads to a larger thrust. For small values of $U\sigma/g$ the k_1-, k_2-waves dominate. Hence in this region the free surface will lower the efficiency (increase E) and lower the thrust. For larger values of $U\sigma/g$, however, the k_4-wave may dominate. As an example on the latter we find that for $\sigma l/U$ (the reduced frequency) equal to unity or larger and $Fr=U/(gl)^{\frac{1}{2}}=1$ (l the half chord length), the momentum transport in the waves is responsible for about 40% of the thrust. When the k_1- and k_2-waves dominate, the waste of energy due to the waves may be larger than the waste due to the vortex wake.

We mention also that for $U\sigma/g$ being very small and Fr small, the waves disappear. With these values of the parameters the free surface acts as a rigid boundary. Hence the thrust is considerably increased when the foil is close to the free surface whereas the power is almost unchanged. It turns out that the effect of the free surface is rather different when the foil is moving in heave without pitch or if the motion is composed of a heave and pitch motion.

When the foil is oscillating in incoming waves, these waves constitute a new energy source. The mean available energy due to the waves is given by

$$P_0 = E_o |c_g - U|$$

where E_0 is the energy density of the incoming wave and c_g the corresponding group velocity. The case with incoming waves will, however, not be discussed here, except that we shall give some figures comparing our results with those of Wu and some experiments by Isshiki.

As appropriate mathematical tool we have applied integral equations, using as kernel the Green function for a vortex. The governing integral equation is a singular Fredholm equation of first kind. By a simple transformation this is brought into a form of an ordinary Fredholm equation of second kind, which is solved numerically by a collocation method.

REFERENCES

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Discussion

Yeung: In connection with the integral equation for the vortex distribution, does it not appear that you had made the following assumption: the thickness of the airfoil to water-depth ratio is one order smaller than the (local) angle of attack on the airfoil? It seems that under normal assumptions of thin-body theory (small thickness, small angle of attack of the same order), the lifting problem is coupled to the thickness problem in the presence of a free surface.

Palm: We are in the lecture considering the oscillatory problem. It is easy to show from the boundary conditions that in this case we may disregard the thickness problem even if the angle of attack and the thickness are of the same order of magnitude. Professor Yeung's objection would be relevant if also the basic velocity or the thickness was oscillating in time.