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An experimental investigation into the hydrodynamic drag reduction of a flat plate using air-fed cavities

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ABSTRACT

The Air-Cavity Ship (ACS) concept is currently being researched as one of the more promising concepts for economical forms of marine transportation. An Air-Cavity Ship uses an air injection system to isolate the bottom part of the ship's wetted surface from the water and thereby to reduce the frictional resistance. The air cavities are generated injecting air at the keel level of a vessel as such the cavities can extend along considerable portions of the hull bottom thus isolating it from the effect of the fluid. The main objective of an effective air cavity system is therefore to maximize the cavity length whilst minimising the air supply. Building on the lack of published experimental research, this paper presents a recent fundamental experimental investigation on air-cavities underneath a flat plane tested in the Emerson Cavitation Tunnel of Newcastle University. The experimental investigation uses this simplified model to understand the correlation of cavity length and volume with potential drag reduction due to the air cavity. The main objective of the research was to generate both fundamental and practical knowledge that furthered the understanding of the air-cavity phenomenon to help its potential application in practice. In addition an attempt was also made to correlate the findings from this experimental study with air-cavity theory and results from limited previous experimental studies performed in other facilities.

1. Introduction

The quest for faster and more economical forms of marine transportation has led ship designers to find innovative ways of reducing the drag generated by a ship's hull through the components mainly by the wave interactions and the frictional drag generated by the hull passing through the water. Exploiting the technologies has led to the development of innovative hull forms and concepts such as surface effect ships, air cushioned vehicles, hydrofoil-assisted ships etc., as noted by Matveev (2003a).

Within the above framework one of the more promising concepts, which is currently being researched as a new area of interest, is the concept of the Air-Cavity Ship (ACS). In this vessel concept an air injection system is used to isolate the wetted surface of the ship from the water and thereby reduce the frictional resistance and hence the total ship drag. The air cavities on an ACS are generated by injection of air at the keel level of the vessel. The cavities can extend along considerable portions of the hull bottom thus isolating it from the effect of the fluid. The objective of an effective air cavity system on a ship is therefore to maximize the cavity length whilst minimizing the air supply (depending upon the sea state). The air supply mechanism needed to generate and maintain the cavity on an ACS is very simple. Air is injected into the recess through a single opening underneath the hull as such the cavity spreads as evenly as possible underneath the ship bottom. This approach is different from the traditional methods of air/gas lubrication as the air-cavities develop "naturally" as a result of the difference between the ambient pressure and that inside the recess. A more complex profiling of the ship bottom can be designed in order to optimise air-cavity shape and performance as reported in Matveev (2005) and Sverchkov (2010).

The idea of drag reduction by supplying air to wetted hull surfaces was proposed for more than a century. However it was not until the 1950s that the first research on air cavities applications in the field of ship hydrodynamics has been initiated, as described by Butuzov (1975). However Gokcay et al. (2004) claimed that this technique was already adapted on planing boats in 1935 by J.W. Bell. Even in these early trials it was possible to reduce ship resistance by 20% by using just 2% of the ships power to create the air cavities.

The major experimental studies into air cavities for drag reduction were carried out in towing tanks as the presence of a free-surface in testing air cavities is very important for the air-cavity characteristics. Sverchkov (1988, 1991, 1995) reported on numerous research and development activities at Krylov Shipbuilding Research Institute where all major ship types were tested with air-cavities. However cavitation tunnel and circulation channels are also very useful for the air cavity research. For example a relatively big ship model of 6.07 m

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was also tested in the SSPA cavitation tunnel facility and reported in Allenström and Leer-Andersen (2010).

At the early stages of the air-cavity research and development, an under hull cavity system was normally built of series of smaller cavities when it was not possible to cover the whole ship bottom. Sverchkov (1991) investigated various cavity applications on high-speed displacement vessels and catamarans to determine the most favourable ship bottom profiling for either a wave-like cavity or a series of single cavities. Chalov (2000), who proposed a series of different cavity formation approaches, claimed that the latter system was 30% more efficient for slow-steaming flat-bottomed ships. Air-cavity forms of drag reduction are particularly profitable for larger, slow-steaming cargo vessels. For example whilst Chalov (2000) claimed a 15–17% reduction in effective power for a barge, Gorbachyov (1977) claimed a 20% saving in seas with up to 5 m waves for both a ULCC and semi-planning vessel. In a relatively recent full-scale investigation Sverchkov (2003) reported on a series of 50 patrol boats in Russia operating with artificial cavities with displacements ranging from 14 to 100 t and a speed range from 40 to 52 knot.

The use of air cavities has been slow to be adopted in the wider maritime community due to a lack of relevant data and reliable theoretical models. The first approaches in the numerical modelling of air cavities underneath the ship were suggested and developed by Butuzov (1975) who also solved the theoretical problem of an air cavity model travelling with a ship. Butuzov (1988) also presented the theoretical methods for the solution of a linear problem of flow around the air-cavity assisted vessel. Both of these methods were applied to planing boats and slower speed displacement vessels.

Recently the theoretical background for explaining the air-cavity phenomena was also given by Matveev (2005) who treated the problem as a flow around a wedge attached to the lower side of a horizontal wall. Matveev stated that cavitation number (σ) and Froude number (Fr) are the main parameters, which define the air-cavity system. He claimed that the state of the cavity could be described by "*four general modes*" (discussed later in the paper) with different shapes, cavitation number characteristics and behaviour in the tail. Matveev (2003b) also presented the mathematical formulation of the single cavity and series of cavities formed under the wedge, thus helping to determine the cavity and determine the most efficient characteristics.

Building on the lack of published experimental research, this paper presents a recent fundamental experimental investigation on air-cavities underneath a flat plane tested in the Emerson Cavitation Tunnel of Newcastle University, Slyozkin (2011). The experimental investigation uses this simplified model to understand the correlation of cavity length and volume with potential drag reduction due to the air cavity. The main objective of the research was to generate both fundamental and practical knowledge that furthered the understanding of the air-cavity phenomenon to help its potential application in practice. In addition an attempt was also made to correlate the findings from this experimental study with air-cavity theory and results from limited previous experimental studies performed in other facilities.

Following this introduction, in Section 1, the next section presents the experimental set-up, while the description of the experiments and the presentation and discussion of the test results are presented in Section 3. The uncertainty analyses of the experiments are given in Section 4 and conclusions of the investigations are presented in Section 5. Finally the entire test data produced during the experimental campaign are included in the Appendix to the paper in the form of tables, figures and photographs.

2. Experimental set-up

The air cavity experiment was conducted in the Emerson Cavitation Tunnel (ECT) facility of Newcastle University. The ECT is a closed circuit depressurised tunnel which has a measuring section of 3.10 m × 1.22 m × 0.81 m with a contraction ratio of 4.271:1 and is therefore considered a medium sized facility. The tunnel can circulate approximately 60 t of fresh water and has a hatch located at the highest point to release the raising air to be trapped in the hatch. Fig. 1 gives a general view of the tunnel circuit and Table 1 gives the basic specification for the ECT. Full details of the ECT with an emphasis on the recent upgrading are given in Atlar (2011). Conducting the air cavity tests in a cavitation tunnel allows excellent observation of the flow and the cavity as well as the ability to change the pressure, flow speed and control of the air supply effectively.

The air-cavity test-rig was designed and constructed at Newcastle University. A schematic of the test-rig, is given in Fig. 2. The test-rig was designed to withstand flow forces at a maximum flow speed of 6 m/s, it was manufactured from mild steel as described in detail by Slyozkin (2011) following a detailed CFD and FE analysis. The main plate of the test-rig, that held the air cavity underneath, was machined flat allowing smooth flow entrance and closure. The main

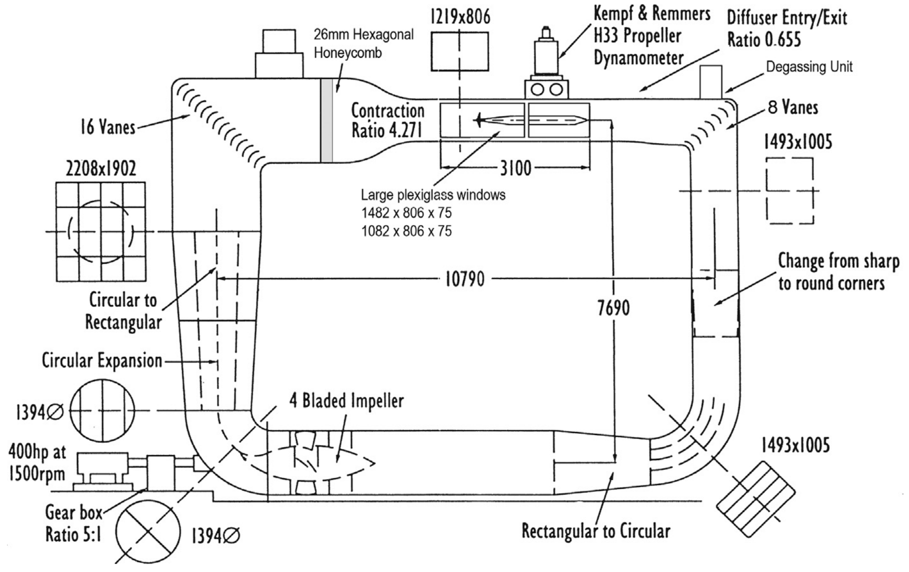

Fig. 1. Layout of the Emerson Cavitation Tunnel.