Why long UUVs can't dive - and how to get them to

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***Abstract*—Large UUVs are susceptible to surface-trapping. We provide an explanation for this, and present a surface-detrapping algorithm.**

Keywords—UUV; diving

I. Introduction

With the widespread adoption of UUVs into military and oil&gas conops, requests for very long UUV missions, larger payloads, or operations in deeper waters are increasing vehicle length-over-diameter ratios (L/D): whereas L/D of order 6-9 were typical a few years back, vehicles in the range 12-15 are now routinely deployed.

The consequences of larger L/Ds are multifold: larger bending moments during launch and recovery – requiring larger lifting structures –, larger drag coefficients – reducing mission endurance –, and *surface-trapping*. This paper addresses surface-trapping.

Surface-trapping happens when a UUV is unable to dive: launched normally, the UUV accelerates at first, and then pitches down as it would normally, but never actually leaves the surface. Surface-trapping is particularly acute in quiet seas, and with larger L/D.

Ad-hoc surface-trapping workarounds have been developed. Some are effective but non-optimal, such as diving in reverse. Some are somewhat effective but operationally impractical, such as pushing the vehicle down with a rod or swimming into the wake of a vessel. Some important mission elements, such as getting a GPS while underway, do not have workarounds yet.

In this paper we analyze surface-trapping and elucidate its root-cause: Section II discusses the Physics of surface-trapping; Section III shows the results of diving simulations; and Section IV introduces a *surface-detrapping* algorithm and discusses its performance.

II. Surface-Trapping physics

A. Model

We consider a standard UUV, i.e. a streamlined body of revolution with an aft propulsion and control section. When the UUV swims near a free-surface, the parts of the hull above the surface produce a downward force and a restoring pitching moment. These effects are function of vehicle immersion and pitch: increasing immersion decreases the force, and increasing pitch – up or down – increases both the force and the moment.

B. Trapping Physics

First consider a fully submerged UUV (Figure 1 - top). To achieve straight-and-level flight, the vehicle pushes down with the elevator and pitches down: pushing down balances buoyancy, and pitching down creates the necessary Munk moment to balance the elevator moment.

Next consider the same vehicle near a free-surface (Figure 1 - bottom). To achieve straight-and-level flight, the vehicle pushes *up* with the elevator - the upward force is needed to initiate the pitch-down. As the tail lifts, vehicle immersion also increases.

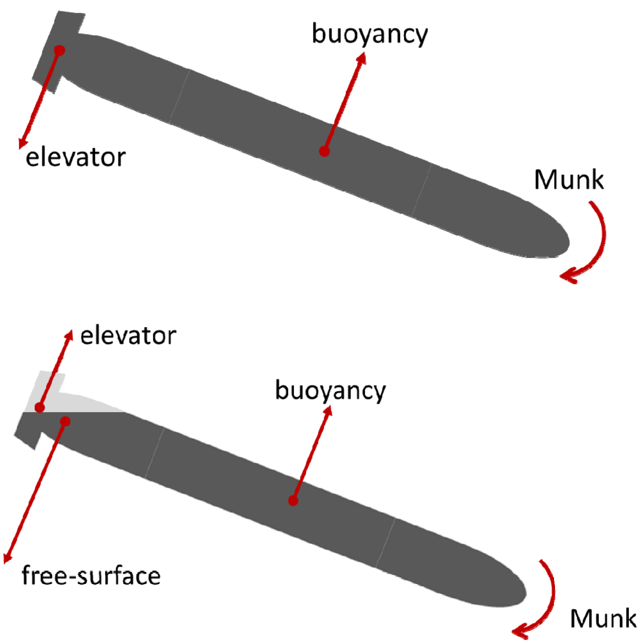

Fig. 1. Free-body diagram normal to the body axis in straight-and-level flight. Top: fully-submerged vehicle. Bottom: vehicle near a free-surface (bottom). Cross-drag and righting moment are not shown given their small role.

This and the competition between pitch and immersion explain surface-trapping: In the initial part of a dive (Figure 2), increasing pitch increases the amount of free-surface force, and therefore the amount of elevator required. As immersion increases, the free-surface force, and therefore the amount of elevator required, decreases. Between the two, the elevator reaches a maximum. Surface-trapping happens when the elevator does not have the control authority to overcome the maximum.

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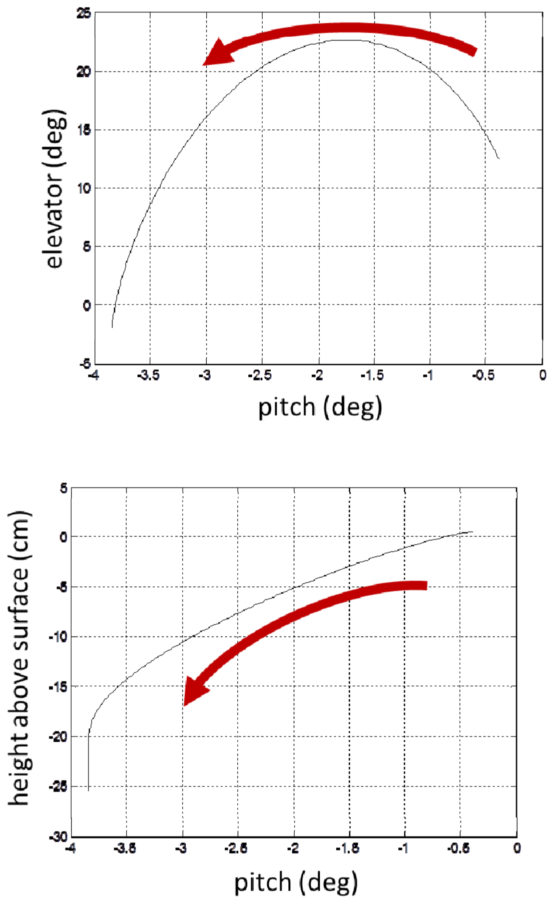

Fig. 2. Top: Steady-state elevator angle versus vehicle pitch during a dive. Bottom: Steady-state height above the surface versus pitch. Computed for a 21" diameter vehicle, at 3 knots, with buoyancy/displacement = 0.4%, and L/D = 12.

C. Predictions

This simple picture is predictive:

1. Consider a family of vehicles of increasing diameter and identical L/D ratio. As diameter increases, both the elevator and the free-surface torque increase, however the free-surface increases faster - see the Appendix. This implies that the relative effectiveness of the elevator decreases for larger vehicles. Thus, larger vehicles are predicted to be more susceptible to surface-trapping.
2. Consider a family of vehicles of identical diameters but different L/D ratio. As L/D increases, both the elevator and the free-surface torque increase but the free-surface increases faster - see the Appendix. This implies that the relative effectiveness of the elevator decreases for longer vehicles. Thus, longer vehicles are predicted to be more susceptible to surface-trapping.
3. When a large wave crosses the vehicle, it temporarily suspends the free-surface moment. This allows the elevator to cross the barrier. Thus, stronger seas are predicted to decrease surface-trapping.
4. For the same reason, increasing vehicle buoyancy is predicted to increase surface-trapping.
5. As elevator control authority increase quadratically with vehicle speed, higher speeds are predicted to lessen surface-trapping.

III. Simulations

Figure 3 shows the result of a 6DOF computer simulation on two 21" diameter vehicles. The first vehicle has L/D=10 (top), and the second 12 (bottom). The simulator includes all standard terms: rigid-body dynamics, hydrostatics, added mass, Munk moment, longitudinal and cross-drag terms, ducted propeller terms, hull profile effect, and local angle of attack effects.

The vehicle starts at the surface at zero speed. After an initial acceleration period, the elevator is commanded to push up at maximum deflection. When L/D = 10, the vehicle is able to dive; when L/D = 12 it isn't.

Based on the model discussed in Section II, the shorter vehicle has the control authority to overcome the free-surface moment and the longer doesn't.

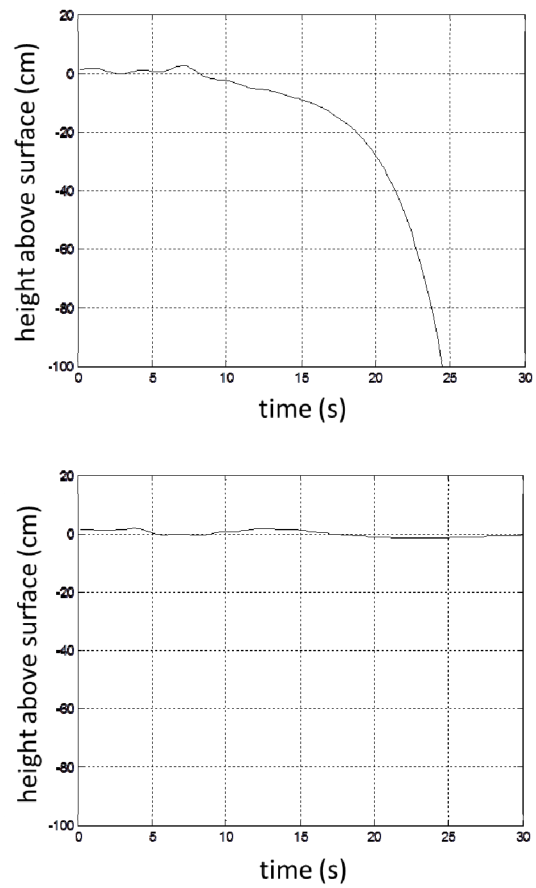

Fig. 3. Performance of a UUV attempting to dive at 3 knots with the elevator locked at -12 degrees and B/displacement = 0.4%. Top: The vehicle with L/D = 10 is short enough to overcome surface-trapping. Bottom: The vehicle with L/D = 12 does not have the control authority to overcome the free-surface moment.

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IV. SURFACE-DETRAPPING

The elevator force-vs-pitch curve has the form of a barrier: if the elevator does not have the required control authority to overcome it, it cannot cross the barrier i.e. it is trapped

For a given value of the elevator, two values of pitch are possible, one on each side of the barrier. Given that the system has two attractors, and in analogy with results from dynamical system theory, we propose that a properly applied time-dependent disturbance should induce barrier-crossing.

Barrier-crossing can be achieved by exciting a resonant transfer from the elevator to the vehicle's pitching mode. The details of the method will not be discussed here, however Figure 4 shows the results: applied to the same vehicle that fails to dive with a locked elevator – see Figure 3, bottom –, resonant transfer allows the pitch to increase long enough for the system to overcome the barrier.

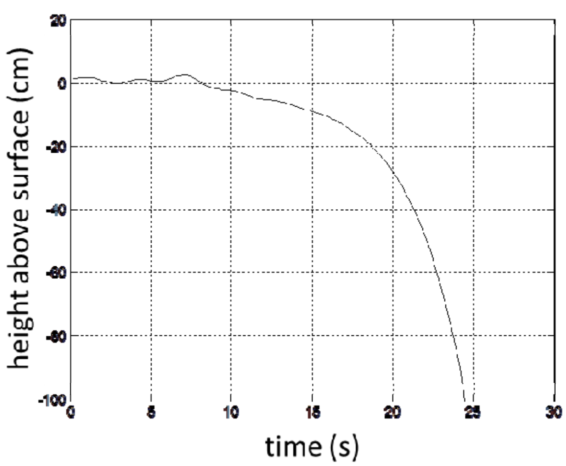

Fig. 4. Surface-detrapping algorithm applied to a vehicle that fails to dive with a locked elevator.

The surface de-trapping algorithm was tested extensively in simulations, and shown to produce reliable de-trapping versus the following: increased L/D, increased diameter, increased buoyancy, and decreased speed.

Sea-trials are currently slated to test the algorithm's performance.

V. APPENDIX

For a cylindrical hull of length L, pitched at θ that's exposed h at mid-length, the free-surface force and moment are:

$$F = -K \begin{cases} 0 & h < -L/2|\theta| \\ \int_{-L/2}^{L/2} dx\left(h+|\theta|x\right)^{3/2} & h > L/2|\theta| \\ \int_{-h/|\theta|}^{L/2} dx\left(h+|\theta|x\right)^{3/2} & |h| < L/2|\theta| \end{cases}$$

$$M = -\operatorname{sgn}(\theta) K \begin{cases} 0 & h < -L/2|\theta| \\ \int_{-L/2}^{L/2} dx\left(h+|\theta|x\right)^{3/2} x & h > L/2|\theta| \\ \int_{-h/|\theta|}^{L/2} dx\left(h+|\theta|x\right)^{3/2} x & |h| < L/2|\theta| \end{cases}$$

where K= $8/3\, D^{1/2}$.

With increasing diameter and L/D, the moment scales as $D^4\left(L/D\right)^{7/2}$. In comparison, the elevator moment scales as $D^3\left(L/D\right)$.

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