Floating Body Dynamics Inside Whirlpools Found in Mythology and Literature

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Abstract

In mythology and folklore tales, the fact and fiction are intertwined forming a Gordian knot. We, however, can learn a great deal from the ancient accounts, if the two are unraveled. In the present paper we elaborate between the truth and fantasy of events described in oceanic whirlpools in the epic poem of Odyssey and in the short story A Descent into a Maelström. Based on the theory of intense vortices and floating body dynamics we analyze the decisions taken and the navigational strategy drawn by Odysseus. We discover the majority of the dynamic characteristics of floating bodies in a whirlpool, previously thought to be false are shown to be true. This study reveals that besides the supernatural origin of the ancient whirlpools, old sailors understood a great deal of their fluid dynamic properties, and thus were able to navigate them with considerable skill.

1. Introduction

A layman probably understands a vortex to represent the circular motion of water as it drains out from a bathtub. To a physicist, the word vortex might also include terrestrial tornadoes and hurricanes, the red spot in Jupiter's atmosphere, or even the spiral galaxies in the heavens. The entire known cosmos is inhabited by whirlpools. Their size vary from approximately a few angstroms in quantized vortices of super fluid helium, to light-years in the case of galactic vortices, thus making this phenomenon appear throughout the spectrum of physics, i.e., in the realm of "infinitely" small (quantum mechanics), the zone of middle dimensions (classical mechanics), and that of the "infinitely" large (relativistic mechanics).

The mystery and destructive power associated with naturally occurring vortices have both mystified and terrified humans since the dawn of civilization. It is therefore no surprise to find the vortex to be one of the fundamental postulates in Anaxagoras' (499-428 BC) model of the universe, or in the atomic theory of Democritus (460-370 BC). This natural occurrence may also have inspired the artists and craftsmen of antiquity in the design of spiral ornamentation (see Lught, H., J. (1993)). Although whirls of air or water have been widely used as the Deus Ex Machina in myths and legends, no other vortex has been so frequently cited as the tidal whirlpool.

According to Greek mythology, Charybdis in Homer's Odyssey was the offspring of Earth and Poseidon. In order to satisfy her healthy appetite, she stole several of Hercules' cattle. As she was ready to devour them, she was struck by one of Zeus' bolts. Subsequently, she was thrown into the straits of Messina and became the horrendous whirlpool. A considerably stronger whirlpool than Charybdis, known as the Maelström-originally

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described by Magnus (1490-1558 AD), develops in the northern coast of Norway between Lofoten Point and the island of Vøroy. Nordic tales attribute its existence to two magical mill-stones that sank either north of Scotland or off the northwestern coast of Norway. Large sea surface eddies are generated by their unrelenting grinding of salt. Other tidal vortices worth mentioning include those occurring in the Naruto Straits in the Inland Sea of Japan, the Saint Malo in the English Channel, the Swilkie of Pentland Firth between Scotland and the Orkney Islands, and in the Bay of Fundy of eastern Canada. An excellent historical account can be found in Lugt (1993).

As scientific thought replaced the primeval mystical perceptions, it was then understood that circular fluid motion is one of the most basic mechanisms to effectively transport mass and energy in nature and technology. Today, ocean whirlpools are certainly not considered to be the outcome of any demonic or magical forces. Instead, these are naturally occurring phenomena that originate from the synergetic interaction of the gravitational attraction and wind-shear coupled with the morphology of the location, and probably enhanced by variations of the physical properties of the water such as differences in temperature and salinity near the site.

Naturally, the old mariners exaggerated the destructive power and size of these whirlpools. However, if one takes into consideration the relatively small size of crafts in antiquity, their modest thrust, the monstrous origin of these vortices along with the fear of the unknown, it is human nature to amplify their size and voracity. Even today, ocean whirls present a danger to fishing boats, yachts, and swimmers.

In this article will deal with the oldest report of a tidal vortex found in the epic poem *Odyssey*. It will concentrate on Rhapsody XII, and more precisely on the whirlpool Charybdis. Based on current understanding of the phenomenon and floating body dynamics, it will attempt to validate several of the observations made by the old sailors. Odysseus' strategy to navigate past Charybdis will be analyzed. The experience and observations of a Norwegian fisherman while inside the Maelström, as described by Edgar Allan Poe (1841) in his celebrated short story *A Descent into a Maelström*, will also be examined. It is interesting to note that aside from the supernatural origin, the old mariners made some surprisingly accurate descriptions of these whirlpools, displaying an intimate familiarity with the important dynamic properties of the event. But first let us look closer at the general properties involved in the theory of whirlpools.

2. Whirlpool Theory

The substantial mathematical complexities involved with the details of vortex phenomena have prevented the formulation of a general analytical model. Instead, many researchers in the past have developed semi-empirical theories that are only applicable to special circumstances such as for the case of strong isolated vortices. The simplest of the models that is still in use is credited to the great experimenter Rankine (1858). His idealized theory suggests that on approaching the center of the whirlpool from the periphery, the fluid velocity increases hyperbolically, reaching a maximum at a radius $R_c$ (also known as the core radius), and then to decline linearly to zero at the center of rotation. Because nature abhors abrupt changes, a more pragmatic simulation is provided
by the vortex model of Vatistas et al (1991) that is diagrammatically illustrated in figure 1.

There are three main forces involved in the formation of the liquid surface in a whirlpool. The force of gravity is pulling the fluid particles down thus trying to keep the liquid surface horizontal. The centrifugal force, due to the liquid rotation, pushes the fluid particles away from the center. The combined action of these two forces along with Archimedes' buoyancy, directs the system into a state of permanence, in which the free water surface attains the inverted bell-like shape of figure 2. Under this equilibrium condition, every fluid particle within the flow domain experiences no net force. Upon arrival of the system to the state of equilibrium all fluid particles will thus retain their last position at every subsequent time.

Due to centrifugal instability, vortices are also known to host a variety of waves (Lord Kelvin (1880) and Vatistas (1990)). These are generated near the axis of rotation and are then convected outwards. Inclusion of the latter effect, the free surface of the liquid is seen to be modulated by these waves as shown in figure 3. The actual surface profile of the tidal vortex near St. Malo in the English Channel is shown in figure 4. The resemblance of figures 4 and 3 is self-evident.

The dynamics of a floating body inside a whirlpool are given by Newton's second law which are mathematically represented by a set of two non-linear ordinary equations and a static condition given by an algebraic equation. Solution of these equations, along with the appropriate initial conditions enables us to investigate the ship dynamics (Vatistas (2001)).

Let us now assume for a moment that a ship is rotating around a whirlpool. Due to the slippage existing between the boat and the liquid, the velocity of the ship is lagging behind that of the fluid. Since the centrifugal force developed by the rotation of the ship is less than the value required to place the vessel into orbit around the pool, the three forces will not balance (figure 5). As a result, there will be a net force that acts along the liquid free-surface and makes the ship gravitate towards the center of rotation. The variation of this force, is shown graphically in figure 6, while a typical trajectory traced by the floating body while traveling towards the center of the vortex is presented in figure 7.

Archimedes' principle, provides the means to obtain the variation of the volume displaced by the boat. Figure 8 shows that the latter decreases with the radius, reaching a minimum value followed by an increase as the center of the pool is approached.

3. Homeric Gharybdis

Odysseus, the returning hero of the Trojan expedition, had to deal with the fury of the sea god Poseidon. The tragic encounters and misfortunes of the Greek hero can be found in the epic poem Odyssey. A trip across the Aegean sea up to Cape Maleas, and then sailing north through the Ionian sea towards the island of Ithaki that would normally have taken a few days lasted for ten years. Rhapsody VII of Homer's epic poem, among other matters, deals with Odysseus' handling of the two sea monsters Scylla and Charybdis. Although this is not the first encounter of ancient mariners with Charybdis, it is certainly the first clear recorded description of the tidal vortex. The earliest reference to this sea
monster is found in the tale of the Western world's foremost sea-journey of the Argonautika (Apollonius). Odysseus first hears about the tidal whirlpool Charybdis from the sub-goddess Circe who described her as follows:

"... this divine Charybdis sucks down the black water. Thrice a day she belches it forth, and thrice she sucks it down terribly. Mayest thou not be there when she sucks it down, for no one could save thee from ruin" (verse 105)

There must be a reason behind the cause of the phenomenon. During the draining process of a liquid from a container, a funnel-like free-surface develops with a strong downwards fluid motion. Floating matter is seen to be drawn inexorably into the funnel by the downwards moving current. But one needs a source to produce the required suction. In the absence of any other rational explanation from more primitive principles, the divine intervention of the sea-born beast named Charybdis is very convenient. From the above account, it is also obvious that this event is periodic and also reasonably coincidental with the frequency of ocean tides. The suction and belching parts of the cycle are indeed very convincing attributes of the model since it can explain why ships with their crews are brought to the depths of the sea followed by their reappearance in a disintegrated form subsequent to the burping phase. Circe also provides Odysseus instructions on how to effectively sail around the horrible monster,

"Nay, draw very close to Scylla's cliff, and drive thy ship past quickly; ..." (verse 110)

The presence of the phenomenon requires a physical evidence of its cause. In verse 205 Homer describes vividly a great wave that has all the properties of an incoming tidal bore:

"But when we had left the island (of Sirenes'), I presently saw smoke and a great billow and heard a booming. Then from the hands of my men in their terror the oars flew, and splashed one and all in the swirl, and the ship stood still ... " (verse 205)

Here the translator replaces the original κατὰ ρ’ ο’ον with in the swirl. The most accurate translation is however along the current (Tsigounis 1969). He also assigns the word booming for the original δούπον which, in my opinion, is not the most appropriate phonetic description of the actual ancient word. The expression δούπος is very particular and refers to the sound produced by dropping a dead animal on the ground. This characteristic sound can be phonetically reproduced using Cyrillic characters to form the sound "thwooop". An analogous sound is produced by a wave striking a rocky shore that has partially exposed under-water caverns. Since Homer mentions the presence of smoke (vapor), we infer that probably a tidal wave that was already had broken, struck with force on the shore opposite to Scylla's abrupt cliffs, and thus Charybdis was generated.

Homer's very clear observations regarding the whirlpool's physical manifestations are found in the following excerpt:

"We then sailed on up the narrow strait with wailing. For one side lay Scylla and on the other divine Charybdis terribly sucked down the salt water of the sea. Verily whenever she belched it forth, like a cauldron on a great fire she would seethe and bubble in utter turmoil, and high over head the spray would fall on the tops of both the cliffs. But as often as she sucked down the salt water of the sea, within she could all be seen in utter turmoil, and round about the rock roared terribly, while beneath the earth appeared black with sand; pale fear seized my men" (verse 235)
Since the phenomenon is dynamic in nature, it undergoes several phases of development. The powerful tidal bore in conjunction with the morphological characteristics of the site cause the generation of a vortex. In the presence of the centrifugal field the water surface begins to take the inverted "bell-like" shape. The central dip starts to propagate towards the sea bottom reaching a limiting value that depends on the vortex strength (figure 9). For extremely strong matured vortices, even the bottom of the sea may be exposed. The phrase "within she could all be seen in utter turmoil" needs closer attention. It is therefore reasonable to assume that Homer is describing the effects of instability waves that are known (Lord Kelvin (1880) and Vatistas (1990)) to accompany every vortex (figures 3 and 4).

Before we analyze the ship's trajectory and the instructions of Odysseus to his crew, it is important to summarize briefly the most salient fluid and ship dynamic properties. As mentioned previously, on the surface of the tidal vortex all forces acting on any fluid particle add up to zero. Therefore, no matter where the fluid particle resides, it will stay on the surface at all times. This is however not true for the floating body. Let us now assume that a ship is riding the whirlpool's surface. Because there is always a slippage between a boat and the current, the centrifugal acceleration due to the vessel's rotation about the whirlpool's axis will be less than that required to set the craft in orbit. Accordingly, its weight will drive the ship towards the interior of the vortex. If we now take into consideration the maximum available thrust generated by the oarsmen, the boat's hydrodynamic characteristics, and given its location on the surface, then we have the following three possibilities:

i. the tangential velocity of the approaching boat is less than the local velocity of the current,
ii. the tangential velocity of the boat is equal to the local velocity of the current,
iii. the tangential velocity of the approaching boat, is greater than the local velocity of the current.

In case i, the boat will be "attracted" by the whirlpool. In the second scenario, the ship will be put in orbit around the whirlpool. The third case is the rescuing possibility since a force greater than the whirlpool's centrifugal acceleration will "sling-shot" the vessel outwards. Given the hydrodynamic properties of a ship, the power available, and the strength of the vortex, every vessel is associated with a limiting circle (figure 10). For a trajectory of the boat along the current that is larger than this circle, the crew will survive to tell about the event and hence the designation "event horizon." The latter is reasonably analogous to the event horizon around neutron stars that are believed to dwell in the centers of galaxies.

Navigation through the fully developed Charybdis can be presented as a classical mini-max problem with a constraint. Given that they had to go through a fully developed Charybdis, Odysseus' navigational strategy must be drawn in such a way as to maximize their chances for survival. Steering the ship through the sea opposite to Scylla's shore would have presented a maximum resistance to the boat since it had to confront a head-on current (figure 10). This was not a viable option. Odysseus had to sail along the whirlpool's current. The ship's net attractive force parallel to the free-surface diminish as the radial location of the vessel increases. Odysseus must thus maximize the radial distance of the ship from the center of Charybdis and maximize the speed of his ship. The
only route available was thus to the right, i.e., steering the ship close to Scyllas' reef, "and drive thy ship past quickly". The first thing that Odysseus needed was to assure an uninterrupted maximum thrust. Therefore, he gives the following orders to the oarsmen: "Do you keep your seats on the benches and smite with your oars the deep surf of the sea, in the hope that Zeus may grant us to escape and avoid this death." (verse 215) ... But of Scylla I went not on to speak, a cureless bane, lest haply my comrades, seized with fear, should cease from rowing and huddle together in the hold." (verse 225)

There is one more matter that required his attention. Because the rotational speed of the water varies with the radius coupled with the presence of the helical instability waves, it is very possible that the ship could be rolled or swayed towards Scylla's reef or even towards the center of Charybdis, if the steer-man is not very attentive. Based on the previous properties, Odysseus gives the following orders to the helmsman: "And to thee, steers-man, I give this command, and do thou lay it to heart, since thou wieldest the steering oar of the hollow ship. From this smoke and surf keep the ship well away and hug the cliff, lest, ere thou know it, the ship swerve off to the other side and thou cast us into destruction." (verse 215)

The ancient Greeks were accustomed to the three forces involved, i.e., gravity, centrifugal, and buoyancy. There is also ample evidence that they had a qualitative knowledge of the main whirlpool properties, such as the formation of the dip at the center of a liquid vortex by observing the evolution of the free-surface while stirring wine. Did they however, hug Scylla's rock like one tries to avoid falling off a cliff by walking by instinct near the innermost side of a path at a fast pace, or did they act in this way by using the empirical love (attraction) and strife (repulsion) properties of the whirlpool? Whatever the reasons behind Odysseus' strategy he acted wisely. Giving the correct orders as described in Homer's Odyssey indicates that the ancient mariners had empirically developed their navigational skills through oceanic whirlpools.

Knowing what they knew about Charybdis, why then did Odysseus not wait for the apparently safer belching phase to cross the whirlpool? After all, that is exactly what he did when the currents drifted his raft for the second time towards Charybdis (see Rhapsody XII, verses 430 - 445). Did Homer take poetic license in order to make the adventure more dramatic or did they really sail during the belching phase but the strategy was drawn in such a way as to safely cross the channel even if the capricious Charybdis decided to begin the sucking phase prematurely? I am afraid that these questions cannot be answered without resorting to speculation.

4. Gharybdis of the North - The Maelström

Nordic tales refer to the existence of an enormous whirlpool that develops off the northern coast of Norway and is known as the Maelström. Recent results of large scale dynamic simulations by Gjevic et al (1997), as well as satellite images reveal the presence of these eddies. Their predicted fluid current values however fall short in comparison to the eddies described in the old literature. Nevertheless, lack of adequate data hampers the full validation of the numerical model. Furthermore, whirlpools like Charybdis or Maelström may require the synergy of tidal currents and excessive wind...
shear (probably of hurricane strength) thus making the phenomenon to be a rather rare occurrence.

Information concerning the interior properties of tidal vortices can be found in Poe’s (1841) short story. His narration focuses in the peerless experiences of an unfortunate Norwegian fisherman inside the whirlpool of Ström, who lived to tell his ordeal. Many scholars believe that Poe has exaggerated Maelström’s power, nevertheless we find that several descriptions and observations are in agreement with present day vortex theory.

The Norwegians, like the ancient Greeks, were very familiar with the manifestations and perils associated with tidal whirlpools and were very cautious when they had to navigate areas known to spawn oceanic whirls:

"You perceive that in crossing the Ström channel, we always went a long way up above the whirl, even in the calmest weather, and then we had to wait and watch carefully for the slack ..." (§ 30)

The expected circular orbit of the ship around the vortex as it slips by gravity towards the center is clearly described in the following passage:

"How often we made the circuit of the belt it is impossible to say. We cereered round and round for perhaps an hour, flying rather than floating, getting gradually more and more into the middle of the surge, and then nearer and nearer to its horrible inner edge." (§40).

But there must be more here than the circular trajectory that is described by the fisherman. Because the displaced volume of the ship reduces inwards together with the hyperbolic increase of the tangential velocity, it might have given the impression that the boat was flying than floating. Another indication that displacement of the boat decreases can be found in a preceding paragraph:

"the boat did not seem to sink into the water at all, but to skim like an air-bubble upon the surface of the surge." (§36).

After all, a skilled sailor will immediately detect anything abnormal that is occurring to the floating craft.

Sliding towards the core radius, the ship will increase in velocity but will be lagging behind that of the liquid. Depending on the rate of descent, and as the point of maximum velocity is passed, the boat's rotational velocity will approximately match that of the liquid inside the core, and go into orbit. If this happens, one will experience the following sensation,

"The sense of falling had ceased; and the motion of the vessel seemed much as it had been before while in the belt of foam, with the exception that she (the boat) now lay more along." (§40)

and the perception that

"The boat appeared to be hanging, as if by magic, midway down, upon the interior surface of a funnel vast in circumference, prodigious in depth, ..." (§42)

Depending on the hydrodynamic characteristics of the boat and the physical properties of the vortex, it is indeed possible that the boat, while spiraling towards the center, it might go into orbit at a specific radius, see figure 11. The physical reason behind such a peculiar situation is correctly identified, as well:
"I could not help observing, nevertheless, that I had scarcely more difficulty in maintaining my hold and footing in this situation, than if we had been upon a dead level; and this, I suppose, was owing to the speed at which we revolved." (§43)

Next the observations made about the interaction of the centrifugal instability waves at the center of the vortex due to the processing core are precisely described:
"The rays of the moon seemed to search the very bottom of the profound gulf; but still I could make out nothing distinctly, on account of a thick mist in which everything was enveloped, ... This mist, or spray, was no doubt occasioned by the clashing of the great walls of the funnel, as they all met together at the bottom - ..." (§43)

The small scale experiments in a laboratory whirlpool by Vatistas (1989) revealed a similar effect to take place near the axis of rotation.

When the fisherman's original terror had subsided, he then begun to make some observations regarding the dynamics of floating bodies inside the whirlpool. Upon reflection, the mariner crystallized on the following three most important general observations:
"I made also, three important observations. The first was, that as a general rule, the larger the bodies were, the more rapid their descent; - the second, that, two masses of equal extent, the one spherical, and the other of any other shape, the superiority in speed of descent was with the sphere: - the third, that, between two masses of equal size, the one cylindrical, and the other of any other shape, the cylinder was absorbed the more slowly. " (§47)

The velocity lag of a floating body with the stream of the whirlpool is a dynamic process, massive bodies take more time to increase their tangential velocity and the slip factor will in general be smaller than those of lesser mass. This will produce a larger net force along the free-surface that will drive the more massive ship downwards faster. Numerical simulations of two geometrically similar bodies one twice as large in linear dimensions (and therefore having a larger mass) than the other are shown in figure 12. It is clearly evident from the results that the descent into the whirlpool of the more massive body will be quicker than that of the smaller body.

The second observation is also due to different values of the velocity slip factor but now among bodies of different geometrical forms. A sphere being a more stream-lined body than a cylinder, it will present less drag and thus descend quicker into the whirlpool. The theoretical verification of the second observation, is presented in figure 13. It is also true that the more the drag of the object, the larger of is its orbit radius:
" ... at every revolution, we passed something like a barrel, or else the broken yard or the mast of a vessel, while many of these things, which had been on our level when I first opened my eyes upon the wonders of the whirlpool, were now high up above us, and seemed to have moved but little from their original station. " (§47)

Based on the results of the present analysis, the generalization given in the third observation appears however not to be true since a prismatic body is expected to descent even slower than the cylinder.

Realizing that cylindrical bodies descend slower than any other shape, the mariner plunges into the sea riding a barrel. After some time, the whirlpool begins to regress. The observations made during the whirlpool decaying process are also consistent with the vortex theory,
"The slope of the sides of the vast funnel became momentarily less and less steep. The gyrations of the whirl grew, gradually, less and less violent. ... , and the bottom of the gulf seemed slowly to uprise." (§51)

Based on the theory for a decaying vortex it is obvious that this is exactly what it is expected to happen. As time evolves, the tangential velocity (the gyrations) of the whirlpool decreases see figure 14 (a), the sides of the inverted bell-like surface become less steep, and the central surface depression gradually rises, see figure 14 (b).

Evidence of the first attempt by someone to explain aspects of the dynamics of floating bodies in a tidal whirlpool based on epistemological principles is in the following excerpt:

"Since my escape, I have had several conversations on this subject with an old schoolmaster of the district; ... He explained to me ... how what I observed was, in fact, the natural consequence of the forms of the floating fragments—and showed me how it happened that a cylinder, swimming in a vortex, offered more resistance to its suction, and was drawn in with greater difficulty than an equally bulky body, of any form whatever." (§48)

At this point, Poe cites the Latin translation of Archimedes' (300 BC), book II entitled "De Incidentibus in Fluido". We find the comment made by Andrade (1936) that "... there could hardly be anything less relevant to Poe's story..." unnecessarily critical. Poe, in paragraph 46, cites Archimedes' buoyant force as the sole fundamental principle to account for the slower descent of certain shaped bodies. Although this force is indeed present, it cannot single-handedly explain the observations, nevertheless it is not irrelevant.

Thomson (1973) writes on the fisherman's close escape from the whirlpool "Although he survives (probably by mere accident rather than by his careful observation of and submission to nature, since the mechanics of the hydraulic effect on geometric form is false), ...". We find Thomson's statement not to be correct since it has been shown that the observations made by the fisherman are consistent with the physics of the phenomenon.

It has been customary in the past to call narratives dealing with scientific themes tales of pseudo (false) -science that had as their main aim to deceive the reader by creating a false sense of reality through the employment of deceptive scientific principles. Poe, however, is not known to take such an approach in writing his remarkable tales of imaginative science. Instead, he would shape his story based on accessible facts adhering always heuristically to the method of constructive scientific thinking, Cody (1924). These attributes are amply evident in the story under consideration. According to Gjevic et al (1997), Poe in his story exhibits an intimate familiarity with the local landscape, stories, and fishing practices, that according to them can be traced to rather fictitious Nordic sources. Are all sources available to Poe fictional (Mabbott(1978), or were there some elements that refer to real experiences of old mariners like the fisherman's vivid descriptions and observations? The present analysis revealed that the most important remarks made by the Norwegian sailor are surprisingly consistent with the theory. There are two possible explanations for this, either that Poe used reverse science to construct his story, or he is describing the actual encounters of a mariner. If the former was the case, then it also reasonable to expect him to correctly identify the cause of the
observations given in paragraph 48. Furthermore, several of the details concerning the fluid mechanics of vortex flows were not available in 1841. Considering a balance of probabilities makes the second of the explanations to be the most credible.

5. Conclusions

Aside the supernatural origin of tidal whirlpools in antiquity and the not so distant past, it is evident from the descriptions of the phenomenon by Homer and Poe, which is also supported by our analysis, that the old sailors understood empirically a great deal of the dynamic properties of the naturally occurring phenomenon, and thus were able navigate oceanic whirlpools with considerable skill. Many scholars are of the opinion that Poe has exaggerated Maelström's power. However, all the principal observations made by the Norwegian mariner while inside the whirlpool of Ström were found to conform with the theory. We find that both Rhapsody XII of Homer’s *Odyssey* and Edgar Allan Poe's *A Descent into Maelstöm* contain credible information on oceanic vortices. Furthermore, in spite of approximately three thousand years of development in science, we find ourselves in the awkward position of not being able to suggest to Odysseus a substantially better navigational plan.

Dedication

The present work is dedicate to the memory of my grand father Georgios Charalampou Vatistas, a good natured man, a skillful mariner who, like Odysseus, knew to navigate by the stars, and to all of those seafarers from the region of Vatica who perished in the open seas.

REFERENCES


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Figure 1. Variation of the tangential velocity inside a strong vortex.

Figure 2. Inverted bell-like liquid free-surface profile.

Figure 3. Simulated interface shape under the influence of waves.

Figure 4. Actual surface profile of the tidal whirlpool near St. Malo in the English Channel (from Lugi (1993), Life Magazine ©1969 Time Inc.).

Figure 5. Forces acting on the floating body.

Figure 6. Variation of the attractive force with the radius.
Figure 7 A typical trajectory for a fast descent of the body.

Figure 8 Change of the vessel's submerged volume along the free surface.

Figure 9 Liquid interface shape as a function of the vortex strength.

Figure 10 Navigational map of the trajectory for Odysseus' ship.

Figure 11 A typical trajectory showing the solid body's orbit.
Figure 12 Axial velocity distributions as a function of time for two geometrically similar bodies with different mass.

Figure 13 Time history of the radial location of three solid bodies of different hydrodynamic resistance.

Figure 14 Velocity variation during the vortex decaying phase (a), free-surface attenuation during the whirlpool's spin-down phase (b).