##### Abstract

[Abstract I](#_Toc529005566)

[List of symbols III](#_Toc529005567)

[List of figures III](#_Toc529005568)

[List of tables VII](#_Toc529005569)

[1. Introduction 1](#_Toc529005570)

[1.1 Motivation of this work 1](#_Toc529005571)

[1.2 How do fish detect objects in water without using vision? 2](#_Toc529005572)

[1.3 Sensory organs of the LL 3](#_Toc529005573)

[1.4 Blind fish can detect non-moving obstacles 5](#_Toc529005574)

[1.5 Hydrodynamic imaging. 6](#_Toc529005575)

[1.6 Hydrodynamic stimuli 7](#_Toc529005576)

[1.7 Distance of detection 7](#_Toc529005577)

[1.8 Discrimination of shapes 9](#_Toc529005578)

[1.9 Role of neuromasts in object detection 10](#_Toc529005579)

[1.10 The shape of underwater robots 10](#_Toc529005580)

[1.11 Detection and identifying a body using bioinspired sensors. 11](#_Toc529005581)

[2. Theoretical works on hydrodynamic imaging 11](#_Toc529005582)

[2.1 Slender bodies approaching a wall 11](#_Toc529005583)

[2.1.1 Sphere approaching a wall or another sphere 15](#_Toc529005584)

[2.2 Detection of a body in the presence of current 15](#_Toc529005585)

[3. Objectives of this work 17](#_Toc529005586)

[4. A mathematical model of detecting of a sphere by a sphere 18](#_Toc529005587)

[4.1 Problem formulation 18](#_Toc529005588)

[4.2 Testing cases 23](#_Toc529005589)

[5. Numerical results 25](#_Toc529005590)

[5.1 The coefficients of the added mass and the repulsive force 25](#_Toc529005591)

[5.2 Sphere approaching a wall 28](#_Toc529005592)

[5.3 Two spheres 31](#_Toc529005593)

[6. Experimental investigation 34](#_Toc529005594)

[6.1 Experimental layout 35](#_Toc529005595)

[6.2 Construction of the sphere 36](#_Toc529005596)

[6.3 Pressure sensor 38](#_Toc529005597)

[6.4 Experimental results 39](#_Toc529005598)

[6.4.1 Pressure difference 39](#_Toc529005599)

[6.4.2 Detection distance 43](#_Toc529005600)

[7. Fish moving in a tube with current 44](#_Toc529005601)

[7.1 Experimental apparatus 44](#_Toc529005602)

[7.2 Experimental protocol and fish filming 45](#_Toc529005603)

[7.3 Image processing of fish trajectories. 47](#_Toc529005604)

[7.4 Results 50](#_Toc529005605)

[7.4.1 No obstacle in the pipe 50](#_Toc529005606)

[7.4.2 Trajectories in the pipe with an obstacle. 51](#_Toc529005607)

[8. References 54](#_Toc529005608)

[Appendises. 58](#_Toc529005609)

[8.1 Appendix A – Pump data sheet 58](#_Toc529005610)

##### List of symbols

*a* - radius of sphere *A*

*b* - radius of sphere *B*

*c* - distance between the spheres

 - location of sphere *A*

 - location of sphere *B*

 - added mass coefficient

-radius of a sphere

*h* - distance between the sphere and a virtual wall (or wall)

- detection distance

*L -* fish characteristic length

 - Reynolds number

*t -* time

 - velocity field vector

 - velocity of sphere *A*

 - velocity of sphere *B*

 - velocity potential of sphere *A*

 - velocity potential of sphere *B*

 - boundary layer thickness

 - total velocity potential

##### List of figures

[Figure 1. Prey and predator revealing each other in darkness. 2](#_Toc529005509)

[Figure 2. A Mexican Tetra (](#_Toc529005510)*[Astyanax mexicanus](#_Toc529005510)*[) gliding parallel to a wall in a corner of an aquarium (photo by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). The distance between the head of the fish and the front wall is approximately 25 mm in A, 14 mm in B, 8 mm in C, and 4 mm in D. 3](#_Toc529005510)

[Figure 3. The LL periphery according to Bleckman and Zelick (2009). The drawing shows the pores of the LL canals (circles) and the spatial distribution of superficial neuromast (dots). In most fish species, one canal runs above the eye (supraorbital), one canal runs below the eye (infraorbital), and one canal runs on the lower jaw (mandibular) (see also Montgomery, Coombs, and Baker, 2001). In some fishes, the trunk canal does not run the full length of the body (Bleckman and Zelick, 2009). Most fish have relatively few superficial neuromasts concentrated near the head and near the trunk of the LL system. 3](#_Toc529005511)

[Figure 4. Sketch of a superficial neuromast (not to scale). A typical superficial neuromast may be up to high and wide and may contain tens of hair cells (Triantafyllou, Weymouth and Miao, 2016). 4](#_Toc529005512)

[Figure 5. Superficial neuromast in a boundary layer of thickness . A. The velocity in the boundary layer of thickness  is zero on the skin of the body and reaches some value  on the conditional margin of the boundary layer and bending of a neuromast in the boundary layer due to the moment acting on it. B. Hydrodynamic force *D* acting on the cross-section of a neuromast. 4](#_Toc529005513)

[Figure 6. A sketch of a canal neuromast (not to scale). A CN is located between two adjacent pores in an under skin canal. It is larger than the SN, is of hundreds of microns in diameter, and contains hundreds to thousands of hair cells (van Natten, 2006). 5](#_Toc529005514)

[Figure 7. Schematic diagram of the LL of a Mexican Tetra illustrated on an image of a gliding Mexican Tetra in an aquarium of the laboratory of the Marine Hydrodynamics. The location of the pores and superficial neuromast is rather approximate and inspired by the drawings of Windsor et al. (2010a) and Schemmel (1967). 6](#_Toc529005515)

[Figure 8. The collision of a Mexican Tetra with a corner wall (photos by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). In frame C, the fish propels itself too close to the wall, and in frame D, the fish collides with it. In frames E–H, it does not move forward. Noticeably, in frame G, the fish moves slightly backward to provide more space for maneuvering (in the subsequent frames D–H, the fish does not move forward) 8](#_Toc529005516)

[Figure 9. Mexican Tetra approaching a corner wall (photos by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). The subsequent positions of the fish are shown from the upper left photograph A to the lower right photograph in the clockwise direction H. 8](#_Toc529005517)

[Figure 10. A. Ship avoiding maneuver with a turning radius double its length for typical ships and submarines. B. Fish avoiding maneuver with a turning radius half its length. 10](#_Toc529005518)

[Figure 11. Omni-Directional Intelligent Navigator (ODIN), which is owned and maintained by the Autonomous Systems Laboratory, College of Engineering, University of Hawaii 11](#_Toc529005519)

[Figure 12. Three images of fish A with respect to plane walls forming a corner. Image B provides the zero normal velocity on the vertical read line of the corner A. Image C provides the zero normal velocity on the horizontal blue line of the corner A. Image D provides the zero normal condition on the red line of the corner C and on the horizontal blue line of the corner B. Image C violates the boundary condition on the red line of the A-B corners and image D violates the boundary conditions of the A-C corners. Therefore, for small distances from the wall, the method of images is associated with an error. Nevertheless, for streamlined bodies that weakly disturb the fluid, the method of images gives reasonable accuracy and a transparent explanation of the physics of a body moving near the corner. The images also show that the flow in corner A is disturbed by the motion of four fish. If fish A is equipped with velocity and pressure sensors, it may perceive the variations of the velocity and pressure fields induced by fishes B, C, and D. 12](#_Toc529005520)

[Figure 13. Pressure coefficient and canal pores density along the body of a schematic fish (view from above). Solid line – pressure coefficient; dashed line – canal pores density (arbitrary units). The distribution density of the canal pores neuromasts correlates well with the location of the maximum differential hydrodynamic pressure on the fish’s body ( Ristroph, Liao, and Zhang, 2015; Dubois, Cavagna, and Fox, 1974). 13](#_Toc529005521)

[Figure 14. The normalized velocity  and the pressure coefficient  calculated for a two-dimensional and three-dimensional body according to Milne-Thomson (1968). Solid line – Joukovskii two-dimensional profile; dashed line– airship form. Each of the two bodies can be characterized by its slenderness, i.e., the ratio between the length of the body and its maximal width (or diameter). As long as these parameters for the bodies are close, the behavior of the pressure coefficients for them is qualitatively similar. For most slender fish, the rate of change of the pressure is the largest in their front part with a decrease towards the tail. 13](#_Toc529005522)

[Figure 15. Pressure distribution about a streamlined body of revolution representing the so-called airship form (redrawn and modified from Schlichting, 1979). 14](#_Toc529005523)

[Figure 16. Pressure distribution on a circumference of a sphere as a function of the polar angle calculated in the clockwise direction (in the forward stagnation, the polar angle). A. Dash-dotted line– subcritical (experiment); solid line–supercritical  (experiment); dashed line–potential flow theory (redrawn and modified from Schlichting, 1979) B. Subcritical (numerical solution of the Navier-Stokes equations, redrawn and modified from Bazilevs et al., 2014). 14](#_Toc529005524)

[Figure 17. The wake of a cylinder in a stream for different Reynolds numbers (adopted from Vogel, 1994). 16](#_Toc529005525)

[Figure 18. The coordinate system. The centers of both spheres are located on the](#_Toc529005526) *[](#_Toc529005526)* [axis of the fixed in space coordinate system . Another coordinate system  is attached to the body](#_Toc529005526) *[A](#_Toc529005526)* [and moves with it as a whole;  are unit vectors normal to the surfaces of the corresponding spheres](#_Toc529005526) *[A](#_Toc529005526)* [and](#_Toc529005526) *[B.](#_Toc529005526)* [The distance between the centers of the spheres is denoted as](#_Toc529005526) *[c](#_Toc529005526)*[, and the minimal distance between the surfaces of the spheres is denoted as](#_Toc529005526) *[h.](#_Toc529005526)* [18](#_Toc529005526)

[Figure 19. A. Two equal spheres moving in opposite directions with equal speeds and high Reynolds numbers. Due to symmetry, on the dashed line, velocities that are normal to it that are induced by the spheres cancel each other. In this case, this line can be imagined as a rigid wall on which the zero normal velocity is satisfied in the left and right half-spaces. B. A sphere moving away from the wall with velocity](#_Toc529005527) *[U.](#_Toc529005527)* [C. A finite radius sphere approaching a large one (); the latter can be considered as a rigid wall. 18](#_Toc529005527)

[Figure 20. Illustration of the method of images. Dipole](#_Toc529005528) *[A](#_Toc529005528)* [with intensity  is located in the point](#_Toc529005528) *[A](#_Toc529005528)* [at a distance](#_Toc529005528) *[C](#_Toc529005528)* [from the center of the sphere](#_Toc529005528) *[B](#_Toc529005528)* [of diameter](#_Toc529005528) *[b](#_Toc529005528)*[. 20](#_Toc529005528)

[Figure 21. Successive images introduced to satisfy the boundary conditions on moving sphere](#_Toc529005529) *[A](#_Toc529005529)* [and sphere](#_Toc529005529) *[B](#_Toc529005529)* [if its velocity . 21](#_Toc529005529)

[Figure 22. The element of the surface is  and the projection of the external normal to the sphere on the](#_Toc529005530) *[ox](#_Toc529005530)* [axis is . 24](#_Toc529005530)

[Figure 23. Added mass coefficient and velocity at the fore edge of the sphere at a small distance from the wall () with a changing number of images](#_Toc529005531) *[N](#_Toc529005531)*[. Solid line - ; dashed line -  . 26](#_Toc529005531)

[Figure 24. Added mass coefficient as a function of the normalized distance to the wall. The solid line – represents the calculation, the dashed line () represents the result by Kharlamov (2007) containing a method of images with the accelerated convergence of series, and the dash-dotted line () Yang (2006), dotted line () represents the result by Milne-Thomson (1968). 27](#_Toc529005532)

[Figure 25. The coefficient of the force acting on a sphere approaching a wall perpendicularly. Solid line – Lagrange’s equation; open circles – pressure integration. 27](#_Toc529005533)

[Figure 26. Normalized velocity on the meridian circumference of a sphere approaching a wall as a function of the distance](#_Toc529005534) *[h](#_Toc529005534)* [and the coordinate](#_Toc529005534) *[x](#_Toc529005534)*[: . For , the velocity on the meridional circumference coincides with that for . 28](#_Toc529005534)

[Figure 27. A and B: Streamlines in the plane  of a sphere approaching a wall from the left. C and D. Pressure coefficient on the same sphere. 29](#_Toc529005535)

[Figure 28. Pressure coefficient along the meridian circumference for different distances from a wall. 30](#_Toc529005536)

[Figure 29. Pressure coefficient in the stagnation point for small . The broken line – repesents the calculated pressure coefficient, and the square line – represents the approximated pressure coefficient . The figure shows the pressure coefficient behaves as  for small distances to the wall  30](#_Toc529005537)

[Figure 30. A sphere of radius](#_Toc529005538) *[a](#_Toc529005538)* [approaching another non-moving sphere of much larger radius A–B. Streamlines. C–D. Pressure coefficient. The more detailed analysis shows that the results presented in Figure 27 and Figure 30 are almost identical. 32](#_Toc529005538)

[Figure 31. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. . 33](#_Toc529005539)

[Figure 32. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. . 34](#_Toc529005540)

[Figure 33. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. . 34](#_Toc529005541)

[Figure 34. The experimental system. 35](#_Toc529005542)

[Figure 35. A sphere approaching a brittle wall. A. View from above. B. Side view. 1. Moving carriage; 2. Connecting tube; 3. Sphere; 4. Rigid wall; 5. Breakable wall. The center of the sphere was 0.35 m below the water free surface. 36](#_Toc529005543)

[Figure 36. Parts of the sphere. 1. Pressure holes (see Figure 37). 2. Front part of the sphere. 3. Sealed box containing the pressure transducers. 4. O-Ring preventing leaks between the two main parts of the sphere. 5. Inner connector. 6. Rear part of the sphere. 7. Connecting tube, connecting of the entire sphere to the moving carriage. 36](#_Toc529005544)

[Figure 37. Locations of the holes in the sphere. 37](#_Toc529005545)

[Figure 38. Schematic diagram of measured data processing. 37](#_Toc529005546)

[Figure 39. The Freescale MP3V5004G pressure sensor. A. An image of the sensor. B. A schematic description of the pressure sensor; a silicone diaphragm deforms according to the pressure difference. 38](#_Toc529005547)

[Figure 40. Sensor calibration. 39](#_Toc529005549)

[Figure 41. Pressure coefficient difference as a function of the time while the sphere approaches the wall (](#_Toc529005550)*[U](#_Toc529005550)*[= 0.5 m/s). The red circle indicates the contact of the sphere with the wall. A. Row signal. B. The same in logarithmic scale with error bars. 40](#_Toc529005550)

[Figure 42. Comparison of the experimental and theoretical pressure difference coefficients. The time  when the pressure difference attains the maximum. Solid line – theory; open circles – experimental results. A.](#_Toc529005551) *[U](#_Toc529005551)*[=0.5 m/s. B.](#_Toc529005551) *[U](#_Toc529005551)*[=0.6 m/s. C.](#_Toc529005551) *[U](#_Toc529005551)*[=0.5 m/s. D.](#_Toc529005551) *[U](#_Toc529005551)*[=0.6 m/s. 42](#_Toc529005551)

[Figure 43. Experimental pressure difference coefficient measured until the time of contact (](#_Toc529005552)*[U](#_Toc529005552)*[= 0.5 m/s). The open circle indicates the location and time when  43](#_Toc529005552)

[Figure 44. Schematic experimental setup. A. Top view. B. Side view. 44](#_Toc529005553)

[Figure 45. A blind Mexican cave fish avoiding an obstacle in a tube. The fish  long is swimming in a pipe with a diameter of . Photos displayed with a difference of 0.2 sec. 1. Fish approaches the obstacle. 2. Fish starts the avoiding maneuver. 3 and 4. End of the avoiding maneuver. 5. Fish moves towards the wall of the tube. 6. Fish perceives the tube and starts the avoiding maneuver. 7 and 8. End of the avoiding maneuver. 45](#_Toc529005554)

[Figure 46. Flow visualization past a cylindrical obstacle placed in a tube. , . 46](#_Toc529005555)

[Figure 47. Fish colliding with the obstacle while swimming against the stream in a tube with fluorescein. . Photos displayed with a difference of 0.2 sec. 1 and 2. fish gliding towards the obstacle. 3. Tail beat close to the obstacle. 4. fish collides with the obstacle. 5 and 6. Fish swims backward. 7 through 9. Fish performs an avoiding maneuver. 47](#_Toc529005557)

[Figure 48. Fish avoiding an obstacle. 47](#_Toc529005558)

[Figure 49. The coordinate system of an image with a fish. The origin of the coordinate system](#_Toc529005559) *[Oxy](#_Toc529005559)* [is chosen in the upper corner of the image. The red star denotes the fish nose. 48](#_Toc529005559)

[Figure 50. Image processing steps. A. Original image. B. The result of comparison between the image and the background image using the Matlab function "imabsdiff”. C. Converting the resultant image B to a black-white image using the Matlab function “im2bw”. D. Building the contour (red dashed line) and locating the nose of the fish (astrix), the endpoint of the body (circle) and the centroid (cross) using the Matlab functions “bwboundaries.m” and “regionprops.m”. The Matlab code is shown in Appendix A. 49](#_Toc529005560)

[Figure 51. The trajectory of the nose of a fish swimming in the tube. A. Top view. B. Side view 50](#_Toc529005561)

[Figure 52. The trajectory of the nose of the fish in a tube without an obstacle. 50](#_Toc529005562)

[Figure 53. Fish approaching an obstacle in the pipe without current (). 51](#_Toc529005563)

[Figure 54. Trajectories of fish in the pipe with an obstacle . A. fish approaches an obstacle in the direction of water flow. B. fish approaches an obstacle against the direction of water flow 51](#_Toc529005564)

[Figure 55. The trajectory of fish in a tube with an obstacle and a current of . A. Swimming in the direction of the current; B. Swimming against the current. 52](#_Toc529005565)

##### List of tables

[Table 1. The minimum number of images  required for calculating the pressure coefficient and the velocity on a sphere with  as a function of the distance to the wall  is presented in the second and third columns. 26](#_Toc529005611)

[Table 2. Parameters of the spheres and the corresponding figure numbers 31](#_Toc529005612)

[Table ‎3. Average detection time and distance at three velocities 43](#_Toc529005613)

[Table 4. The probability of the fish entering an imaginary cylinder around the obstacle. 53](#_Toc529005614)

[Table 5. Chance of collision with an obstacle depending on the direction of motion. 53](#_Toc529005615)

# 

# Introduction

## Motivation of this work

Inspecting marine infrastructures such as dams, ports, marine gas/oil platforms, and piping systems have become important marine operations in the 21st century. Underwater system systems require frequent inspection and replacement subsea components. Given that divers may work only at limited depths and for a limited time and considering the potential risk of underwater labor, remotely operated underwater vehicles (ROVs) and autonomous underwater vehicles (AUVs) are considered potentially important instruments for sea exploration (Griffiths, 2002.). Offshore oil and gas installations are presently serviced mainly by remotely operated vehicles (ROVs) that receive power through a cable that connects an ROV with the operating center. The long tether is not simple to operate, especially for large depths, motivating the use of autonomous underwater vehicles (AUVs). Nowadays, AUVs are frequently named as robots, and the entire field related to the manufacturing and exploiting of AUVs is robotics. In fact, AUVs are nothing more than unmanned automated submarines and are always becoming more and more sophisticated. AUVs are currently used for scientific survey tasks, oceanographic sampling, underwater archeology, under-ice survey, mine detection, and landing site survey. Today, approximately 200 AUVs are operational. Although many of them are still experimental, the progress in the design and the use of AUVs is rapid. In order to navigate without collision in a complex sea environment near other moving and nonmoving objects, an AUV must be able to detect them, to estimate the distance to them, and to avoid collision with them and to reconstruct their form. To create an image of an inspected objects, ROVs/AUVs are typically equipped with sonars and/or photo cameras. Although considerable progress has been achieved in developing underwater cameras, the related software for the processing of digital images (Kocak et al., 2008) vision in murky or deep water with low illumination is still much less effective than that in the air. Thus far, sonars serve as a primary tool for underwater navigation (Paull et al., 2014).

However, in sonars of AUV also have limitations. Due to the wide beam frequently used in sonars, their directional resolution may be insufficient for certain purposes of decocting and recognizing objects. For instance, because of the specular reflection of the acoustic wave sent to a smooth plane surface at oblique angles of incidence, the reflected signal does not return to the transmitter, making an object with planar surfaces invisible for an AUV. In addition, in domains of complex geometry, the multiple reflections can produce images of non-existing objects.

In this context, marine engineers are interested in studying technologies of detecting underwater objects by AUVs that do not use optical or acoustic means. Nature seems to indicate that these means exist, but it is still unclear how to harness this technology and means.

## How do fish detect objects in water without using vision?

As it is difficult to imagine that eyes, although useless, could be in any way injurious to animals living in the darkness, I attribute their loss wholly to disuse.

Darwin (1859)

Typically, most aquatic animals use vision for orientation in space, hunting, foraging, and avoiding predators.

|  |
| --- |
|  |

Figure 1. Prey and predator revealing each other in darkness.

However, in addition to vision, cartilaginous/bony fishes and aquatic amphibians developed a means that allows them to perceive the motion of other animals even in full darkness. This means is called the *mechanosensory lateral line*, or commonly called the LL. Living fishes constitute about 25,000 species comprising about 50% of all vertebrates, and they all have an LL, suggesting that it is the most ancient and important sensory organ of fish (e.g., Dijkgraaf, 1963; Bleckmann, 2006; Coombs and Mongomery, 2014). Although the LL has been known and has been described more than three and a half centuries ago (e.g., Parker, 1904) it still attracts the close attention of biologists, physicists, and engineers (for further general information, refer to the recent book by Bleckmann, Mogdans, and Coombs in 2014). Today, the terminologies of physics, engineering, and shipbuilding has been enriched with a new expression of *artificial LL,* referring to continuous attempts to create man-made sensors that mimic the LL system.

The structure of the fishes’ lateral line has been described in such a huge body of works that not all of them can be acknowledged here. Therefore, the reader is sent only to a few of them that are considered the most relevant for our study (e.g., Dijkgraaf, 1963; Montgomery, Coombs, and Baker, 2001; van Netten, 2006; Bleckmann, 2006; McHenry, Strother, and van Netten, 2008; Coombs and Mongomery, 2014). According to a generally accepted paradigm in the biology of aquatic animals, the LL allows them to detect the water velocity field and pressure gradients in a thin boundary layer of viscous fluid adjusted to their skin.

From the mechanic and hydrodynamic perspective, a fish is a time-varying deformable body. To describe in full detail its motion and, correspondingly, the functioning of the LL is extremely difficult, if possible. Therefore, to understand the hydrodynamic functioning of the LL, simplifications of fish motion seem inevitable. The so-called fish gliding motion is one of such useful simplifications, which is frequently used in fish hydrodynamics. During the so-called gliding regime, a fish moves approximately along a straight line whereas its body preserves approximately the same shape. An example of such a motion is illustrated in Figure 2.

|  |  |
| --- | --- |
| A | B |
| C | D |

Figure 2. A Mexican Tetra (*Astyanax mexicanus*) gliding parallel to a wall in a corner of an aquarium (photo by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). The distance between the head of the fish and the front wall is approximately 25 mm in A, 14 mm in B, 8 mm in C, and 4 mm in D.

The gliding motion concept allows dimensionless hydrodynamic quantities to be introduced, and this concept is generally accepted in the hydrodynamics of rigid bodies.

## Sensory organs of the LL

The sensory organs of the LL are called neuromasts and consist of two types. Neuromasts that are located on a fish's skin are called *surface neuromasts* (SN), while neuromasts that are located beneath the skin in small diameter canals are called *canal neuromasts* (CN). A sketch of the distribution of the superficial and canal neuromasts is shown in Figure 3.

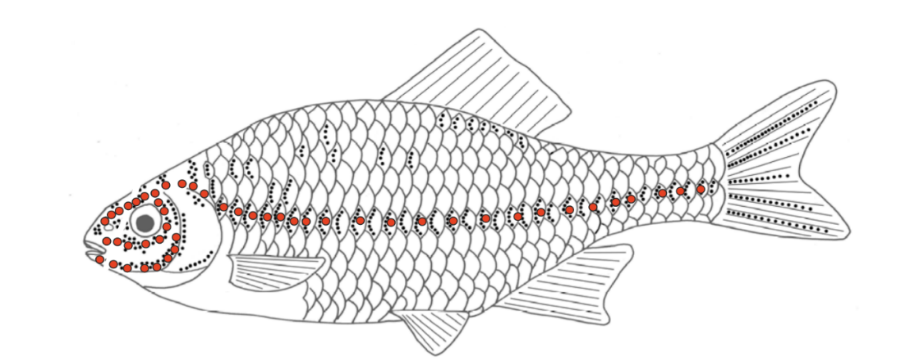


Figure 3. The LL periphery according to Bleckman and Zelick (2009). The drawing shows the pores of the LL canals (circles) and the spatial distribution of superficial neuromast (dots). In most fish species, one canal runs above the eye (supraorbital), one canal runs below the eye (infraorbital), and one canal runs on the lower jaw (mandibular) (see also Montgomery, Coombs, and Baker, 2001). In some fishes, the trunk canal does not run the full length of the body (Bleckman and Zelick, 2009). Most fish have relatively few superficial neuromasts concentrated near the head and near the trunk of the LL system.

Both types of neuromasts consist of a *cupula* and sense hairs inside it. LL neuromasts are innervated by afferent nerve fibers. When the hairs deform, the nerves obtain a signal that is transferred to the fish’s nerve system (Montgomery 2000; Montgomery, Coombs, and Baker, 2001; van Netten, 2006; McHenry Strother and van Netten, 2008). Figure 4 illustrates the function of a superficial neuromast. Different local drag forces in different cross-sections along a cupula create a bending moment acting on it. This bending leads to the deformation of the cupula and deformation of the bundle of sensing hairs. Because the drag and the fluid velocity in the boundary layer of a fish's skin are directly related, the surface neuromasts are viewed as the sensors of the fluid velocity near the fish.

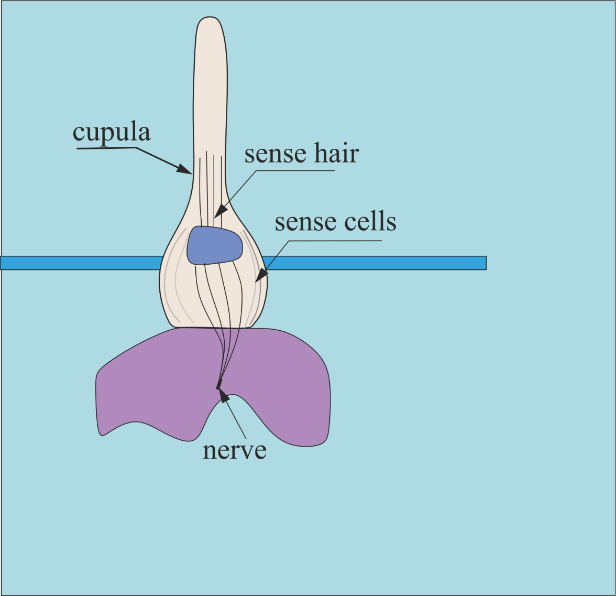


Figure 4. Sketch of a superficial neuromast (not to scale). A typical superficial neuromast may be up to high and wide and may contain tens of hair cells (Triantafyllou, Weymouth and Miao, 2016).

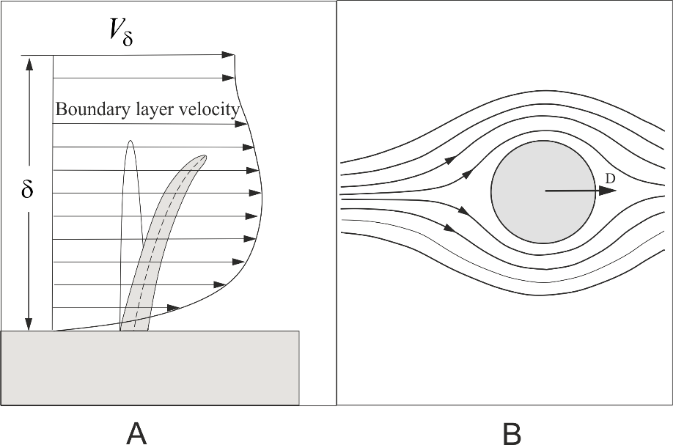


Figure 5. Superficial neuromast in a boundary layer of thickness . A. The velocity in the boundary layer of thickness  is zero on the skin of the body and reaches some value  on the conditional margin of the boundary layer and bending of a neuromast in the boundary layer due to the moment acting on it.  
B. Hydrodynamic force *D* acting on the cross-section of a neuromast.

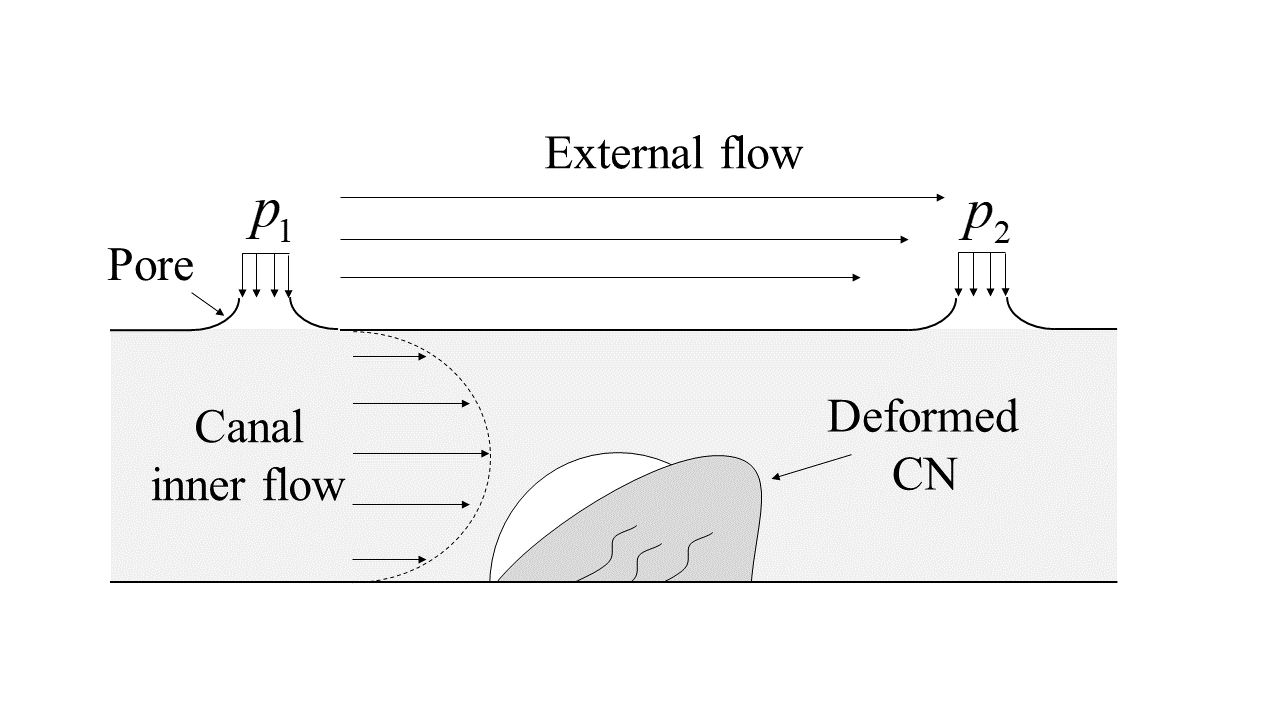


Figure 6. A sketch of a canal neuromast (not to scale). A CN is located between two adjacent pores in an under skin canal. It is larger than the SN, is of hundreds of microns in diameter, and contains hundreds to thousands of hair cells (van Natten, 2006).

The pressure gradient in the canal, as illustrated in Figure 6, induces slow motion of a fluid inside it. The normal and shear stresses on the surface of a cupula related to this flow lead to a deformation and bending of the sensing hairs inside it (Bleckmann 2006, Montgomery 2000; Montgomery, Coombs & Baker, 2001 McHenry 2008; van Netten, 2005, 2006; McHenry, Strother and van Netten, 2008). Therefore, canal neuromasts are considered sensors of pressure gradients.

## Blind fish can detect non-moving obstacles

By using their LL, fish can detect moving objects, creating water motion. In his seminal review of his own and previous works of others biologists, Dijkgraaf (1963) reported that Hofer (Hofer, 1908) in 1908 observed a pike with dimmed vision that swam in a tub at a certain distance from the wall without touching it. Moreover, a ruler of 4 cm width held in the animal’s way was perceived at a distance of about 0.5–1 cm. These avoiding reactions disappeared after the cauterization of the canal organs of the LL on the head of the fish. Thus, Hofer (1908) concluded that the fish observed could "feel at a distance" with its LLs.Referring to his own work performed in 1934, Dijkgraaf (1963) describes a distant perception of the walls of an aquarium by blinded fish *Corvina* (25cm in length). When a *Corvina* fish approached the aquarium wall perpendicularly, this obstacle was detected at a distance of about 1–2 cm. In addition, experiments with sighted but surgically blinded fishes are harmful to the animal and technically difficult. Thus, it is much more convenient to perform experiments with a non-surgically operated and 100% healthy fish than with a surgically or chemically treated fish. Ideally, experiments with fish that were born blind would be desirable.

The Blind Mexican Tetra (*Astyanax mexicanus*) or Mexican Tetra gives such a unique opportunity. Mexican Tetra fish live in caves at full darkness and do not need eyes to survive, and over 530 papers and reports have been published on the Mexican Tetra since 1936 (Keene, Yoshizawa and McGaugh, 2015). Discussing all of them even in the context of the present study is unnecessary; consequently, this review only considers the most recent works relating directly to the present study.

It is generally accepted that Mexican Tetra does not emit any sound or electrical signal and that its LL system solely enables them to sense moving and non-moving objects (e.g., Dijkgraaf, 1963; Campenhausen, Riess and Weissert, 1981; Teyke, 1985). As in all cartilaginous and bony fish, the LL of Mexican Tetra consists of superficial and canal neuromasts (Figure 7).



Figure 7. Schematic diagram of the LL of a Mexican Tetra illustrated on an image of a gliding Mexican Tetra in an aquarium of the laboratory of the Marine Hydrodynamics. The location of the pores and superficial neuromast is rather approximate and inspired by the drawings of Windsor et al. (2010a) and Schemmel (1967).

The length of this Mexican Tetra illustrated Figure 7 is approximately 6 cm, the maximum width is approximately 0.9 cm, and the ratio of its height to length is about 0.25. The speed of the Mexican Tetra fish in laboratory conditions varies from 2 cm/s to 10 cm/s. The original photo of Mexican Tetra was manipulated to add the canal pores (blue circles with white outlines) and superficial neuromasts (small blue dots), and it is assumed that a canal neuromast is located approximately midway between each pair of pores.

Comparing the LLs of a sighted fish (Figure 3) and of Mexican Tetra (Figure 7) shows that their principal features are the same. The distribution of canal neuromasts on the blind Mexican Tetra is similar to most fish (Montgomery, Coombs, and Baker, 2001). However, the SN neuromasts of Mexican Tetra are larger and the density of neuromasts in the head area of the Mexican Tetra is higher and assumingly more sensitive than those of surface fish (Yoshizawa et al., 2014).

## Hydrodynamic imaging.

The name given by Dijkgraaf (1963) to the ability of blinded fish to detect non-moving obstacles was *distant touch*. Apparently, this figurative expression is deeper and more informative than the rather formal term *hydrodynamic imaging*, which is accepted today in the scientific literature to describe the same phenomenon. In fact, obstacle avoiding is associated with a distant touch (which actually implies no touch), and a real touch of obstacles by a fish's head and fins when a fish explores them for the first time. In this respect, Dijkgraaf (1963) makes an important remark:

"Of course, ... care must be taken to avoid animals’ learning by trial and error where the obstacles are and memorizing their spatial relationship... They may become so well acquainted with this relationship that they collide with solid surfaces after a re-arrangement of the aquarium because they depend on memory rather than on mechanical sensory cues... "

Teyke (1988) confirmed Dijkgraaf's observation and concluded that the Mexican Tetra creates a cognitive internal map and keeps the memory of that map for about two days. Windsor, Tan, and Montgomery (2008) reported that the fins of the Mexican Tetraoften contact the wall as the fish swims near it, leading them to conclude that numerous tactile contacts of a Mexican Tetra with obstacles may be used to create and memorize a map of its surroundings. In agreement with Windsor (2008), Patton et al. (2010) demonstrated that depending on the shape of an aquarium, blind Mexican cave fish could follow the walls of an aquarium even after inactivating the LL system. However, Windsor, Paris, and de Perera (2011) later argued that constructing a map only by touching the obstacles may have place only when the LL of a fish is disabled; when it is functioning, the LL based hydrodynamic imaging dominated the wall detecting process.

In this work, the expression hydrodynamic imaging is used. It implies that the image of the surrounding is formed in the blind fish’s brains only by means of the LL without tactile stimuli.

## Hydrodynamic stimuli

As a fish moves through water, it creates hydrodynamic disturbances. When considering a gliding fish, it can be assumed that the velocity field and the pressure gradient in a coordinate system attached to the fish are stationary. When a fish glides in unbounded fluid with constant velocity *U*, it is a good approximation to represent the water velocity **V** and water pressure *p* in a fish's boundary layer as being proportional to *U* and , correspondingly:

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where the normalized velocity  and the pressure coefficient  depend mainly only on the parameters defining the fish body shape and on the Reynolds number

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where *L* is the characteristic length of the fish and  is the water kinematic viscosity. When a fish moves in a confined area in the presence of other bodies, the normalized velocity and the pressure coefficient depend on the fish's body shape and on the time-varying geometric parameters, defining the disposition of the fish with respect to other bodies. For instance, in Figure 2,  depend on the distance between the head of the fish and its side from the two walls of the corner.

## Distance of detection

A fish approaching a wall hits it approximately 15% of events, and an example of a collision event is shown in Figure 8.

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| E | F | G | H |

Figure 8. The collision of a Mexican Tetra with a corner wall (photos by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). In frame C, the fish propels itself too close to the wall, and in frame D, the fish collides with it. In frames E–H, it does not move forward. Noticeably, in frame G, the fish moves slightly backward to provide more space for maneuvering (in the subsequent frames D–H, the fish does not move forward)

According to many experiments, Teyke (1985) revealed that the collision event strongly depends on the distance from an obstacle at which a fish beats its tail for the last time approaching a wall. Tayke (1985) found that when this distance is less than approximately half the fish’s body length, the collision was almost unavoidable. In Figure 9, subsequent positions of Mexican Tetra approaching a corner are shown.

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| E | F | G | H |

Figure 9. Mexican Tetra approaching a corner wall (photos by G. Zilman, Laboratory of Marine Hydrodynamic, Dept. Mechanical Engineering, Tel Aviv University). The consequent positions of the fish are shown from the upper left photograph A to the lower right photograph in the clockwise direction H.

It is difficult to determine only based on the photos at which distance from the corner the fish detects it. An indirect indication of the corner detection may be the moment when the fish starts to open the fins to prepare the turning maneuver. In Figure 9, this opening occurs between positions E and F. If this assumption is true, then the fish detected the corner when the distance between its head and the wall perpendicular to the direction of the fish's motion is about 2.7 cm, approximately half its body length, which is consistent with observations of Teyke (1985), Hassan (1986), and Windsor (2008). If the assumption that fish try to avoid collisions is made, then it follows that they have to stop to propel themselves deliberately at a certain safe distance. According to Montgomery, fishes can detect the motion of another fish at a distance approximately equal to its body length. The mathematical model of the distant touch and observations of Teyke (1983) and similar observations illustrated in Figure 9 are consistent with Montgomery’s observations. In such a case, it is unclear why Mexican Tetra performs an avoiding maneuver at much smaller distances of the order of 2–4 mm when they can detect obstacles at distances of the order of their length.

Surprisingly, these distances do not depend on fish velocity (Teyke 1985, 1988, 1989; Windsor, Tan, and Montgomery, 2008; Windsor, 2014 and others) and according to independent observations. Seemingly, this experimental evidence strongly contradicts with the hypothesis that the stimuli of the LL of fish are the water velocity and pressure gradient on their bodies. The velocity of the thin boundary layer of a fish's body is proportional to the speed of the fish, and the pressure gradient is equal to the velocity squared. Nonetheless, it is unclear why fish perform the avoiding maneuver at the same distance from a wall independent of their speed.

The only explanation that is given so far in the scientific literature is formulated in the purely biological language by invoking the concept of just noticeable difference (JND) of Weber's fractions (Windsor at al. 2010). It is based on the discovery of German anatomist and physiologist E. H. Weber who studied the ability of humans to discriminate between weights in each hand. He found that a person is unable to discriminate between two weights if the relative difference between them is less than 5%. For instance, a person cannot discriminate between 41 g and 40 g weights (the relative difference in weights is 2.5%), but they can usually discriminate between 21 and 20 g or 63 and 60 g (the relative difference is 5%). From these observations in 1834, Weber formulated a law that a given intensity of stimulation is proportional to the original stimulus for the JND. Remarkably similar results were discovered for sound, light, smell, and taste stimuli. In general, it was discovered that if *S* is the magnitude of a stimulus and (JND) is the JND for discrimination, then the ratio of the JND and the initial stimulus is constant

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where k is a certain constant that varies for different physical processes of sense. The noticeable differences in sensation occur only when the increases (or changes) in stimuli are a constant percentage of the stimulus itself. If Mexican Tetra detects objects using hydrodynamic stimuli, then and *S* are proportional to the same power of a fish's speed and their ratio does not depend on it. However, although Weber's law can be applied for stimuli such as sound, light, smell, and taste stimuli, there is still no direct proof that it can be applied to the stimuli of the LL of fish. The problem with maximum detecting range is strongly related to the ability of fish to memorize maps whose scales are much larger than the minimal distance of the avoiding maneuver, i.e., approximately a tenth of the body length (Windsor et al., 2008, Windsor, 2014).

Recently, Holzman, Finkel, and Zilman (2014) noticed that Mexican Tetra fish swimming in an unfamiliar environment open and close their mouth at a higher frequency than in open water, particularly when a fish was heading to an obstacle. Based on these observations, Holzman, Finkel, and Zilman (2014) hypothesized that the Mexican Tetra uses mouth suction to create a hydrodynamic signal that varies with the distance to an obstacle and is weakly dependent on a fish's velocity.

## Discrimination of shapes

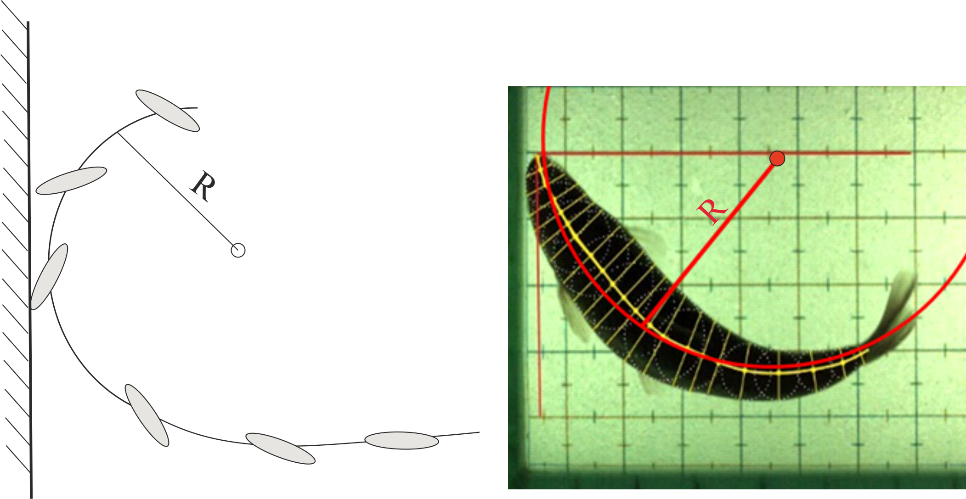
Hassan (1986); Von Campenhausen, Riess, and Weissert (1981); and Weissert and von Campenhausen (1981) in a series of experiments demonstrated that Mexican Tetra can discriminate the shape of a horizontal or vertical rectangular door and different grids of vertical bars. De Perera (2004) checked the ability of the blind cave fish to encode size and shape by placing four landmarks (Lego bricks) in a water tank and checking the fish’s behavior after altering the landmarks’ configuration. After changing the arrangement of landmarks, the fish started to swim faster, exploring the area as an unknown area. The increase in the speed of Mexican cave fish was explained by Teyke (1988) as an attempt to increase the hydrodynamic stimuli. Using only this argument, de Perera claimed that Mexican Tetra fish can detect a change in distance between objects. This explanation contradicts the experimental evidence that the distance of detecting objects does not depend on a fish’s swimming velocity.

## Role of neuromasts in object detection

There is an overlap of the SN and CN functions (Montgomery, Coombs, and Baker, 2001), and to determine the role of SN and CN in the fish’s object detection, researchers disabled the neuromasts, physically or chemically, and then observed the fish’s behavior. Fish with disabled SN can detect objects as fish with acting SN, but fish with disabled CN completely or partially lose their ability to do that. Today, it is agreed that the CN function is mostly related to the investigating of the surroundings and that SN detects oscillating stimulations in the water (Abdel-Latif, Hassan, and von Campenhausen, 1990; Hassan, Abdel-Latif, and Biebricher, 1992; Montgomery, Coombs, and Baker, 2001, Windsor, Tan, and Montgomery, 2008).

## The shape of underwater robots

It is not sufficient to detect an obstacle by a moving body. It is necessary to avoid it. Then, if the distance of detection is small, performing an avoiding maneuver may be a problem. For example, most ships and fishes are slender, as dictated by the need to reduce the energy demanded to maintain their speed. As a body is more slender, it is more stable at traveling on a straight course and is more difficult to turn. For most slender bodies, the turning radius is double the length (Figure 10A), while the turning radius of a fish is approximately half the fish length (Figure 10 B).



A B

Figure 10. A. Ship avoiding maneuver with a turning radius twice its length for typical ships and submarines. B. Fish avoiding maneuver with a turning radius half the fish’s length.

It is technically difficult and expensive to build a submarine that can change its shape as a living fish. Therefore, the engineering community started to design spherical underwater vehicles with high turning capabilities. One of the possible solutions of this problem is to use a spherical underwater vehicle instead of a typical slender body because the turning radius of a spherical marine vehicle can be orders of magnitude smaller than that of a slender body of the same length (see e.g., Choi and Yuh, Yue, Guo and Du, 2012, 1993; Chyba et al., 2008; Lin et al., 2009; Guo et al., 2011; Rust and Asada, 2011; Mazumadar et al., 2013; Yue, Guo and Shi, 2013; Li, Guo and Yue, 2015, patent <http://www.google.com.pg/patents/US4455962).(need> to read and add them to the bibliography).

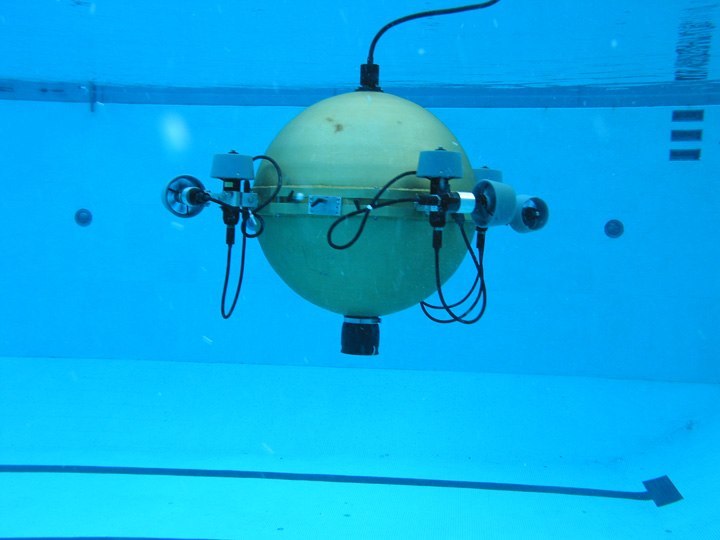


Figure 11. Omni-directional intelligent navigator (ODIN) that is owned and maintained by the Autonomous Systems Laboratory, College of Engineering, University of Hawaii.

https://math.hawaii.edu/stomp/STOMP/gallery/O8.html

In this context, the classical solutions of a sphere approaching an obstacle have gained new interest.

## Detection and identifying a body using bioinspired sensors.

Bioinspired and biomimetic sensors were described by many studies investigating several concepts including thermal, piezoresistive, capacitive, magnetic, piezoelectric, MEMS, and commercial pressure sensors-transducers. Detailed reviews of all investigations in this field are beyond the scope of the present work. Recent reviews by Tao and Yu (2012); Bleckmann, Mogdans, and Coombs (eds.) (2014); and Triantafyllou, Weymouth, and Miao (2016) present considerable relevant information on this subject.

# Theoretical works on hydrodynamic imaging

## Slender bodies approaching a wall

When a fish approaches an obstacle, the obstacle alters the velocity and pressure fields on the fish skin and creates a temporal signal. It is also generally accepted that Mexican Tetra can detect signals using its LL and translate them into knowing its distance from the obstacle. One of the simplest methods used to understand the physics of hydrodynamic imaging is based on the premises of potential flow and method of images, and the method is illustrated in Figure 12.

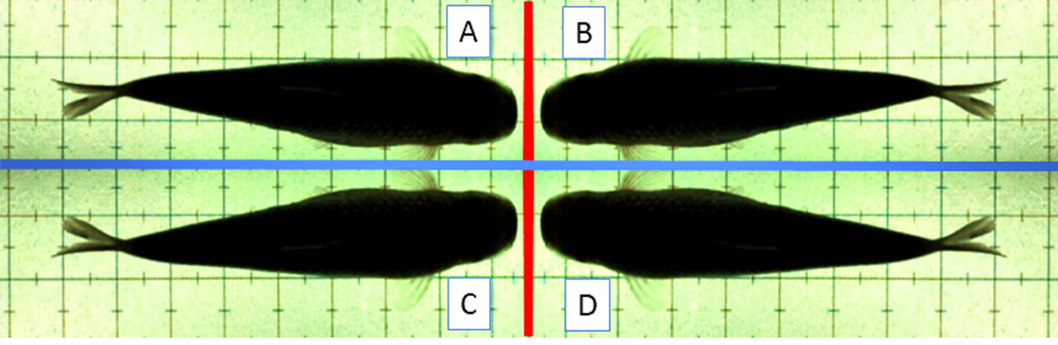


Figure 12. Three images of fish A with respect to plane walls forming a corner. Image B provides the zero normal velocity on the vertical read line of the corner A. Image C provides the zero normal velocity on the horizontal blue line of the corner A. Image D provides the zero normal condition on the red line of the corner C and on the horizontal blue line of the corner B. Image C violates the boundary condition on the red line of the A-B corners and image D violates the boundary conditions of the A-C corners. Therefore, for small distances from the wall, the method of images is associated with an error. Nevertheless, for streamlined bodies that weakly disturb the fluid, the method of images gives reasonable accuracy and a transparent explanation of the physics of a body moving near the corner. The images also show that the flow in corner A is disturbed by the motions of the four fish. If velocity and pressure sensors are placed on fish A, they may perceive the variations of the velocity and pressure fields induced by fishes B, C, and D.

Using the method of images is valid for large distances of a fish to the walls of the corner. Handelsman and Keller (1967) considered a slender body of revolutions approaching perpendicularly or parallel to a wall and giving an asymptotic solution of the problem as an expansion of the velocity potential in Taylor series with respect to a small parameter that was the inverse slenderness of the body. Based on Handelsman and Keller (1967), Hassan (1992) attempted to calculate the pressure on a slender body of revolution approaching a wall. Also, according to Hassan (1992), there is a pressure rise in the stagnation point of the body up to a distance of about 0.05 body lengths from the wall but a decrease in pressure for closer distances. However, this result is unclear and was not explained in Hassan’s (1992) work.

Windsor et al. (2010) calculated the pressure and velocity on a fish's body using Navier-Stokes equations and measured the velocity field using a particle imaging velocimetry technique. In particular, Windsor et al. (2010) demonstrated that the pressure gradient in the stagnation point of the body of revolution approaching a wall drastically increases as the distance to the wall decreases. Then, as approaching the wall from a distance of 0.3 to 0.02 body lengths of the fish, the pressure coefficient  at the stagnation point increased from 1.0 to over 4.0, but for pressure downstream, the stagnation point remained approximately the same as in open water. In contrast to the results of Hassan, no pressure drop was revealed. Furthermore, Windsor et al. (2010) found that for relatively small Reynolds numbers of the problem and small distances to a wall, the viscosity may influence the pressure quantity close to the stagnation although the general behavior of the pressure coefficient remains the same. This result can be explained by the small thickness of the boundary layer in the front part of the body where the most drastic changes of the pressure coefficient occur. It is important to note that the density of the Mexican Tetra pressure and velocity sensors, the canal and surface neuromasts, is highest in the front part of the fish’s body.

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Figure 13. Pressure coefficient and canal pores density along the body of a schematic fish (view from above). Solid line – pressure coefficient; dashed line – canal pores density (arbitrary units). The distribution density of the canal pores neuromasts correlates well with the location of the maximum differential hydrodynamic pressure on the fish’s body (Ristroph, Liao, and Zhang, 2015; Dubois, Cavagna, and Fox, 1974).

The behavior of the pressure coefficient of slender bodies is rather robust and is qualitatively similar for different body shapes, which is illustrated in Figure 14.

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Figure 14. The normalized velocity  and the pressure coefficient  calculated for a two-dimensional and three-dimensional body according to Milne-Thomson (1968). Solid line – Joukovskii two-dimensional profile; dashed line – airship form. Each of the two bodies can be characterized by its slenderness. That is by the ratio between the length of the body and its maximal width (or diameter). As long as these parameters for the bodies are close, the behavior of the pressure coefficients for them is qualitatively similar. For most slender fish, the rate of change of the pressure is the largest in their front part with a decrease towards the tail.

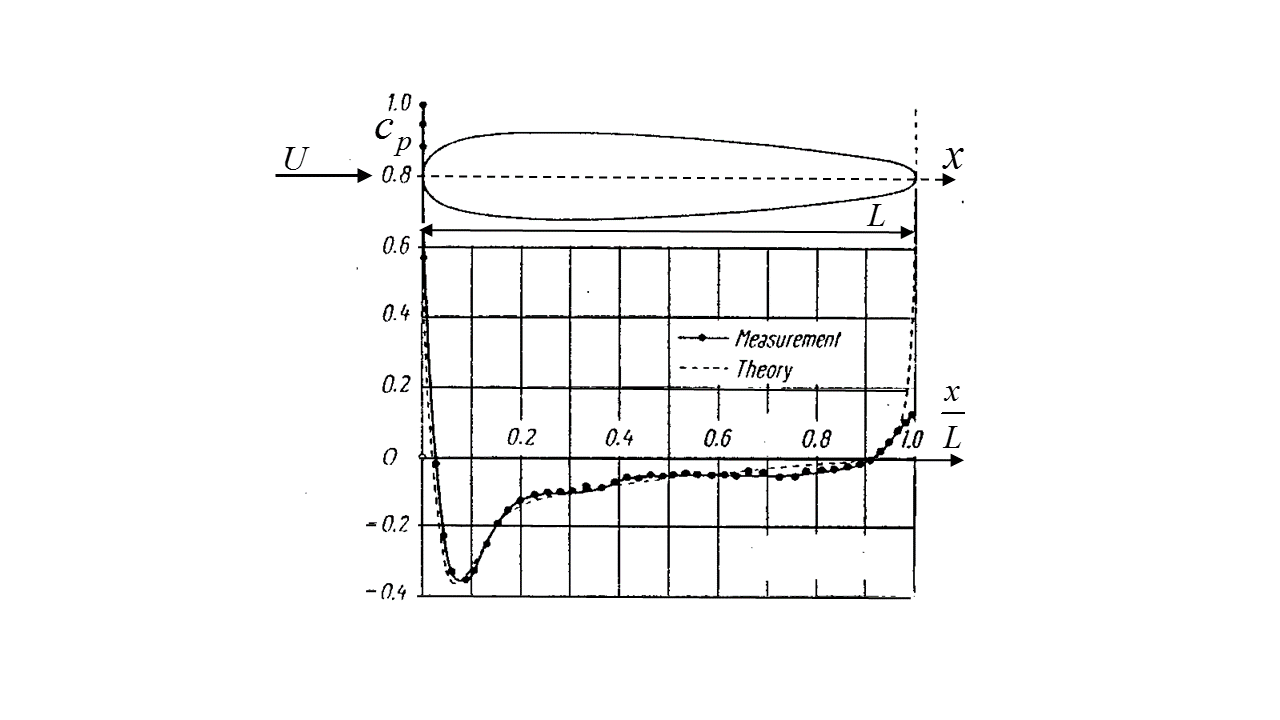


Figure 15. Pressure distribution about a streamlined body of revolution representing the so-called airship form (redrawn and modified from Schlichting, 1979).

Concerning the influence of viscosity on the pressure around a streamlined body, viscosity’s role on the pressure on the body is essential only on its rear part. In the front part of the body, the pressure can be represented qualitatively and quantitatively by using the premises of the inviscid irrational flow (see Figure 15 and Figure 16). Moreover, the same is true even for a sphere, as illustrated in Figure 16.

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| A | B |

Figure 16. Pressure distribution on a circumference of a sphere as a function of the polar angle calculated in the clockwise direction (in the forward stagnation, the polar angle ). A. Dash-dotted line – subcritical (experiment); solid line–supercritical  (experiment); dashed line–potential flow theory (redrawn and modified from Schlichting, 1979). B. Subcritical (numerical solution of the Navier-Stokes equations, redrawn and modified from Bazilevs et al., 2014).

As shown in Figure 16, for angles approximately up to , for both subcritical and supercritical Reynolds numbers, the pressure on the meridional circumference is in full agreement with that obtained theoretically for a sphere in potential flow.

### Sphere approaching a wall or another sphere

A sphere moving in inviscid fluid close to a plane wall is a classical problem of hydrodynamics (e.g., Lamb, 1916; Milne-Thompson, 1968). This event is based on the Stoke's method of images, and by using the method of images, Hicks (1879) found general expressions for the added mass of the fluid for a sphere approaching another sphere. Basset (1888) offered an approximation of the kinetic energy of two spheres moving along the line of centers also using the method of images. Endo (1938) then calculated the velocity potential of two moving spheres using bipolar coordinates and calculated the pressure and the forces acting on two fixed spheres in uniform flow. Afterward, Weihs and Small (1975) considered the problem of two moving spheres using a bi-spherical coordinate system, and by using spherical harmonics, Miloh (1977) expressed the potential of a sphere approaching a wall as a series of Legendre polynomials whose coefficients can be found as a solution of a system of linear algebraic equations with an infinite number of unknowns. Furthermore, by using a similar technique, Bentwich and Miloh (1978) solved the same problem using the stream function instead of the velocity potential and calculated the kinetic energy and the force acting on the sphere approaching a wall and gave examples of the force acting of a sphere approaching a wall. Recently, Kharlamov, Chara, and Vlasak (2008) using Lamb's (1916) solution calculated the added mass of a sphere moving parallel and perpendicular to a wall using infinite series of images in a sphere.

*Surprisingly, among all referred works, none of them deal directly with an exact solution of the problem representing the main interest in hydrodynamics imaging to precisely calculate the pressure on a sphere approaching a wall.*

## Detection of a body in the presence of current

Thus far, all observations of a fish avoiding obstacles have been performed in still water. In that case, the only water flow is generated by the fish itself and the entire velocity field depends only on the fish motion. If a body-obstacle is placed in the ambient current, to detect a body, the fish must process the stimuli of the lateral line while incorporating those stimuli pertaining to the self-induced velocity field and to the ambient velocity field. Depending on the Reynolds number of the obstacle and the ambient turbulent intensity, the character and the intensity of body-generated hydrodynamics disturbances may be rather different, as shown in Figure 17.

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| C:\Users\Gregory\Desktop\Tomer\images\Vogel - wake.PNG |

Figure 17. The wake of a cylinder in a stream for different Reynolds numbers (adopted from Vogel, 1994).

The hydrodynamic field created by the object can be considered as a feature of the obstacle that either helps a Mexican Tetra to reveal the object or a noise that masks it undetectable. To our best knowledge, these alternative experiments were not checked experimentally.

# Objectives of this work

1. To exploit the exact solution of Lamb (1916) to calculate the velocity and pressure variations on a sphere approaching another sphere or a plane wall, which this work has not been done before.

2. To verify the obtained theoretical solution experimentally, which was also done for the first time.

3. To establish the conditions of detectability of a wall by a sphere using commercial pressure sensors.

4. To observe and record for the first time the process of fish avoiding an obstacle in the presence of current.

# A mathematical model of detecting of a sphere by a sphere

## Problem formulation

We consider rigid spheres A and B of radii . The spheres move with velocities  and  along a line connecting their centers (Figure 18).

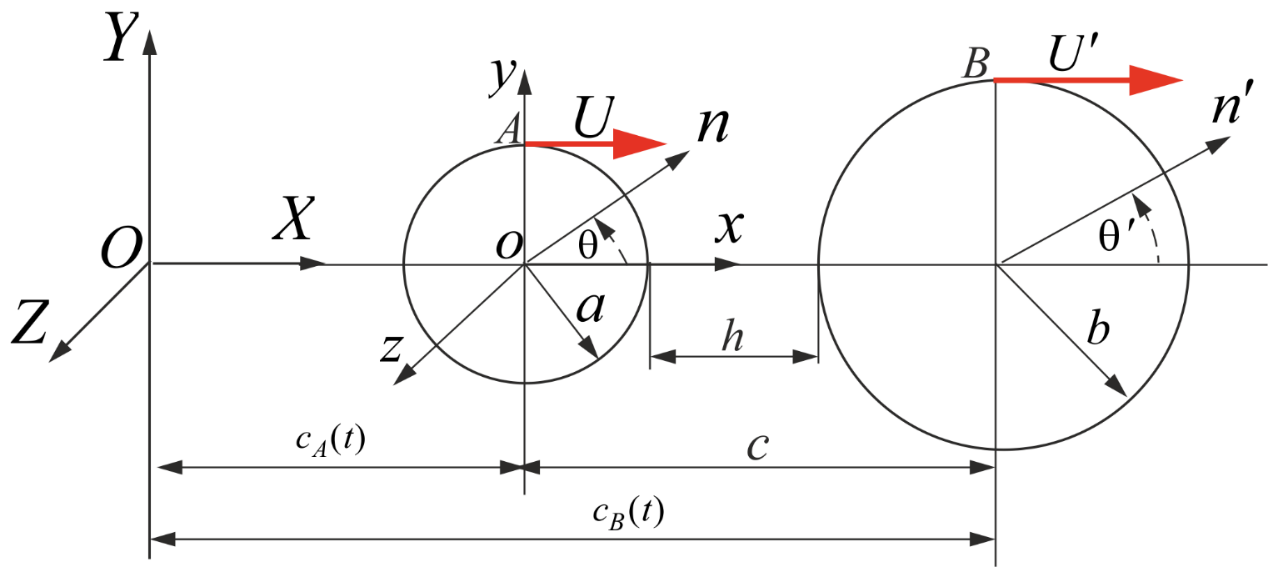


Figure 18. The coordinate system. The centers of both spheres are located on the ** axis of the fixed in space coordinate system . Another coordinate system  is attached to the body *A* and moves with it as a whole; then,  are unit vectors normal to the surfaces of the corresponding spheres *A* and *B.* The distance between the centers of the spheres is denoted as *c*, and the minimal distance between the surfaces of the spheres is denoted as *h.*

Two limiting cases are of particular interest for the present study.

1. Two equal spheres *A* and *B* move in opposite directions with equal speeds *U* and , respectively (Figure 19 A).

2. Sphere *A* moves towards a still sphere *B* whose radius is much larger than that of sphere *A* (Figure 19 B).

In both limiting cases, it is possible to consider the motion of a single sphere approaching a wall or moving away from it.

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|  |  |
| A B | C |

Figure 19. A. Two equal spheres moving in opposite directions with equal speeds and high Reynolds numbers. Due to symmetry, on the dashed line, the velocities normal to it that are induced by the spheres cancel each other. In this case, this line can be imagined as a rigid wall on which the zero normal velocity is satisfied in the left and right half-spaces. B. A sphere moving away from the wall with velocity *U.* C. A finite radius sphere approaching a large one (); the latter can be considered as a rigid wall.

The locations of both spheres change in time  as follows:

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where  is the distance between the centers of the spheres.

The two coordinate systems *OXYZ* and *oxyz* are related as

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Furthermore, the following relation is frequently used:



Then, given that  are time-dependent, the following relations also hold:

For the rest of your work, the time derivative of a quantity is denoted by an overdot.

The fluid motion is irrotational and the fluid velocity is determined by its potential as



Due to the linearity of the problem, the total velocity potential  can be represented as the sum of two unit potentials, with  pertaining to the motion of sphere *A* and  pertaining to the motion of sphere *B*:

. 

Each of the potentials satisfies the Laplace equation

;

therefore, the potential  satisfies the Laplace equation. Each of the unit potentials satisfies the boundary condition of zero normal velocity on the surface of the corresponding sphere. Also, for convenience, this boundary value problem is formulated initially in the moving coordinate system.



where

 .

For , the spatial and time derivatives of the unit potentials tend to approach zero. Once the potential  is known in the moving coordinate system, it can be expressed in the fixed in space coordinate system . The pressure in the fluid can also be calculated in the fixed in space coordinate system using Bernoulli's integral:

,

where  is the static pressure far from the spheres. Without loss of generality, the following can be assumed:. In unbounded fluid, the velocity potential of a sphere of radius *a* moves along the *OX* axis with velocity *U* and can be represented as a velocity potential of a doublet of strength



moving with the same velocity in the direction of thesame axis. Based on Equation in the moving coordinate system, the potential of the doublet can be expressed as the following (Milne-Thomson, 1968):

 ,

where



If another dipole with density



and coordinate  moving with velocity  along *OX* axis is also introduced in the flow, then its potential is



Also, the boundary conditions of zero normal velocity on the spheres are satisfied only if the distance c between them is infinite. To satisfy for finite *c*, additional measures should be taken.

In this work, the method of images was used because it gives an exact solution to the problem although its form is unwieldy (Milne-Thomson (1968) paragraph 16.30). However, what was unwieldy for numerical calculations in 1950 when Milne-Thomson wrote the first edition of his book became the most practical and convenient form of computing a variable using a recurrent formula



that in any computer language can be expressed as a loop

*for n=1, N*

*q(n+1)=function q(n)*

*end*

According to Hicks (1879), Stokes initially studied the motion of two spheres in 1843, and Stokes studied the motion of two spheres in the inviscid irrotational fluid by using an image of a doublet in a sphere, as is illustrated in Figure 20 (Lamb 1945) and briefly explained in the following paragraph.

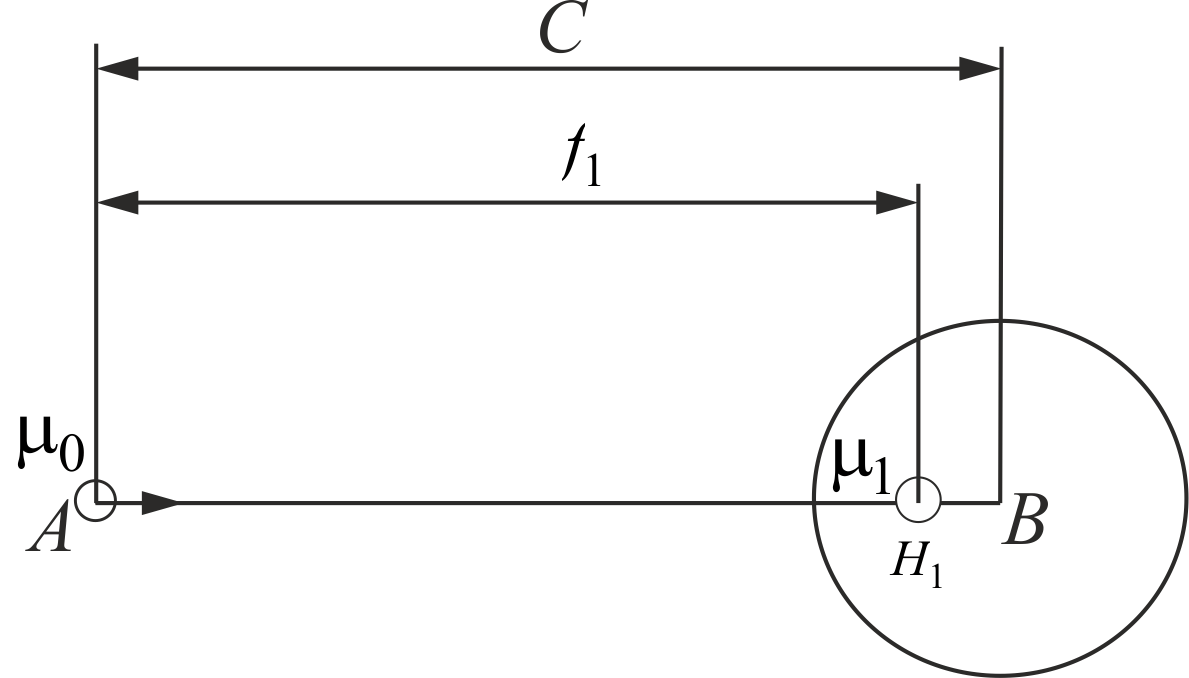


Figure 20. Illustration of the method of images. Dipole *A* with intensity  is located in the point *A* at a distance *C* from the center of the sphere *B* of diameter *b*.

If both sphere *B* and the dipole do not move,the zero normal velocity condition on the sphere’s surface is satisfied under the following conditions: another dipole with intensity is placed inside it at point  such that  and the distance between the  and *A* is  However, the dipole  violates the boundary condition on sphere *A.* To neutralize the influence of the dipole, an image of  in the interior of sphere *A* can be introduced. This image, namely , also violates the boundary condition on *B* that can be compensated by introducing a dipole , which is an image of  (Figure 21). A similar problem can be formulated when sphere *B* moves with velocity  and sphere *A* is at rest. In the center of sphere *B*, a dipole with intensity  and a system of images  can be introduced that are located at distances  from the center of sphere *A*.

For odd dipole numbers , the density of images and their distances  from the center of *A* are expressed as follows (Lamb 1945):





For even dipole numbers , the corresponding quantities are





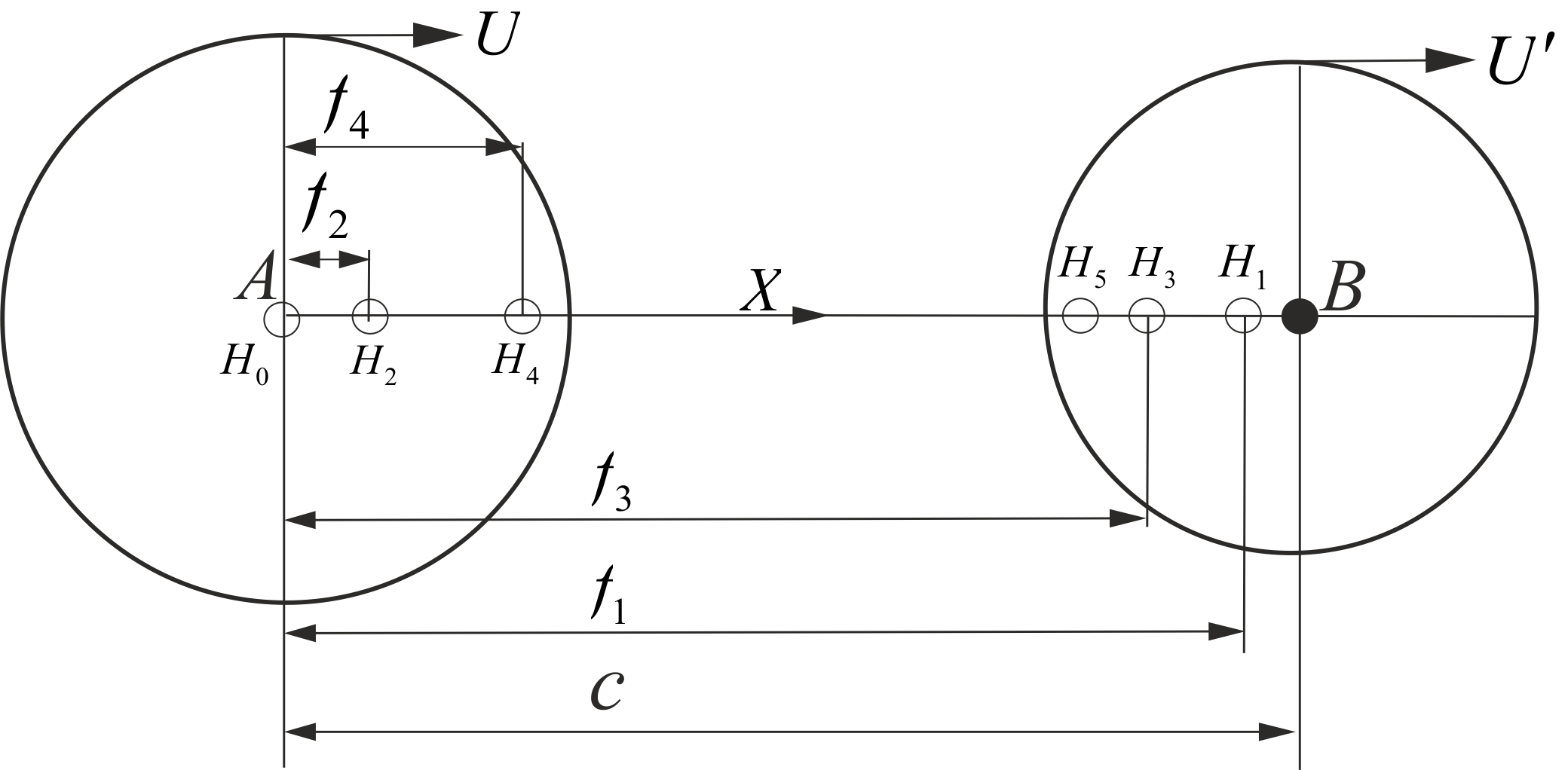


Figure 21. Successive images introduced to satisfy the boundary conditions on the moving sphere *A* and sphere *B* if its velocity .

Finally, the fluid velocity potential of the series of dipoles can be written as follows:



where for ,  and  are defined by , and for  as

Here



are the distances of the doublets from the origin of the fixed in space coordinate system with



and  do not depend on time, that is, 

The pressure on a moving sphere must be considered the moving coordinate system whereas the Bernoulli equations refer to the fixed in space coordinate system. In view of and , the spatial and derivative involved in the Bernoulli equation can be written as









Furthermore, for brevity, the partial derivatives with respect to time are also denoted by overddot as

. To illustrate the general scheme of calculating and , consider unit potentials

 ,

where

 .

and the subscript *n* and superscript in prime are tacitly omitted. With these notations, the gradient of the velocity potential referred to the moving coordinate system can be written using and . To calculate the time derivatives of the potentials , it is necessary to consider that time-dependent is not only the distances of the images to the wall and their intensities:



In view of and considering that , also,



The time derivatives of distances, and dipoles  can be obtained from – for odd and even *n* asfollows:

For odd 





For even 





Equations – and – can be used for calculating and then the velocity potential .

Once  and  are defined by – and their time derivatives  and  are defined by –, then –, , , and hence are also defined.

## Testing cases

All previous studies considered the force *F* acting on a sphere approaching a wall with a right oblique angle. This problem is adopted here as a benchmark to compare this force obtained by other researchers with our results. For this purpose, consider the first two equal spheres of the same radii *a* moving in the opposite direction () along the line connecting their centers, and the plane bisecting *AB* is the plane of symmetry and may be taken as a fixed boundary on either side Lamb (1945). Also, the kinetic energy of the fluid  in the left side is half of the total fluid energy *T* on both sides of the plane can be calculated as Lamb (1945):

 ,

where

 ,

,



The kinetic energy is associated with the added mass  of a single sphere as



Once *T* and hence  are known, the force acting on a sphere approaching a wall with a right angle can be calculated by using the Lagrange equations of the second kind (Lamb, 1945). Then, by introducing the generalized coordinates  and , the hydrodynamic force acting on a sphere approaching a wall can be written as follows:



Substituting into then gives

,

where the added mass depends on the distance  of the center of the sphere to the wall. For the added mass coefficient



two limiting values are exact Hicks, W. (1879):



The hydrodynamic forces acting on a sphere as a function of  can be calculated whether by using or by direct integration of the pressure over the surface of the sphere



In Figure 22, the calculation of in the spherical coordinate system is illustrated.

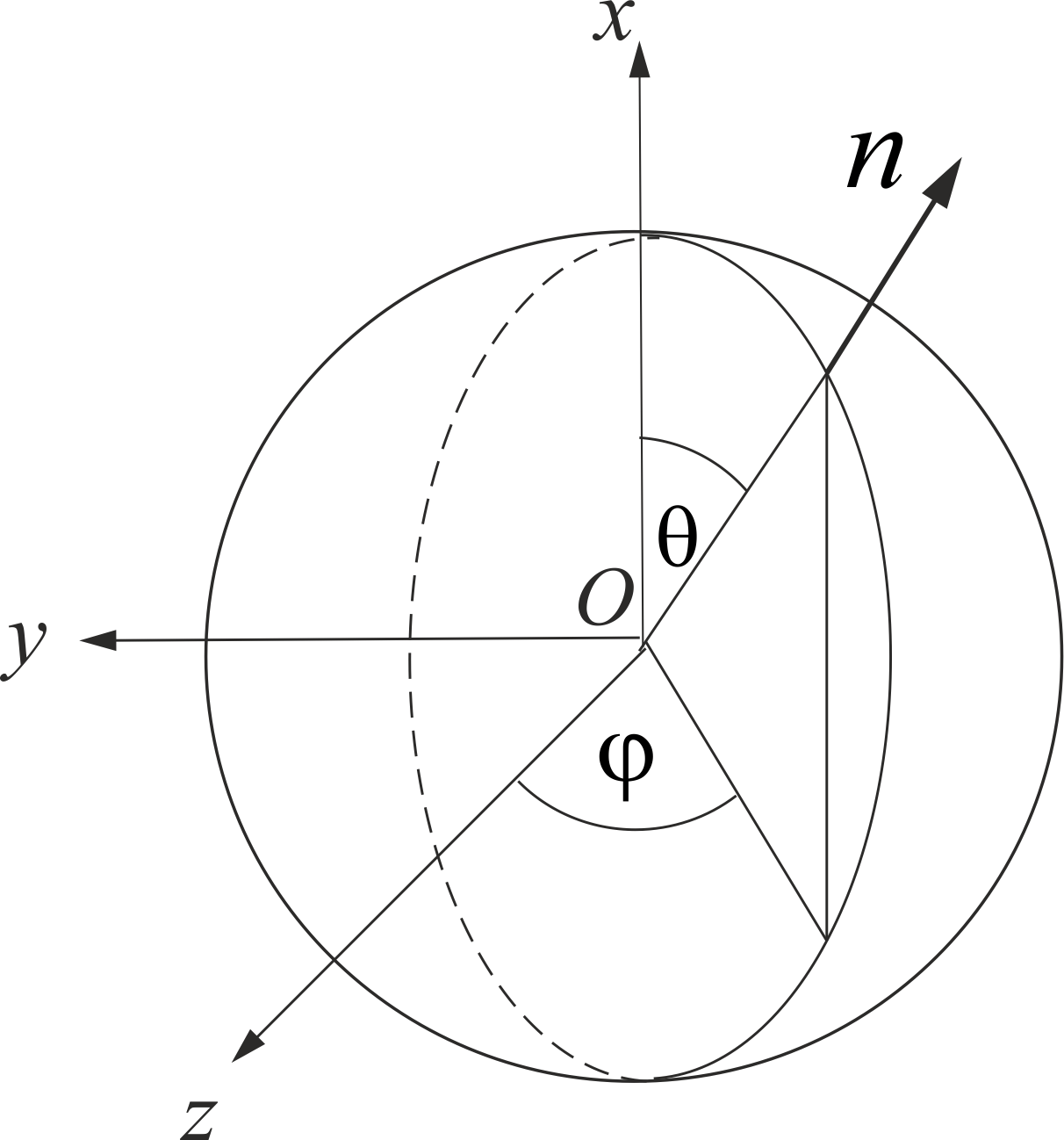


Figure 22. The element of the surface is  and the projection of the external normal to the sphere on the *ox* axis is .

In such a case as that presented in Figure 22, can be written as



Because the flow is axisymmetric with respect to the Ox axis and does not depend on , from , it follows that 



The hydrodynamic added mass coefficients and the hydrodynamic coefficients



,

are used here for validating of the present algorithm.

# Numerical results

In this section, several numerical examples are given.

1. The added mass coefficient  for a sphere approaching a wall as a function of the distance to the wall.

2. The coefficient of the hydrodynamic force  acting on a sphere approaching a wall as a function of the distance to the wall.

The pressure coefficient on a sphere approaching a wall is

.

3. The fluid velocity components in the plane *Z*=0:

4. The instantaneous streamlines in the plane *Z*=0:

5. The pressure coefficient on a sphere approaching another sphere along the line connecting their centers

All computations presented in this work were performed using MATLAB and Visual Fortran compilers with double precision. To determine the number of images *N* required to provide the relative accuracy of calculations, all quantities of interest were computed with consequently increasing *N* until the relative error  was attained. Then, as expected, the number of required images increases with the normalized distance  decreasing. The integral characteristics such as the added mass coefficient or the force acting on a sphere required fewer images than the fluid velocity or the pressure coefficient. Also, the maximum number of images was necessary to calculate the fluid velocity and the pressure in the closest vicinity of the stagnation point.

## The coefficients of the added mass and the repulsive force

To calculate the added mass coefficient for =0, it is sufficient to consider about 100 images, giving . The exact value of the same coefficient calculated by Hicks (1879) is , and the relative error is less than . Also, calculating the velocity *V* in the stagnation point is subject to an error due to the numerical rounding of the computer calculations. However, even for such small distances such as , the condition for the fluid velocity in the stagnation point  is satisfied with an accuracy up to 14 digits for 800 images.

With these limitations, the number of images  was sufficient for all the consequent computations. Also, no practical difficulties were experienced in computing all the quantities of interest using standard personal computers. Typically, calculating the velocity and the pressure along the meridional circumference of a sphere on a standard PC took a couple of seconds. Therefore, any attempt to accelerate the commutations by accelerating the series convergence was not attempted. Also, Figure 23 and Table 1 present examples of the convergence algorithm for calculating the quantities of interest.

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Figure 23. Added mass coefficient and velocity at the fore edge of the sphere at a small distance from the wall () with a changing number of images *N*. Solid line - ; dashed line -  .

Table 1. The minimum number of images  required for calculating the pressure coefficient and the velocity on a sphere with  as a function of the distance to the wall  is presented in the second and third columns.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| 2 | 1 | 1 |
| 1.5 | 2.0 | 2.0 |
| 0.5 | 4 | 3 |
|  | 9 | 8 |
|  | 29 | 26 |
|  | 94 | 83 |
|  | 299 | 265 |
|  | 914 | 832 |

The values of the added mass coefficient calculated using the present algorithm agree well with those reported by other authors (Figure 24).

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Figure 24. Added mass coefficient as a function of the normalized distance to the wall. The solid line – presents the calculation by this work, the dashed line () represents the result by Kharlamov (2007) representing the method of images with accelerated convergence of series, the dash-dotted line () represents the result by Yang (2006), and the dotted line () represents the result by Milne-Thomson (1968).

As shown in Figure 24, the agreement between the present calculations and those reported by other authors is very good except for the lowest order approximation by Milne-Thomson (1968) that is not valid for .

In Figure 25, the results of calculating the repelling force coefficient  are presented.

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|  |

Figure 25. The coefficient of the force acting on a sphere approaching a wall perpendicularly. Solid line – Lagrange’s equation; open circles – pressure integration.

Figure 25 shows that the agreement between the present calculation and those reported by other authors are also in very good agreement. For instance, the discrepancies cannot be noticed in the scale of the figures and the thickness of the lines.

## Sphere approaching a wall

The calculated velocities on the circumference of a sphere approaching a wall are illustrated in Figure 26.

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Figure 26. Normalized velocity on the meridian circumference of a sphere approaching a wall as a function of the distance *h* and the coordinate *x*: . For , the velocity on the meridional circumference coincides with that for .

Figure 26 demonstrates an interesting feature: In the stagnation (critical) points, the velocity of the fluid is equal to the velocity of the sphere. However, in the closet vicinity to the forward critical point, the velocity rises, and at a certain coordinate , the velocity reaches an extremum. Also, at small distances of , the velocity change reaches .

To calculate the streamlines around a sphere approaching a wall, a standard Matlab tool (*streamslice.m* ) was invoked, and examples of the streamlines are presented in Figure 27.

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| A. | B. |
| C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\"C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines1_N1000.png"  made from: C:\Users\Tomer\Dropbox\TEZA\Plots for teza\Theo - streamlines\Streamlines_plot_better_res.m | C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines2_N1000.png  Made from: C:\Users\Tomer\Dropbox\TEZA\Plots for teza\Theo - streamlines\Streamlines_plot_better_res.m |
| C. | D. |

Figure 27. A and B: Streamlines in the plane  of a sphere approaching a wall from the left. C and D. Pressure coefficient on the same sphere.

As shown in Figure 27, the streamlines become denser as the distance to the wall decreases, agreeing with the velocity variation along the circumference shown in Figure 26. The denser streamlines indicate the pressure rise, becoming particularly drastic in the closest vicinity of the stagnation point, and the pressure coefficient  is plotted in Figure 28.

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Figure 28. Pressure coefficient along the meridian circumference for different distances from a wall.

In Figure 29, the pressure coefficient is plotted in log-log scale.

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Figure 29. Pressure coefficient in the stagnation point for small . The broken line – represents the calculated pressure coefficient, and the square line – represents the approximated pressure coefficient . The figure shows that for small distances to the wall .

In contrast, for , the pressure in the stagnation point tends to infinity and the integral of the pressure over its surface is finite, which can be explained in the following way. When , the integration over the entire surface of the sphere can be replaced by the integration over its surface with the excluded singular point plus an integral over a semisphere of infinitesimal radius *h* and corresponding surface . Given that the value of the pressure on the small semi-sphere is proportional to *,* the value of the integral over the semi-sphere is proportional to . Thus, the contribution of the singular pressure to the total integral of the pressure over the sphere is negligible.

## Two spheres

Two spheres with ratios *b/a* presented in Table 2, and the corresponding streamlines and pressure coefficients in the plane *Z*=0 are presented in Figures 30–33.

Table 2. Parameters of the spheres and the corresponding figure numbers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Figure number | 32 | 33 | 34 | 35 |
| *b/a* | 1000 | 1.0 | 0.5 | 0.1 |

The case of a sphere approaching a much larger sphere provides a verification of the algorithms and the code because the larger sphere can be considered as a rigid wall in this case.

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| A. () | B. () |
| C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines1_N1000_b1000.png  made from: C:\Users\Tomer\Dropbox\TEZA\Plots for teza\Theo - streamlines\Streamlines_plot_better_res_Non_Symmetric.m | C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines2_N1000_b1000.png  made from: C:\Users\Tomer\Dropbox\TEZA\Plots for teza\Theo - streamlines\Streamlines_plot_better_res_Non_Symmetric.m |
| C. () | D. () |

Figure 30. A sphere of radius *a* approaching another non-moving sphere of much larger radius A–B. Streamlines. C–D. Pressure coefficient. The more detailed analysis shows that the results presented in Figure 27 and Figure 30 are almost identical.

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| A | B |
| C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines1_N1000_b1.png | C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines2_N1000_b1.png |
| C | D |

Figure 31. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. .

|  |  |
| --- | --- |
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| A | B |
|  |  |
| C | D |

Figure 32. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. .

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| C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Cp_h_no_lines1_N1000_b01.png |  |

Figure 33. Streamlines and the pressure coefficient around a sphere approaching another still sphere . A. and C. ; B. and D. .

The presented results in Figure 30–33 clearly indicate that a rigid wall or another sphere can be revealed by a moving spherical detector, although the distance of detection depends on the ratio *b/a* and the velocity of the detector.

# Experimental investigation

The goals of the experiment described in this section were as follows:

1. To verify the discussed mathematical model for calculating the pressure on a sphere approaching a wall.

2. To verify the feasibility of detection of a wall by a moving sphere using commercial transducers.

## Experimental layout

The experiment was performed in the water tank of the Water Waves Research Laboratory of the School of Mechanical Engineering at Tel Aviv University. The length of the water tank is 21.0 m, its width is 1.0 m, and its depth is 0.6 m. Also, the walls of the tank are made from transparent glass (Figure 34).



Figure 34. The experimental system.

A carriage whose velocity may vary from 0.5 cm/s to 1.0 m/s moves along the tank, and the velocity of the carriage and its position along the tank are recorded with an error of less than 1%. The object of experiments was a rigid sphere of diameter  rigidly attached to the carriage and moving towards a fixed in space wall (Figure 35). A rigid but brittle plastic plane was inserted into a metallic frame of width ~2*d* mounted on the bottom of the tank (see Figure 35).

|  |  |
| --- | --- |
|  |  |
| A | B |

Figure 35. A sphere approaching a brittle wall. A. View from above. B. Side view. 1. Moving carriage; 2. Connecting tube; 3. Sphere; 4. Rigid wall; 5. Breakable wall. The center of the sphere was 0.35 m below the water free surface.

The wall was covered by an aluminum foil, and two small thin separate metal sheets separated by a 0.5° distance were attached to the fore edge of the sphere. Both of the sheets were connected to a 5V power source. Then, once the sphere touched the aluminum foil, the circuit was shortened and an electric signal indicating the contact was recorded.

## Construction of the sphere

The sphere was manufactured using a three-dimensional printer printed at “Dfus 3D” company (Herzelia). The sphere was made from polylactic acid with a condense exterior to prevent leaking. After being printed, the sphere was covered with layers of varnish to further seal its surface, and the sphere was designed as two connecting parts to allow the insertion of the pressure sensors into the sphere (Figure 36).

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Figure 36. Parts of the sphere. 1. Pressure holes (see Figure 37). 2. Front part of the sphere. 3. Sealed box containing the pressure transducers. 4. O-Ring preventing leaks between the two main parts of the sphere. 5. Inner connector. 6. Rear part of the sphere. 7. Connecting tube, connecting of the entire sphere to the moving carriage.

The sphere was printed with eleven holes on the meridian circumference of the sphere. The first hole is located at the polar angle , and the rest of the holes are shown in Figure 37.

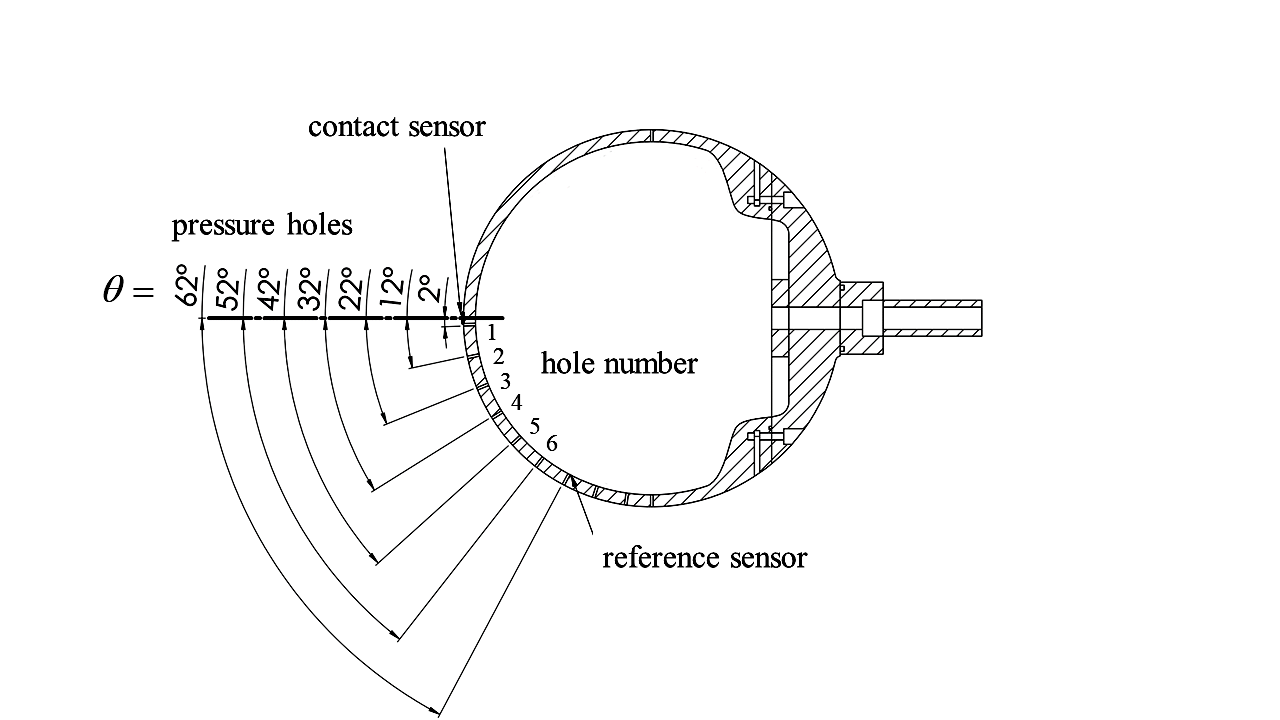


Figure 37. Locations of the holes in the sphere.

Ends of thin 2 mm silicone pipes were inserted in each hole. The other end of the pipe leads to pressure transducers and was placed in the sealed box (see also Figure 36, item 3). The signals from the pressure sensors were recorded and processed by a computerized system of data acquisition, as illustrated in Figure 38.

The pressure transducers were electrically connected to a computer through the connecting pipe.

|  |
| --- |
| experimental system schematic |

Figure 38. Schematic diagram of measured data processing.

The aim of the experiment is to determine if it is possible to detect the wall by the used pressure sensors, and the following criteria of detection are adopted. Assume that for each pair of six sensors it is possible to measure the pressure difference  between two points corresponding to two polar angles . To verify the measurements regardless of the specific conditions of the experiment, the pressure difference is normalized with the dynamic pressure and can be expressed as

 ,

where . The relative pressure difference



is defined here as a criterion for detecting the wall. Then, if  exceeds a certain threshold , then equation



gives the maximal distance of detection.

The feasibility of detection and the distance of detection depend on the accuracy of measurements and are determined by the sensitivity of the used sensor and the noise of measurements. Then, in this context, may have one, many, or no robust solutions.

Most of the experiments presented here were performed with Re  . Also, as shown in Figure 16, this Reynolds number can be used and the flow may be considered as the potential till the angle , where . Correspondingly, the pressure difference



was used to calibrate the pressure sensors in water.

## Pressure sensor­

In the present experiment, a Freescale MP3V5004G pressure sensor was used, and the range of measurements was 0–4 kPa. According to factory specifications, the maximum error of the sensor was Pa. However, in practice, according to our calibration, the error of the measurements was two times smaller and did not exceed  Pa. Also, the approximate dimensions of the sensor were  mm, allowing for several of them to be placed in the interior of the sphere (Figure 39). Then, two 1.5V batteries connected in parallel powered the sensors.

|  |  |
| --- | --- |
| PressureSensor |  |
| A | B |

Figure 39. The Freescale MP3V5004G pressure sensor. A. An image of the sensor. B. A schematic description of the pressure sensor; a silicone diaphragm deforms according to the pressure difference.

A stress-strain gauge connected to the diaphragm converts this deformation into an electrical signal that converts to pressure readings. Also, the pressure sensors were supplied by the factory calibration curve representing the pressure in Pa as a function of electric voltage. In other words,



where  and  are constant coefficients. Eq. being normalized with the dynamic pressure can be rewritten as



where  and  are the normalized coefficients of proportionality.

Each new experiment started from the calibration of sensors dried in air for at least twelve hours. First, the initial voltage measured  was subtracted from the voltage reading for each -th sensor. After that, in a series of  experiments, the proportionality coefficient  was calculated for each -th sensor as

.

Once  and are found, the differential pressure for each sensor can be estimated using , and an example of calibration of six sensors is presented in Figure 40.

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|  |

Figure 40. Sensor calibration.

Using this and other measurements, it was found that the maximum error of measurements of  do not exceed ~0.1. As it follows from theoretical calculation presented in the previous sections, for , the theoretical value of the pressure coefficient is of the order of 1.0 and grows as  . Therefore, for distances , it can be assumed that the sensitivity and accuracy of the pressure sensors are sufficient for comparing the theoretical and experimental results.

## Experimental results

### Pressure difference

A raw time-dependent signal when the sphere approaches the wall is illustrated in Figure 41, where a sharp rise of the pressure on time can be observed, which agrees with the theoretical prediction.

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Figure 41. Pressure coefficient difference as a function of the time while the sphere approaches the wall (*U*= 0.5 m/s). The red circle indicates the contact of the sphere with the wall. A. Row signal. B. The same in logarithmic scale with error bars.

Figure 41 shows that the differential pressure coefficient becomes a maximum after the contact of the sphere with the wall. This peculiarity may be caused by the rather fast variation of the pressure in time at small distances from the wall. Also, the air compressibility and water, which is inevitably presented in the pipes connecting pressure holes of the sphere, may lead to the time lag in response of the measuring system to the pressure variation. In the experiments performed in this work, it was difficult to estimate a constant time lag. To not increase the degree of uncertainty, the measurements are yet reliable till the maximum of .

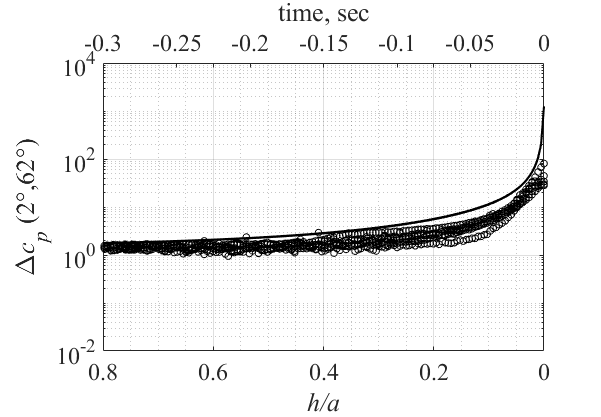
An example of a comparison of the theoretical and experimental data is shown in Figure 42. In Figure 42 A and B, where the pressure difference is presented, the agreement between the theoretical and experimental data can be considered as satisfactory qualitatively and quantitatively. Then, in Figure 42 C and D where the pressure difference  is presented, the agreement is satisfactory qualitatively.

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A



B

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D

Figure 42. Comparison of the experimental and theoretical pressure difference coefficients. The time  when the pressure difference attains the maximum. The solid line represents theory, while the open circles represent experimental results. A. *U*=0.5 m/s. B. *U*=0.6 m/s. C. *U*=0.5 m/s. D. *U*=0.6 m/s.

These figures show good agreement between the theoretical calculation and the measured results, and the agreement is best at  while larger angles show less agreement. Then, the relative error is larger at higher angles since the  values are smaller.

### Detection distance

According to the results of theoretical and experimental investigations, the maximum pressure difference is attained when the pressure sensor is located in the point . Thus, the pressure difference between this point and the reference point  is used as the most representative estimate of the detection distance  given by the equation



where  is the noticeable dimensionless difference. Because both parts of are proportional to , the detection distance that can be found from this equation does not depend on *U.*

An example of the estimation the detection distance based on the experimental results for  is shown in Figure 43.

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Figure 43. Experimental pressure difference coefficient measured until the time of contact (*U*= 0.5 m/s). The open circle indicates the location and time when 

The same processing of the pressure data was made for all the experiments that were held. For each measurement, the distance from the wall and the corresponding time were calculated, and the time presented in Table 3 is the time remaining before the sphere hit the wall.

Table 3. Average detection time and distance at three velocities.

|  |  |  |
| --- | --- | --- |
| velocity *U*, m/s | time before hitting the wall, sec | normalized distance from the wall at detection, *h/a* |
| *U*=0.5 | 0.15 | 0.34 |
| *U*=0.6 | 0.11 | 0.30 |

# Fish moving in a tube with current

## Experimental apparatus

The experimental system consists of a closed transparent tube connected to a water pump, allowing a water current in the tube to be created (Figure 44).

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| A | B |

Figure 44. Schematic experimental setup. A. Top view. B. Side view.

1. Four transparent straight Perspex tubes with an inner diameter  were connected by four  semitransparent bends. The bends were specially designed and 3D printed from semitransparent ABS.

2. An open section was created in a part of the tube to insert a fish through it.

3. The entire tube was submerged into a  transparent tank filled by water to overcome the optic distortion created by the round tube.

4. A centrifugal pump is connected to the tube to create a water flow (see parameters in Appendix ? )

5. Holders of the tube.

6 and 7. The pump takes the water from the water tank (6) and returns it back to the tank after passing through the tube (7).

8. A flowmeter is located between the pump and the tube.

9. An ABS printed cylindrical obstacle with a circular cross-section mm and height equal to the pipe’s inner diameter 54mm was placed into the tube.

10. A  section of the tube was filmed by two hi-speed (100 fps) synchronized digital video cameras  pixel CMOS, Optronics GmBh, Germany (see 11 and 12) equipped with 60mm/f2.8 and 20 24mm/f1.8 lenses (Nikkor, Japan).

11. Camera located above the water tank.

12. Camera located at the side of the water tank.

The mean velocity of the flow  in the tube is calculated as the ratio of the flow rate *Q* measured by the flowmeter to the area of the inner cross-section of the tube. The corresponding Reynolds number is calculated as , where  is the water kinematic viscosity.

## Experimental protocol and fish filming

There were 32 Mexican Tetra cave fish obtained from a local pet trade and the fish were kept in two separate aquariums, with 16 fish in each aquarium. The water temperature in the aquariums was then kept at, and the fish were fed daily commercial “Tetra flakes”. Water quality tests were checked weekly. The experiments with fish described in this section complied with IACUC approved guidelines for the use and care of animals in research at Tel Aviv University, Israel. The flow in the tube was visualized by injecting fluorescein sodium (product of Sigma Aldrich) that is non-toxic to fish, and an example of flow visualization is shown in Figure 46.

The experiments were performed in the tube with and without an obstacle, in still water, and in running water (mean flow velocity ,  and , ) with five different fish in each particular experiment. To avoid testing of the same fish twice, for each particular experiment, a fish was taken from one aquarium and transported to a separate aquarium after the experiment.

Examples of the filming of fish in a tube are given in Figures 45–47.

|  |  |  |
| --- | --- | --- |
| C:\Users\Gregory\Desktop\Tomer\images\Fish in pipe\03-03-14-03-10.332_478.png  1 | 2 | 3 |
| 4 | 5 | 6 |
| 7 | 8 | 9 |

Figure 45. A blind Mexican cave fish avoiding an obstacle in a tube. The fish  long is swimming in a pipe with a diameter of . Photos displayed with a difference of 0.2 sec. 1. Fish approaches the obstacle. 2. Fish starts the avoiding maneuver. 3 and 4. End of the avoiding maneuver. 5. Fish moves towards the wall of the tube. 6. Fish perceives the tube and starts the avoiding maneuver. 7 and 8. End of the avoiding maneuver.

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Figure 46. Flow visualization past a cylindrical obstacle placed in a tube. , .



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Figure 47. Fish colliding with the obstacle while swimming against the stream in a tube with fluorescein. . Photos displayed with a difference of 0.2 sec. 1 and 2. fish gliding towards the obstacle. 3. Tail beat close to the obstacle. 4. fish collides with the obstacle. 5 and 6. Fish swims backward. 7 through 9. Fish performs an avoiding maneuver.

## Image processing of fish trajectories.

The aims of imaging a fish's motion in a pipe are to determine the coordinates of the fish's nose, the rear end of its body, the fish's contours in the two mutually perpendicular planes and the centroid of the area bounded by the contour. The fish trajectory is defined as the trajectory of its nose, as illustrated in Figure 48.

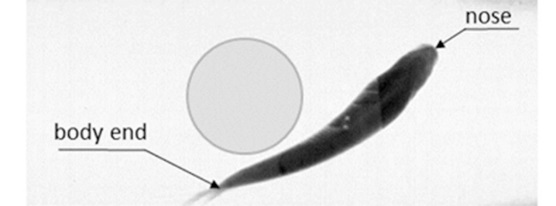


Figure 48. Fish avoiding an obstacle.

The trajectory of the nose is determined if its coordinates are determined in a chosen coordinate system illustrated in Figure 49.

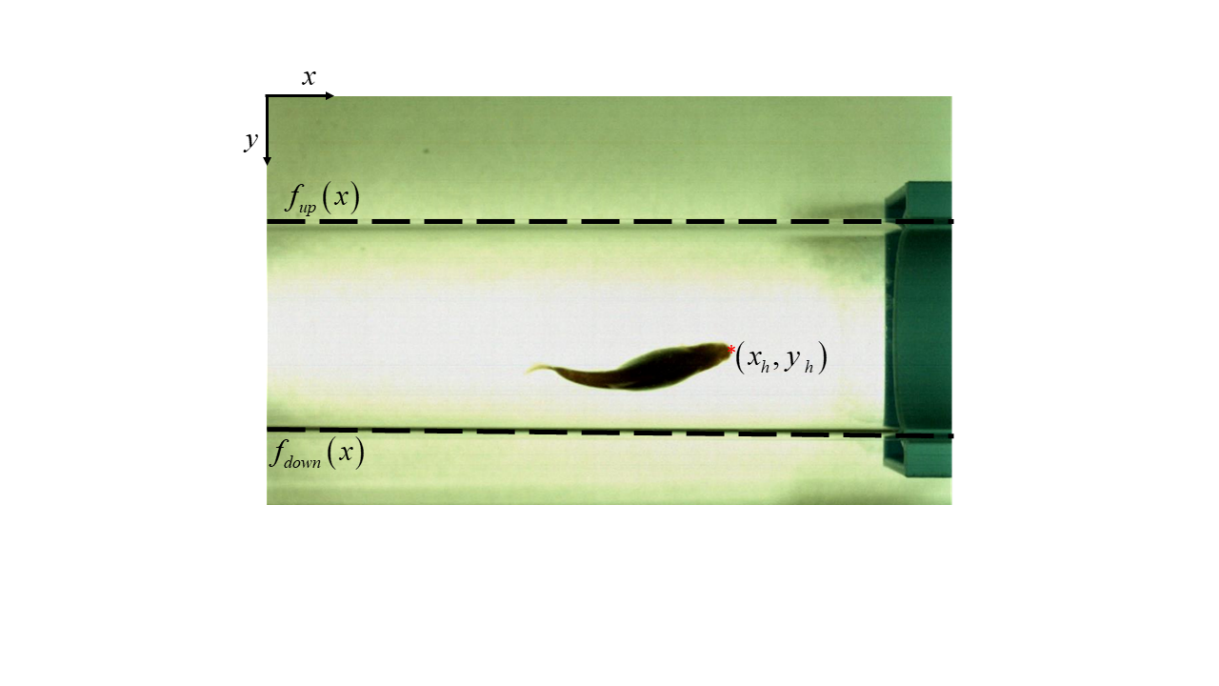


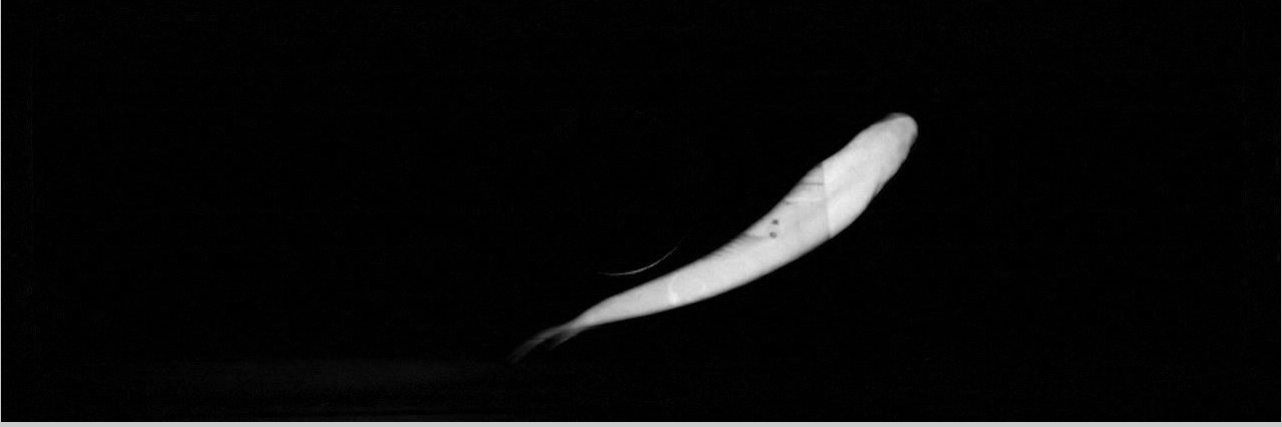
Figure 49. The coordinate system of an image with a fish. The origin of the coordinate system *Oxy* is chosen in the upper corner of the image. The red star denotes the fish nose.

A Matlab code was created to process the fish’s motion in the pipe. The image processing procedure starts by generating an image of the filmed area without a fish and without an obstacle. On the next steps of processing, this image serves as a background of other images of the fish in a tube with and without the obstacle. To determine the actual dimensions in the images, an image with a plastic ruler was processed and scaled according to the ruler units.

The main steps of the algorithm of image processing of a fish's motion in a tube are described in Figure 50.



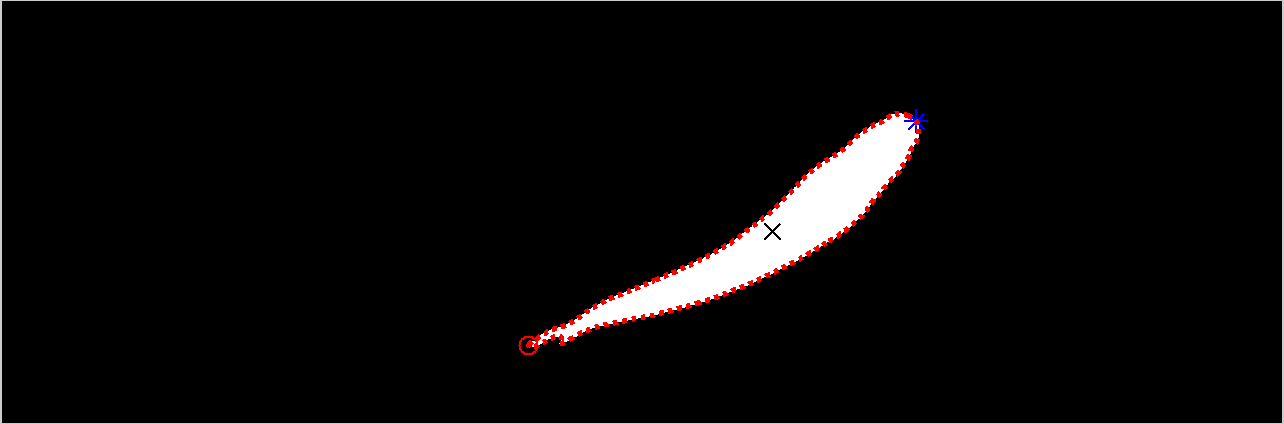
A



B



C



D

Figure 50. Image processing steps. A. Original image. B. The result of comparison between the image and the background image by using the Matlab function "imabsdiff”. C. Converting the resultant image B to a black-white image by using the Matlab function “im2bw”. D. Building the contour (red dashed line) and locating the nose of the fish (astrix), the endpoint of the body (circle) and the centroid (cross) through Matlab functions “bwboundaries.m” and “regionprops.m”. The Matlab code is shown in Appendix A.

The obtained image processing fish trajectories are shown in Figure 51.

|  |  |  |
| --- | --- | --- |
|  | |  |
| A | B | |

Figure 51. The trajectory of the nose of a fish swimming in the tube. A. Top view. B. Side view

## Results

### No obstacle in the pipe

The trajectory of the fish’s head movement in the tube without the obstacle is shown in Figure 52.

Top view Side view

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Figure 52. The trajectory of the nose of the fish in a tube without an obstacle.

In a tube without an obstacle, the only visible difference is in the density of trajectories of fish based on the side view. In a tube without current, fish prefer to move closer to the bottom of the tube. This phenomenon was not analyzed, but this work concentrated rather on the drastic difference in the trajectories’ patterns in the pipe without an obstacle and with it.

### Trajectories in the pipe with an obstacle.

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Figure 53. Fish approaching an obstacle in the pipe without current ().

|  |
| --- |
| A |
| C:\Users\Tomer\Dropbox\TEZA\lyx\Images\Converted\Fish_pics_top_obs_400_against.png  made in powerpoint  B |

Figure 54. Trajectories of fish in the pipe with an obstacle . A. fish approaches an obstacle in the direction of water flow. B. fish approaches an obstacle against the direction of water flow

|  |
| --- |
| A |
| B |

Figure 55. The trajectory of fish in a tube with an obstacle and a current of . A. Swimming in the direction of the current; B. Swimming against the current.

Comparing Figure 53 and Figure 55 yields the following two conclusions.

1. When a fish approaches the obstacle without current, the distance it starts the avoiding maneuver is smaller compared to that when it moves in the direction of the current.

2. When a fish approaches the obstacle against the current, the distance it starts the avoiding maneuver is smaller compared to that when it moves in a pipe without current in the direction of the current.

|  |
| --- |
| C:\Users\Gregory\Desktop\Tomer\images\One_fish_with_circles.png |

Figure 56. 3 imaginary cylinders around the obstacle. Dashed line (---) . Solid line (–) . Dotted line (…) . In this image, the fish entered the cylinders 1 and 0.5 cm from the obstacle but did not collide with it.

It is difficult to determine if there was actual contact between the fish and the obstacle using image processing. Furthermore, it is difficult to define when the fish starts an avoiding maneuver before hitting the obstacle. These locations can be found by plotting imaginary cylinders around the obstacle, and three cylinders of radii were plotted around the obstacle. Then, a collision was defined as when the fish entered the  cylinder. The probability of the fish entering these imaginary cylinders is shown in Table 4.

Table 4. The probability of the fish entering an imaginary cylinder around the obstacle.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Probability, % | | |
| Distance from sphere, cm | No current | With current | Against current |
| 1 | 78 | 45 | 80 |
| 0.5 | 58 | 15 | 64 |

When swimming with the current, the fish stays further away from the obstacle than when swimming against the current. This can also be seen in subfigure A in Figure 54 and Figure 55 where there is an area that the fish rarely enters when approaching the obstacle.

These observations are correlated with the highest number of collisions of fish with an obstacle when it swims against the current in the wake of the cylinder.

Table 5. Chance of collision with an obstacle depending on the direction of motion.

|  |  |  |  |
| --- | --- | --- | --- |
| Current | Number of trajectories | Number of collisions | Probability, % |
| No current | 55 | 8 | 15 |
| With current 20-35 mm /s | 44 | 1 | 2 |
| Against current 20-35 mm /s | 47 | 12 | 25 |

The probability of the fish colliding with the obstacle is larger when it approaches from downstream. Also, this work assumes that vortices created in the wake of the cylinder create hydrodynamic noise. This noise comprises the fish’s ability to detect the obstacle.

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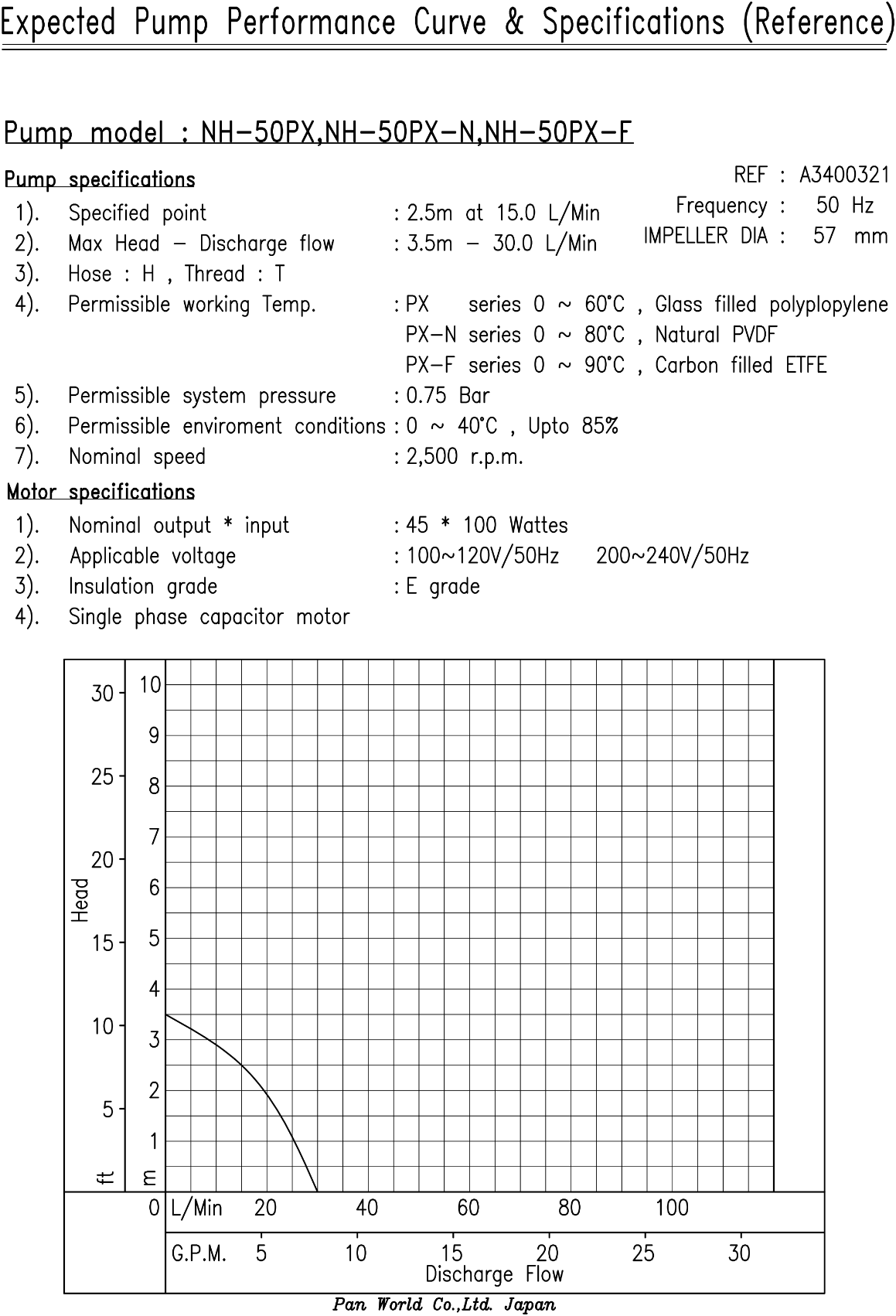
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# Appendices.

## Appendix A – Pump datasheet



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