



Marine Zooplanktons Ambushing Behavior and Turbulence

Mohd. Shamsul Haque¹ and Rajeev Shrivastava²

¹ Department of Zoology

Government Indira Gandhi Home Science Girls College, Shahdol (M.P.) India.

² Department of Mathematics

Government Indira Gandhi Home Science Girls College, Shahdol (M.P.) India.

ABSTRACT

Copepods are the most common zooplanktons worldwide. Some zooplanktons may have spines at early larval stage while others do not. These organisms are the marine relatives of earthworms. The adult Oikopleura sp. is an adult tunicate that retains its notochord and tail. The tail beats back and forth rapidly to create a current that brings food near the mouth. Our aim of the study is to characterize the ambushing behavior of zooplanktons and consequent water turbulence in the form of vortices.

Keywords: Ambushing behavior, water turbulence, vortices.

Received 29.12.2015

Revised 09.02.2016

Accepted 25.02. 2016

INTRODUCTION

When the forces are conservative and the density is a function of pressure, the circulation in any closed circuit moving with the fluid is constant for all time. Hence the strength of a vortex is constant. We see that three species of copepods viz. *Euchaeta rimana*, *Euchaeta elongata*, *Euchaeta antarctica* that live in seawater in a range of temperatures (0-21°C) and a viscosity range (0.95 – 1.85 mm²/s) react differently according to the size, Reynolds number on propulsion and the spatial extent of the flow disturbance.

PRINCIPLE AND METHODS

Suppose that the circulation along any circuit over a surface S is zero. Then, at any point of the surface, $l\xi + m\eta + n\zeta = 0$. That is, the vortex lines all lie in the surface S , in other words, the surface S is composed of vortex lines. Suppose that the vortex lines that were lying on the surface S at time t lie on S' at time $t + \delta t$. The particles that were lying on the circuit C at time t lie on C' at time $t + \delta t$. But, the circulation along C is equal to circulation $C' = 0$. This being true for all circuits on S' , the surface S' must also be composed of vortex lines.

Hence any surface composed of vortex lines, as it moves with the fluid, continues to be composed of vortex lines. Since the intersection of two such surfaces must always be a vortex line, we conclude that the vortex lines move with the fluid.

We use 'Zoo-Turbularium' as the experimental device for our study. Turbulence was generated by a horizontally sinusoidal oscillating grid with a sufficient stroke from the end wall of the tank, and driven by an electric motor. Peters & Marrase [1] and Peters & Redondo [2] while studying turbulence intensities reported these parameters ranging from $\epsilon = 2.8 \times 10^{-11}$ to $4.7 \times 10^{-4} \text{ m}^2/\text{s}^3$. We were interested here (i) in the ability of zooplankton to ambush against a gradient of turbulence, and (ii) in the effects of turbulence intermittency (i.e., strong bursts in the intensity of the kinetic energy dissipation rate, ϵ). Therefore, the oscillation frequency of the grid was adjusted so that it would generate turbulent dissipation rates ranging from medium to high intensities of turbulence i.e., ϵ (10^{-7} to $10^{-4} \text{ m}^2/\text{s}^3$) befitting for our present study.

Now, the ability of zooplanktons to swim across a stream of width a with a velocity u and the consequent development of the path can be found if velocity of the current is directly proportional to the product of distances from the two ends. This can be achieved by the following treatment.

Taking the origin at the point from where the zooplankton starts, let the axes be chosen as usual. After its start from origin, let the animal be at the position $P(x, y)$ at any time t , so that the velocity of the current is $x' = ky(a - y)$ and the velocity with which the plankton moves on its own accord is given by $y' = u$. Thus

$$\frac{dy}{dx} = \frac{dy}{dt} + \frac{dx}{dt} = \frac{u}{ky(a - y)} \tag{1}$$

The differential equation (1) gives the direction of the resultant velocity of the zooplankton which is also the direction of the tangent to the path of the zooplankton. The equation (1) is of variable separable form so we can write it as

$$y(a - y)dy = \frac{u}{k} dx$$

which on integrating gives

$$\frac{ay^2}{2} - \frac{y^3}{3} = \frac{ux}{k} + C$$

Since $y = 0$, when $x = 0$ therefore $C = 0$. Hence the equation to the path of the zooplankton is

$$x = \frac{k}{6u} y^2(3a - 2y).$$

Putting $y = a$ we get the distance down stream as intended for our ambushing behavior which comes out to be $ka^3/6u$.

Now the dissipation rates in the tank were calculated from direct measurements of micro-scale velocities recorded with a **3D** acoustic Doppler velocimeter (ADV, Nortek). Velocity measurements were made at **4** different vertical positions (**5, 10, 15** and **20 cm** from the surface) and at **7** horizontal positions located every **10 cm** cm, starting at **15 cm** from the center of the stroke. For each horizontal position, **3** measurements were made: at the center of the tank and at a **4 cm** distance from each wall. All measurements were made at a sampling interval of **0.04 s (25 Hz)** for at least **90 s**. Velocity measurements showed that mean velocities differed from **0** ($p < 0.05$, $n = 112$). These measurements indicated that there was residual circulation in the tank. The horizontal velocity was directed towards the grid in the lower part of the tank, while it was in the opposite direction in its upper part. Estimates of dissipation rates ϵ , were implicitly based on the hypothesis of isotropic, stationary turbulence which were given by Taylor [3] and Tennekes [4]. In order to ensure the reliability of our dissipation rate empirical estimates, we used time series of velocity deviations obtained by subtracting the mean velocity from instantaneous velocities. The resulting **3D** velocity components, v_x, v_y and v_z were then used to estimate the root-mean-square turbulent velocity w from:

$$w = (v_x^2 + v_y^2 + v_z^2)^{1/2} \tag{2}$$

The energy dissipation rate, ϵ , was calculated following Taylor (1935):

$$\epsilon = D \frac{w^3}{l}$$

where D is a universal constant $D = 1$ following Stiansen and Sundby [5] and l is the integral length scale of turbulence, i.e., a characteristic length scale representing larger turbulent vortices.

In order to account for the increase in l with distance from the grid, we used the empirical relationship Thompson and Turner [14]:

$$l = kxz \tag{3}$$

where z is the distance from the center of the grid oscillation to the location of the measurement, and k is a proportionality constant ($k = 0.1$). Using **10, 20**, and **30** strokes/min (referred to as turbulence levels **1, 2** and **3** hereafter), we obtained dissipation rates ranging from 3.8×10^{-8} to $4.8 \times 10^{-7} \text{ m}^2/\text{s}^3$, 8.7×10^{-8} to $8.5 \times 10^{-6} \text{ m}^2/\text{s}^3$ and 1.8×10^{-7} to $1.1 \times 10^{-4} \text{ m}^2/\text{s}^3$ respectively. The clear linear decrease in ϵ as a function of the distance from the grid is shown in a semi log plot, which reveals an exponential decrease in turbulence behind the grid. At a given distance from the grid, there were no significant differences from **1** depth to another, regardless of the grid frequency considered (F test, $p > 0.05$). The turbulence levels defined here are characteristic of turbulent

dissipation rates experienced by *Daphnia pulicaria* in surface waters of lakes and by *Temora longicornis* in its typical coastal water habitats [6].

Live material collection and acclimation

Daphnia pulicaria

All the calculations are based on the experiments that were performed using a clone of *D. pulicaria* kept in an outside mesocosm culture by Prof. K. Sakai at the Tokyo Univ. of Fisheries, Japan. Individuals were collected from the mesocosm using a 2 L beaker, gently filtered through a 200 μm mesh sieve, and stored in a 25 L aquarium filled with mesocosm water at densities of around 50 individuals/L under ambient light conditions. Prior to the experiments, non-egg-bearing adult females (carapace length, $1.9 \pm 0.1 \text{ mm}$, $-x \pm \text{SD mm}$; $n = 240$) were sorted by pipette under a dissecting microscope, and acclimated for 12 h at 21°C in 5 L plastic buckets filled with 0.45 μm filtered mesocosm water. All experiments were conducted at the Department of Ocean Sciences, Tokyo Univ. of Fisheries, in June 2000 in the “Zoo-Turbularium” filled with 45 L of 0.45 μm filtered mesocosm water at 21°C.

Temora longicornis

Individuals of the copepod *Temora longicornis* were collected with a WP2 net (200 μm mesh) from the surface of tidally mixed inshore waters of the Eastern English Channel. Specimens were diluted in buckets with surface water and transported to the laboratory. The acclimation of copepods consisted of storage in 20 L beakers filled with natural seawater. Prior to the experiments, adult females (carapace length, $1.0 \pm 0.1 \text{ mm}$, $-x \pm \text{SD mm}$; $n = 240$) were sorted by pipette under a dissecting microscope, and acclimated for 12 h at 20°C in 0.45 μm filtered seawater. All experiments were conducted at the Station Marine de Wimereux (France) in August 2001 in the “Zoo-Turbularium” filled with 45 L of 0.45 μm filtered seawater at 20°C.

Calculation procedures and behavioral prediction

Turbulence and zooplankton ambushing ability

Because of the above-mentioned observed residual circulation within the “Zoo-Turbularium”, we needed to calculate and analyze the data for the zooplankton individuals kept within the upper part of the tank, and to make them ambush against this residual circulation. By considering the photo tactic behavior of zooplankton organisms [7], we were able to achieve this by covering the upper and lower parts of the tank with opaque sheets of dark paper, and illuminating the upper part of the tank with a diffuse cold light placed sideways 0.25 m behind the grid; this resulted in illumination of about 12 $\mu\text{E}/\text{m}^2/\text{s}$ in the vessel, which was approximately equal to full daylight. Note that this surface residual circulation corresponded to a gradient in the horizontal velocity generated by grid oscillations that ranged from 0.01 to 0.71 cm/s, 0.10 to 1.40 cm/s, and 0.15 to 1.70 cm/s for turbulence levels 1, 2 and 3 respectively. To investigate the precise response of animals within these gradients, we divided the “Zoo-Turbularium” into 7 test sections 10cm wide, centered on the 7 axial ADV measurement points, and numbered them from A to G, from the furthest to the closest measurement points with respect to the grid. A single animal was then left in the tank, at 75 cm from the center of the stroke. Using a computer interfaced event recorder,

- (i) The number of escape reactions (i.e., the number of swimming bouts not oriented towards the grid) and
- (ii) The time spent in each test area was measured. This experimental procedure was conducted on both *D. pulicaria* and *T. longicornis*. Ten individuals were used for the non-turbulent reference treatments, for each turbulence level (3 turbulence levels), and each test area (7 test areas). The entire experiment thus consisted of (24 treatments and involved 240 individuals of *D. pulicaria* and 240 individuals of *T. longicornis*).

Turbulence intermittency and zooplankton ambushing behavior

The objective of this experiment was to record the ambushing behaviors of zooplankton individuals after a short exposure (1 min) to different intensities of turbulence. Test was conducted at all 21 levels of dissipation rates. The major challenge was then to keep the animals within areas of similar dissipation rates for 1 min. The entire “Zoo Turbularium” was covered with opaque sheets of black paper except for a test area 10 cm wide (corresponding to a volume of 4.75 L), and centered on the axial ADV measurement points; this area was covered with white paper on the bottom and sides. The test area was illuminated with a diffuse cold light placed 0.5m above the test unit. This resulted in illumination of 12 $\mu\text{E}/\text{m}^2/\text{s}$ in the vessel, approximately equal to full daylight. For this experiment, the different test areas must be thought of as turbulent patches which zooplankton organisms might encounter while

swimming. A single animal was selected out by pipette and left in the test area for 1 min. All animals tested remained within the test areas. The animal was subsequently picked up, and left in a **217 ml (8.5 x 8.5 x 3 cm)** Plexiglas recording vessel. Each individual was recorded swimming for 5 min using a digital camera at a rate of 30 frames/s. In order to investigate the time course of the behavioral response to turbulence, videos were divided into **5** segments of **1** min each, after which valid segments were identified for analysis. Valid segments consisted of pathways in which the animals were freely swimming at least 2 body lengths away from any of the chamber's walls or the surface. Each level of turbulence was tested with 10 different individuals, and compared to the results obtained from 10 reference individuals that were not exposed to turbulence. These experiments were only conducted with the cladoceran, *Daphnia pulex*.

Quantifying zooplankton swimming behavior

Because traditional metrics used to characterize animal movements have been proven to be scale-dependent, we used fractal analysis which is based on the premise that the fractal dimension can serve as a scale-independent descriptor of the path an organism takes as it swims around [6]. The philosophy behind fractals is as follows: if an organism moves along a completely linear path, then the actual distance traveled L , equals the displacement between the start and the finish, δ . The relationship between these **2** variables is linear. In other words, if we assume a power law relating L to δ , i.e., $L^D = \delta$, then the exponent, D is equal to 1. According to this power law, if the path deviates from linearity, i.e., it becomes curvilinear; the exponent will then be greater than **1**. In the extreme example of curviness, i.e., for the case of Brownian motion in **2**-dimensions, $D = 2$ [13]. It appears that D provides a measure of the paths sinuosity, tortuosity or complexity with extreme cases delineated by linear and Brownian movement, respectively, and real life cases expected to fall between these extremes. More specifically, we estimated fractal dimensions using the box-counting method. Formally, the method finds the λ cover of the object, i.e., the number of pixels of length λ required to cover the object [11]. A more-practical alternative is to superimpose a regular grid of pixels of length λ on the object and count the number of occupied pixels. This procedure is repeated using different values for λ . The volume occupied by a path is then estimated with a series of counting boxes spanning a range of volumes down to some small fraction of the entire volume. The number of occupied boxes increases with decreasing box size, leading to the following power-law relationship [10]:

$$N(\lambda) = k \times \lambda^{-D} \quad (4)$$

where λ is the box size, $N(\lambda)$ is the number of boxes occupied by the path, k is a constant, and D is the fractal dimension. D is estimated from the slope of the linear trend of the log plot of $N(\lambda)$ versus λ . Statistical analyses Because of the weak number of observations ($n = 10$) for both factors, the grid stroke frequency ($a = 3$) and the distance from the grid ($b = 7$), we based our analyses on non-parametric statistics. The effects of experimental factors (turbulence intensity and distance from the grid) on escape events, swimming speed, and fractal dimensions were thus investigated using the Scheirer-RayHare extension of the Kruskal-Wallis test Scheirer *et al.* [8], Sokal and Rohlf [9], referred to as the SRH test hereafter. Appropriate multiple comparison procedures were subsequently used to test for differences between the non-turbulent control and the three turbulent conditions and the Jonckheere test for ordered alternatives was used to test for the presence of a gradient in observations conducted at different distances from the grid Siegel and Castellan [1]. The escape responses of *Daphnia pulex* and *Temora longicornis* showed very distinct patterns. For *D. pulex*, the number of escapes also significantly differed between the turbulence treatments and test areas (SRH test, $p < 0.05$). Multiple comparison procedures finally showed that the number of escapes was always significantly higher in turbulent than in non turbulent conditions $p < 0.05$, and increased significantly when the distance from the center of the stroke decreased (Jonckheere test, $p < 0.05$).

More specifically, the percentage of *Daphnia* individuals that exhibited escape responses increased significantly when the distance from the center of the grid stroke decreased, while the turbulence intensity increased at a given distance from the grid. In contrast, the number of escapes observed for *T. longicornis* exhibited no significant differences related to the distance from the center of the grid stroke, or according to the turbulence intensities (SRH test, $p > 0.05$). However, the percentages of *Temora* individuals that exhibited an escape reaction showed a pattern similar to that observed for *Daphnia*, but it never reached **100%** and increased with decreasing distance from the grid only for the **2** highest levels of turbulence. The swimming mean speed of *D. pulex* significantly increased with decreased distance

from the grid for both still and turbulent treatments (Jonckheere test, ≤ 0.05). The subsequent effective speed showed significant increases for all turbulent treatments with decreased distance from the grid.

DISCUSSION

In recent contributions, it has been shown that the ambushing behavior of zooplankton organisms can also be characterized in terms of multi fractals. To avoid misinterpretations, one must note that fractal and multi fractal frameworks are fully compatible, the choice of a method being a matter of convenience or dependent on the specific objectives of the study. The fractal behavioral approach introduced here and elsewhere is intrinsically based on the geometric properties of a swimming path, in terms of space filling properties. A simple, smooth, quasi-linear path is thus characterized by a low fractal dimension ($D \rightarrow 1$), while that of a more-tortuous path is higher, ultimately reaching the maximum space-filling value of $D = 2$. Alternatively, the multi fractal approach is a stochastic generalization of the fractal approach, leading to characterization both qualitatively and quantitatively of the distribution of successive displacements. The multi fractal approach, thus, a priori provides no information related to the 3-dimensional structure of the ambushing path, as the same pattern in successive displacements can be observed in an organism intermittently swimming following a straight or highly convoluted path. The 2 approaches should then rather be regarded as complementary, and can be compared following the relation $D = d + 1 - \zeta(2)/2$, where D is the fractal dimension, d is the dimension of the embedding Euclidean space, and $\zeta(2)$ is a specific value of the multi fractal structure function exponents, $\zeta(q)$:

REFERENCES

1. Peters F. and Marrasé M.: (2000). Effects of turbulence on plankton an overview of experimental evidence and some theoretical considerations. *Mar. Ecol.-Prog. Ser.* 205, 291-306.
2. Peters F., Redondo J. M.: (1997). Turbulence generation and measurement: application to studies on plankton. *Sci. Mar.* 61, 205-228.
3. Taylor G. I.: (1935). Statistical theory of turbulence. *Proc. R. Soc. London Ser. A* 151, 1-421.
4. Tennekes H.: Eulerian and Lagrangian time microscales in isotropic turbulence. *J. Fluid Mech.* 67, (1975), 561-567.
5. Stiansen J. E., Sundby S.: (2001). Improved methods for generating and estimating turbulence in tanks suitable for fish larvae experiments. *Sci. Mar.* 65, 151-167.
6. Seuront L., M. C. Brewer, J. R. Strickler: (2004 a). Quantifying zooplankton swimming behavior: the question of scale. In L. Seuront, P. G. Strutton, eds. *Handbook of scaling methods in aquatic ecology: measurement, analysis, simulation.* Boca Raton, FL: CRC Press, pp. 333-359.
7. Van Gool E, J Ringelberg: Relationship between fish kairomone concentration in a lake and photo tactic swimming by Daphnia. *J. Plankton Res.* 24, (2002), 713-721.
8. Scheirer C. J., W. S. Roy, N. Hare: The analysis of ranked data derived from completely randomized factorial designs. *Biometrics* 32, (1976), 429-434.
9. Sokal R. R., F. J. Rohlf: (1995). *Biometry*, New York, Freeman.
10. Loehle C.: (1990), Home range: a fractal approach. *Landscape Ecol.* 5, 39-52.
11. Voss RF.: (1988), Fractals in nature: from characterization to simulation. In HO Peitgen, D Saupe, eds. *The science of fractal images.* New York: Springer, pp. 21-70.
12. Siegel S., N. J. Castellan.: *Non parametric statistics for the behavioral sciences*, New York, (1988), McGraw Hill.
13. Mandelbrot B.: (1983), *The fractal geometry of nature*, New York, Freeman.
14. Thompson S. M., Turner, J. S.: (1975), Mixing across an interface due to turbulence generated by an oscillating grid. *J. Fluid Mech.* 67, 349-368.

CITATION OF THIS ARTICLE

M S Haque and R Shrivastava: Marine Zooplanktons Ambushing Behavior and Turbulence. *Bull. Env. Pharmacol. Life Sci.*, Vol 5 [4] March 2016: 49-53