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Hydrodynamic Effect on V-Shape Pattern Formation of Swarm Autonomous Surface Vehicles (ASVs)

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Abstract

Swarm robot has been studied for last few decades because it possesses robustness, scalability and flexibility characteristics as compared to other types of robotic system. One of the swarm robots research areas includes a pattern formation. This paper presents an investigation of hydrodynamic effect (i.e. viscous drag) on the swarm Autonomous Surface Vehicles (ASVs) while performing pattern formation based on leader-follower control approach. The study specifically focus on the hydrodynamic effect of V-shape pattern formation as naturally observed in flying method of migrating birds. This study is important to ensure stability of the pattern formation while swarm of ASVs navigate on the water's surface. The parameters of interest are relative distance and relative angle between the ASV's leader and follower. Simulation results show that as the distance between the ASVs increases, the drag effect on the followers are decreases. It is also observed that, as the angle between leader and follower increases, the drag effect experiences by the follower ASVs decreases up to a certain value of angle before increasing again. However, the drag effect encountered by the leader is continuously decreases as the angle increases except at the initial state.

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Keywords: Autonomous Surface Vehicle; swarm formation; V-shape formation; hydrodynamic effect; leader-follower formation

1. Introduction

The concept of swarm robotics can be very useful in search tasks such as in case of sound or odor source localization, where the spatial pattern of the source is complex [1]. In a particular searching process, robots are usually deployed in a regular and repetitive manner where each robot needs to keep a specific distance and angle relative to each other to maintain desired shape of formation. From swarm robotic perspective, this method of deployment is known as pattern formation [2]. Pattern formation could takes place in various forms and shapes depending on the objective and purpose of the deployment. Fig. 1 illustrates some examples of pattern formation using a multi-robots system as studied in [3].

Pattern formation is essential for a systematic searching, robot coordination and simpler navigation control implementation. The searching event could possibly take place either on the ground, on the water's surface, in an underwater environment etc. Apart from geometrical and communication consideration, the dynamic properties of the environment contributes a significant effect on the pattern formation stability especially in a fluidic environment. Depending on the fluid density and viscosity, the effects of the fluid hydrodynamic on the moving object are significant [4]. In common practice, the resistance or drag effect on a moving object caused by surrounding air is neglected at low speed motion. However, in dealing with high density fluid such as

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water, the resistance caused by the fluid is significant even at low speed motion. In addition, during leader-follower formation the leading robot creates a continuous wake as it moves and introduces an additional hydrodynamic effect on the follower robots. Thus, underwater vehicles and surface vessels experiences a significant hydrodynamic effect as it moves compared the ground and aerial types of robots.

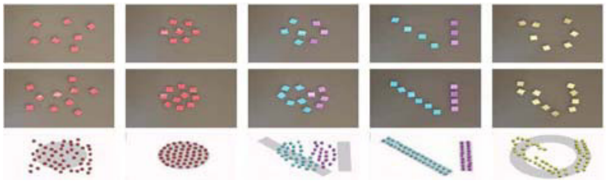


Fig. 1. Examples of swarm robot pattern formation

The hydrodynamic effect could be in term of friction between the fluid and the body (or hull), wave, current and wake created by the leading robot [5]. To overcome these effects robots consume more energy and consequently reduced operation time as the battery depleted rapidly. In other words, the hydrodynamic effect is directly related to the power efficiency of the robot either as an individual or as a group in pattern formation. Therefore, by investigating how the hydrodynamic effect is related to the pattern formation, power consumption could be optimized and longer operation time could be attained.

Computational Fluid Dynamic (CFD) approach is commonly used to study the hydrodynamic effect or aerodynamic effect on a moving object in a fluid. For example, a study of both the hydrodynamic and aerodynamic effect on catamaran is presented in [6] and the shape optimization analysis of vertical profiler is discussed in [7]. In addition, the investigations of drag force effect on the cooperative Autonomous Underwater Vehicles (AUVs) is studied in [5] while hull resistance analysis is found in [8]. CFD also has been widely used to approximate hydrodynamic coefficient [9]-[11] and system modeling [12]. Most of the commercially available CFD codes such as FLUENT, FLOW3D and STAR-CD use finite volume method as a solver [13]. The finite volume solver discretizes and solves the governing equations formulated by mass conservation and momentum conservation principle. The solution in initialized and solved based on the boundary conditions set by user.

In this paper, research work involves the study of a group of ASVs moving on the water while maintaining specific formation (i.e. V-shape pattern formation) based on leader follower concept. Thus, the hydrodynamic effect on each of the robot is an important factor to be considered for a stable formation realization. The aim of the study is to investigate the effect of drag force on both leader and follower robots as relative distance and relative angle between the leader and follower robots are varied. It is assumed that each robot moves at a constant speed and subjected to the drag effects cause by robot movement and fluid flow.

2. Problem Formulation

There are many forms of pattern formation could be found in literatures related to the swarm robotic system. In this study, the investigation is limited to a V-shape (or skein) flock formation as observe in a flying pattern of geese, ducks and other migratory birds [14]. The illustration of the V-shape pattern formation is shown in Fig. 2. An early study shows that the migration birds use this type of formation to save energy by avoiding the wake developed by the leading birds [15]. As the birds fly collectively, the preceding birds follow the succeeding birds at a certain distant and angle. The optimal selection of these two parameters determines how efficient the energy could be saved. The more wake could be avoided by the follower birds, the less energy would be devoted to overcome the wake effect and thus, farther the distance could be reached with the same amount of energy. From other point of view, V-shape formation allows efficient communication between the birds as reported in [16].

Inspired from this type of nature formation, it is believed that a similar pattern formation could be employed on the swarm of ASVs for navigation during the source searching operation. As explained earlier, a moving object on the water is not subjected to the negligible hydrodynamic effect. For leader-follower formation concept, the effect of the wake generated by the leader motion on the followers will be studied. Through the study a more stable formation could be obtained by determining optimal distance and angle between the leader and the followers at which the hydrodynamic effect is negligible.

The two important parameters to be investigated for optimal ASVs pattern formation are distance (denoted as L) and angle (denoted as ϕ) between the ASVs as shown in Fig. 3. Since the formation involves repetitive arrangement of the leader-follower stages and the formation is approximately symmetry about the leader path line, only the first layer of the leader-follower will be considered. To recap, the main objective of the work is to determine what is the optimum separation distance, L and at what angle ϕ the follower robot should be placed so that the effect of drag and wake is minimal. Alternatively, it is possible to set the distance d of instead of L since relationship between the distance d and horizontal distance L is given by

$$L = d\cos(\phi) \tag{1}$$

For simplicity, θ is taken (angle between the vertical line and formation line) to be varied instead of ϕ where the relationship between the two angles is given by

$$\theta = 90^\circ - \phi \tag{2}$$

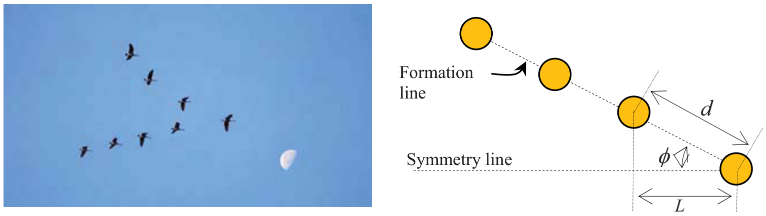


Fig. 2. V-shape flying formation of migration birds (*www.livescience.com*)

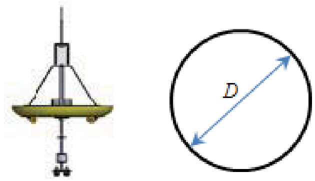
To achieve this objective, the drag effect of both leader and follower will be observed. Two types of corresponding viscous drags act on a body in fluid are the pressure drag and skin friction drag. The pressure drag is due to the force components while the skin friction drag is the integral components of the shear stresses over the body's surfaces measured in the drag direction. In this study, the 2D viscous drag is mathematically given by

$$vicous\ \ drag = skin\ \ friction\ \ drag + pressure\ \ drag \tag{3}$$

3. Simulation Setup

Some important consideration will be highlighted in this section to setup necessary parameters for simulation. In this study, ANSYS Fluent software is used to simulate the hydrodynamic characteristic as the distance and angle between the leader and follower changes. Simulation is conducted by changing one variable while the other is kept constant and recording the drag coefficient experiences by both leader and follower. To determine the drag coefficient, the distance d is fixed at a certain value and the angle θ is varies. The angle increment is fixed at a constant interval i.e. every 5°. The range of the angle is limited within $0^o \leq \theta \leq 80^o$. Increment of the angle is stop at 80° because at 90° angle, the followers intersect each other on the symmetry line. Once completed, value of the distance is increase by a step of 0.5 m and the process is repeated again for different values of angles. Increment of the distance is stop at $d = 4.0$ m as farther than this point, hydrodynamic effect caused by the leader on the followers is very small and negligible. The water's angle of attack is zero since motion is considered only in the x-direction.

The simulation model is simplified from a complex geometry design of the actual prototype. The actual prototype is shown in Fig. 3(a) which consists of a cylindrical shape hull design. The cylindrical shape design has advantages in term of smaller turning radius (almost zero) compared to a standard surface vessel design. Small turning radius is important for rapid movement of the swarm robots implementation which requires fast turning capability. For the purpose of simulation, the model is simplified as two-dimensional circular shape model with diameter, $D = 0.5$ m as shown in Fig. 3(b). The nominal operation speed of the ASVs is $v = 0.5$ m/s. Here, all ASVs are assumed to have the same speed despite in reality there is margin for differences.



(a) (b)

Fig. 3. ASV (a) Actual prototype (b) Hull model used for CFD analysis

3.1. Boundary Condition

To conduct CFD analysis, the geometrical and boundary condition setup is shown in Fig. 4 according to suggestion used in [17]. However, since the position of follower robots will change according to the set value of θ angle, the dimension of the wall should also changes accordingly. For example, at $\theta = 30^o$ the angle $\phi = 60^o$, vertical distance from symmetry line will be $d\sin(\phi)$ and the horizontal distance L will be $d\cos(\phi)$. Thus, the length of the bounded region will be $9D+d\sin(\phi)$ and $3L+d\sin(\phi)$. This convention is used to ensure the distance between the body and the outer boundary remains the same even though the distance between the ASVs leader and follower changes. The velocity inlet acts toward positive x-direction with magnitude of 0.5 m/s. The wall is set as free slip wall to represensts unbounded open channel.

3.2. Meshing

Fig. 5 shows the generated mesh used for CFD simulation in this study. The mesh is constructed from unstructured triangular elements. This type of mesh was chosen because of position order complexity of the ASVs formation. First Layer Thickness

Inflation with height of 1 mm was applied to the boundary of the ASVs for better accuracy. The meshing scheme and inflation implemented in the simulation is shown in Fig. 5(a) and Fig. 5(b) respectively. According to [18], the best quality of mesh gives a more accurate result which is a step closer to the experimental data. The orthogonal quality of the mesh generated is maintained above 0.65 as the distance and angle between ASVs are changing. The mesh shown in Fig. 5 consists of 17188 nodes and 256905 elements.

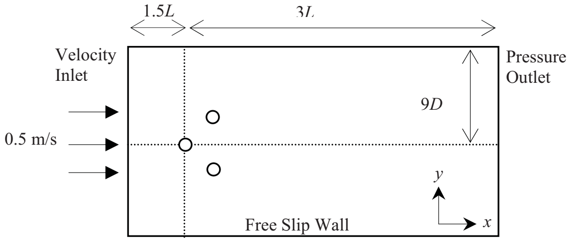
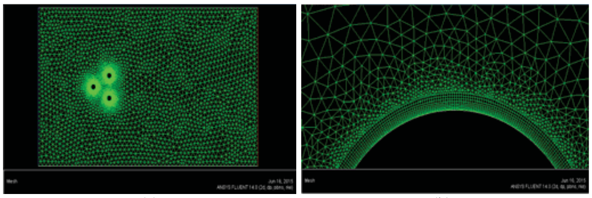


Fig. 4. Boundary condition for numerical simulation



(a) (b)

Fig. 5. Mesh domain (a) Full domain (b) Mesh at the hull boundary

3.3. System Setup

In this paper, the k-ε turbulent model was used. Furthermore, Realizable and Standard Wall Function was chosen for the simulation. The convergence criteria are setup to be $1.0\text{x}10^{-5}$ which is small enough error to guarantee accuracy of the results. Water liquid with the properties listed in Table 1 is used for simulation.

Table 1 Simulation setup parameters

Properties [unit]	Value
Viscosity [kg/m-s]	0.001003
Density [kg/m^3]	998.2
Velocity Inlet [m/s]	0.5

4. Results and Discussion

Evaluations of the results in this paper are based on the drag force coefficient, C_d values act on the ASV's hull in the direction of the fluid flow i.e. +x-direction. Fig. 6 shows the variation of the drag coefficient as the angle changes for different values of distances i.e. 1 m, 2 m, 3 m and 4 m. Note that the pattern of C_d values of the followers are almost similar at different distances because they are symmetrical to each other and ideally should experience similar drag effect. A similar pattern of C_d values are observed at distances of 1.5 m, 2.5 m and 3.5 m but not illustrated here. In general, simulation results show that as the angle θ increases while the distance between the ASVs is keep constant, the drag forces experiences by the follower robots decrease until a certain value of angle before it starts to rise again. This situation could be understood as the angle increases, the impact of wake caused by the leader movement is decreases with respect the follower position. However, after certain angle the wake and turbulence effect is increasing and thus the pressure around the follower robot is increasing again.

Note that, the drag coefficient is higher when the leader and follower are close together compared to when they are farther from each other. For example, at starting point ($\theta = 0^o$) when the distance $d = 1$ m the C_d of the follower is around 0.3 while at the same angle but at the distance of $d = 4$ m, the C_d value is close to 0.24. The reason behind this situation is that when the ASVs are closer to each other, the wake generates from each ASV affect other ASVs as they move together. As distance increases, the effect is gradually reduced and thus, less drag is experience by each of the ASVs.

Another important point is initial value of the drag coefficient for the leader is always higher compared to the followers. Logically, this observation could be explained as the leader position is located at the middle of formation i.e. between the two followers. As consequence, it faced the drag impact from both the left and right followers. The C_d of the leader initially increases as the angle increase before it starts to decrease after certain value of angle. At the distance of 4 m as seen in Fig. 6(d), all ASVs experiences similar drag effect at the beginning since this distance is large enough that caused the wake impact on each other is insignificant. At this point each of the ASVs only experienced drag effect due to their own movement alone.

In general, from the results observation, the estimated optimum angle lies between 40^o to 60^o before the drag effect increases again on the followers ASVs. The optimal angle is large when the distance is large and become small when the distance between the leader and the follower closer to each other as could be observed from Fig. 6. In case of the leader, the C_d values show a continuously decreasing pattern regardless value of the angles and distances.

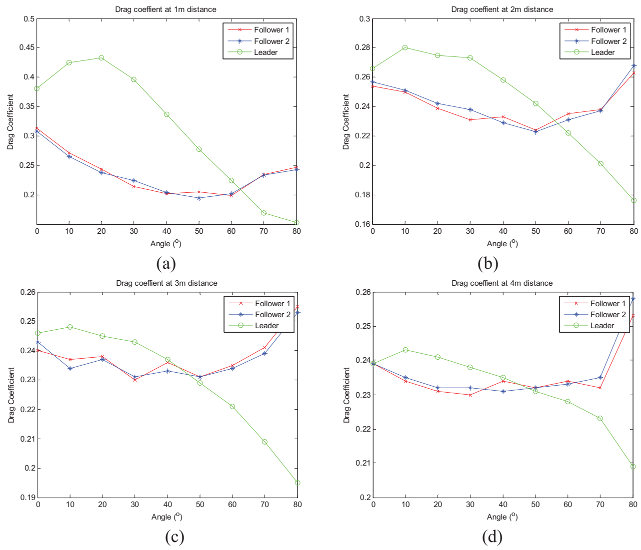
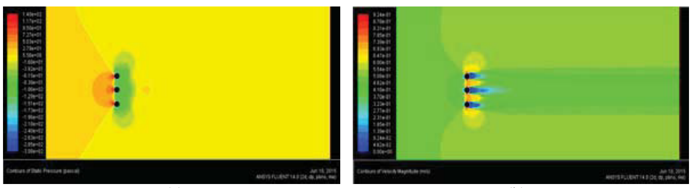


Fig. 6. Drag coefficient at separation distance of (a) 1m (b) 2m (c) 3m (d) 4m

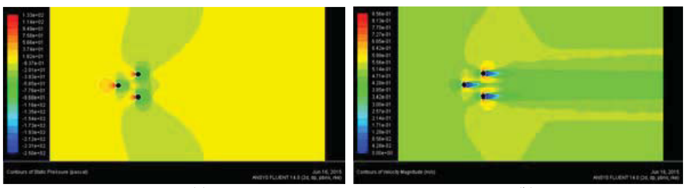
Fig. 7 and Fig. 8 graphically shows the pressure and velocity contours at the angle of $\theta = 0^o$ and $\theta = 30^o$ respectively for a distance of $d = 1$ m. In these figures, a symmetrical pattern of the velocity and pressure contours which ideally represents the symmetrical shape of the pattern formation could be observed. It is graphically clear from these contours plot, how the drag or wake effect creates by the leader in forward movement influence the follower performance. From Fig. 7(a) it shows that the effect of closer distance developed a higher pressure around the ASVs compared to the one farther away as in Fig. 8(a). In addition, Fig. 7(b) illustrates how the fluid flow affects the neighbouring robots when the robot located closer to each other in a parallel formation (the angle between them is zero). However, the effect is reduced when the follower is positioned at certain angle with respect to the leader position. This finding theoretically explains why the migrating birds fly in the V-shape formation. However, this positioned is not optimum since only single follower position has been consider. To determine the optimum position and angle, the relationship between these parameters and the drag coefficient has to be determined.

The relationship between the angle, distance and drag coefficient is shown in Fig. 9 for both leader and follower for the range of $0^o \leq \theta \leq 80^o$ and $1\text{m} \leq d \leq 4\text{m}$. For the leader, the optimal distance and angle is not importance because it depends on the follower angles. As discussed earlier the effect of drag on the leader is continuously decreasing regardless the angle and distance. So the decision of the optimal angles and distance now relies on the performance of the followers. From Fig. 9(b), it is observed that the optimum distance and angle occurs at approximately 1.5 m and 60^o respectively where drag coefficient is lowest.



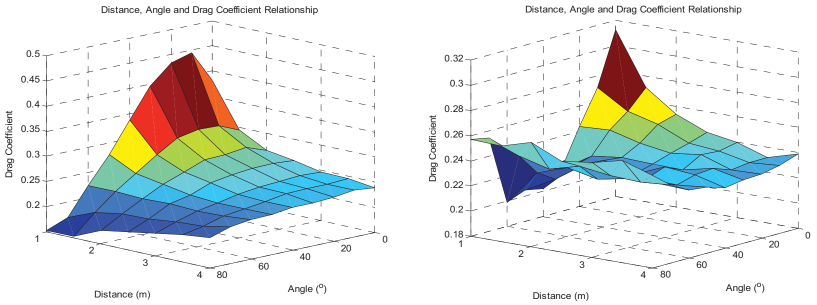
(a) (b)

Fig. 7. Contours at $\theta = 0^o$ and $d = 1$ m (a) Pressure (b) Velocity



(a) (b)

Fig. 8. Contours at $\theta = 30^o$ and $d = 1$ m (a) Pressure (b) Velocity



(a) (b)

Fig. 9. θ, d and C_d relationship for (a) Leader (b) Follower

5. Conclusion

The investigation of the hydrodynamic effect on the V-shape pattern formation of swarming ASVs adopting leader-follower concept has been studied. The simulation results shows that as the angle increases while distance between the leader and follower is keep constant, the drag forces act on the follower are continuously decreasing until reaching a certain value of angle before increasing again. Similar pattern is observed but with different drag values when the distance increases. The drag effect on the leader increases at the beginning and starts to continuously decrease after certain step of angle increment. From the analysis, optimum distance and angle is found to be 1.5 m and 60^o respectively. Future work wills includes the experimental validation of the simulation results presented in this paper and incorporating the effect of waves and current.

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