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Investigation of the Flow Structures for Two Tandem Arrangements of Torpedo-Like Geometries

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Research Article

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ABSTRACT

In this study, flow structures of a streamlined torpedo-like geometry having an elliptical nose and tampered stern at a length to the diameter aspect ratio of L/D=5 for a single and double tandem arrangement with various spacings have been investigated using Particle Image Velocimetry (PIV) method in a closed loop water channel. Reynolds number defined for the length of the geometry (L=200 mm), free stream water velocity of 100 mm/s was taken as Re=20000, the spacing (G) between two identical torpedo-like geometries is changed from 0 to 120 mm. Instantaneous 1000 images and their time-averaged results are comparatively presented for all configurations of the torpedo-like geometry. It is demonstrated that the tandem arrangements depending on the dimensionless spacing ratios (G/L) between 0 to 0.6 is significantly different from the single torpedo-like geometry for the flow patterns of instantaneous and time-averaged velocity field, dimensionless streamwise velocity component and streamline topology. For the contacting case in which the following model nose is placed on the trailing edge of the front model, the wake region of the back geometry is similar to the single model wake but the all of time-averaged flow patterns elongated and symmetrical flow patterns are slightly deformed. When flow area is provided between two models for spacing ratios of $0.15 \leq G/L \leq 0.30$, chaotic and rotational flow patterns occur due to the impinging of separated flow patterns from the front geometry to the nose of the downstream one. As the gap distance increases to the largest value at G/L=0.6, the wake region of both the single and tandem arrangement becomes almost identical. More detailed information for the flow characteristics of the examined torpedo-like geometry can be determined by using computational fluid dynamics after validation with PIV results in the present study.

Torpido Benzeri Geometrilerin İki Tandem Düzenlemesi İçin Akış Yapılarının İncelenmesi

Araştırma Makalesi

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ÖZET

Bu çalışmada, çeşitli aralıklarla tek ve çift tandem düzenlemesi için uzunluk-çap en boy oranı L/D=5 olan, eliptik bir burna ve konik kıç kısmına sahip aerodinamik torpido benzeri bir geometrinin akış yapıları, bir kapalı çevrim su kanalı içinde Parçacık Görüntülemeli Hız ölçme (PIV), yöntemi kullanılarak

Anahtar Kelimeler:
Eliptik burun
PIV
Tandem düzenleme
Torpido benzeri geometri
Türbülanslı akış
Viskoz akış

incelenmektedir. Geometrinin uzunluğu için tanımlanan Reynolds sayısı (L=200 mm) Re=20000 değeri, serbest su akış hızı 100 mm/s, olarak alınmaktadır. İki özdeş torpido benzeri geometri arasındaki mesafe (G) 0-120 mm aralığında değişmektedir. Torpido benzeri geometrinin tüm konfigürasyonları için anlık ve 1000 görüntüden hesaplanan zaman ortalamalı sonuçlar karşılaştırmalı olarak sunulmaktadır. Boyutsuz boşluk oranlarına (G/L) 0 ila 0,6 arasındaki bağlı tandem düzenlemelerinin, anlık hız alanı (V), zaman ortalamalı hız alanı <V>, boyutsuz akış yönündeki hız bileşeni <u/U∞> ve akım çizgisi topolojilerinin <Ψ> tek torpido benzeri geometriden önemli ölçüde farklı olduğu gösterilmektedir. Öndeki modelin firar ucu arkadaki modelin burnuna temas durumu için arka geometrinin art izi bölgesi tek model art izine benzer, ancak tüm zaman ortalamalı akış yapıları uzamakta ve simetrik akış yapıları biraz deforme olmaktadır. Boyutsuz boşluk $0,15 \leq G/L \leq 0,30$ aralık oranları için iki model arasında akış alanı sağlandığında, öndeki geometriden ayrılmış akış yapılarının arkadaki geometrinin burnuna çarpması nedeniyle karmaşık ve dönümlü akış yapıları oluşmaktadır. Boşluk oranı en büyük değer G/L=0,6'ya yükseldikçe hem tekli hem de art arda düzenlemesinin art izi bölgesi hemen hemen aynı hale gelmektedir. İncelenen torpido benzeri geometrinin akış özellikleri için daha ayrıntılı bilgi, bu çalışmadaki PIV sonuçlarıyla doğrulama yapıldıktan sonra hesaplamalı akışkanlar dinamiği kullanılarak belirlenebilmektedir.

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Introduction

The investigation related to unmanned vehicles in all fields of civil, industry, and military such as air, land, and sea applications for designing equipment, control systems, structures, aerodynamic and hydrodynamic behaviours has been performed by researchers for many years. Fluid mechanics applications have an important role to obtain an optimized geometry of aerodynamic and hydrodynamic characteristics of vehicles. Technological developments in all fields have been affected the production of manned or unmanned autonomous underwater vehicles (AUVs). Therefore, many researchers have been directed to design, apply and improve the new generations AUVs in defense, industry and research areas (Ozgoren et al. 2010; Rattanasiri et al. 2012; Tian et al. 2017; Akbudak et al. 2021; Kilavuz et al. 2022). One of the AUVs is a torpedo-like geometry that has to reach the pre-determined target with stored energy on the body in time. Controlling flow characteristics and diminishing the negative effects such as flow separation, fluid-structure interaction and larger unsteady drag forces require a detailed investigation. The obtained data can be used to control the maneuvering and cruising paths of AUVs for single or multiple arrangements. Rattanasiri et al. (2012) stated that AUVs performed many confidential missions with equipment such as different sensors, carried by many small AUVs instead of one large AUV resulting in better levels of resilience and redundancy. The arrangement of the movement of multiple AUVs in the flow environment was inspired by animals that swim and/or fly as herds. With the help of this observation, there are many research results that show more energetic performance benefits of the configurations such as different spacings of inline, tandem or staggered arrangement (Partridge et al. 1983; Hanrahan and Juanes 2001; Andersson and

Wallander, 2003; Alexander, 2004; Weihs, 2004; Rattanasiri et al. 2012). The drag characteristics of a pair of prolate spheroids having a length (L) of 1.2 m with a length-diameter ratio of 6:1 at a Reynolds Number (Re) of 3.2×10^6 were examined by Molland and Utama (1997). They recorded that the drag coefficients according to the wetted surface area were 8%, 4% and 2% larger than that of a single spheroid, in consequence, for the spacing ratios of side by side arrangement for S/L of 0.27, 0.37 and 0.47. A numerical simulation study for multiple torpedo shape AUVs was done by Husaini (2009). It was displayed that the drag forces on both AUVs concerning the arrangement spacings were influenced significantly. Rattanasiri et al. (2012) conducted a study using same sized prolate spheroids and classified the results depending on the individual drag and combined drags with five regions which were low interaction region, parallel region, drafting region, echelon region, and push region. They recommended from their results that operators of AUVs can settle a possible fleet traveling arrangement accordingly energy consumption like swimming of dolphins.

A novel method that is Particle Image Velocimetry (PIV) has been using many fluid mechanic applications, recently. Yagmur (2016) studied the flow behaviors around a special torpedo-like geometry placed in a uniform flow for various angles of attack $\alpha=0^{o}$, 4^{o}, 8^{o}, 12^{o} and passive flow control modifying the geometry and adding tail via PIV and Computational Fluid Dynamics (CFD) by using ANSYS-Fluent program for Reynolds numbers of $Re=2 \times 10^4$ and $Re=4 \times 10^4$, time-dependently. Instantaneous and time-averaged vector fields, vorticity, contours for time-averaged scalar values of streamwise and cross-stream wise velocity components, and its root mean squares components, Reynolds stress correlation, Turbulence Kinetic Energy (TKE) scalar values and streamline topology were discussed. The results exhibited that the pressure coefficient took its maximum value ($C_P = 1$) at the stagnation point placed the leading edge of the torpedo-like geometry and it had negative values after the region that flow separation occurs along the fuselage region of the body for the torpedo-like geometry. With the increase in attack angles, both the drag and lift coefficients increased and lower pressure regions formed under the body. Because of the flow separation, Reynolds stress and TKE values in the trailing and leading region of the model became stronger with the increased attack angle. An experimental study with PIV method for comparison of different configurations of two spheres at Re= 5000 in a uniform flow was performed by Ozgoren et al. (2004), in which the turbulent flow characteristics around the both spheres were strongly dependent on the distance and arrangement angle. Another study by Yagmur et al. (2016), increasing angle of attack disrupted the symmetrical distribution of flow characteristics around the torpedo-like geometry so that the saddle point (S) at the tip of the nose of the geometry moved upwards, and that the trace area approached the body due to the increase in the Reynolds number. Kilavuz et al. (2021) investigated the flow characteristics of torpedo-like geometry placed near the free-surface for immersion ratios of $0.75 \leq h/D \leq 3.5$ and angles of attack $\alpha=0°, 4°, 8°$, and $12°$. Variation of Froude numbers (Fr) depending on the immersion ratio was found that Fr number and corresponding drag coefficient had higher values for the lower immersion ratio. Multiple arrangements of the circular cylinders, square cylinders, spheres, elliptic or oval cylinders were investigated by Zobeyer et al. (2021), Hossain et al. (2021), Zhengi and Alam (2019), Ozgoren et al. (2014), Pinar et al. (2013), Ibrahim and Gomaa (2009), Georgios et al. (2006), Jianfeng et al. (2005), Mittal and Kumar (2001), Zdravkovich (1977). These articles highlighted the various phenomena, flow characteristics, forces and turbulence associated with vortex-induced oscillations depending on the distance between the bodies, Reynolds number, geometry shape and arrangement with experimental and numerical methods. Zdravkovich (1977) examined the flow-interaction results in a steady flow for various arrangements of two cylinders such as staggered, side-by-side and tandem. It was recorded that when more than one identical bluff body model was located in a fluid flow, the induced forces and vortex shedding structures are distinguishably different for a single geometry at the same Reynolds number. Furthermore, flow characteristics and flow-structure interaction are highly dependable on the arrangement between two fixed cylinders. Yaniktepe and Rockwel (2005), Mitchell and Delery (2001), Siegel et al. (2001), Polat et al. (2021), Ozalp et al. (2021) performed experimental studies using PIV method around unmanned combat air vehicle models in water channel and wind tunnel.

Investigation of flow characteristics of two tandem torpedo-like geometries which is a representative of fleet AUVs has been done using PIV method in uniform condition at Re=2x10^4. This will be one of the first study for the PIV application such a body arrangement, which has not been encountered in the literature. The results quantitively and comparatively have been presented depending on the spacing ratio by using instantaneous and time-averaged flow structures.

Material and Methods

The geometry and size of the torpedo-like model were determined to form a streamlined underwater vehicle model by using the Myring (1976) equations 1 and 2 given below.

$$r_{\mathrm{N}}(x) = \frac{1}{2}D\left[1-\left(\frac{x-L_N}{L_N}\right)^2\right]^{1/n} \tag{1}$$

$$r_{\mathrm{S}}(x) = \frac{1}{2}D-\left[\frac{3D}{2{L_S}^2}-\frac{tan\theta}{L_S}\right](x-L_N-L_H)^2+\left[\frac{D}{{L_S}^3}-\frac{tan\theta}{{L_S}^2}\right](x-L_N-L_H)^3 \tag{2}$$

Here, where n=2. The angular parameter of the tail is given in equation 2, where θ≅30° is taken. In these equations, x is the axial distance from the nose to the stern end. Myring angular parameter of the stern and the overall potential parameter of the geometry are taken as θ≅30° and n=2, respectively. The experiments were done at free-stream velocity of U_∞=100 mm/s corresponding to Reynolds numbers ($Re = U_\infty L/\upsilon$) 2.0x10^4, L=200 mm is the length and υ is the kinematic viscosity of water (υ=1x10^{-6} m^2/s^2). The PIV measurement was conducted using the water channel and a Nd:YAG laser working in synchronization with a camera in the Advanced Mechanical Engineering laboratory of Osmaniye Korkut Ata University. The channel consisting of transparent Plexiglas to allow observation has a width of 0.8 m, length of 6 m, and depth of 1 m. During the experiment, water depth (h_W) is fixed as 80 cm. The 10 µm diameter silver coated hollow glass sphere particles with a density of around 1100 kg/m^3. The double pulse YAG laser with a 532 nm wavelength, a 145 mJ pulse energy and 15 Hz frequency were used to illuminate the flow field as seen in Figures 2 and 3. The experimental setup of the water channel for laser illumination and PIV measurement of field of views is shown in Figure 4. The space between the torpedo-like geometries is denoted by G. The thickness of the laser sheet was kept at approximately 1.5 mm. A Charged Couple Device (CCD) camera having 1600x1200 pixels resolution was used to capture images. Interrogation window areas of 32x32 pixels were used with 50% overlap for the double-frame images to produce velocity vectors. The obtained velocity field contained as many as 7326 (99x74) vectors. Throughout the measurement 1000 double-frame images were taken in 66.6 seconds. The obtained 1000 images containing instantaneous velocity vectors were used for the time-averaged velocity vector field, streamline topology and streamwise velocity component. The Dantec Dynamic Studio software was used to obtain the velocity field. Spurious velocity vectors (less than 3%) caused by shadows, reflections from the free-surface and model, laser sheet distortions and image processing were detected using the local median-filter technique, developed by Westerweel (1994). The uncertainty of velocity measurement in PIV is estimated to be around 2% as stated by Westerweel (1994) and Ozgoren (2006). From instantaneous PIV images, the time-averaged streamwise velocity is calculated as follows;

$$\langle u(i,j)\rangle = \frac{1}{N}\sum_{n=1}^{N} u_n(i,j) \tag{3}$$

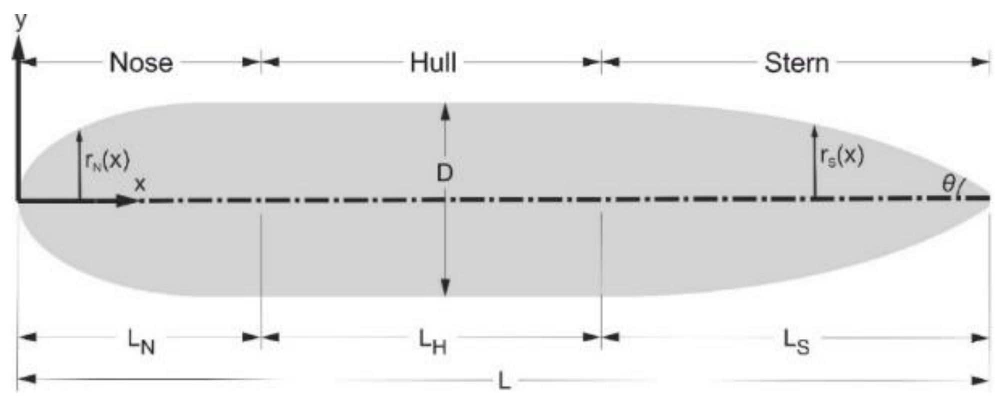


Figure 1. Parameters of a geometrical design of a torpedo-like geometry. The nose, hull and stern lengths of the model with a D=40 mm diameter are L_N=40 mm, L_H=80 mm and L_S=80 mm, respectively.

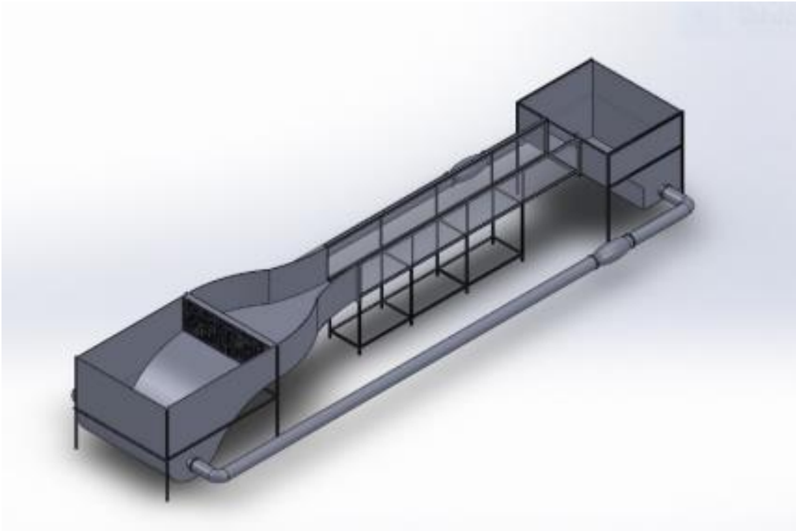
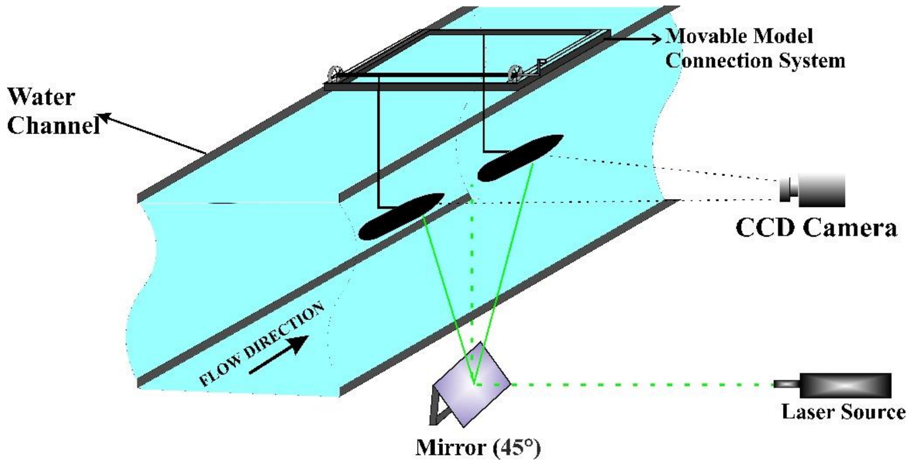
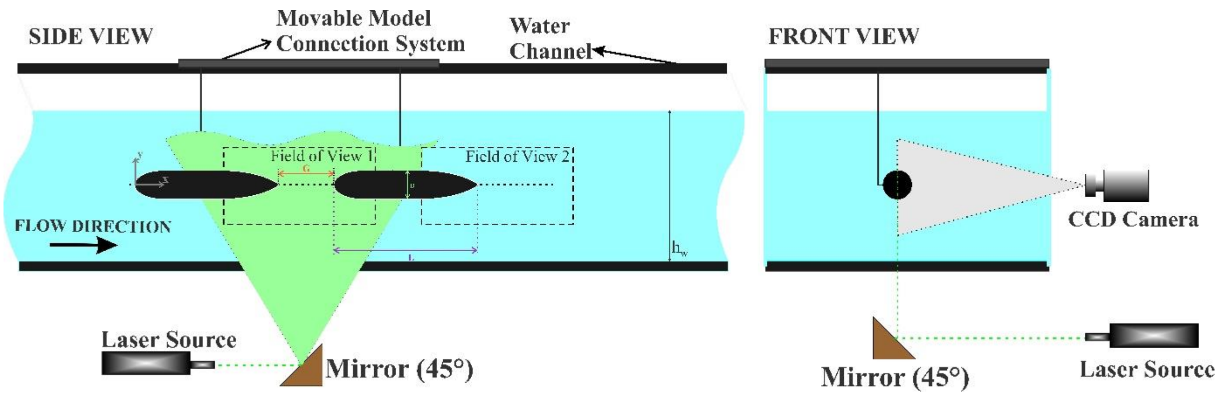


Figure 2. Water channel view for PIV measurement (Sekeroglu, 2019)



(a)



(b)

Figure 3. Experimental setup of the water channel for laser illumination and PIV measurement

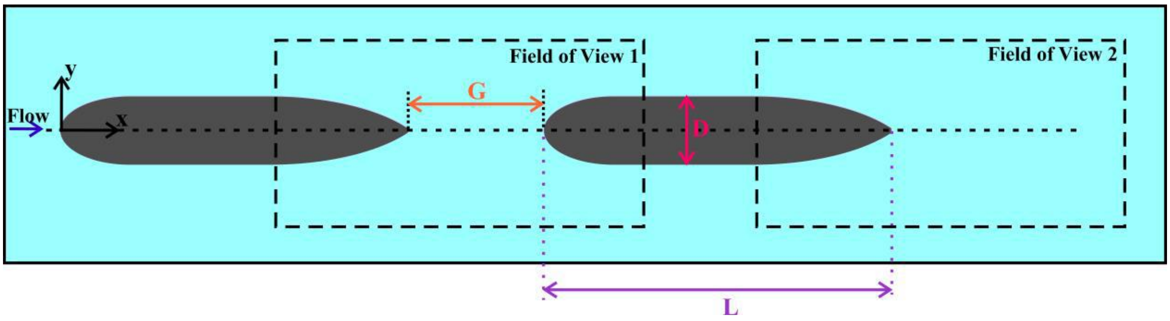


Figure 4. Field of views for the tandem arrangement of two torpedo-like geometries for PIV measurement

Results and Discussion

PIV results of a single torpedo-like geometry in the wake region (a) instantaneous velocity vector field (V) and time-averaged (b) velocity vector field <V>, (c) dimensionless streamwise velocity component ($<u/U_\infty>$), and (d) streamline topology ($<\Psi>$) at $Re=2x10^4$ is presented in Figure 5. Instantaneous velocity vectors have a reversed flow and low level in the near wake of the downstream and then the flow progress in wavy motion. The time-averaged velocity vectors eliminate the alternating direction of the flow structures and the reserved flow region is restricted in approximately one diameter length. Time-averaged streamline topology includes a focus point and asymmetric pattern, which might be misalignment of the geometry during the experiment. The time-averaged streamwise velocity component does have a small negative value contour due to the lessening effect of the flow separation providing the streamlined body. Magnitudes of the contour levels increase gradually to reach almost the uniform velocity value. The vortex formation length in the wake region extends as long as one-length of the geometry.

In the wake region of the torpedo-like geometry, the stagnation point created by the diverging streamlines in the flow are indicated by the letter "S" for a saddle point, the point where the flow is accumulated at a single point by the convergence of the streamlines called Node and denoted with a letter "N", and the vortices formed by the streamlines of the rotational flow in the clockwise and anticlockwise directions called focus are indicated by the letter "F".

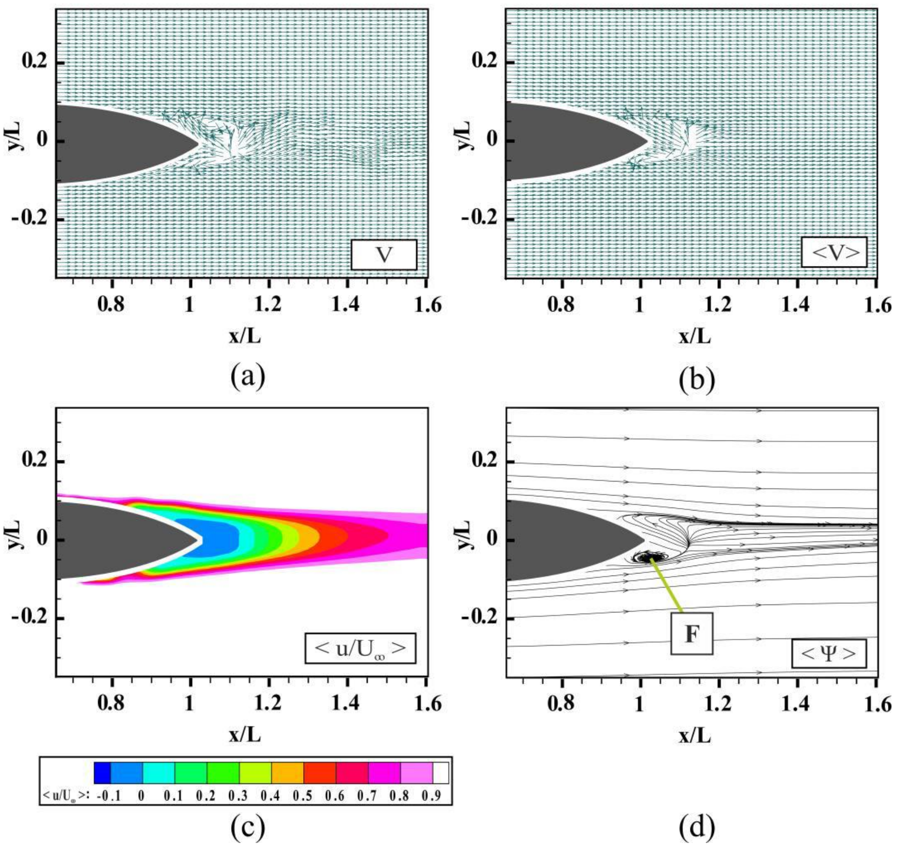


Figure 5. PIV results of an induvial torpedo-like geometry in the wake region (a) instantaneous velocity field (V) and time-averaged (b) velocity field <V>, (c) dimensionless streamwise velocity component (<u/U_{∞}>), and (d) streamline topology (<Ψ>) at Re=2x10^4.

Comparison of the spacing ratio in the range of 0≤G/L≤0.6 effects on instantaneous velocity vector field (V) for a tandem arrangement of two torpedo-like geometries at Re=2x10^4 is shown in Figure 6. As seen in Figure 6, if the torpedo-like geometries are far apart at G/L=0.6, the flow around either of them is similar to that of a single torpedo-like geometry. If the torpedo-like geometries are close or if the second torpedo-like geometry is neighbor to or within the wake of the front torpedo-like geometry, the interference between the two bodies can be one of the three types: proximity interference, wake interference, proximity and wake interference similar to the cases of the two tandem various bodies in the literature. Wake interference occurs for two torpedo-like geometries in tandem when the streamwise spacing between the two torpedo-like geometries is sufficiently large. The upstream torpedo-like geometry is unaffected by the presence of the downstream one. The trajectory of the upstream torpedo-like geometry at G/L=0.6 resembles a horizontal S shape as in the Von Karman Vortex Street. The downstream torpedo-like geometry lies in the wake of the upstream one and therefore suffers interference effects. When the downstream torpedo-like geometry is close to the upstream torpedo-like geometry and lies in its wake, both the geometries affect the flow past each other. This results in proximity and wake disturbance and can occur for the torpedo-like geometries in tandem arrangement. All of these results are similar to the findings of the circular cylinders in the studies of Zdravkovich (1977), Mittal and Kumar (2001).

Torpedo-like geometry in the downstream placed in the wake region of the upstream torpedo-like geometry creates higher level turbulent flow characteristics compared to the single torpedo-like geometry. The separated flow from the upstream torpedo-like geometry impinges to the downstream one and tries to return back to the wake region between the two torpedo-like geometry whereas simultaneously the momentum of the incoming flow pushes the separated flow through the nose and fuselage of the downstream geometry. The PIV data are dominated by small-scale structures. In the wake region of downstream torpedo-like geometry, the accumulation of small vortices into larger ones seems to be an important feature of the forming of coherent structures. Such combination occurs most frequently when the shear layers from the upstream and downstream bodies are locally receptive to scales close to the subharmonic of existing scales in the flow as also stated by Cimbala et al. (1988). The wake view demonstrates the decay of the Von Karman Vortex Street, growth of secondary structures and finally recovering to the uniform condition. Hydrodynamic instability of the wake profile is responsible for interference and the formation of the downstream structure. The big vortex structure in the far wake is a result of accumulation of Kelvin Helmholtz vortices into bigger vortical structures. As the wake shrinks with downstream distance, the size of the big structures must also decay. Hydrodynamic instability of the developing wake profile causes this phenomenon. Hydrodynamic flow characteristics such as drag and lift forces change significantly when the separated flow crumbles the nose of a body.

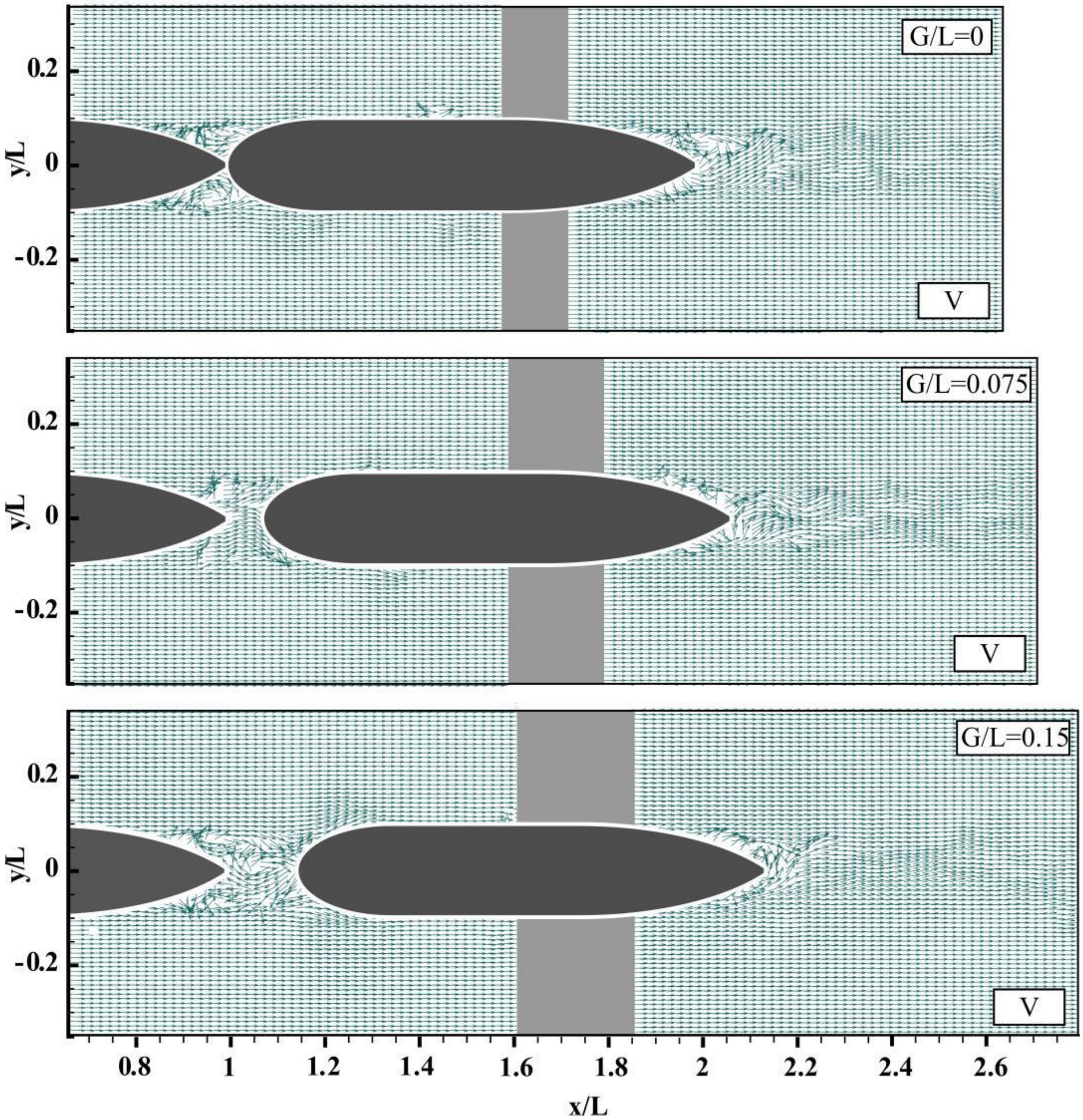


Figure 6a. Comparison of the spacing ratio in the range of $0 \le G/L \le 0.15$ effects on instantaneous vector field (V) for a tandem arrangement of two torpedo-like geometries at $Re=2x10^4$.

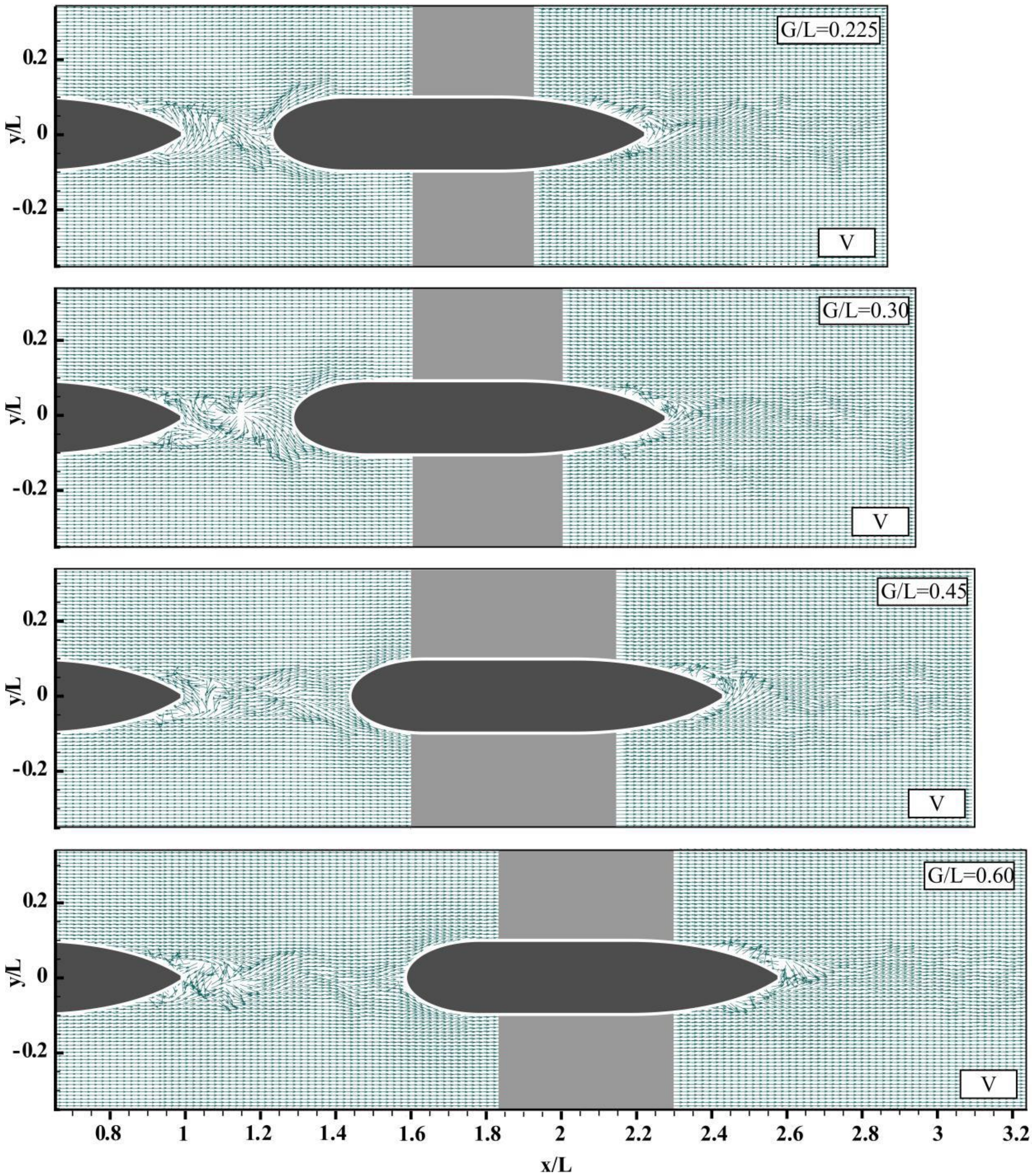


Figure 6b. Continued of 6a for the spacing ratio in the range of $0.225 \leq G/L \leq 0.6$

Comparison of the spacing ratios in the range of $0 \leq G/L \leq 0.15$ effects on the dimensionless time-averaged vector field <V>, time-averaged streamline topology <Ψ> and the time-averaged streamwise velocity $<u/U_{\infty}>$ for a tandem arrangement of two torpedo-like geometries at $Re=2x10^4$ is given in Figures 7, 8 and 9. The time-averaged vector field <V> in Figure 7a for spacing ratio G/L=0, the effect of the upstream model in the FoV_1 region distorts the velocity vectors in the flow direction and tends to form a swirling flow around the stern, the flow follows the hull of the downstream and separates through the wake. Wake region of the downstream torpedo-like geometry is similar for the cases of G/L=0, G/L=0.075 and G/L=0.15 while the wake region of the upstream body forms a complex velocity field for G/L=0.075 and G/L=0.15. For G/L=0.075, in the FoV_1 image, the incoming flow in the lower part of the geometry is directed towards the wake region since the pressure in the intermediate region between the bodies is lower. Later, the accelerated flow hits the nose downstream and disperses around the nose. The time-averaged streamline patterns for G/L=0.075 create nodes (N_1 and N_2). The increased spacing ratio for G/L=0.15 decreases the impingement flow momentum on the downstream torpedo-like geometry and the streamline topology forms two limited foci (F_1 and F_2). That is one in a clockwise direction on the upper side and the other in an anti-clockwise direction in the lower side. The wake region of the downstream torpedo-like geometry for time-averaged streamline topology creates a saddle point (S_1) and a focus point (F_2).

Shedding flow goes upwards to the nose of the downstream model, the flow which tries to return by hitting the object, is directed up or down due to flow instability because it does not have the energy to move against the flow direction. As expected, time-averaged streamwise velocity variation near to the stern profile in Figure 9 is a sharp curve both induvial and tandem arrangement for spacing ratios larger than G/L=0.15. As the shear layers on either side of the wake begin to combine, the wake gradually recovers as seen in Figure 8. At the spacing ratio of G/L=0.6, the time-averaged streamline topology in the wake region of the downstream torpedo-like geometry is smaller and closer to the trailing-edge than the induvial body as shown in Figure 5. Variations and trends of streamwise velocity component $<u/U_\infty>$ in Figure 5c are smaller than two tandem torpedo-like geometries in Figure 9 since the interference effect on the upstream and downstream model disturbs the wake properties, considerably. Vortex formation in the wake region of the induvial torpedo-like geometry is faster than the tandem arrangement for larger than G/L=0.3. At spacing ratios of G/L=0.45 and 0.60, the three-dimensional separated flow from the upstream torpedo-like geometry is recovered and merged nearly 0.8D away from the stern edge and it is around 0.3D away for the downstream one as exhibited in Figure 8. Later, the separated flow strikes to the downstream torpedo-like geometry similar to the uniform flow condition so that it induces wake region of the downstream torpedo-like geometry seeming to be the induvial one in Figure 5.

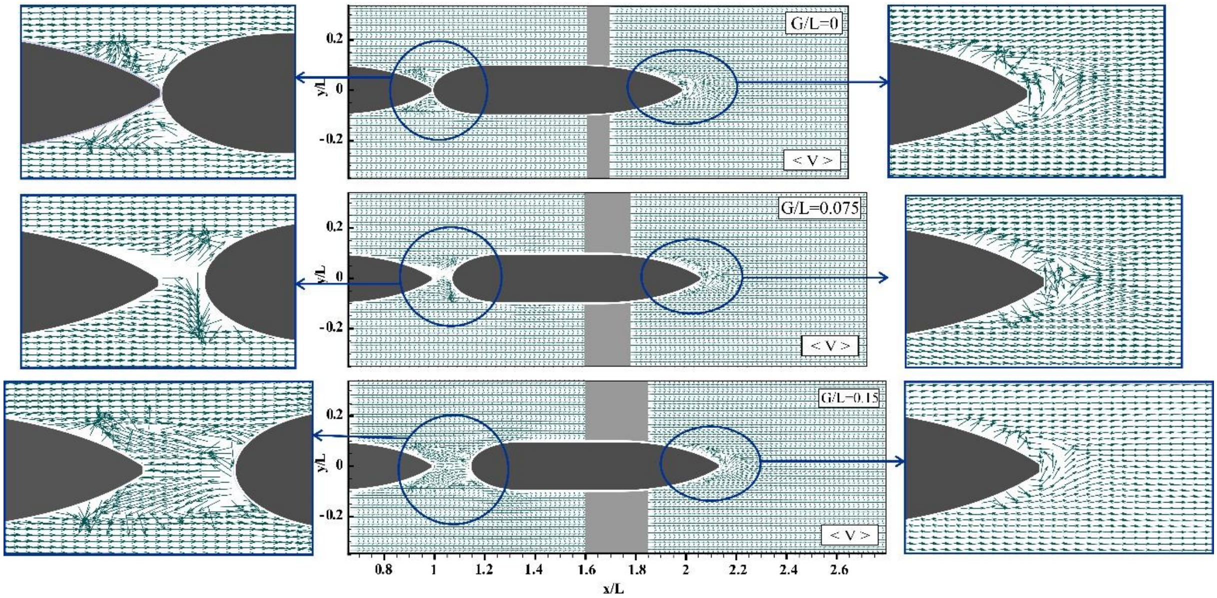


Figure 7a. Comparison of the spacing ratio in the range of 0≤G/L≤0.15 effects on the time-averaged vector field <V> for a tandem arrangement of two torpedo-like geometries at Re=2x10^4. Left-hand side and right-hand side images show the focused flow region.

Overview of the time-averaged streamline topology, it is observed that the wake region both the upstream and downstream torpedo-like geometries reveal asymmetrical patterns for all spacing ratios due to the disturbance effect of the fluctuated turbulent flow. The vertical and three-dimensional size of the induvial wake region of the time-averaged velocity field is longer and bigger than the arrangement at spacing rations of G/L=0.30-0.45. Vortex shedding frequencies in the tandem arrangement may have more than one dominant frequency whereas the induvial torpedo-like geometry yields commonly only one dominant vortex shedding frequency. Three-dimensional relieving effect of the tampered stern either induvial torpedo-like geometry or the tandem arrangement forms a narrower and shorter wake region compared to the sharp-edged trailing body. Compared to the flow properties of the cylinder or sphere wake region for a tandem arrangement, the streamlined shape of the nose and stern of the torpedo-like geometry may cause lower forces fluctuations and less energy consumption during traveling.

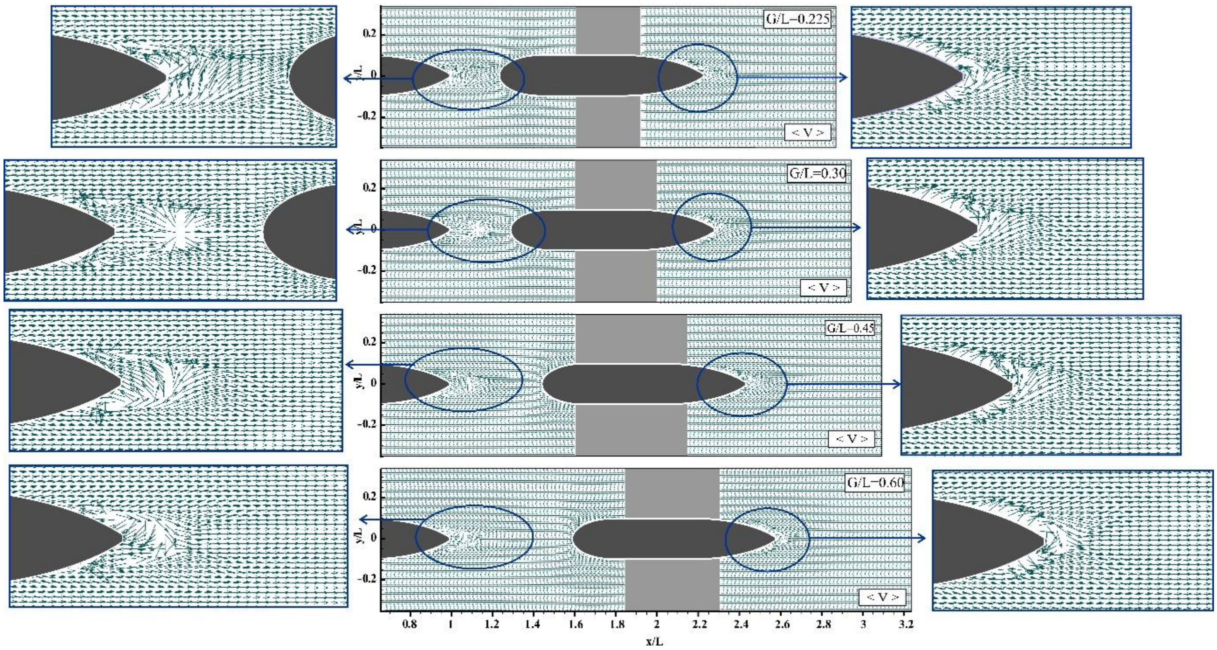


Figure 7b. Continued of 7a for the spacing ratio in the range of 0.225≤G/L≤0.6. Left-hand side and right-hand side images show the focused flow region.

It is demonstrated from the time-averaged velocity field in Figure 7, distance between upper and lower sides free-shear layer is shorter than the diameter of the torpedo-like geometry due to the retarded flow separation. Merging of the three-dimensional free-shear layer develops a saddle point that is locating different positions for both the geometries depending on spacing ratio. Magnitudes of the velocity inside the free-shear layer are lower than the uniform flow value downstream of the torpedo-like geometry due to the well-known wake region properties.

More detailed information on the topology of three-dimensional separated flows was given by Tobak and Peake (1982). In Figure 8a., three foci points (F_1, F_2 and F_3) and a saddle (S) are formed for the spacing ratio of G/L=0 and two foci behind the upstream torpedo-like geometry (F_1 and F_2) and present a symmetrical topology in the restricted region between the stern of upstream body and in front of the downstream body as seen in FoV_1. The effect of the flow striking the nose of the downstream model, asymmetrical wake occurs a clear appearance of saddle point (S) and focus (F_3) in the wake region of the FoV_2. When the spacing ratio is increased to G/L=0.15, uncompleted foci occur between two models and asymmetrical saddle point emerges in the wake region of the downstream body. Cross-comparison of the spacing ratios for G/L=0 and G/L=0.15 shows a larger circulation in F_1 for G/L=0.15 than F_1 for G/L=0 in the wake region of the upstream model. In Figure 8b., for G/L=0.225, the F_1 formed with the effect of the upstream turbulence is very small and close to the edge of the stern part of the upstream torpedo-like geometry. For G/L=0.30, a node point "N" is happened approximately 0.7D away from the tail-end of the upstream torpedo-like geometry.

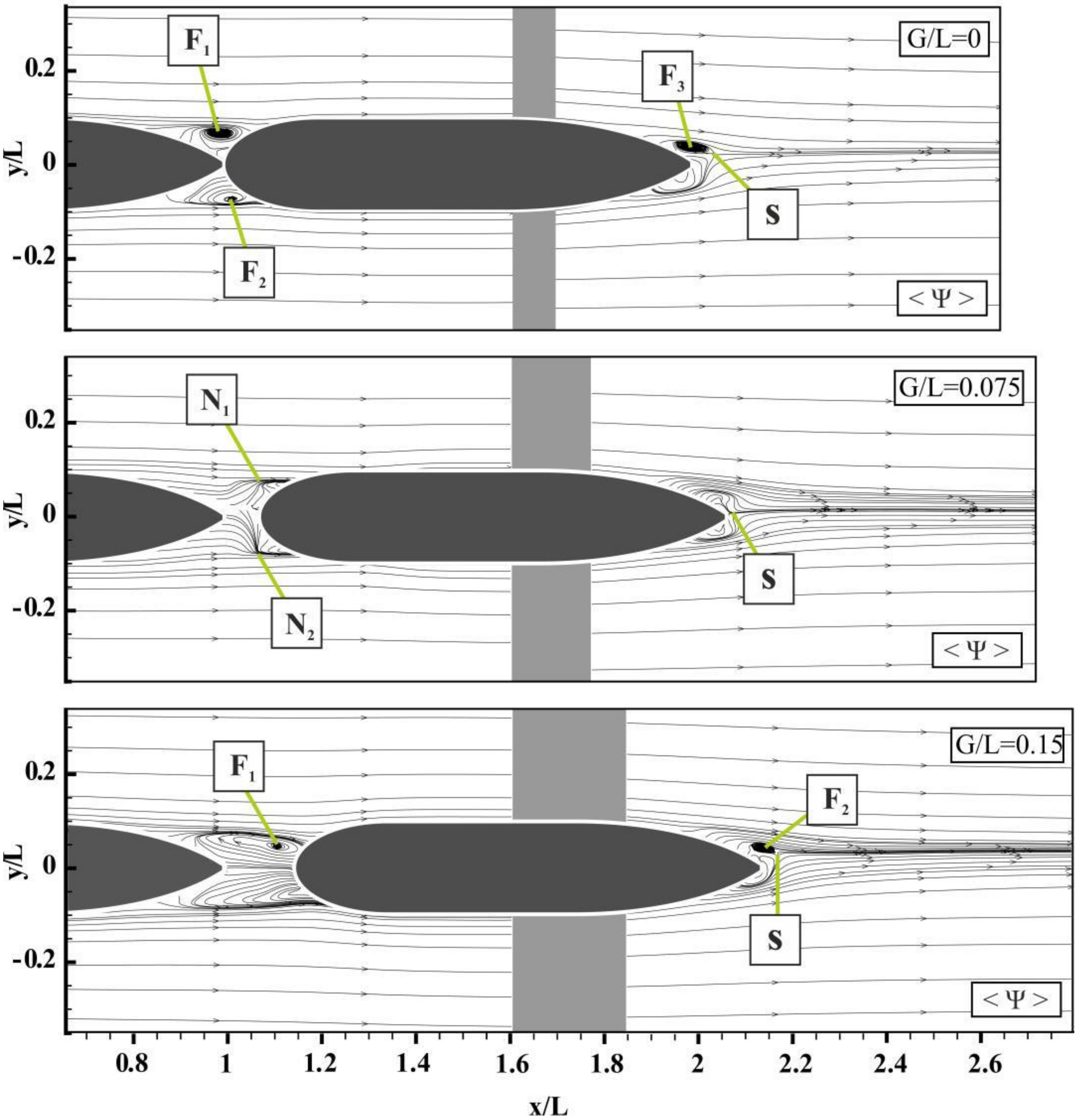


Figure 8a. Comparison of the spacing ratio in the range of 0.0≤G/L≤0.15 effects on the time-averaged streamline topology <Ψ> for a tandem arrangement of two torpedo-like geometries at Re=$2x10^4$.

In Figure 9, negative contours of the time-averaged streamwise velocity $<u/U_\infty>$ occur as small as $<u/U_\infty>=-0.1$ in the wake region of the upstream torpedo-like geometry. The separated flow between the models for G/L=0.075 causes very fluctuated flows and their mean values eliminate each other so that the time-averaged values become closer to the zero values in the range of $0\leq (<u/U_\infty>) \leq 0.1$. The velocity profiles having a negative value indicate that a recirculation area occurs in the wake region. The recirculation region of the upstream torpedo-like geometry is larger than the downstream one in the flow direction. The minimum value of the $<u/U_\infty>$ for an induvial torpedo-like geometry is

<u/U∞>=-0.05 while they are respectively <u/U∞>=-0.04 and <u/U∞>=-0.02 for the upstream and downstream of the torpedo-like geometries.

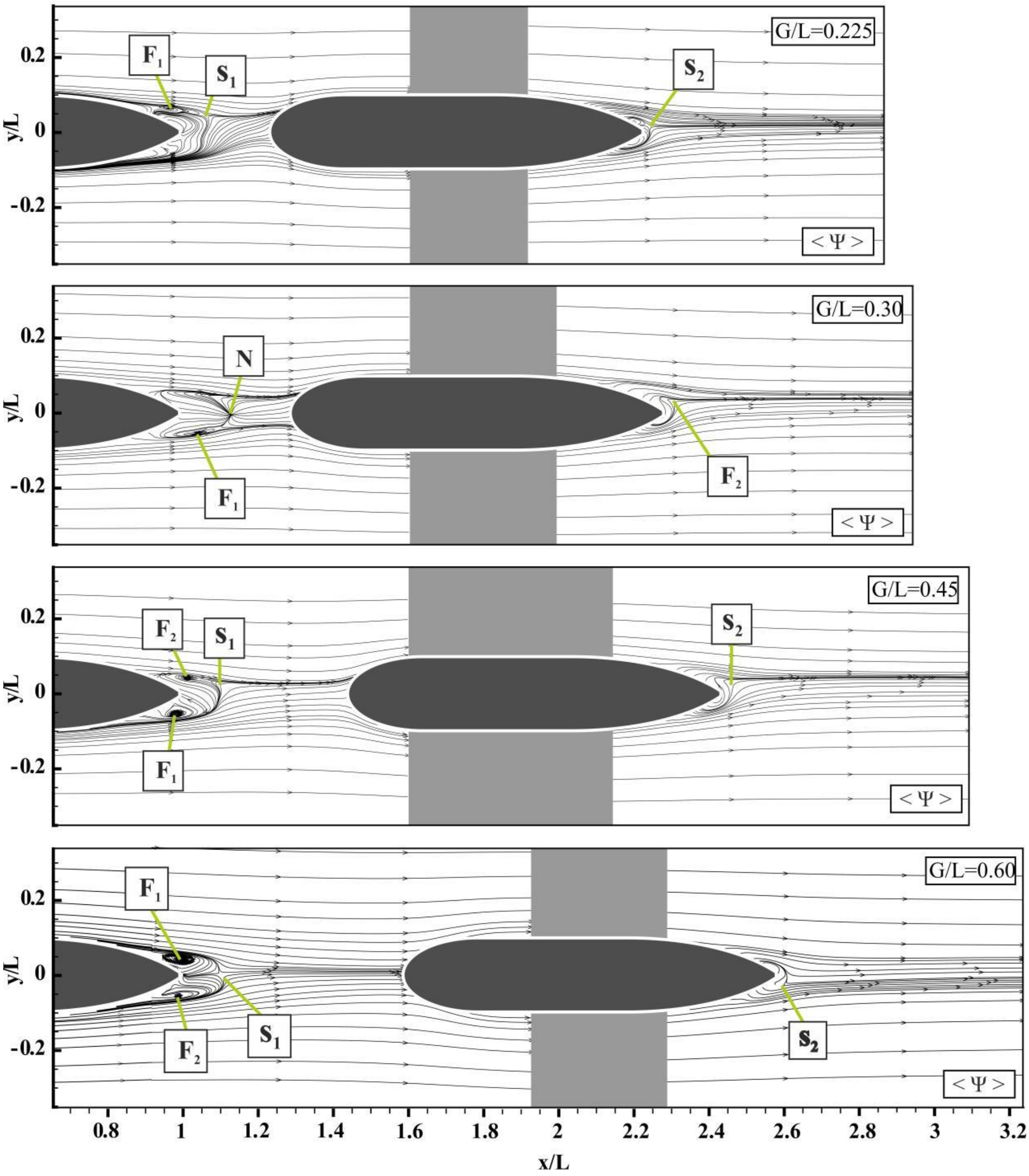


Figure 8b. Continued of 8a for the spacing ratio in the range of 0.225≤G/L≤0.6.

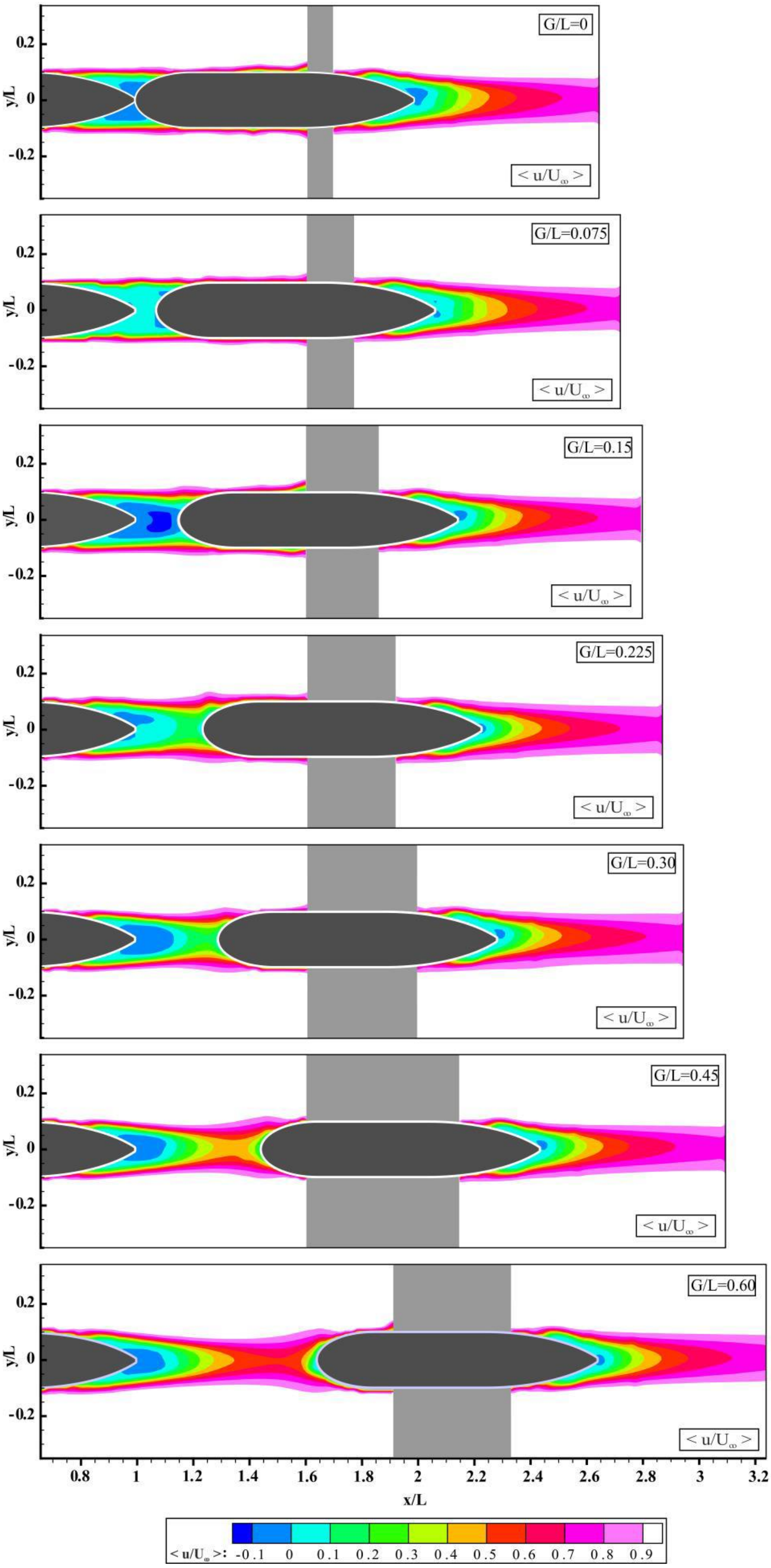


Figure 9. Comparison of the spacing ratio in the range of 0.0≤G/L≤0.60 effects on the time-averaged streamwise velocity contours $<u/U_\infty>$ for a tandem arrangement of two torpedo-like geometries at Re=2x10^4

Conclusion

In this study, PIV experiments were conducted to examine flow behaviours in a uniform flow condition around two torpedo-like geometries placed in a tandem arrangement in an open water channel at $Re=2x10^4$ based on the length of the body. The results for the induvial and tandem models are summarized as follows.

1) The instantaneous flow structures of instantaneous velocity vector fields around two tandem torpedo-like geometries continuously change due to the development of flow phenomena in the wake-influenced region and reveal an unsteady wavy structure in the wake region.

2) For the touching case at the spacing ratio of G/L=0 in the region between the trailing-edge of the upstream geometry and nose of the downstream one, the time-averaged streamline topology has two stable foci with a rotation inward direction, while asymmetrical streamline topology occurs in the wake region of the downstream model.

3) The concentrations of the rotational vector fields between the two bodies and in the wake region of the downstream model are more dominant for the small spacing ratio of G/L<0.3. For the spacing ratios of G/L=0.45 and 0.60, the flow passing the torpedo-like geometry has similar undulating motion in a swirling manner in the wake region of both models.

4) The flow characteristics show the size of the wake flow region, locations of the saddle, focus, foci and node as a function of the spacing ratios in the range of 0.30≤G/L≤0.6. It is seen that the wakes of both torpedo-like geometries were very complicated and sensitive to the spacing ratios due to the rotational flow impingement and the induced separation from the nose of the back geometry and finally occurrence of higher-level hydrodynamic forces.

5) The results revealed that the magnitudes of the time-averaged streamwise velocity gradually in the wake area of both geometries become almost identical as the spacing ratio increases to the G/L=0.6.

6) Time-averaged velocity vector fields, streamline topology and streamwise velocity component data will be useful to validate the numerical applications and later assess especially for lift and drag forces, flow-induced vibration effects and pressure variation.

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Conflict of Interest

There is no conflict of interest between the authors.

Author’s Contributions

The contribution of the authors is equal.

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