

# Aerodynamic Optimization over Frigate Helicopter Flight Deck by Hangar Shape Modifications

Rafael Bardera Mora<sup>\*1</sup>, Juan Carlos Matías García<sup>\*2</sup>, and Adelaida García-Magariño<sup>\*3</sup>,  
*\*National Institute for Aerospace Technology (INTA), Torrejón de Ardoz, Madrid, Spain*

Helicopters operations on frigates imply complex maneuvers for pilots. During the aircraft approach to the frigate, the helicopter rotor is immersed in a changing aerodynamic flow, with high speed and turbulence intensity gradients. This occurs as a consequence of the non-aerodynamic surfaces that compose the frigates and generate detached flow on their decks. Typically, the helicopter operations on frigates are located at the stern. That is, after the superstructure of the ship, and more specifically just behind the hangar where the helicopter can be hosted. Using a simplified frigate shape model, tests have been carried out in the National Institute of Aerospace Technology (INTA) low-speed wind tunnel (T1) by modifying the hangar geometry in a bubble-shaped way to optimize it aerodynamically and improve the flow over the frigate aft-deck. Roof and side walls have been modified by linear (A), circular (C) and elliptical (E) geometries. Particle Image Velocimetry (PIV) technique has been used for obtaining the flow velocity field above and behind the hangars proposed to evaluate the effectiveness of each geometry modification proposed. Finally, a numerical comparison with the PIV results and parameters such as the storage capacity reduction of the hangar due to its geometry change has been carried out.

## I. Nomenclature

|       |   |                                          |
|-------|---|------------------------------------------|
| $A_i$ | = | <i>Weights for optimization function</i> |
| $AR$  | = | <i>Angled Roof</i>                       |
| $AW$  | = | <i>Angled Walls</i>                      |
| $AF$  | = | <i>Angled Full</i>                       |
| $BFS$ | = | <i>Backward-facing-step</i>              |

<sup>1</sup> PhD aerospace engineer. Experimental Aerodynamics, barderar@inta.es

<sup>2</sup> Aerospace engineer, Experimental Aerodynamics, matiasgjc@inta.es

<sup>3</sup> PhD aerospace engineer. Experimental Aerodynamics, AIAA member, garciamga@inta.es

|             |   |                                                   |
|-------------|---|---------------------------------------------------|
| <i>CCD</i>  | = | <i>Charged Couple Device</i>                      |
| <i>CF</i>   | = | <i>Circular Full</i>                              |
| <i>CFD</i>  | = | <i>Computational Fluid Dynamics</i>               |
| <i>CPF</i>  | = | <i>Canadian Patrol Frigate</i>                    |
| <i>CR</i>   | = | <i>Circular Roof</i>                              |
| <i>CW</i>   | = | <i>Circular Walls</i>                             |
| <i>ER</i>   | = | <i>Elliptical Roof</i>                            |
| <i>EW</i>   | = | <i>Elliptical Walls</i>                           |
| <i>EF</i>   | = | <i>Elliptical Full</i>                            |
| <i>FFT</i>  | = | <i>Fast Fourier Transform</i>                     |
| <i>INTA</i> | = | <i>National Institute of Aerospace Technology</i> |
| <i>LDA</i>  | = | <i>Laser Doppler Anemometry</i>                   |
| <i>LSA</i>  | = | <i>Low Speed Area</i>                             |
| <i>PIV</i>  | = | <i>Particle Image Velocimetry</i>                 |
| <i>SFS</i>  | = | <i>Simplified Frigate Shape</i>                   |
| <i>NATO</i> | = | <i>North Atlantic Treaty Organization</i>         |
| $V^*$       | = | <i>Non-dimensional velocity</i>                   |
| $\sigma$    | = | <i>Standard Deviation</i>                         |
| <i>Vol</i>  | = | <i>Interior volume of the hangar</i>              |

## **II.Introduction**

Helicopter pilots performing maneuvers in the vicinity of a frigate must be expert pilots. This is because, during the helicopter landing approach to a frigate, the aircraft is immersed in turbulent aerodynamic flow with large changes in flow velocity and direction [1]. This flow is generated due to the sharp geometries of the frigate, which far from being aerodynamic, disturb the incident airflow enormously and complicate the maneuvers of aircraft over the frigate flight deck. Therefore, it is very important to characterize the conditions under which a helicopter has to operate on the frigate in order to limit its operation only to safe situations [2]. For that reason, many experimental and numerical studies are focused on the airwake generated by the frigate [3, 4] and its interaction with the area in which the

helicopter has to perform the launch and recovery [5]. Rhoades et al. [6] made a detailed investigation of the flow patterns over the aft-flight deck of a frigate scale-model. They used three-dimensional hot-wire measurements and atmospheric boundary layer simulation to obtain velocity and turbulence intensity values at four points where the helicopter blades have to work during the landing approach under six different incident wind angle conditions. Using a simplified frigate shape (SFS) Bardera [7] performed experimental tests based on oil film visualization, Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) in order to establish a data source for numerical computation. These results are presented in combination with full-scale measurements that can help to improve the CFD flow prediction and results accuracy of the flow over the frigate flight deck. In situ velocity measurements are also presented in [8] in which three-component anemometers were used to obtain full-scale measurements in the near wake generated behind the hangar of a naval training vessel. The goal was to measure velocities and turbulence intensities to estimate the vortex formation and reattachment point over the flight deck, helping to validate computational fluid dynamics simulations. A comparison between experimental wind tunnel tests results and full-scale data is also presented in [9]. A CFD prediction of the unsteady flow field generated by ships during beam winds is explained in detail. Zhang et al. [10] studied the flow behind a simplified ship using PANS and LES simulations and compared the results with experimental data. They discovered a bi-stable behavior in the turbulent wake with high asymmetry of the flow. Another example of a hybrid between numerical and experimental study is presented in [11] and [12]. For a static frigate, computational and experimental data of their airwake were extracted by Yuan et al. [11]. Turbulence distributions under different wind angles conditions were obtained. They performed numerical calculations with OpenFOAM for simulating firstly the airwake of a simple frigate shape 2 (SFS2) to validate the model, and finally to a Canadian Patrol Frigate (CPF) to compare with experimental results.

The changes in flow patterns over the flight deck have been also analyzed with the presence of a helicopter rotor operating there. Silva [12] presents results of wind tunnel measurements to characterize the aerodynamic interferences between a ship and three models of tiltrotors. They made force and moment measurements and extract data from the flow field by means of Particle Image Velocimetry. Other experimental tests for measuring a ship airwake with a tandem-rotor helicopter on the flight deck were carried out by Wadcock [13]. He used three-component Particle Image Velocimetry under different ship yaw angles. Despite being from 2005, an interesting review focused on aerodynamic issues of modeling and simulation the dynamic interface between helicopter and ships is presented in [14]. The review summarizes the challenges presented to simulate rotary-wing operations near small and large ships. The pilot modeling

and flight simulators [15-17] can help to reduce the number of expensive flight test campaigns. Forsythe et al. [18] made a fully coupled hovering simulation of the rotorcraft and ship airwake to analyze numerically the helicopter approach to a ship. In order to validate the model it was compared to blade element momentum disk simulations and resolved rotor blades. Another example of a numerical study is based on the ship and rotor interaction calculated with a Navier-Stokes solver and steady and unsteady rotor model (SRM and URM) to compare their velocity and vorticity results differences [19]. With an Unsteady Reynolds-averaged Navier-Stokes (URANS) model, Su et al. [20] showed the coupling effects of a fully-articulated rotor blades operating near a frigate, and were compared with experimental data. Finally, as the helicopter operates around the ship with a low altitude, Ji et al. [21] generated a real-time simulation model for the analysis of helicopter recovery maneuvers during turbulent atmospheric environment conditions. They also validated the generated data with flight test data.

As the problem of helicopter operating near ships has been widely analyzed, some studies try to modify and improve the flow on the flight deck adding aerodynamic flow control systems to the hangar [22]. In the same direction, Forrest et al. [23] analyzed five different hangar-edge modifications in a simplified frigate shape with CFD and flight simulation. To select the best modification of all tested, they measured the helicopter loads and pilot workload during the maneuver. Therefore, adding chamfer or flap to the hangar edge produced a benefit for the helicopter operations. In contrast, tabs, sawtooth and cylinder increase the turbulence and the pilot workload. Other authors have tested active flow control. Gallas et al. [24] used stereo particle image velocimetry, hot-wire anemometry and pressure sensors to analyze the positive effects for helicopters operations on frigates of adding an active flow control system on the hangar sides of a simplified frigate shape. By blowing, the recirculation region generated behind the hangar was highly reduced.

However, this paper is going to be focused on passive flow control of the flow over a simplified frigate based on hangar geometry modifications. A similar study, but performed by numerical computation, is the work made by Wang [25]. In it, a simplified frigate shape 2 was modeled to examine the modifications produced in the airwake by changing the hangar rear edge curvature. The results showed that changing the curvature improves the airwake over the flight deck of the frigate, reducing the turbulence intensity and then the pilot workload during launch and recovery operations. From all different curvature tested, 90° case obtained the best results for the helicopter performance.

This paper will present proposals and experimental tests carried out with passive flow control over the flight deck of a simplified frigate shape 2. In particular, a series of changes to the geometry of the hangar (roof and side walls)

are proposed and tested in wind tunnel facilities with Particle Image Velocimetry (PIV). The final goal will be to improve the aerodynamic flow over the frigate flight deck for helicopter operations.

### III. Experimental Set-up

#### A. Wind Tunnel and particle Image Velocimetry (PIV)

Experimental tests have been carried out at wind tunnel T1 test facilities of the National Institute of Aerospace Technology “Esteban Terradas” in Madrid, Spain. This low-speed wind tunnel has a closed circuit and open elliptic test section ( $2 \times 3 \text{ m}^2$ ) in which it is possible to achieve 60 m/s with low turbulence intensity, Figure 1.

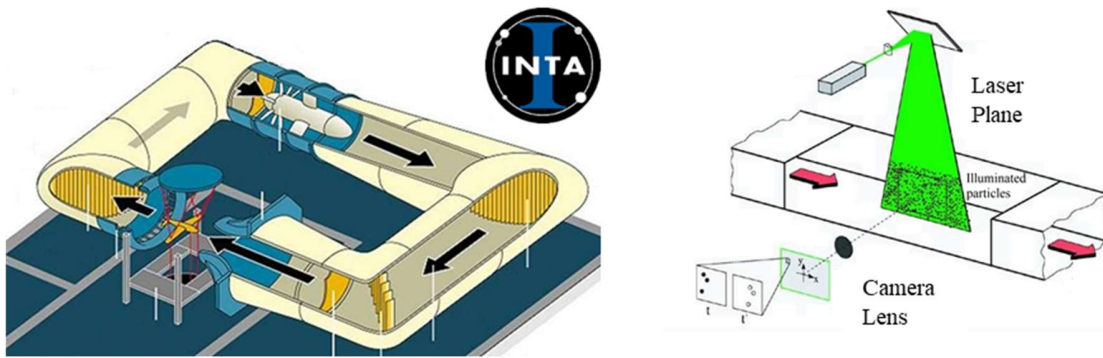


**Fig. 1 Wind Tunnel 1 at INTA (left) and Particle Image Velocimetry working scheme (PIV) (right)**

To obtain measurements and velocity maps of the flow, Particle Image Velocimetry (PIV) has been used [26-29], Figure 1. This advanced and non-intrusive velocity measurement technique requires seeding the flow with small tracer particles. Tracer particles with a diameter of  $1 \mu\text{m}$  used for testing were generated by Laskin atomizers [30, 31] with olive oil. These particles are illuminated by a powerful laser plane (Nd: YAG) in order to capture their position in pairs of images with a camera with a  $2048 \times 2048$  pixels CCD (Charged Couple Device) sensor. By correlating the position of the particles of each image pair using the FFT (Fast Fourier Transform), it is possible to get a cross-correlation peak that indicates the particles' displacement. Finally, as the time between the images of the pair is known, it is possible to get the velocity of the particles which corresponds to the velocity of the flow. A synchronizer is used to adjust the proper triggering times of the camera and laser pulses. Finally, the image pairs are processed with Insight3G software in a computer.

## B. Simplified Frigate Shape

Figure 2 shows the 1:85th scaled Simplified Frigate Shape 2 (SFS2) used during wind tunnel testing [7, 32-33]. It was a model proposed by NATO with the goal to make advances on frigate aerodynamic research. The simplicity of this model does not prevent it from having the main elements of a frigate: the bow, the superstructure, the stack gases outlet, the hangar and helicopter flight deck at the stern. In the same Figure 2, the PIV window of interest aligned with the free-stream velocity in all tested WOD angles has been marked behind the hangar and over the helicopter flight deck at the stern to define the position of interest for obtaining the velocity maps.

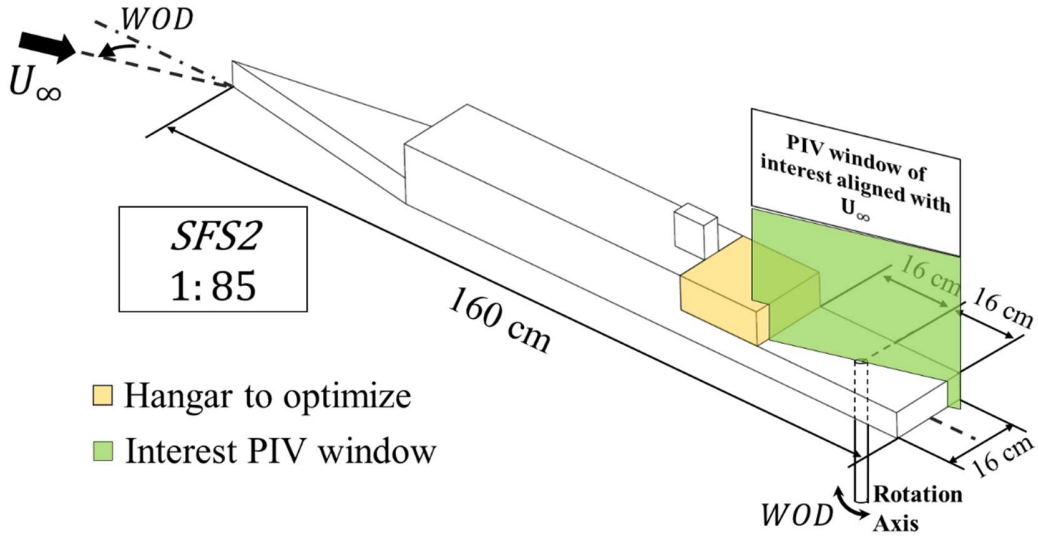


**Fig. 2 Simplified Frigate Shape 2 (SFS2) with changeable Wind Over Deck (WOD) used for testing and interest PIV windows**

## C. Bubble-shaped Hangars Design and Manufacturing

For the dimensioning aerodynamically optimized hangars, it was intended to make hangars with their back part with a similar shape to the recirculation bubble generated after the ship's superstructure. For doing this, horizontal and vertical PIV maps of this bubble obtained from previous tests with the same frigate model were used, Figure 3. In these maps, the recirculation bubble characterized by a low-velocity region appears in dark gray tones. In addition, three geometrical shapes were selected for the preliminary design of the bubble-hangars. Lines, circular arcs and elliptical arcs were used to follow the bubble shape. This will result in Angled (A), Circular (C) and Elliptical (E) hangars. A minimum height of 50 mm has been imposed to keep maintaining the main hangar door.

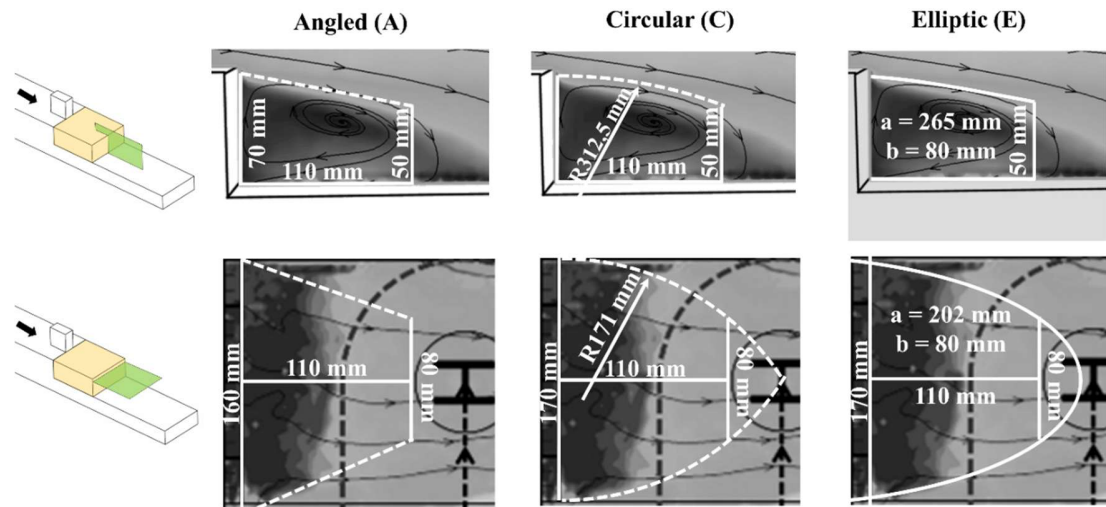


**Fig. 3 Measures taken from the recirculation bubble generated behind frigate superstructure for dimensioning bubble-hangars.**

The resultant bubble-hangars proposed are shown in the following Figure 4. To test the effectiveness of each change of the hangar, different hangars have been tested changing only the roof (AR “Angled Roof”, CR “Circular Roof”, ER “Elliptical Roof”), the side walls (AW “Angled Walls”, CW “Circular Walls” and EW “Elliptical Walls”) and both (AF “Angled Full”, CF “Circular Full”, EF “Elliptical Full”). To build the nine bubble-hangars proposed according to their dimensions, they were manufactured with polystyrene and cutting it with a hot wire computer numerically controlled (CNC). The specific dimensions of each modified hangar are also presented in Figure 5.

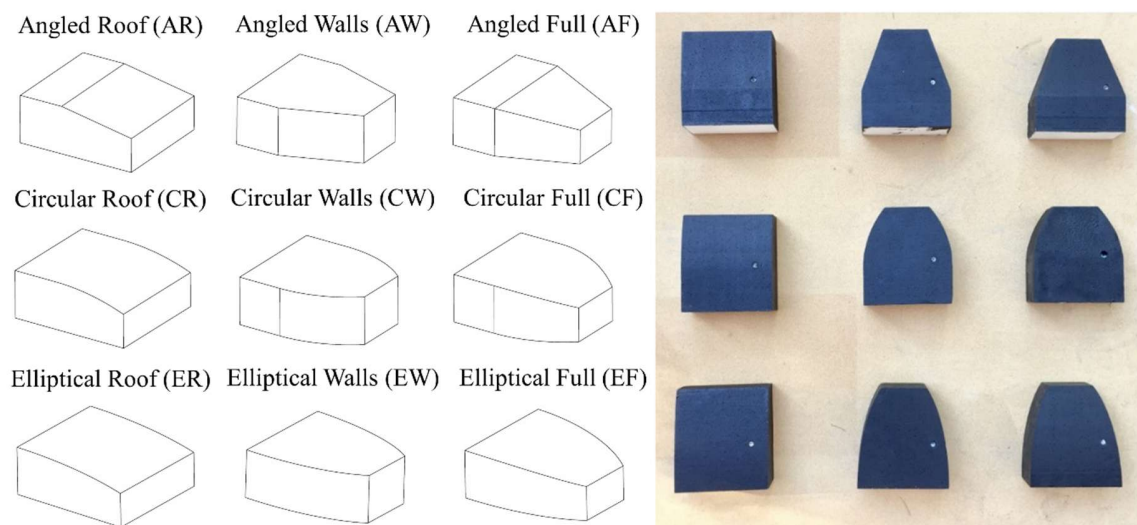


**Fig. 4 Bubble-hangars designs changing the roof (R), side walls (W) and both (F).**

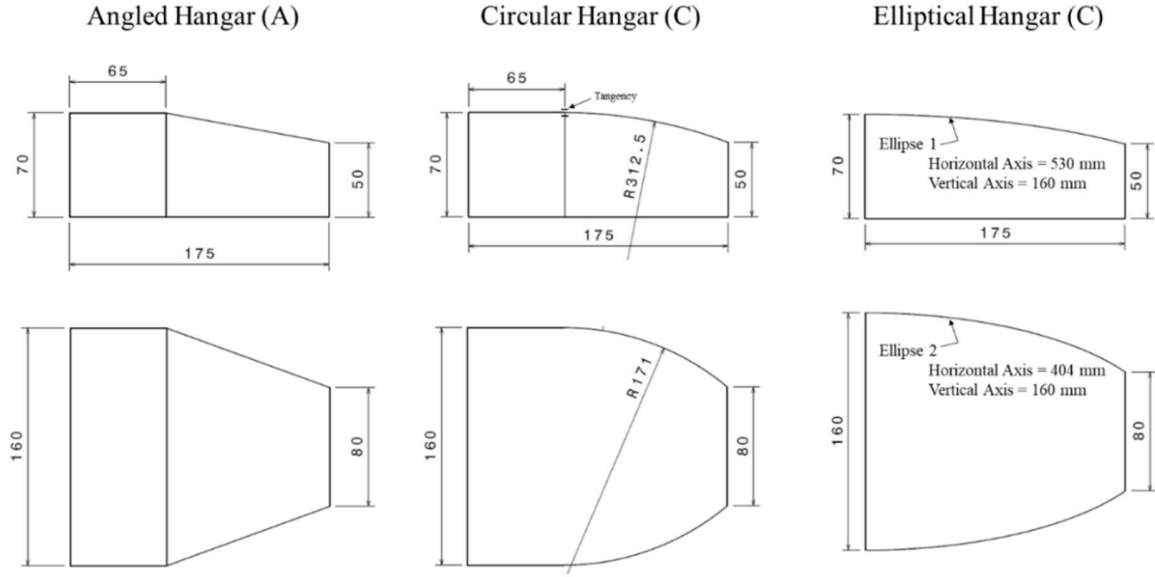


**Fig. 5 Bubble-hangars dimensions for angled (A), circular (C) and elliptical (E) shapes.**

## IV. Results

### A. Non-dimensional velocity maps

To quantify the aerodynamic effectiveness of the different bubble-hangars proposed, reference case (base) non-dimensional velocity maps for  $0^\circ$ ,  $15^\circ$  and  $30^\circ$  cases are shown in Figure 6. In this velocity maps, main flow patterns behind a backward-facing-step (BFS) can be observed. From the top to the bottom,  $0^\circ$  and  $15^\circ$  cases show a region of free-stream velocity (orange), a first shear layer (yellow), a slightly low speed area (green), a second shear layer (light blue) and a big low velocity region with a recirculation bubble (dark blue). This last region centered on  $x = -89$  mm and  $y = 38$  mm is the greatest danger to helicopter operations on the stern deck. In this region, there is a recirculation of the flow and the flow velocity does not exceed 30 % of the frigate incident wind velocity. Due to the high velocity gradient over the deck, the helicopter suffers oscillations and low-frequency movements during helicopter launch and recovery operations. The  $30^\circ$  base case does not show the recirculation bubble but the low-velocity region on the deck is still present. This change of the flow must be due to the amount of air that enters from the port side of the frigate aft-deck under  $30^\circ$  wind condition.

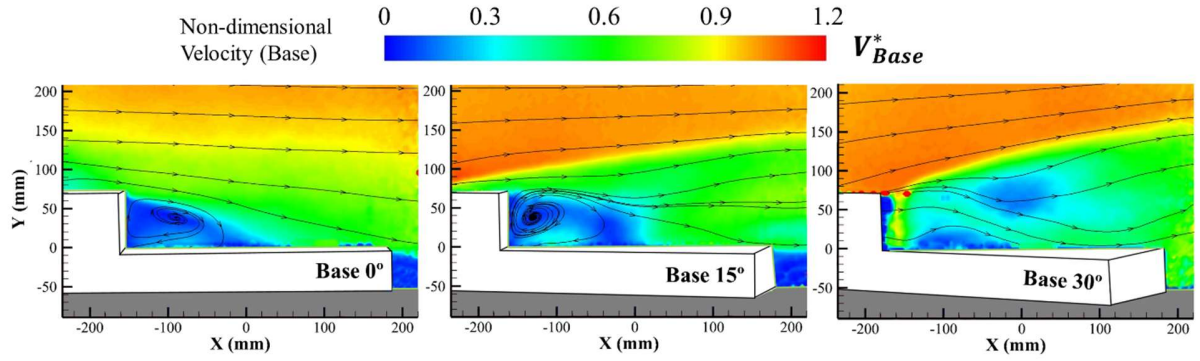


**Fig 6 Non-dimensional velocity maps of the base cases at Wind Over Deck of 0°, 15° and 30°.**

Figure 7 shows the non-dimensional velocity maps for the angled hangars ( $V^*$ , left) and their differences in magnitude against the base case ( $D = V^* - V_{Base}^*$ , right). Angled roof (AR), angled walls (AW) and angled full (AF) hangars were tested under 0°, 15° and 30° wind conditions. A reduction in the recirculation bubble size or even its suppression can be observed in the different cases tested. Specifically for the 0° case, it is clear that with angled bubbled-hangars a flow acceleration between 30 and 60 % against the base case (light blue and green tones at difference maps) is obtained and up to 80-100 % (orange and red tones at difference maps) for 15° and 30° cases.

Paying attention to the 0° case, changing the roof (AR – 0 deg) the recirculation bubble reduces its height and length and modifying the walls (AW – 0 deg) only its length is reduced. Both minimize the negative bubble effect for the helicopter operating over the landing point ( $x = 0$  mm,  $y = 0$  mm). The full angled hangar (AF – 0 deg) results in a combination of both effects, reducing bubble height and length but with slightly less flow acceleration in magnitude than the individual cases (see difference map of AF – 0 deg).

The following wind condition tested of 15° presents again a flow acceleration over the flight deck. This flow acceleration is now much more significant, reaching non-dimensional velocities up to 1 when the hangar walls are modified (AW – 15 deg).

Under this wind condition, the airflow enters easily over the deck from the port side of the frigate. Finally, with the fully modified hangar (AF – 15 deg), there is less flow acceleration over the flight deck but enough to reach non-dimensional velocities around 0.6 and 0.7 (green colours), that can be better in terms of achieving a uniform airflow behind the frigate superstructure, without high velocity gradients over the flight deck. The last wind condition tested of 30° presents similar trend than the previous cases. The bubble height is reduced when the angled roof (AR – 30 deg) is installed and modifying the hangar walls (AW) has a great effect on the flow acceleration behind it.

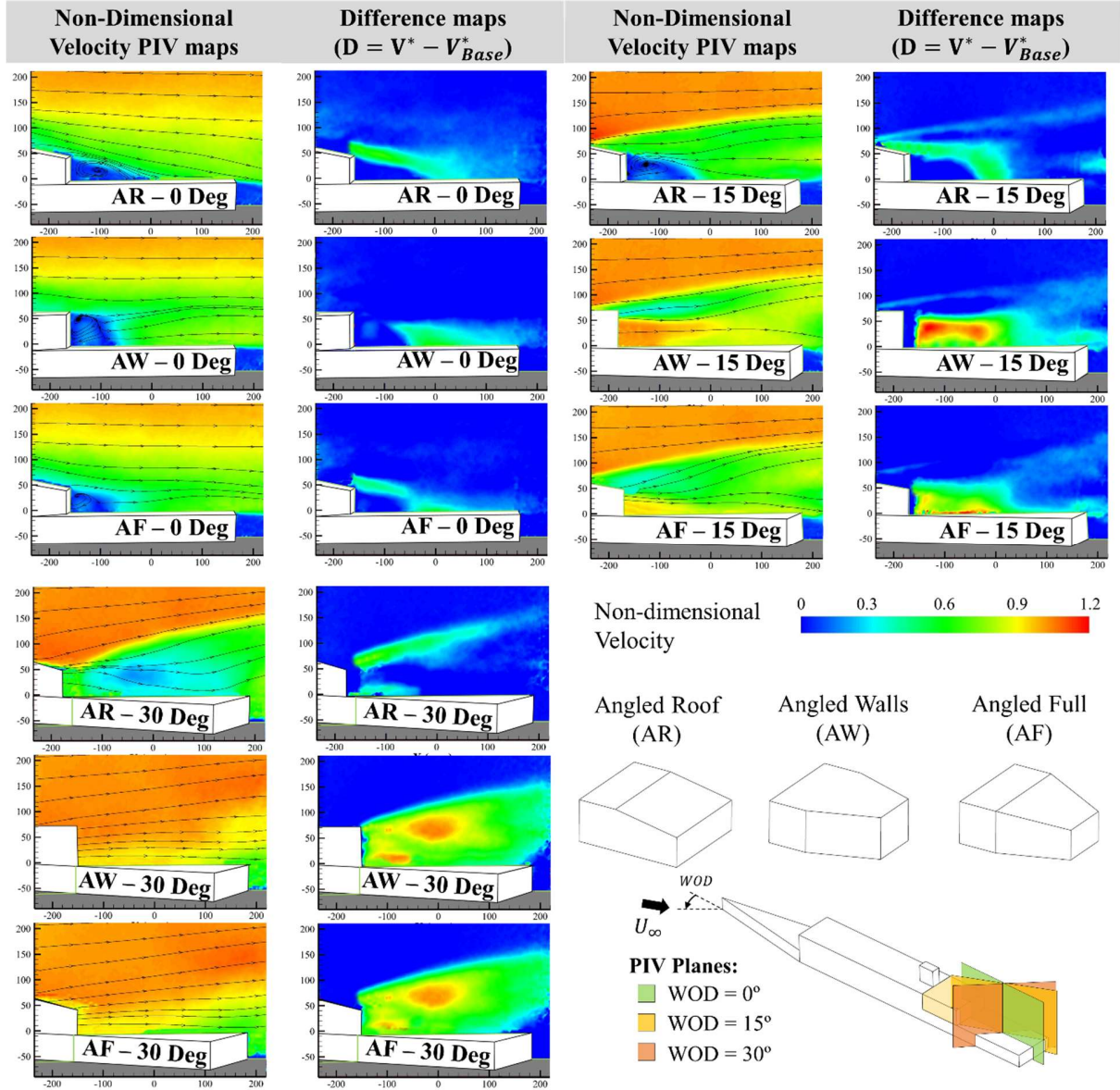


**Fig. 7 Non-dimensional velocity maps and difference maps Angled hangars (A)**

However, under 30° wind condition, the angled walls (AW) and angled full (AF) hangars do not present highly differences from each other, as in the case of 15° wind condition. Under this higher angle, the amount of flow entering by the frigate port side is dominant against the amount of flow entering over the hangar roof.

Figure 8 presents the non-dimensional velocity for the bubble hangars circular shapes (CR, CW and CF) tested. The same flow patterns described in Figure 6 can be observed in these maps. Therefore, a reduction in the bubble size and low-velocity area due to flow acceleration over the flight deck can be observed against the base case. Separating the effects of modifying the roof (R), walls (W) or both (F), it can be seen that modifying the roof (CR) reduces the

bubble height accelerating the flow in its higher part ( $y \sim 60$  mm). Modifying the walls (CW) reduces the low-speed area over the flight deck around the helicopter landing point ( $x = 0$  mm,  $y = 0$  mm). Finally, modifying roof and walls (CF) produce a mixture of both effects but with a lower flow acceleration intensity in each of the mentioned zones. Under the different wind angles tested, a greater effect in flow acceleration when the walls are modified (CW and CF) is also observed for  $15^\circ$  and  $30^\circ$  cases.

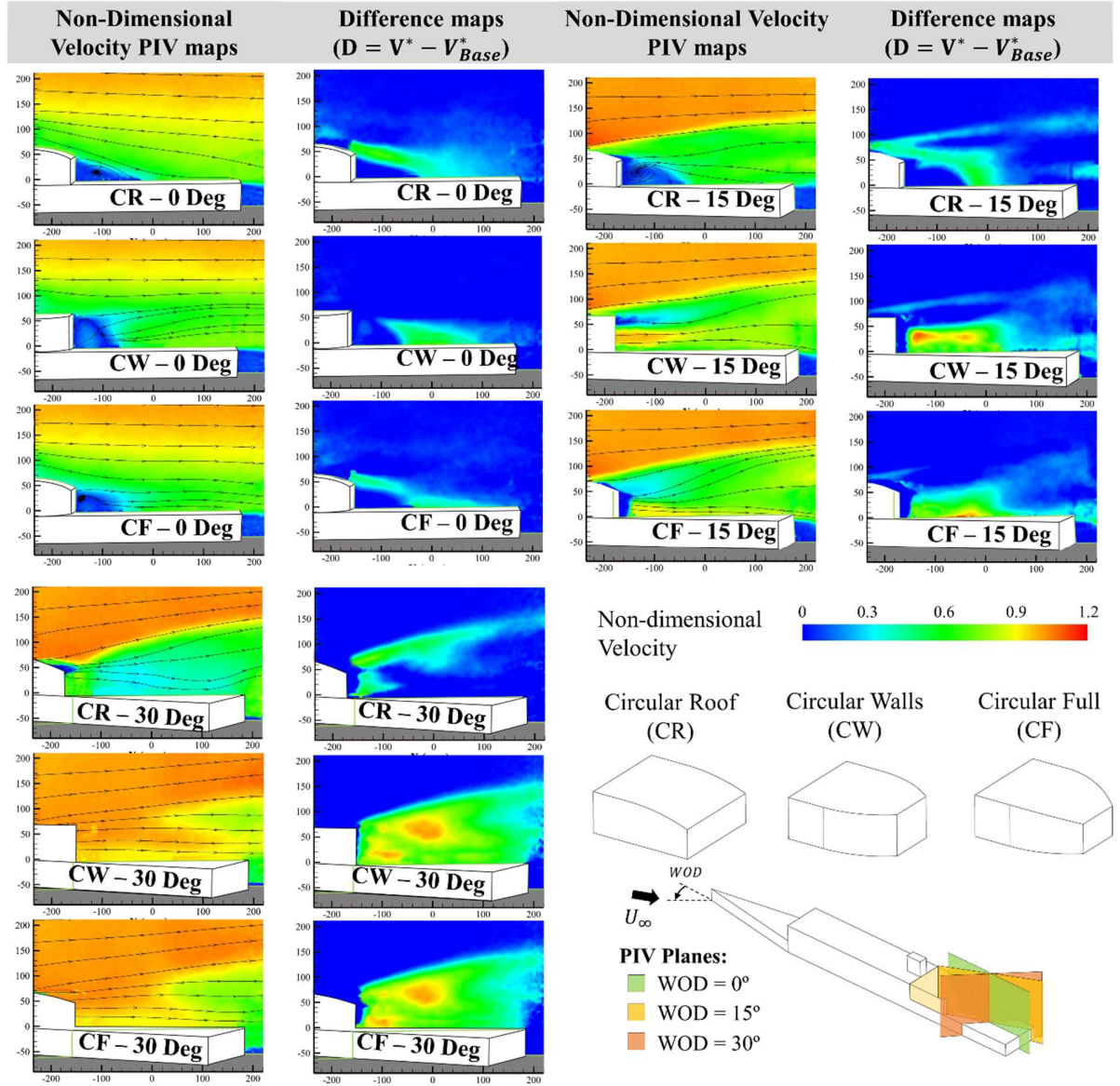


**Fig. 8 Non-dimensional velocity maps and difference maps Circular hangars (C)**

Figure 9 is the last to contain velocity maps and difference maps from experimental tests. This time, the bubbled hangars tested were built with elliptical shapes for the roof (ER), walls (EW) and elliptical roof and walls (EF).

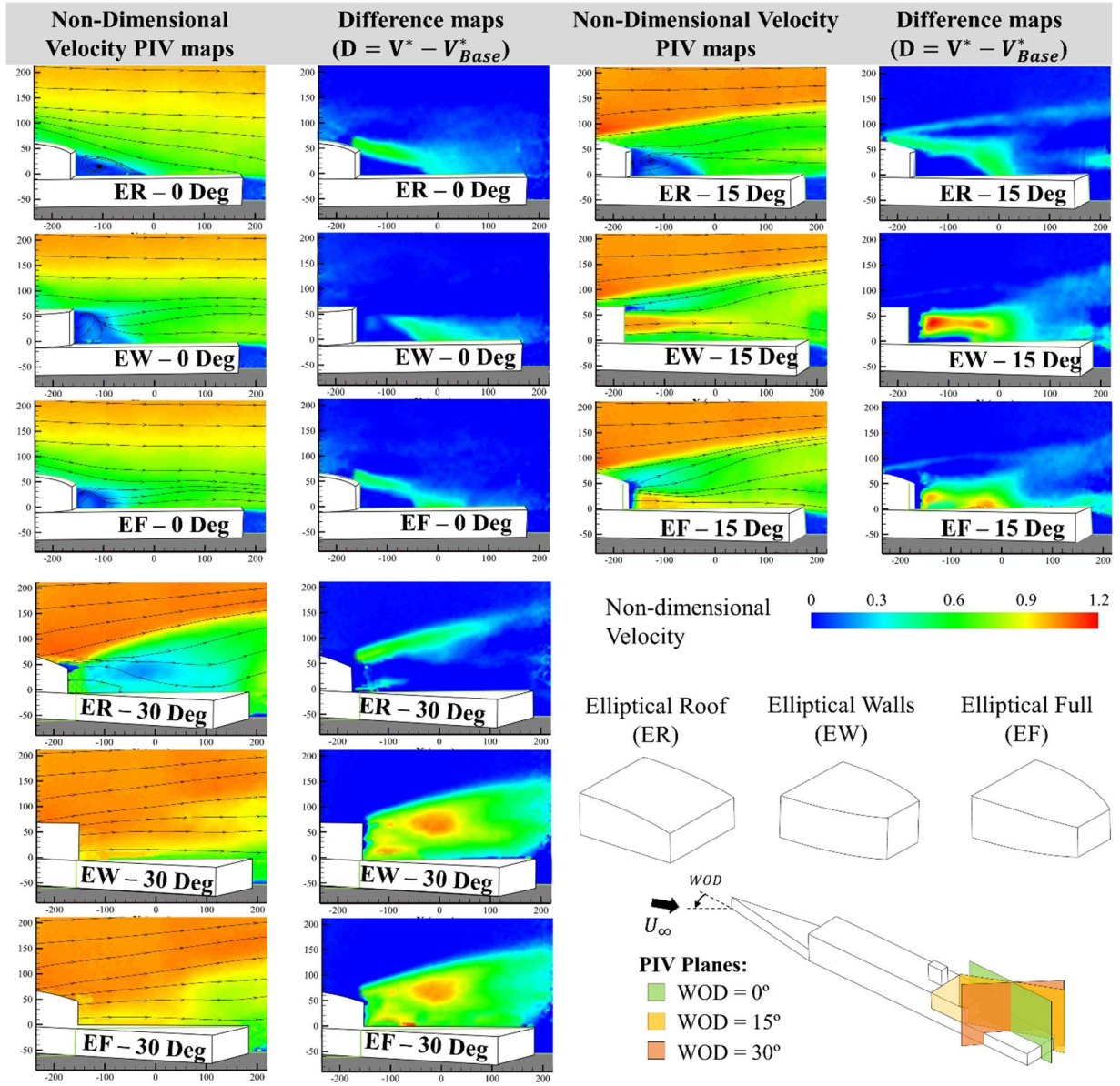


**Fig. 9 Non-dimensional velocity maps and difference maps Elliptical hangars (E)**

As seen in the previous cases of angled and circular shapes, the hangars with elliptical shapes achieve similar effects in the flow over the flight deck. By accelerating the flow, these improved geometries reduce the size and area of the low-velocity region and recirculation bubble behind the frigate superstructure. The same effects and flow patterns can be found again for the different combinations of modified geometries (roof, walls and both) and wind angle conditions tested.

## B. Detailed Comparison

All the results using bubbled hangar have been presented in Figures 7, 8 and 9. They are encouraging results because a significant improvement of the flow over the flight deck is achieved behind them. And as a consequence, the safety of helicopter operations could be increased by developing similar concepts in modern frigates. However, at this stage of the comparison, all tested configurations present more or less similar results and advantages and disadvantages depending on the wind condition studied. Although, it is not clear which of them is the most optimal solution. Extracting numerical data from the previous velocity maps, it is possible to make a more detailed comparison between all cases studied. This section will use the numerical data extracted from the experimental tests to select the optimal hangar between the different solutions proposed.

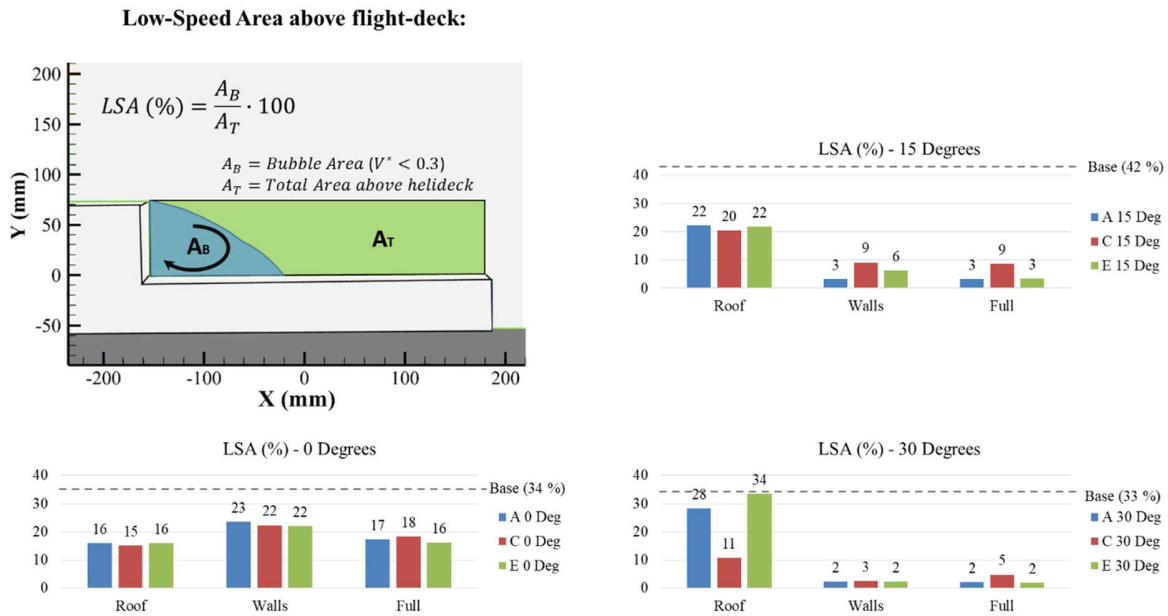


**Fig. 10 Low-Speed Area (LSA %) above flight deck**

In order to make this comparison, three parameters have been taken into account, 1) Low-Speed Area over the flight deck (LSA parameter, in %), 2) Incident wind velocity profiles on the rotor line and 3) Volume or interior hangar storage capacity losses associated with each geometric modification.

The LSA is a ratio between the total area above the flight deck and the area affected by points of low non-dimensional velocity ( $V^* < 0.3$ ). LSA results for all cases tested are shown in Figure 10. These plots present LSA number for angled (A), circular (C) and elliptical (E) hangars modifying the roof, walls and both (full), and the reference LSA number for each base configuration under the three wind conditions tested of 0°, 15° and 30°. The LSA

obtained for  $0^\circ$  case oscillates between 15 and 23 %. The best results were obtained with the modified roof followed by the cases of full modification (roof and walls modified). All of them represent an important improvement compared to the base case (34 %). The results are practically independent of the shape of the modification (A, C or E) with differences around the 1 or 2 % of LSA parameter. Under  $15^\circ$  case the LSA parameter presents a different trend. The change of the walls' geometry has much more effect on reducing the LSA parameter than the change of the roof. Thus, hangars with modified walls and also with roof and wall modified (full) achieve a reduction compared to the base case of up to 39 %, indicating that the low-velocity region has been almost deleted. The best results for this case were obtained with the angled and elliptical hangars with modified walls (AW and EW) and fully modified (AF and EF). The last case of  $30^\circ$  of wind condition presents similar results to the  $15^\circ$  case. Once again the low-velocity area is eliminated (almost null LSA value) behind the frigate superstructure with bubbled hangars with the walls modified (AW, CW and EW) and fully modified hangars (AF, CF and EF). In view of the results, it should be noted that on 0 degrees case there are low 3-D effects and the shape of the walls (angled, circular or elliptical) does not practically affect the LSA value. However, the  $15^\circ$  and  $30^\circ$  cases have greater three-dimensional effects that, with the walls modifications, reduce the size of the recirculation bubble by introducing more undisturbed airflow from the side that reach the centerline of the deck.

The incident velocity profiles on the rotor line have been plotted representing 86 velocity data points of the PIV maps on a line  $y = 58$  mm, that is the height where the helicopter rotor operates at the full-scale case ( $\sim 5$  m). The plots presented in Figures 11 to 13 show these velocity profiles on the rotor line for the base configuration and each hangar tested installed.

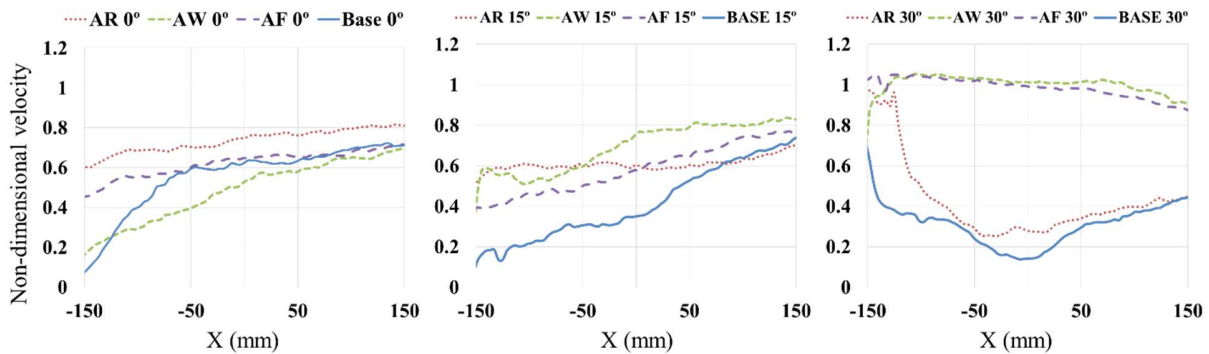


**Fig. 11 Non-dimensional velocity profiles of incident wind velocity to the helicopter rotor ( $y = 58$  mm) behind Angled Hangars (A).**

The base configuration shows a curve with a velocity decrease near the hangar wall ( $x \sim -150$  mm) due to the presence of the low-velocity region that has been presented on PIV maps. The goal here is to obtain uniform, constant and low gradient velocity profiles above the full deck, correcting the left part of the base plot.

Figure 11 presents the velocity profiles obtained with the angled hangars with the roof modified (AR), walls (AW) and both (AF) for the  $0^\circ$ ,  $15^\circ$  and  $30^\circ$  cases tested.

For the  $0^\circ$  case, only the hangar with the roof modified (AR) and the fully modified (AF) achieve a constant and low gradient velocity profile. The  $15^\circ$  case presents better results in terms of profile uniformity for the three hangars (AR, AW and AF). Finally, attending to the plots for the  $30^\circ$  case, only the angled hangar with modified walls (AW) and fully modified (AF) make an improvement against the base case. The different effectiveness of roof hangars on  $0^\circ$ , walls, and fully modified on  $15^\circ$  and  $30^\circ$  must be caused by the three-dimensional effects that appear under non-zero wind angle conditions above mentioned.

Figure 12 shows the velocity profiles obtained of the circular hangars with the roof modified (CR), walls (CW) and both (CF) for the  $0^\circ$ ,  $15^\circ$  and  $30^\circ$  cases tested. Similarly than for the angled hangars presented in Figure 11, circular hangars with roof (CR) and fully modified (CF) achieve a more or less uniform velocity profile for  $0^\circ$  case, and circular hangar with walls (CW) and fully modified (CF) for  $30^\circ$  case. However, under  $15^\circ$  condition, the walls modification (CW) and full (CF) do not provide a constant velocity profile for the helicopter rotor and only the modification of the roof (CR) presents better results in terms of profile uniformity. Figure 13 presents the velocity profiles resultant of the elliptical hangars with the roof modified (ER), walls (EW) and both (EF) for the  $0^\circ$ ,  $15^\circ$  and  $30^\circ$  cases tested.

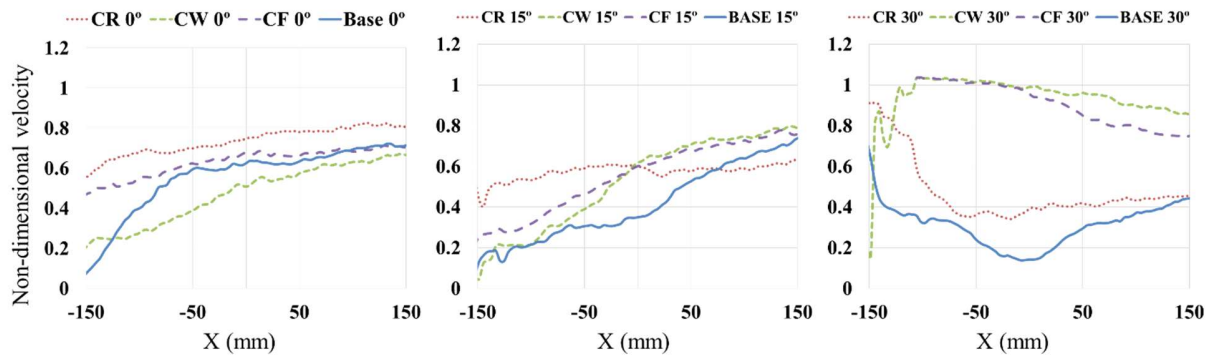


**Fig. 12 Non-dimensional velocity profiles of incident wind velocity to the helicopter rotor ( $y = 58$  mm) behind Circular Hangars (C).**

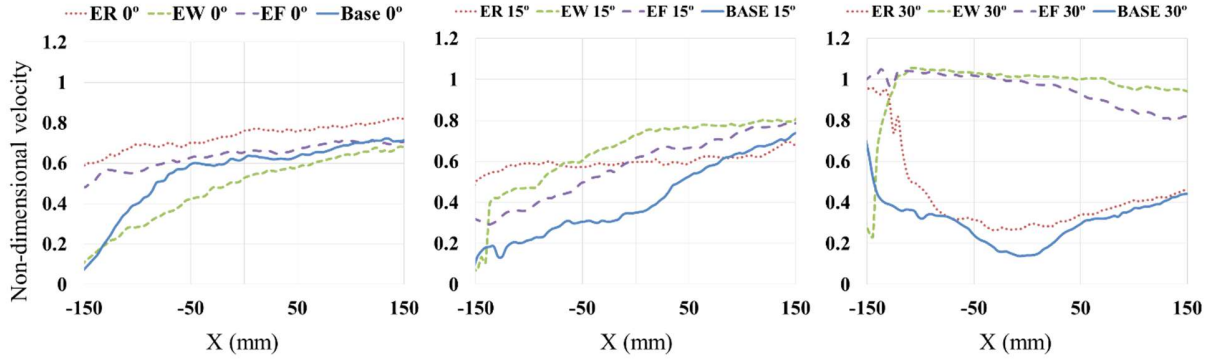


**Fig. 13 Non-dimensional velocity profiles of incident wind velocity to the helicopter rotor ( $y=58$  mm) behind Elliptical Hangars (E).**

At  $0^\circ$  condition, the hangar with the elliptic roof (ER) and fully modified (EF) achieve good velocity profiles over the flight deck. Under  $15^\circ$  wind condition, the elliptic hangar with the modified roof (ER) is the most uniform but the three hangars produce better velocity profiles for the rotor than the base case. The  $30^\circ$  wind condition shows the same than for the previous cases of angled and circular hangars. Only the hangar with the walls modified (EW) and fully modified (EF) achieve good results.

In this situation, where each hangar has advantages and disadvantages depending on the wind condition studied, choosing the optimum configuration among analyzed is not an easy task. To decide the best hangar of those tested, a weights function ( $A_i$  in equation 1) has been developed to give each hangar a score taking into account three factors: the percentage reduction of the Low Speed Area (LSA parameter), the uniformity of the velocity profiles at the rotor line measured by the standard deviation of the curves ( $\sigma$ ) and the loss of interior volume associated with the modification of the hangar geometry ( $Vol_i$ ) against the base case.

$$Score = A_1 \left( \frac{LSA_{base} - LSA_i}{LSA_{base}} \right) + A_2 \left( \frac{\sigma_{base} - \sigma_i}{\sigma_{base}} \right) + A_3 \left( \frac{Vol_i - Vol_{base}}{Vol_{base}} \right) \quad (1)$$

By applying equation 1 to all the data extracted from each test, score results for each hangar can be obtained and are presented in Table 1. A higher score is better. The comparison has given more relevance to the aerodynamic performance by applying different weights to each factor ( $A_1 = 0.4$ ,  $A_2 = 0.4$ ,  $A_3 = 0.2$ ).

In table 2 all the results have been ordered from the best score to the worst for each WOD tested. Looking at the scores for the  $0$  degrees cases, the configurations with the roof modified (AR, CR, and ER) show the best aerodynamic performance. The case of  $WOD = 15^\circ$  presents the bests results for the roof modifications (CR and AR) and walls modifications (AW). Finally, for the  $30$  degrees cases, the highest scores have been achieved by the hangars fully

modified (AF and EF) and with the walls modified (AW). As the major of helicopter operations are made under 0 degrees or close, it is clear that the roof modifications are the most important for improving the flow over the aft-deck during headwind condition (WOD = 0°). However, when the 3-D effects are relevant (non-zero WOD) walls modifications produce better results.

**Table 1 Score results for all cases tested with different weights for the three parameters considered ( $A_1 = 0.40$ ;  $A_2 = 0.40$ ;  $A_3 = 0.20$ ) and averaged score for each hangar (AVG)**

|           | LSA (%) |               | Standard Deviation |               | Volume (cm3) |               | SCORE |
|-----------|---------|---------------|--------------------|---------------|--------------|---------------|-------|
| BASE      | 34      | Variation (%) | 0.17               | Variation (%) | 1960         | Variation (%) |       |
| AR 0 Deg  | 16      | 52.7          | 0.06               | 64.7          | 1784         | -9.0          | 45.1  |
| AW 0 Deg  | 23      | 30.5          | 0.16               | 4.6           | 1652         | -15.7         | 10.9  |
| AF 0 Deg  | 17      | 48.9          | 0.07               | 59.2          | 1535         | -21.7         | 38.9  |
| CR 0 Deg  | 15      | 55.4          | 0.07               | 59.4          | 1844         | -5.9          | 44.7  |
| CW 0 Deg  | 22      | 33.9          | 0.15               | 10.2          | 1765         | -9.9          | 15.6  |
| CF 0 Deg  | 18      | 45.9          | 0.07               | 57.9          | 1683         | -14.1         | 38.7  |
| ER 0 Deg  | 16      | 52.9          | 0.06               | 63.2          | 1787         | -8.8          | 44.7  |
| EW 0 Deg  | 22      | 34.8          | 0.17               | 0.1           | 1675         | -14.5         | 11.1  |
| EF 0 Deg  | 16      | 52.0          | 0.06               | 63.5          | 1547         | -21.1         | 42.0  |
|           |         |               |                    |               |              |               |       |
| BASE      | 42      | Variation (%) | 0.20               | Variation (%) | 1960         | Variation (%) |       |
| AR 15 Deg | 22      | 47.4          | 0.04               | 78.1          | 1784         | -9.0          | 48.4  |
| AW 15 Deg | 3       | 92.3          | 0.12               | 38.4          | 1652         | -15.7         | 49.1  |
| AF 15 Deg | 3       | 92.4          | 0.13               | 36.5          | 1535         | -21.7         | 47.2  |
| CR 15 Deg | 20      | 51.5          | 0.05               | 77.6          | 1844         | -5.9          | 50.4  |
| CW 15 Deg | 9       | 78.3          | 0.23               | -12.9         | 1765         | -9.9          | 24.2  |
| CF 15 Deg | 9       | 79.7          | 0.18               | 13.0          | 1683         | -14.1         | 34.3  |
| ER 15 Deg | 22      | 48.4          | 0.05               | 76.8          | 1787         | -8.8          | 48.3  |
| EW 15 Deg | 6       | 85.0          | 0.17               | 13.6          | 1675         | -14.5         | 36.6  |
| EF 15 Deg | 3       | 92.0          | 0.16               | 20.6          | 1547         | -21.1         | 40.8  |
|           |         |               |                    |               |              |               |       |
| BASE      | 33      | Variation (%) | 0.11               | Variation (%) | 1960         | Variation (%) |       |
| AR 30 Deg | 28      | 15.3          | 0.19               | -66.9         | 1784         | -9.0          | -22.4 |
| AW 30 Deg | 2       | 93.1          | 0.06               | 44.3          | 1652         | -15.7         | 51.8  |
| AF 30 Deg | 2       | 93.6          | 0.06               | 50.7          | 1535         | -21.7         | 53.4  |
| CR 30 Deg | 11      | 68.0          | 0.15               | -32.1         | 1844         | -5.9          | 13.1  |
| CW 30 Deg | 3       | 92.5          | 0.14               | -21.3         | 1765         | -9.9          | 26.5  |
| CF 30 Deg | 5       | 85.6          | 0.11               | 2.1           | 1683         | -14.1         | 32.3  |
| ER 30 Deg | 34      | -0.2          | 0.18               | -62.3         | 1787         | -8.8          | -26.7 |
| EW 30 Deg | 2       | 92.7          | 0.15               | -28.9         | 1675         | -14.5         | 22.6  |
| EF 30 Deg | 2       | 94.2          | 0.08               | 25.4          | 1547         | -21.1         | 43.6  |

Finally, table 3 shows the global average of the results of each hangar under the three wind conditions tested in order to select the best configuration of all tested in global terms. Then, with the scoring method selected the optimal

hangar is the Angled Full (AF). This means that this hangar achieves the best combination between low-velocity area reduction, incident wind velocity profiles for the helicopter rotor and volume capability losses inside the hangar.

In short, if a frigate manufacturer wants to improve the helicopter operations with headwind, roof modifications would be the best option. And if the designers want to suppress the low-velocity regions behind the hangar for a wider range of WOD, they should modify the walls or both (roof and walls), as can be seen in table 3 where the full modifications achieve the best results in average for all tests (AF and EF).

**Table 2 Results ordered by score at each WOD angle (0°, 15° and 30°)**

| 0 DEG  |       |          |
|--------|-------|----------|
| HANGAR | SCORE | POSITION |
| AR     | 45.1  | 1        |
| CR     | 44.7  | 2        |
| ER     | 44.7  | 3        |
| EF     | 42.0  | 4        |
| AF     | 38.9  | 5        |
| CF     | 38.7  | 6        |
| CW     | 15.6  | 7        |
| EW     | 11.1  | 8        |
| AW     | 10.9  | 9        |

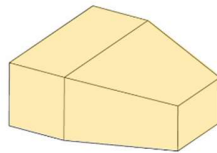
| 15 DEG |       |          |
|--------|-------|----------|
| HANGAR | SCORE | POSITION |
| CR     | 50.4  | 1        |
| AW     | 49.1  | 2        |
| AR     | 48.4  | 3        |
| ER     | 48.3  | 4        |
| AF     | 47.2  | 5        |
| EF     | 40.8  | 6        |
| EW     | 36.6  | 7        |
| CF     | 34.3  | 8        |
| CW     | 24.2  | 9        |

| 30 DEG |       |          |
|--------|-------|----------|
| HANGAR | SCORE | POSITION |
| AF     | 53.4  | 1        |
| AW     | 51.8  | 2        |
| EF     | 43.6  | 3        |
| CF     | 32.3  | 4        |
| CW     | 26.5  | 5        |
| EW     | 22.6  | 6        |
| CR     | 13.1  | 7        |
| AR     | -22.4 | 8        |
| ER     | -26.7 | 9        |

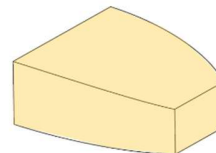
**Table 3 Averaged results ordered by score**

| AVG 0°, 15°, 30° |           |          |
|------------------|-----------|----------|
| HANGAR           | AVG SCORE | POSITION |
| AF               | 46.5      | 1        |
| EF               | 42.1      | 2        |
| AW               | 37.3      | 3        |
| CR               | 36.1      | 4        |
| CF               | 35.1      | 5        |
| AR               | 23.7      | 6        |
| EW               | 23.4      | 7        |
| CW               | 22.1      | 8        |
| ER               | 22.1      | 9        |

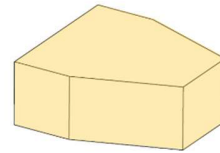
1<sup>st</sup> Angled Full (AF)



2<sup>nd</sup> Elliptical Full (EF)



3<sup>rd</sup> Angled Walls (AW)



## V. Conclusions

In this paper, the aerodynamic effects of modifying the frigate hangar geometry have been analyzed. Taking the base case as a reference, different *bubble-shaped* hangars have been tested. Specifically, nine different hangars with angled, circular and elliptical roofs and side walls have been tested. With data from wind tunnel testing and the Particle Image Velocimetry (PIV) measurement technique, it has been possible to compare their effects. Thus, the reduction in the low-speed area behind the frigate superstructure and the changes in the incident wind velocity profiles on the helicopter rotor during its landing approach have been quantified. For the comparison, the losses of interior volume

capability for the different hangars tested have been also taken into account. The results obtained for headwind ( $WOD = 0^\circ$ ) show that hangars with roof modifications obtain the best results. For the non-zero wind angle cases ( $15^\circ$  and  $30^\circ$ ), as the three-dimensional effects are more evident with the wind entering over the deck by the side, hangars with walls modifications have much better aerodynamic performance. Overall, the best results from the average of all cases tested were obtained for the angled and elliptical hangars with roof and walls modified (AF and EF) followed by the Angled hangar with walls modified (AW). That means that if the designers of a frigate are interested in suppress the low-velocity regions behind the hangar for a wider range of WOD, a good option is to modify roof and walls geometries. For the comparison, it was given more importance to the aerodynamic performance of each hangar tested. The choice of one hangar or another may vary depending on the importance given to the different optimization parameters selected for the comparison or the design complexity desired for a new frigate design. Another important thing to mention is that the comparison made in this paper is based on steady-state data obtained from an average of 100 pairs of PIV images. The averaged situation is important to study since the helicopter recovery several seconds and even sometimes the helicopter is stopped at certain points of the maneuver. However, unsteady effects should be studied in future research. Finally, It is also important to highlight that this kind of multiparametric optimization can be useful for choosing the best designs at the preliminary design stages of future frigates. And the designs proposed here can be a good starting point and a trend for the design of future hangars in frigates, helping to improve the safety of helicopter operations on frigates.

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