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CHARACTERIZATION OF THE WIND FLOW ON THE FLIGHT DECK OF A FRIGATE

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Abstract

Helicopter operations in frigate-type boats can be critical depending on the sea and wind conditions. Due to the non-steadiness and wide variations of the mean velocity, the flight envelope is limited, being the approach to the flight deck one of the most complex and risky operations a helicopter can perform. Usually, the flight deck in the frigates is located in the stern. As a consequence, the wind flow in the surroundings of the flight deck is highly conditioned by the wake generated by the freeboard of the boat. This wake is highly turbulent and full of strong vortexes. These vortexes depend on the geometry of the boat upstream the flight deck. The correct characterization of this complex flow is related to the safety of the operation of the aircraft and allows to set the limits in which the deck can be operative or be certified. In this work, some partial results of an extensive wind tunnel test campaign are presented. In this campaign, a model of the frigate has been tested. The aim is to characterize the flow in the surroundings of the flight deck of the frigate. For that, visualization tests with wool tufts and smoke, hot wire anemometry and particle image velocimetry (PIV) have been performed. All the tests have been done in the experimental aerodynamics facilities of the Instituto Universitario "Ignacio Da Riva", belonging to the Universidad Politécnica de Madrid. Based on the information obtained in the tests, small modifications in the freeboard are suggested, in order to optimize the flow in the flight deck, which can make the approach operation easier for the pilots.

1. Introduction

The need of performing the aerodynamic optimization of the flight deck of a frigate is has been proved by accidents such as the one of the helicopter MH-60S Knighthawk (see Fig. 1), which participated in the Operation "Enduring Freedom", on the flight deck of the USS William P. Lawrence, on September 22^{nd}, 2013, after receive a *rogue wave* just after the helicopter had landed on the flight deck. The combination of the wave itself, the speed of the ship and the fall of the course that kept the ship in *quartering seas*allowing the waves to reach the deck and slide it off the deck.

Figure 1: MH-60S Knighthawk Helicopter (Source: US Navy)

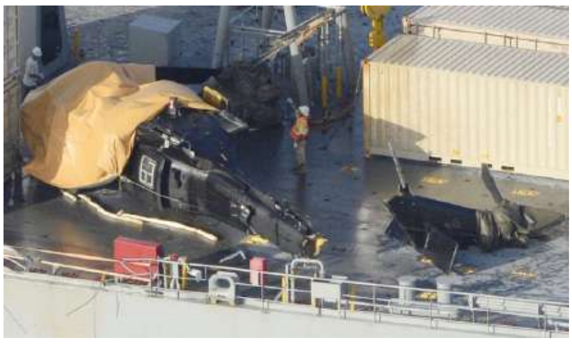

Figure 2: Remains of the H-60 on the cover of the US Red Cloud (Source: US Navy)

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Another illustrative example happened to the helicopter U.S. Army H-60 that crashed with the flight deck of the Military Sealift Command (MSC), US Red Cloud (T-AKR-313). The accident caused 7 injured during the exercise carried out on August 12th, 2015 at 20 miles east of Okinawa, Japan. The damages in the structure after the crash are clearly seen in Fig 2.

The previous examples show the need of analyzing and optimizing the frigate's flight deck to increase safety in taking off and landing operations. This aerodynamic optimization is a project in itself, which needs simulations and tests with scale models in a wind tunnel. This work deals with the aerodynamics characterization of the flight deck of a typical frigate model. The study is performed based on a complete battery of tests in the experimental facilities of Institute "Ignacio Da Riva" of the Universidad Politécnica de Madrid (IDR/UPM).

2. Experimental facility and model

The experimental tests have been performed in the ACLA-16 wind tunnel. ACLA 16 is a lowspeed closed return wind tunnel with a closed test section, which has a squared cross section with 2.2 m side length and 17 m length (this wind tunnel can be used for atmospheric boundary layer simulation). The wind tunnel is driven with 16 fans, 7.5 kW each one (the total power is 120 kW). The wind speed is controlled electronically by means of a variable frequency drive, and flow velocities up to 30 m/s can be attained. Results with different experimental techniques have been used in this work.

2.1 Frigate model

The test model has been designed on a scale of 1:80, and for its manufacture different modeling techniques have been used: wood components, 3D printing and numerical control milling. The choice of this scale is due to a compromise between the model being as large as possible to preserve the relevant details from the aerodynamic point of view; and that the blockade of the tunnel is bounded. The whole test model has been built in IDR/UPM modeling workshops using various materials such as plywood and MDF chipboard of various thicknesses, isotropic resin (trademark Necuron), and ABS + for 3D printing. The manufacturing and assembly process of the superstructure of the frigate is shown in Fig. 3.

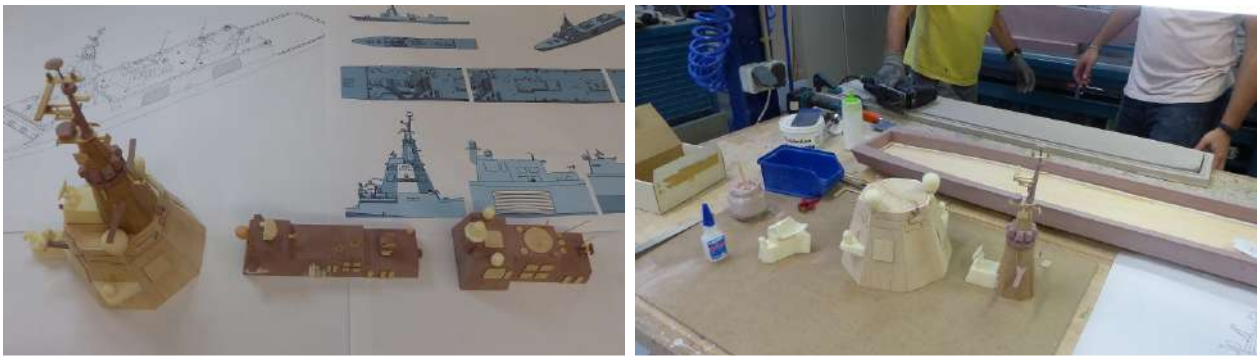

Figure 3: Manufacturing and assembly process of the frigate model

In addition to the model of the frigate, a simplified model of an helicopter has been built to measure the wind loads acting on it during the approximation phase. The helicopter model has been manufactured in ABS by 3D printing. Figure 4 shows images of the model of the helicopter that has been tested.

Different experimental tests are performed in this work including load measurements on the frigate, flow visualization and characterization over the flight deck, and loads on the helicopter model. A preliminary version of this test results was presented by the group of the work in[5]

3. Global loads on the frigate

The frigate model is installed on two loads cells model F/T Sensor Gamma ATI SI-130-10. These sensors allow to precisely determine forces and moments that the frigate undergoes in three axes. Simultaneously, the dynamic pressure was measured using a pitot tube and a differential pressure gauge capsule. By means of these measurements, the aerodynamic coefficients of the frigate can be calculated. According to the nomenclature normally used in cargoes on ships,[1] such coefficients are calculated as follows:

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Figure 4: On the left image of the model of the frigate finished and installed in the test chamber of the ACLA-16 wind tunnel and on the right model of the helicopter on the flight deck.

$$c_X = \frac{f_x}{q_\infty A_f};\; c_Y = \frac{f_y}{q_\infty A_s} \tag{1}$$

$$c_{m,x} = \frac{m_x}{q_\infty A_s (A_s / L_{oa})};\; c_{m,z} = \frac{m_z}{q_\infty A_s L_{oa}}; \tag{2}$$

where f_i is the force measured in each axis ($i = x, y$); m_i is the moment in each axis; q_∞ is the dynamic pressure; A_f is the projected frontal area; A_s is the projected lateral area; L_{oa} is the frigate length. The coefficient c_X, c_Y, $c_{m,x}$ and $c_{m,z}$ are respectively, the coeficient of the longitudinal force, the transversal force, and the moments in longitudinal and vertical direction. The reference frame considered is: the z-axis goes to the vertical direction and pointing downwards, the x-axis goes in the aft-bow direction, pointing towards the latter, and the y-axis right-handed trihedral.

The test is performed for all the possible yaw angles (0°-355°), β, at steps of 5°. $\beta = 0°$ correspond to the wind incident on the bow, $\beta = 180°$ corresponds to the wind incident on the aft and $\beta = 90°$ corresponds to the wind incident on the port side. The measures has been adquired for 60 seconds at a sampling frequency of 1000 Hz. The model is placed on a positioning system able to accurately control the angular position. To avoid the effect of the boundary layer of the wind tunnel the model is mounted in an elevated platform.

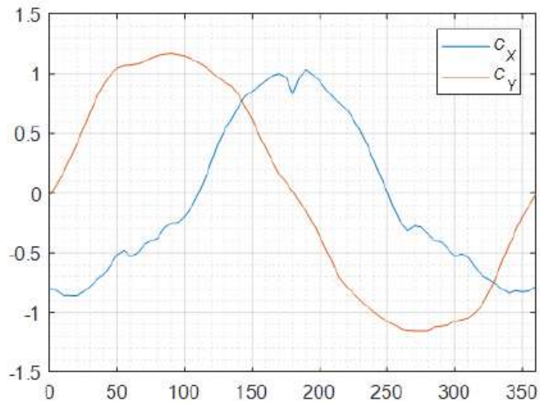

Figure 5: Force coefficients for different flow angles.

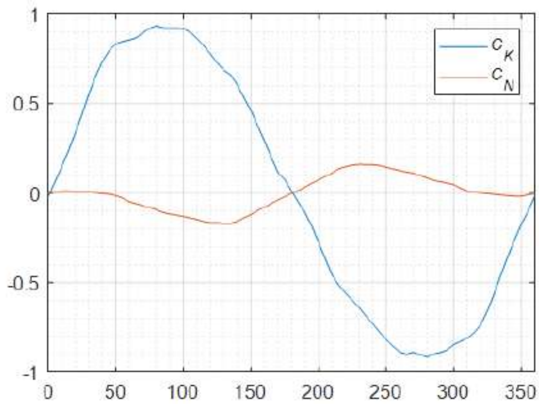

Figure 6: Moment coefficients for different flow angles.

Figure 5 present the force coefficient for the different yaw angles, and Figure 6 presents the moment coefficients. As it was expected, the lateral load (and moment) increases when the wind blows from the port or the starboard side, when it is maximum.

Additionally, tests at different wind speeds have been performed to verify the independence of the Reynolds number, and ensure repeatability of the measurements.

4. Flow characterization and visualization on the flight deck

In this section an experimental characterization of the flow over the flow deck is performed.

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4.1 Flow visualization

To perform a preliminary visualization of the flow on the flight deck, where the characterization of the flow is more relevant, wool plumes have been used. These plumes allow to easily notice the presence of particular flow phenomena (swirls, detachment zones, adhered flow ...). Also an experiment with smoke visualization technique has been used. The smoke is generated by heating glycol, a technique widely used for this purpose.

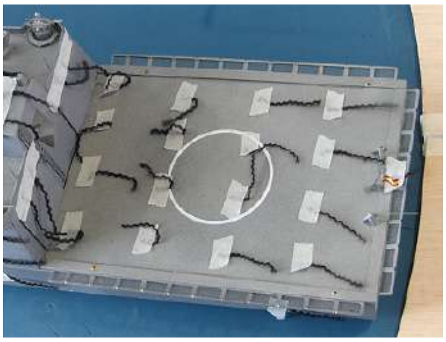

Figure 7: Flow visualization using wool plumes.

Figure 8: Flow visualization using smoke.

Figure 7 shows the flow visualization experiment performed with wool plumes. It can be noticed that plumes closer to the aft remain attached to the deck surface, while the ones closer to the frigate superstructure present an oscillatory behavior. Therefore, we expect to find a flow detached region or recirculation bubble that must be properly characterized to analyze its possible influence in the landing operation.

The shape of the recirculation bubble can also be seen in Figure 8. In the figure. it can be seen that the shear layer emerging from the frigate castle is reattached in the middle of the heliport. The arrows in the figure show, approximately, the averaged the behavior of the flow. The red arrow indicates the area of recirculation and creation of swirls, while the blue arrow indicates the part of the flow that is reattached to the flight deck surface. These results are consistent with the flow visualization through wool plumes.

4.2 Hot wire anemometry

In order to determine quantitatively the velocity in the area of the heliport, three-component hot wire anemometry measurements have been carried out. This technique allows to measure with a high sampling frequency the three components of the velocity field at different points. For this purpose, a hot wire probe model 55P91 from Dantec, as well as an electronic anemometry module CTA from the same manufacturer, has been used. The set-up is complemented with an acquisition system, a pitot tube and a differential gauge pressure capsule from Druck. Due to the sensitivity of the hot wire measurements, the temperature is measured with a Jumo temperature probe. Finally, a three-axis positioning system by Isel allows automatic control of the position of the probe, thus permitting to introduce a matrix of points to measure in advanced. At each point, temperature, velocity components measured by the probe, and gauge pressure difference of the capsule are acquired for 90 s., with a sampling frequency of 1.5 kHz. Once the measurement is completed, the program moves the probe to the next point, and so on.

Two different type of measurements have been taken: in planes perpendicular to the longitudinal axis and in longitudinal planes. Firstly, in planes perpendicular to the longitudinal axis of the frigate for three different yaw angles $\beta = -10°,\ 0°,\ 10°$. The velocity field has been obtained at three different measurement planes to reconstruct the velocity field. The results are presented in Figures 9, 10 and 11 represent the values of the mean velocity for the three yaw angles. In the plan view (right), the flow is comes from right to left and the rectangle represents the flight deck.

Secondly, in the longitudinal planes for a yaw angle, $\beta = 0°$. Measurements are taken in the central plane (longitudinal axis) and another plane laterally displaced at approximately 3/4 of the width of the deck.

4.3 Particle image velocimetry (PIV)

PIV is a technique that allows determining the instantaneous velocity distribution in a plane. The wind tunnel flow is seeded with very small oil particles that follow the flow without buoyancy effects. The flow field is illuminated by a flat laser sheet, whose shots are synchronized with the camera taking two photographs in a small interval of time, Δt. Therefore, between the two images the particles have shifted a displacement Δx and Δy, in the horizontal and

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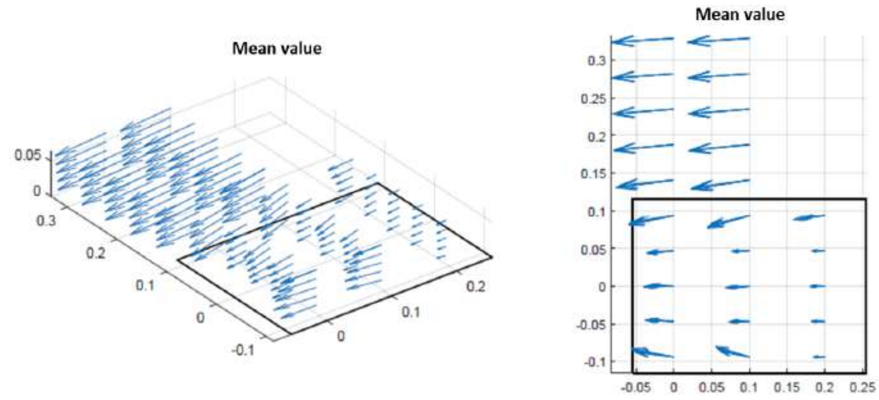

Figure 9: Mean velocity for a yaw angle $\beta = 0°$, isometric view (left) and top view right.

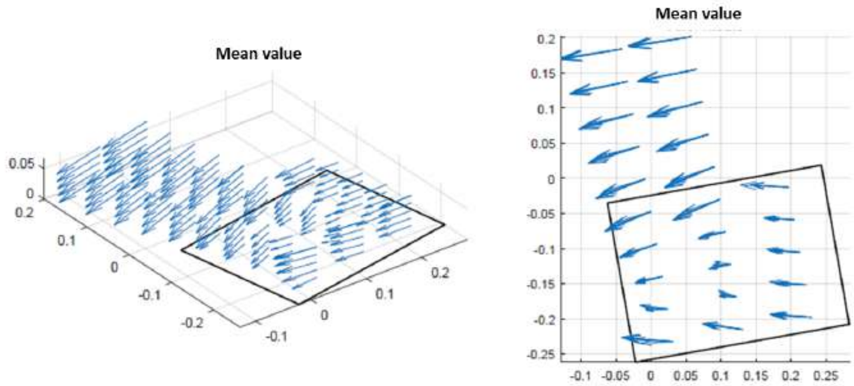

Figure 10: Mean velocity for a yaw angle $\beta = -10°$, isometric view (left) and top view right.

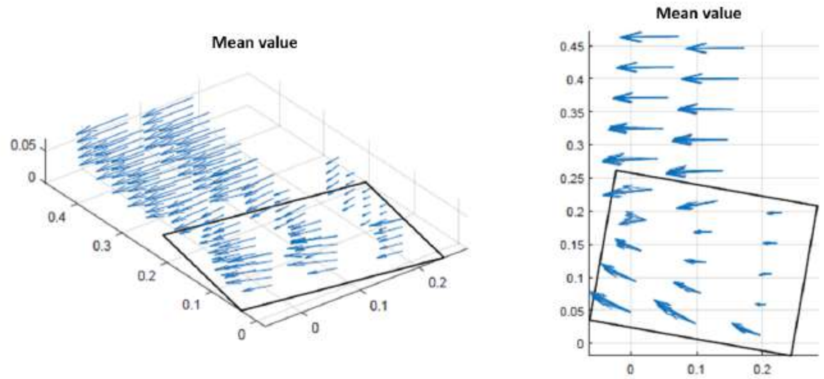

Figure 11: Mean velocity for a yaw angle $\beta = 10°$, isometric view (left) and top view right.

vertical direction respectively. This distances are determined by cross-correlation. More information on this technique can be found in Willert and Gharib.[7,8] The test has been performed at two longitudinal planes, equivalent to those of subsection 4.2. A sampling frequency of 4.83 Hz and 500 pairs of images are taken for each measure. The measurement region is of about 200x200 mm, so two frames for each measurement plane were considered. The acquired images have been later processed to obtain a velocity vector for each grid of 32x32 pixels. The images have been pre-processed, subtracting the minimum intensity, to try to eliminate the static background. A direct correlation procedure has been applied. This procedure has a higher computational cost but also greater precision. A recursive algorithm, processing has been started in a window of 64x64 pixels and then reduced to 32x32. For the post-processing, a median test was used with a cell of 5x5 vectors (the calculated vector is compared with the median of its closest vectors).

The results obtained with PIV are two in-plane velocity components, $u(t)$ and $w(t)$, in the directions x and z.

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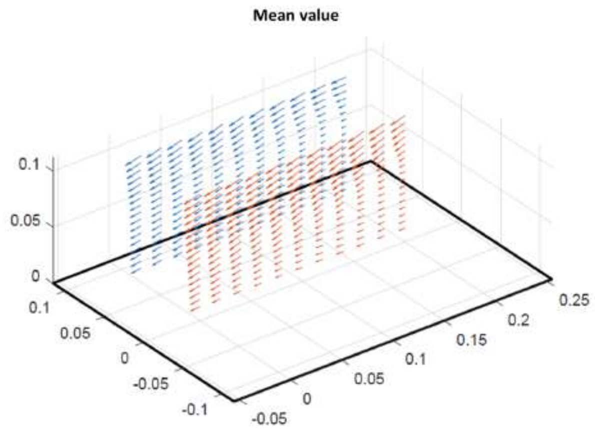

Figure 12: Mean velocity in longitudinal planes for a yaw angle $\beta = 0°$.

Figure 13 shows the velocity components (horizontal component at the left and vertical component at the right) in the central plane of the flight deck, while Figure 14 shows the velocity components in the lateral measurement plane.

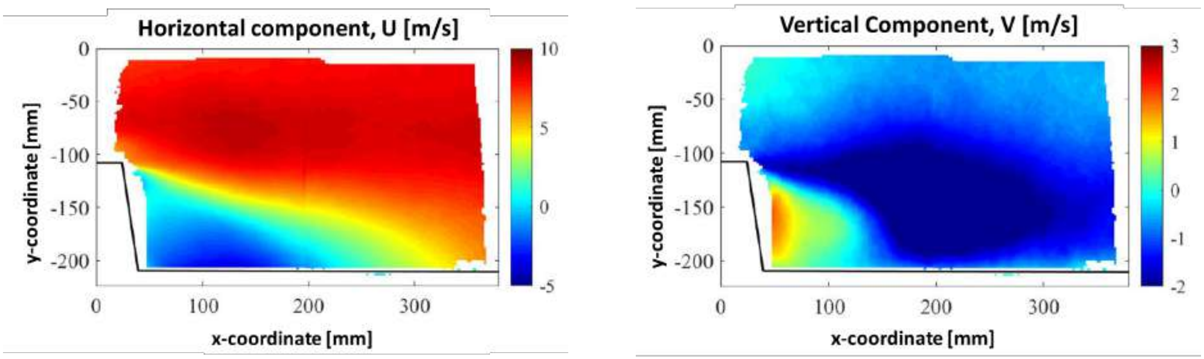

Figure 13: Contours of velocity magnitude in the central plane of the flight deck: horizontal component (left) and vertical component (right).

In these figures we can notice a region with a non-disturbed (or slightly perturbed) flow area (red zone in the horizontal component plot), and an area in which the effects of the frigate's superstructure wake on the flow is obvious. In this last region, the vertical velocity component, both ascending flow (orange-red zone) and descending flow (dark blue zone) can be seen. This results confirm the recirculation bubble commented in Fig. 8.

It is worth noticing that in the central plane, the line of zero horizontal speed, $U = 0$ m/s, reaches beyond 200 mm, while in the lateral plane, it ends in less than 150 mm. This is due to the flow momentum injected from the lateral side of the frigate, *energizing* the wake in the lateral plane, but not reaching the central plane with enough energy.

Figure 15 shows the vector velocity field in the central and lateral measurement plane. The lower line represents the position of the heliport. The size of the vectors is proportional to the velocity magnitude. In the previous figures the center of the bubble (very low speed, small vectors) can be seen in the upper left size. In the central plane we can see that the position of the center of the bubble is more downstream on the flight deck. As previously mentioned, the closure of the bubble, or reattachment point, happens more upstream than in the lateral plane.

5. Loads on the helicopter in approximation operations

As mentioned in Section 2.1, a model of a helicopter has been manufactured to characterize the aerodynamic loads during the approximation phase. The model has been manufactured in ABS using stereo-lithography (3D printing). The loads on the helicopter are measured using an ATI GAMMA load cell fixed to the helicopter. The load cell is located between the helicopter and the 3-axes positioning system. This allows moving the helicopter model with respect to the frigate. The experimental set-up is complemented with a data acquisition system, a pitot tube, an a differential gauge pressure capsule to measure the incoming flow velocity.

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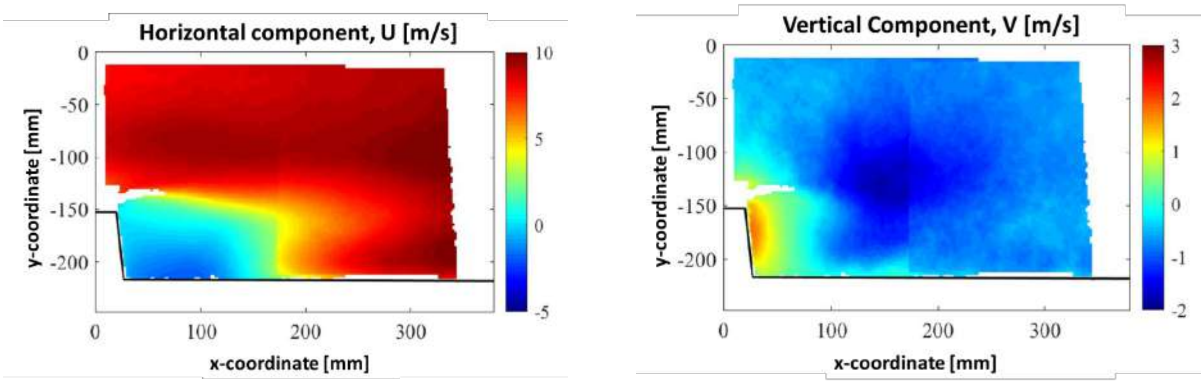

Figure 14: Contours of velocity magnitude in the lateral measuring plane of the flight deck: horizontal component (left) and vertical component (right).

The test procedure consist in defining a set of points where the loads are going to be determined. This points describe the trajectory of the helicopter during the approximation and take off phases. The usual approximating operation is as follows: the helicopter approaches the ship on one of its sides, standing parallel to the center line of the ship. Generally, the port side is prefer due to visibility of the pilot. The helicopter then flies sideways to the vertical of the landing point. A common aspect to the operations of helicopters on flight decks of ships is the height, of about 5 meters, above the flight deck at which the vertical motion (ascent or descent) occurs (see Carico et al.[4]). This landing point is located on the vertical of the geometric center of the deck, Greenwell and Barrett[6] and constitutes a critical point, representative of the aerodynamic flow that the helicopters must support during their operation on the flight decks of ships.

The procedure is repeated for different yaw angles ranging $(-10°, 10°)$. The sampling frequency is set at 1000 Hz and the forces are measured for 66 seconds for each point on the helicopter trajectory. The negative values correspond to cases when the flow reaches the frigate from the starboard side. We consider that the helicopter is always approaching the frigate from the aft side. Three possible trajectories are considered as shown in Fig. 16.

In this figure the trajectory $x = 0$ passes through the geometric center of the flight deck. The trajectories corresponding to $x = 25$ and $x = -25$ represent and advanced plane and another one delayed with respect to the center of the heliport. As representative condition for this set of measures is the evolution of the horizontal force over the helicopter along its trajectory. All measured forces are presented non-dimensionalized with the force measured in the first point of the trajectory (very far from the frigate).

The results show that the loads are reduced as the helicopter approaches the frigate, being smaller the force corresponding to the trajectory $x = 0$ passing through the center of the heliport, reaching a minimum close to the non-dimensional position 0.3.

6. Conclusions

In the present work, an intensive aerodynamic test campaign over the flow field on a frigate has been performed. The test has been performed in the ACLA-16 wind tunnel at IDR/UPM. The characterization included: measurements of the global aerodynamic loads on the frigate, aerodynamic characterization and flow visualization of the flow on the flight deck, and the forces over the helicopter during the approximation operation.

It has been possible to verify the important aerodynamic loads that appear on the frigate. An adequate determination of this loads are very important in the design phases of the ship, and help to correctly dimension the structure. The flow visualization showed that the aerodynamic behavior is complex in the heliport zone. Hot wire anemometry and Particle Image Velocimetry measure has confirmed this complex behavior.

Finally, the forces over the helicopter model in a general approximation operation are measured.

Acknowledgements

The work described in this manuscript has been carried out in the facilities of the Aerodynamics Laboratory of the "Ignacio Da Riva" University Institute of the Polytechnic University of Madrid (IDR/UPM), located in the Montegancedo campus of UPM. Both the construction of the model and the implementation of the testing campaign have been pos-

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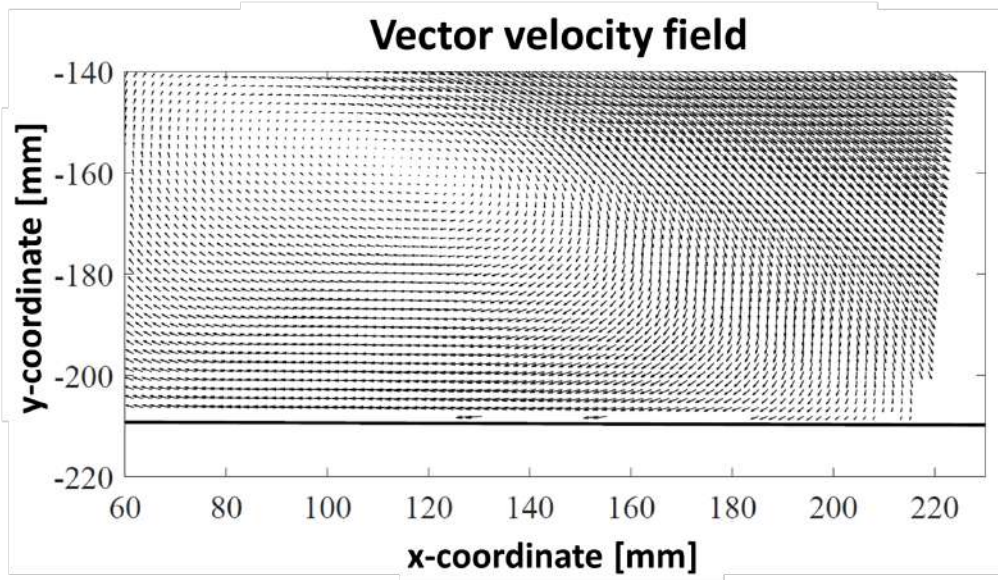

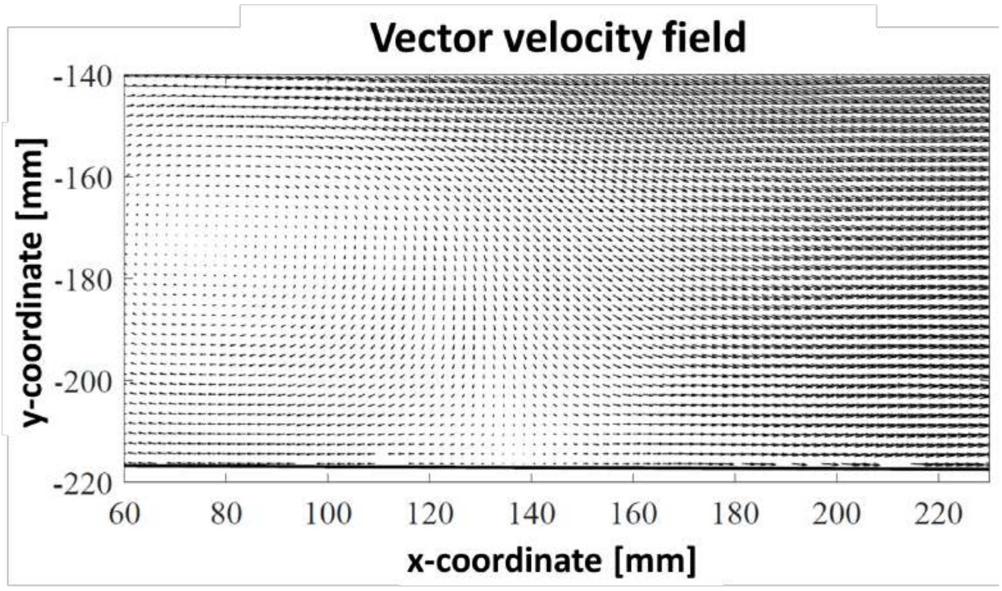

Figure 15: Vector velocity field in the central plane (top) ans lateral plane (bottom) of the frigate deck.

sible thanks to the participation of Javier Pascual Alonso, Carlos Pascual Alonso, Manuel Ortega Hidalgo, and Javier Perez-Álvarez.

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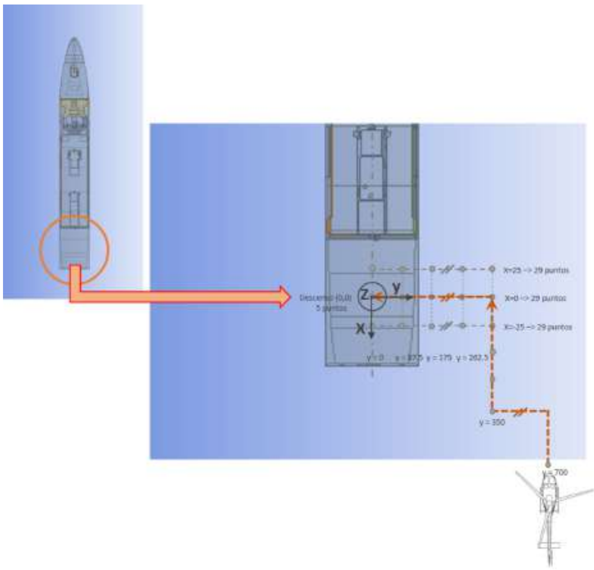

Figure 16: Helicopter trajectory and measurement locations.

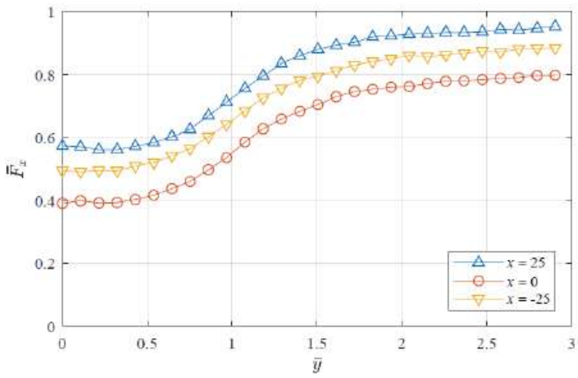

Figure 17: Evolution of the non-dimensional force with the y-coordinate along the 3 trajectories.

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