FLOW FIELD ON HELODECK OF A FRIGATE: A REVIEW

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SUMMARY

The various functions desired from a frontline warship such as a frigate, corvette or a destroyer, coupled with the requirement of very high speeds and economic viability restricting the size, necessitates a very dense arrangement of weapons and sensors on the top deck and superstructure. Accordingly, Navies across the world have faced several problems with respect to functions for which a good aerodynamic design for these structures is essential. Major issues include smoke nuisance created due to impinging of the ship's exhaust gases on to the top deck leading to possible suction by engine intakes and high turbulence in the ship's air-wake leading to ship aircraft interface concerns. The flow field on the helodeck is extremely complex due to its geometry and interaction with the wake of the ship's superstructure. A knowledge of this complexity is essential for ensuring safe helo operations on the helodeck. The problem of ship helicopter interaction has hogged the lime light in recent times, due to rising demand for design of warships for increased stealth, especially in the past two decades. Consequently, several researchers in countries with advanced Navies have invested considerable resources towards evolving both experimental and numerical solutions for the problem. However, given the military nature of the operations, open literature on the subject containing details of such research, which can be used as reference material for present work, are limited. Considering the complexities involved in the problem, an attempt has been made in this paper to holistically review the widely scattered and limited literature in this field. A good amount of literature on marine helo applications emerge from the offshore industry. Keeping in mind that the fields of warship design and offshore structures are dissimilar and have their peculiar problems, informed conclusions have been made in drawing lessons from available literature.

NOMENCLATURE

WOD	Wind Over Deck
RCS	Radar Cross Section
NPS	Naval Postgraduate School, USA
CAA	Civil Aviation Authority, UK
FPSO	Floating Production Storage and Offloading Platform
k	Turbulent Kinetic Energy
I	Turbulence Intensity
u,v,w	Velocity component in x, y, z directions
$\overline{u'u'}, \overline{v'v'}, \overline{w'w'}$	Diagonal components of Reynold's stresses
RANS	Reynold's Averaged Navier Stokes Equations
S_w	Standard Deviation of Vertical Velocity w
U_{ref}	Undisturbed Flow Velocity (m/s)
SHOL	Ship Helo Operating Limit
NATO	North Atlantic Treaty Organisation
NLR	National Aerospace Laboratory, Amsterdam
TTCP	The Technical Co-operation Program

1. INTRODUCTION

Helicopter operations from warships form an integral part of modern Naval Warfare. Equipping frontline warships with the ability to undertake helo (short for helicopter) operations at sea, reinforces the truly three-dimensional nature of a nation's Navy. Countries with modern navies have bestowed several spheres of responsibilities on helo operations from frontline warships, both in war and peace. The surveillance and reconnaissance ability of a warship expands exponentially with the presence of a helicopter onboard. When required, helicopters can be deployed as an eye in the sky for long distances away from the warship with their own sensor payload which are much more effective than shipboard sensors, due to increased height and range. In wartime, helicopters are used for detection and destruction of enemy forces by use of weapon payload such as torpedoes and missiles. Helicopters have proved to be most effective in undertaking Search and Rescue operation (S&R) missions at sea for most Navies and Coast Guards across the world, owing to their agility and hovering capability. History of naval aviation dates back to early 1900s with advanced countries like United States, Britain and Germany taking lead in making naval aviation a vital part of naval war strategy. However, it is pertinent to mention that the early roles envisaged for the naval warfare favoured use of airplanes from warships. This led to the development of aircraft carriers, which later became an important instrument of power projection for advanced countries and were effectively used as weapons during many naval wars which followed. VS-300, designed by Igor Sikorsky, was the world's first practical helicopter which took flight in 1939. Following this development, during the middle of 20th century, amidst the aura of fighter planes operating from aircraft carriers, helicopters carved their own niche for specialised aerial functions which could not be performed easily by the former. Introduction of helicopters opened a new chapter in the history of naval aviation, by allowing the use of smaller warships for aerial operations with much lesser limitations as compared to use of a national asset such as an aircraft carrier which incurs enormous costs to the operating country. The global recognition of aviation component of a fleet as an invaluable tool for power projection and extending surveillance reach, has led many countries to invest heavily into research for making shipboard helo operations more effective.

In order to facilitate helo operations for fulfilling the above designated roles, frontline warships are provided with a helodeck for landing/ taking off operations and a hangar for safe stowage of helo, when not in use. The hangar, in most of the modern non aviation ships (ships which are primarily designed for non aviation functions but carry rotor crafts additionally for capability enhancement), is like a rectangular prism placed just ahead of the helicopter deck as part of the superstructure. Safe helo operations, on such ships, require the ship to move within a particular range of speeds to ensure favourable Wind Over Deck angles (WOD) or relative wind conditions on the helodeck. While doing so, presence of the superstructure in front of helodeck introduces many challenges for the pilot for operation of helicopters primarily emerging from a turbulent recirculation zone with a reduced free stream velocity and an increased downdraft. The flow characteristics are very similar to the classic problem of 2D back facing step. In older ships, the hangar used to be smaller and generally not extending the full breadth, thus ensuring that the resulting recirculation zone was limited (Figure 1).

Figure 1. Older configurations of hangar (Not full Breadth) (http://www.royalnavy.mod.uk)

Contrary to earlier times, in addition to catering for the space requirements for deck fittings and equipment, Navies across the globe have emphasised the need for designing their platforms for making them stealthier by reducing their signatures. Profile view of a typical hangar and helicopter deck configuration on a non-aviation warship can be seen as a backward facing step as shown in Figure 2. As part of design for a reduced RCS, helo hangars on board modern mid-sized warships have been made to extend full breadth of the ship. Although such a design change has reduced the RCS by cutting down on the number of sharp edges, the study of deterioration in flow conditions on the helodeck due to this change, has been largely neglected. This has led to severe restrictions on helo operating conditions, which, in earlier non-stealth ships have not been a cause for serious concern. Hence, unlike helo operations on land, the environment on the helodeck which is available to the pilot for operation on modern warships present numerous challenges. With minimal technology support and fairly limited information to assist them when they undertake operations, the helo crew have to rely heavily on their acquired skills and experience (Whitbread & Coleman, 2000).

Figure 2. Helicopter Deck and Hangar configuration in State of the art frigates/ destroyers (http://en.wikipedia.org/wiki/Formidable-class_frigate)

Figure 3 shows the various flow features which are normally encountered on the helodeck behind superstructure. With the contemporary configuration of helodeck and hangar on Naval vessels, the back facing step results in the formation of reverse flow zone (recirculation zone) on the helodeck with unsteady flow in terms of shedding vortices from the corners and sharp edges of hangar and helodeck. In addition, there is a complex interaction when the helo downwash impinges on the airwake over the helodeck, which are already affected by cross winds entering from the sides of the hangar leading to large changes in the flow structure. Such conditions ensure operation of the rotors in a turbulent and uneven wake thus increasing pilot workload (a measure of difficulty for a pilot to operate in given environmental conditions) manifold as compared to operations on land. The problems are further compounded while operating in heavy seas, since the ship motions provide the pilot with a moving platform for takeoff and landing. Further, these ship motions also contribute towards altering the flow structure on helodeck by oscillating the vortices shed from the edges and corners. Also, while operating in high seas, pilots often face poor visibility due to sea spray and lack of visual cues due to aircraft orientation with respect to the ship. These challenges impose severe limitations on allowable wind conditions on deck for safe helicopter operations. In extreme cases, the conditions may lead to helicopter accidents while operations are underway as have been experienced by Navies around the world.

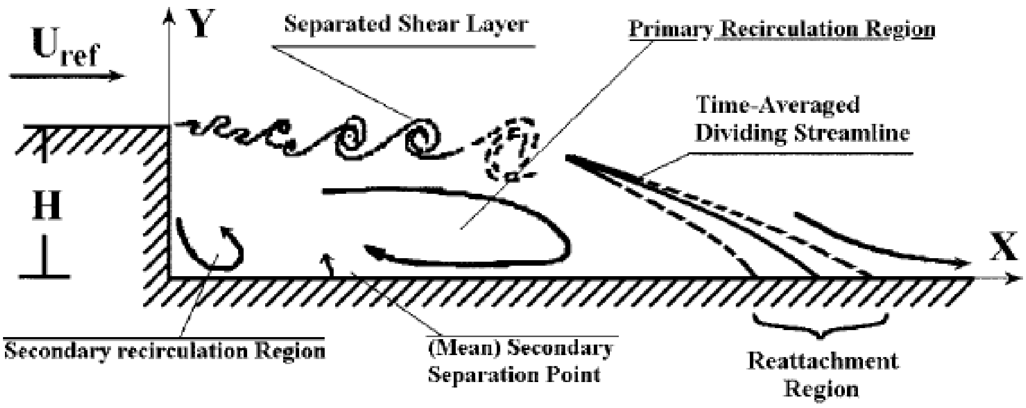

Figure 3. Idealized flow over a backward facing step (Spazzini et al., 2001)

Even in the past, there have been certain rare exceptions of novelty in design of hangar-helodeck configuration as compared to back facing step configuration mentioned above, one example being Kashin-II class destroyers (Figure 4). An 80s' design of Russia, Kashin-II class has a submerged hangar which does not protrude in front of the helodeck, thus eliminating the recirculation zone completely and providing the helo with operating conditions very similar to the ones ashore. However, the possibility of introducing such novel designs are rare and can only be limited to certain ships, where space for stowage of helo can be allowed to be subsumed within the usable volume of warship.

Figure 4. Kashin-II class destroyer with submerged hangar (https://upload.wikimedia.org)

Accidents are never acceptable, although they remain a very real and recurrent hazard in naval aviation. The money spent on aircraft, training and maintenance is simply too high for allowing accidents to occur. The human life, of course, is irreplaceable. However, notwithstanding the challenges, the range of responsibilities conferred on helo operations on warships render them unavoidable even in high seas. Having appreciated the indispensability of ship-borne helo operations, it needs to be clearly recognised that naval aviation is a complex integration of sea and air operations. By their very nature, ship-borne air operations, presently, are undertaken with safety margins much below those considered acceptable ashore. The process of Dynamic Interface Testing undertaken by experienced test pilots, to establish the operational envelope, is also associated with severe time implications and several constraints including the fact that the trials cannot be done at design stages rendering the findings unusable for design modifications. In order to improve the allowable limits of environmental conditions for safe ship-borne helo operations, several research agencies worldwide are undertaking structured research by utilising the available experimental and numerical resources for providing solutions for an improved design of helodeck-hangar configuration for modern ships without compromising on the aspects of stealth. In order to reduce the risk of accidents, such capabilities can further be used to provide information about the mapped flow conditions and probable critical zones for a given hangar configuration to pilots, especially prior to dynamic testing. Information available thus on the flow condition can act similar to road signage on a curvy road indicating danger zones which can be utilised by the pilots for ensuring safer operations.

Considering the complexities involved in the problem, an attempt has been made in the following sections to holistically review the widely scattered and limited literature in this field. A good amount of literature on marine helo applications emerge from the offshore industry. Keeping in mind that the fields of warship design and offshore structures are dissimilar and have their peculiar problems, informed conclusions have been made in drawing lessons from available literature. Also an attempt is made to present a road map for future investigations in the area so as to make the helo operations on warships as safe as possible.

2. STUDIES ON SHIP AIRWAKE

The problem of ship helo interaction finds considerable resonance with classical problems of 2D Backward Facing Step (BFS) and flow around 3D bluff bodies which have been researched extensively in the period 1980 to 2000. Prior to 1980, several countries having advanced Navies have regularly used wind tunnel experiments (mainly flow visualisation) to understand the complex flow conditions on the super structure of warships. However, coinciding with the advent of high power computing, the application of numerical techniques using CFD to attempt solutions for these problems has been a recent development. Praveen et al (2013 & 2014) have undertaken a review of literature commencing from the 2D BFS, separated flow around bluff bodies, and the experimental and numerical studies conducted on ship airwake. Though not made part of the present review, the research literature referred to in the above publications have been indicated in the references (4 to 28) for the sake of completeness. These publications have been frequently referred to by most of the authors working in the field of warship-helo interaction. In the present publication, it is thus intended to take forward the review process (with some additions of even the older literature not covered in the above references) and arrive at definite conclusions from the literature survey which will help researchers in the field to improve the allowable limits of environmental conditions for safe ship-borne helo operations and arrive at novel solutions towards a good design of helodeck on warships without compromising on stealth.

The early literature specific to ship helo interface originated from the Naval Postgraduate School (NPS), USA, in the late 1980s under the guidance of Prof J Val Healy. The works of NPS, during this time, were purely experimental and mainly related to qualitative analysis of helodeck flow using flow visualisation techniques such as smoke, helium bubble, tufts, oil streaks etc. The effect of cross flow components on the Wind over deck (WOD) angles other than 0 degrees, which occur quite frequently on helodeck at sea have been studied by Johns (1988), Daley (1988) and Rhoades (1990). Johns (1988) has undertaken flow visualisation studies on a DD 963 "Spruance" class destroyer with helium bubbles and smoke and concluded that results obtained give a good insight of the flow. He has shown that at moderate WOD angles, large coherent structures are shed from the side edge of the hangar at regular intervals.

Anderson (1989), as part of continuation of the research at NPS, undertook quantitative measurements using hot wire and hot film anemometry at single points in the flow field over the glide paths of 30 degrees port and starboard and stern approach. He analysed various statistical quantities such as mean, standard deviation, autocorrelation etc and derived velocity components, turbulence intensities and energies present in the turbulence which could aid in mathematically modelling of the flow at a later stage. In order to accurately map the flow field, the work involved modelling of atmospheric boundary layer in the low speed wind tunnel. It was ascertained during the course of the literature survey that these statistical estimates for turbulence, form the basis of present day practice of fixing criteria for design of marine environment for helo landing, as observed in Offshore Industry. These aspects have been discussed in the following sections.

Though the NPS literature provides several possible solutions for conducting meaningful flow visualisation in wind tunnel and plausible indication towards the quantities which may matter most for evaluating the pilot workload, the results contained are very limited owing probably to the confidential nature of the work and may not be very relevant to the modern ship forms. However, while connecting up these literature survey findings with the future work, especially with Offshore Industry design standards in vogue, it emerges that the path adopted by NPS for research forms a very good base for work on ship helo interface for non aviation ships and is worthy to emulate in certain parts for the present day research.

Most of the researchers, in the recent times, have conducted both experimental and numerical work on the ship-helo interface. Accordingly, the publications of the researchers cover both these aspects in tandem. Considerable amount of work has been undertaken in the field of shipborne helicopter operations in the United Kingdom and especially at University of Liverpool in the past two decades. Kaaria et al (2013) have undertaken experimental investigations using Airdyn on a model scale helicopter mounted on a six axis force balance to measure the unsteady forces and moments on the rotor due to the airwake of ship with an aim to modify the ship airwake on the helodeck using flow modification devices. Investigations have been undertaken on a baseline model and modified ship geometries. They have also reviewed the previous work undertaken in this field by others. Forrest et al (2016) have examined the effectiveness of five hangar edge modifications using CFD and flight simulation modelling and also piloted flight trials in a motion based simulator. Results are presented, in terms of unsteady helicopter loads and pilot workload ratings, for modifications to the windward vertical rear edge of the hangar with an oblique wind. Of the five flow modification devices, chamfer and flap were observed to reduce turbulence over the flight deck while tabs, saw tooth and cylinder on the vertical edge were observed to increase turbulence.

A comprehensive review of the problem of recovery of large helicopters on small naval ships has been undertaken by Lumsden et al (1998). It also reviews the role of CFD and piloted flight simulations towards safer methods of assessment of ship helo operating limits. Newman (2004) has reviewed the changes in the characteristics of forces and moments acting through the main rotor for helicopters while operating on ship helodeck environment. He has also brought out the procedures adopted for the shipborne helo operations.

Forrest et al (2010) have undertaken CFD simulations using DES on unstructured grids for SFS2 and a Type 23 frigate and have shown a good agreement with experimental data including full scale data of Type 23 frigate. They have further shown that inclusion of atmospheric boundary layer in the CFD simulations improves the agreement with the trials data. Kaaria et al (2012) have undertaken experiments in the water tunnel using Airdyn (specially designed airwake dynamometer) and have measured the unsteady forces and moments on a 1:54 model scale helicopter based on Merlin AW-101 while working in a ship airwake. The causes of the observed loading patterns have been discussed with the results of unsteady CFD simulations. Tai & Carico (1995) and Tai (2001) report simulating the aerodynamic flow around the US Navy destroyer DD-963 using a RANSE code to determine the flow conditions on deck for landing helicopters.

2.1 HELO OPERATIONS ON OFFSHORE PLATFORMS

The Civil Aviation Authority of UK's Safety Regulation Group has compiled a comprehensive Guidance on standards to be achieved for Offshore Helicopter Landing Areas through CAP 437 (2010). The document gives guidance for assessment of standards for offshore helo landing areas located on fixed and mobile offshore installations, and vessels supporting offshore mineral exploitation. The first edition of the document was published in 1981, where-in the size and layout of the helicopter landing areas were determined as function of the overall tip to toe length of helicopter intended for operation. Over the years, and based on various research findings through agency funded projects, the criteria for safe helo landing have been refined.

The UK CAA's guidance document mentioned above has been supported by several high value research publications over the last decade. The research paper CAA 99004 (Whitbread & Coleman, 2000) has reviewed literature available on the subject and brought out that following four principal objectives were set by the CAA in the original specification for the work:-

a) To establish the nature and extent of the environmental problems associated with operations of helicopters on helodecks on offshore platforms.
b) To review the "state of the art" in relation to the techniques and technology that could be deployed to mitigate the identified problems.
c) To plan a course of short, medium- and long-term actions to address the problems associated with the offshore helodeck environment.
d) To improve the quality and scope of the guidance material contained in CAP 437.

The principal sources of environmental hazard have been identified as vertical wind components, local ambient temperature rise and turbulence. It has been further brought out that the greatest risk to helicopter operations is judged to be the point where the helicopter arrives over the helodeck and is required to hover prior to touchdown. The report brings out that the earlier editions of CAP 437, as a guidance document, had a number of limitations and difficulties in application, the most serious limitation being the lack of any quantitative limitation on an acceptable level of turbulence, since the problems most frequently reported by the pilots are those involving handling difficulties which are almost invariably associated with turbulence. Conclusions linking high workloads due to turbulence with the increase in risk of error of judgement by pilots have been indicated.

Having appreciated the limited knowledge base, the research set out by CAA in the year 2000 for helicopter operations on offshore platforms set certain aims and targets for research which can be considered very relevant to be taken as guidance in setting up the path for researchers in the field of warship-helodeck design. These are as follows:-

Basic objective - "establishing technologies and techniques which could potentially be used to either reduce the environmental hazards, improve their control, or mitigate their effects".

Ultimate aim - "To provide support for a strategy for improving the safety of helicopter operations by proposing short, medium- and long-term actions in which the roles and responsibilities of the platform designer, the platform operator, the helicopter operator and the regulators are clearly defined.

The approach identified four key topic areas as follows:-

a) A review of practices and procedures currently adopted for offshore helicopter operations to ensure that the experience of the operators and, more particularly the pilots, was fully taken into account.
b) The sources and nature of different types of environmental hazard to be identified.
c) An assessment of the response of helicopters to various forms of environmental disturbance.
d) Finally, the content of CAP 437 needed to be examined to determine whether there was scope for change or additions to the current environmental criteria.

Based on the research results, the latest edition of CAP 437 adopts a "Turbulence Criteria" on helodeck defined as the standard deviation of the instantaneous vertical velocity and sets an upper limit for the same to 1.75 m/s. In the earlier edition, this value was set higher at 2.4 m/s and was reduced in the sixth edition to allow for flights in reduced cueing conditions (i.e. deterioration in visual appreciation of operating environment for pilots), for the less experienced pilot, and to better align the associated measure of pilot workload with operation experience. The use of the turbulence criteria measured in terms of the standard deviation of the vertical velocity was also indicated in research at NPS, USA by Prof Val Healy earlier for the ship helo interaction problem. An important lesson that can be drawn from the above is that lower the standard deviation of vertical velocity on the planes of rotation of helicopter rotor, lower is the turbulence and hence the pilot workload.

Figure 5 depicts the methodology adopted for the research work which led to the determination of the Turbulence Criteria for CAP 437. The left side column shows the reality of flight operations on offshore helodeck. The right side columns represent the simulation and modelling efforts. This included estimation of pilot effort scales in the given ship environment through piloted flight simulations involving test pilots and desktop simulations with a FLIGHTLAB model of helicopter. As part of validation discussions, the research brings out that both the piloted flight simulation and the desktop simulation depend on the wind tunnel adequately modelling the turbulent flow around the offshore platform. They both also depend on the FLIGHTLAB simulation software being an adequate representation of the aerodynamic properties and dynamic response of the helicopter.

With regards to correctness of the turbulence measurements in the wind tunnel, the document brings out the following:- "So far as is known there have been no direct field measurements of turbulence in the wake of offshore platforms that have been compared with equivalent wind tunnel measurements of turbulence to provide a direct validation of the turbulence measured in the wind tunnel model. It would be quite difficult and expensive to perform such a validation. The key potential scale effect that could cause the model to differ from reality is that due to viscosity, and represented by Reynolds Number. The Reynolds Number is much lower in the wind tunnel than on the full-scale platform. However, classical fluid mechanics tells us that the flow around bluff sharp-edged bodies is not much influenced by Reynolds number, and all the circumstantial evidence (e.g. the independence of drag force on Reynolds number for such shapes) indicates that, provided the natural wind is well represented in the wind tunnel, we can expect the wake flows around the platform to be well represented also." This conclusion has a direct bearing on wind tunnel experiments being conducted on warship-helodeck configurations and indicates that such an exercise is worthwhile in representing the real separated flow behind the hangar on the helodeck.

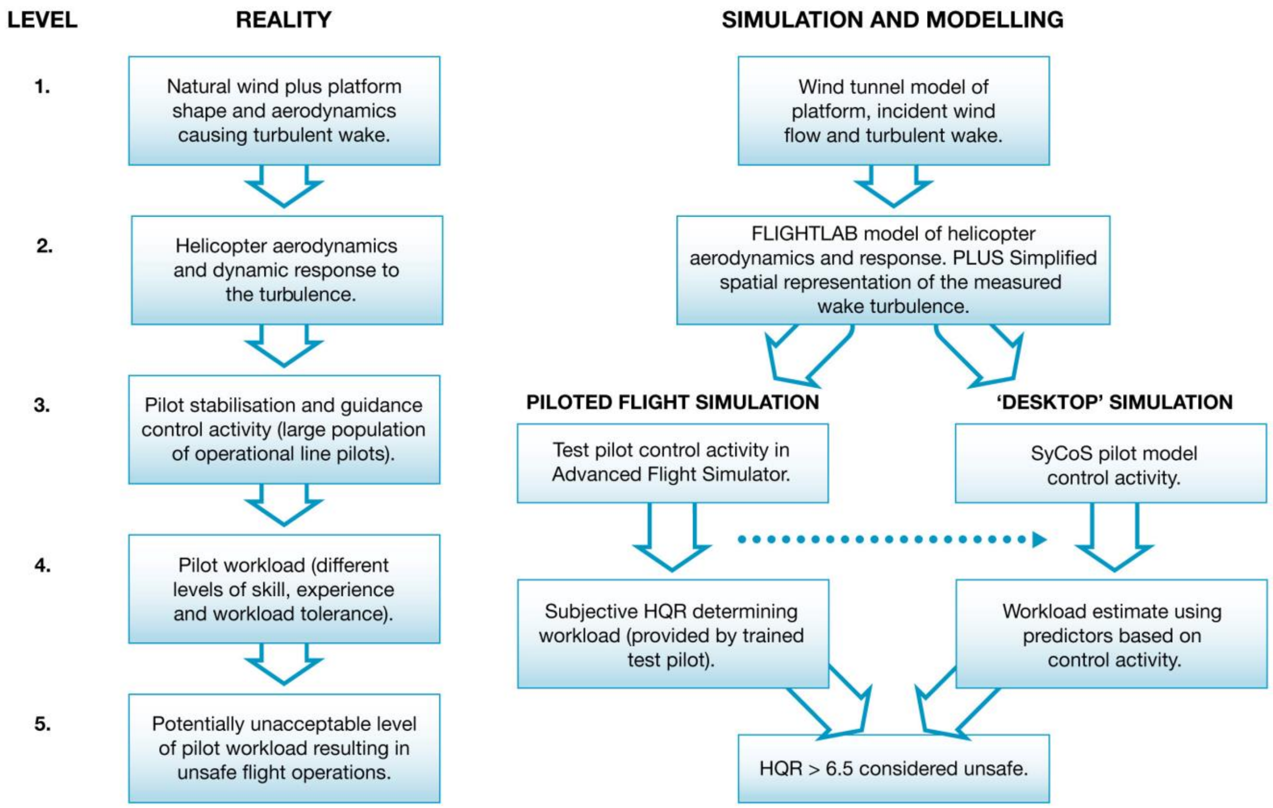

Figure 5. Modelling and Simulation work linking turbulence with pilot workload and flight safety (Courtesy- CAA 2004/03 (CAA, 2004))

As indicated in Figure 5, the simulation model utilises the wind tunnel measurements of turbulence as input to the FLIGHTLAB model in terms of the three axis components of wind speed and gradients of speed experienced at the rotor hub. In this regard, the document states the following:- "This is clearly a simplification of a complicated flow field that will, in reality, vary across the whole rotor disk, but again a degree of qualitative validation was obtained from the test pilots, who stated that the effect of the turbulence on the helicopter felt realistic." An important take-away from this validation exercise indicates that the airwake obtained on the helodeck on the rotor planes in wind tunnel or in CFD can be represented/replaced with single statistical quantities assumed to be acting on the rotor hub. Such quantities can be used in quantitative comparison of competing geometries studied through a parametric investigation spread over a large range of parameters using single representative values for complicated spatial variables such as turbulence.

Holdo (Holdo, 1997) reports modelling helicopter landing conditions onboard offshore structures. The paper presents the CFD modelling of wind interaction with offshore platform and its relevance to the location of the helicopter deck, the CFD modelling of gas turbine exhaust jets for a typical offshore production platform and some comparisons between CFD studies and wind tunnel model tests.

2.2 TURBULENCE INTENSITY AND FLUCTUATING VERTICAL VELOCITY

Silva et al (2010), in their investigation of helodeck of an FPSO, have mentioned the relationship between Turbulence Intensity as obtained in isotropic RANS model and the standard deviation of fluctuating vertical velocity. The CAP 437 guidelines for helodeck design recommends a maximum turbulence level based on the standard deviation of the vertical velocity (CAP 437, 2010). The numerical simulation software generally calculates the turbulence kinetic energy (k) or the turbulence intensity (I). The turbulence kinetic energy is defined by following equation:-

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \qquad (1)$$

Recalling that the turbulence is assumed as fully developed and isotropic in the RANS models, the velocity fluctuations can be assumed to be equal (Silva, et al, 2010). For the steady state regime, the term $\overline{w'w'}$ may be interpreted as the variance of the vertical velocity w. Using these assumptions in Equation 1, the standard deviation of the vertical velocity S_w may be expressed in terms of the turbulence kinetic energy as follows:-

$$S_w = \sqrt{\overline{w'^2}} = \sqrt{\frac{2}{3}k} \qquad (2)$$

The turbulence intensity (I) is expressed in terms of turbulent kinetic energy (k) as follows:-

$$I = \frac{\sqrt{\frac{2}{3}k}}{U_{ref}} \qquad (3)$$

In view of the above, while analysing results of numerical modelling using RANS, the turbulence intensity (I) or the turbulent kinetic energy (k), hence, can be related to the Turbulence Criteria recommended in CAP 437 for offshore helodecks which places a limit on the standard deviation of the vertical velocity S_w.

2.3 HELODECK ENVIRONMENT FOR HELICOPTER PERFORMANCE

Extensive research undertaken by the British CAA for operation of helicopters on offshore platforms bring out some important understanding of the dynamics involved related to the operations aspect. This is an important feature for research in this field since it closes the loop by linking the behaviour of the helicopter, as experienced by the pilot, with the nature of the environmental disturbance, the origins of which can readily be traced back to the basic design of the ship superstructure.

Also, in order to have a better understanding of the helicopter handling qualities on Naval ships, the Research and Technology Organisation (RTO) of the North Atlantic Treaty Organisation (NATO) has published the AGARDograph 300 (2003) which documents the helicopter/ship qualification test procedures including the preparation, execution and data analysis of helicopter/ship flight testing that should be employed, combined with best safety practices to obtain maximum operational capability. Towards this pursuit, the document brings out the following:- "Basic helicopter flight limitations are usually determined in a land-based environment by the aircraft manufacturer and/or by the procuring agency. The land-based limitations are not valid in the shipboard environment due to the individual factors including ship air wake/turbulence, ship motion, confined landing areas and visual cue limitations and the combined effects of these factors. Future NATO operators and force commanders may require the maximum helicopter/ship operational capability that can be accomplished in any environmental condition."

Figure 6 shows the set-up of helicopter/ ship qualification programme as followed by Netherlands' National Aerospace Laboratory (NLR) at Amsterdam. Prior to embarking on Dynamic Interface Testing (SHOL trials), a candidate helicopter flight envelope is developed based on results of land-based hover trials of the particular helicopter and the ship airwake environment defined through wind tunnel tests. In many developing nations, SHOL trials are undertaken directly, without taking help of modern experimental and numerical tools.

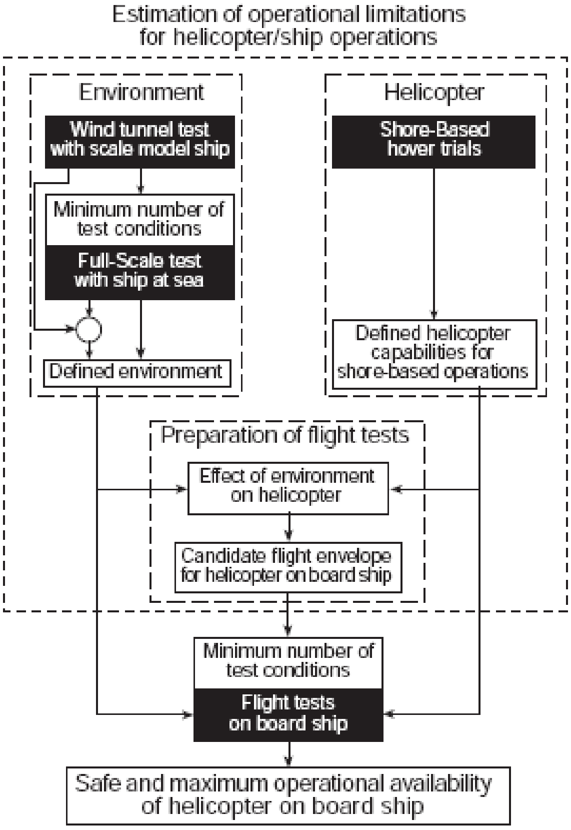

Figure 6. Set-up of helicopter/ ship qualification procedure at NLR, Netherlands (Courtesy- NATO RTO AGARDograph (2003))

Deliberating on use of wind tunnel for defining the helodeck environment, AGARDograph (RTO, 2003) articulates the following:- "Wind tunnel test results of ship models can be used in a similar way to air pattern results. Flow visualisation across the flight deck can show areas of turbulence and down-drafting air, which may create problems for an aircraft. Such results are useful but are treated with caution, as evidence to show a correlation with the real ship is not usually available. Consequently any areas or conditions of likely turbulence would not be excluded from testing but these test points would be approached in an extremely cautious and progressive way. The tunnel test results may also explain unusual results obtained with the aircraft during trials at sea."

The document (RTO, 2003) relies heavily on qualitative analysis of helo handling capabilities in making of the helicopter flight envelope. This is evident from the following:- "Since the ship's environment is much more complex than the environment ashore, it should be determined in what way the take-off and landing envelope as provided in the flight manual for land-based operations is affected. Knowing the ship environment and the relevant performance of the helicopter, the effects on helicopter operations can be estimated, if not quantitatively, then at least qualitatively." The effect of individual environmental factors on the handling capabilities of helo by pilots, as touched upon in the following sections, have been dealt with in detail in these publications. These will lead to important conclusions in respect of defining flow parameters and analysing the results as favourable / unfavourable towards pilot workload.

2.3 (a) *Effect of Headwind Component*

CAA publication 99004 (Whitbread & Coleman, 2000) describes that a good headwind component gives additional forward airspeed to provide a margin for recovery in the event of an engine failure. Wind speeds above 30-35 knots provide a good performance margin, but signal the onset of "free air" turbulence. The document recommends that throughout approach and descent manoeuvres, the pilot must always aim to keep his power demand below the aircraft single engine power requirement. Should an engine failure occur prior to the Committal Point for landing, the combination of sufficient airspeed and single engine power are the basic requirements for a pilot to recover.

Out of wind components (wind directions other than head wind condition) also have to be taken into account to accommodate variable wind angles across a helodeck. Acceptable out of wind components for a given Maximum All Up Weight are determined for specific helicopter types in the Flight Manual. However, out of wind components are not generally preferred for use by helicopter pilots.

As compared to Offshore installations, a naval pilot landing on a ship helodeck faces the superstructure while approaching and hovering. CAA paper 99004 (Whitbread & Coleman, 2000) brings out that such adverse conditions require a much steeper approach to the helodeck to ensure that a landing can be made should a single engine failure occur after the Committal Point. If a single engine failure occurs prior to the Committal Point, adequate obstruction clearance height is required to safely fly away and achieve a recovery.

The paper describes that a takeoff behind an obstruction (note that superstructure is omnipresent in case of a ship helo operation) poses greater problems because it requires a significant power demand to climb almost vertically above the helodeck out of ground effect (normally up to 25ft and dependent on the aircraft type). The climb in hover will usually take the aircraft through turbulence created by the structure, to a point where the helicopter is clear of both turbulence and the superstructure and the pilot can make the transition to forward flight.

Figure 7 presents typical results of land-based hover tests for a helicopter. RTO, AGARDograph of NATO (RTO, 2003), in its analysis of high wind speed from ahead bring out the following:- "In this case, the turbulence caused by the ship superstructure affects the helicopter such that the pilot cannot maintain sufficient control for safe take-off or landing. Relative wind conditions where very high turbulence exists, in combination with spray nuisance and large ship amplitudes, especially in pitch, have to be avoided. In such cases the control inputs required to counteract the helicopter response to turbulence in combination with manoeuvring, necessary to avoid collision with parts of the oscillating ship may be too large (over-torqueing, maximum control margin), and create a hazardous condition."

Imposing a limitation on the low wind speed, it brings out that "high engine power is needed at low relative wind speed and at high helicopter mass (Area A in Figure 7). The power and yaw control margins in that condition might be too small to counteract adequately a certain amount of ship's motions. Therefore helicopter mass and density altitude should be watched very carefully during helicopter ship operations. Furthermore, at low relative wind speed the downwash of the rotor generates spray, which is most bothersome when the helicopter hovers alongside the flight deck."

2.3 (b) *Effect of Yaw Control*

AGARDograph (RTO, 2003) brings out clearly the need for good handling qualities and yaw control to counteract turbulence and ship's motions adequately. During transitions to and from forward flight, take-off and landing, a control margin is required to maintain controllability during any unexpected situation (gusts, turbulence etc). In most cases, control margin limitations occur for pedal controls. Yaw control is an area of concern for helicopters as these employ tail rotors. Those conditions where inadequate yaw control exists (Area E in Figure 7), must be avoided. Therefore the condition of a decelerating flight moving from approach to hover, when the relative wind above the flight deck pertains to the shaded area under Area E (Figure 7), must be avoided as the relative wind condition of the Area E will be traversed. Such an approach to an obstructed flight deck with inadequate yaw control is hazardous. Wind conditions close to those areas where inadequate yaw control exists must be approached very carefully because of yaw control variations needed to counteract turbulence and ship motions adequately.

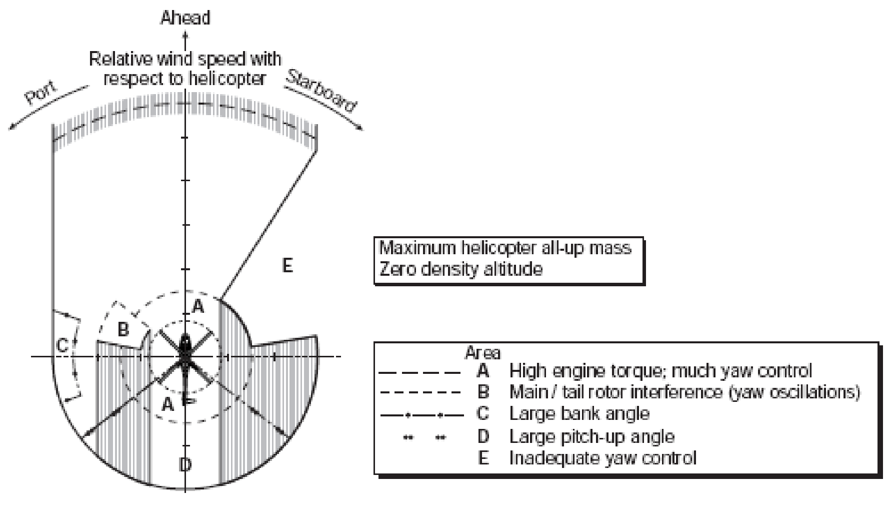

Figure 7. Detailed results from land based hover tests (Courtesy- RTO, AGARDograph, NATO (2003))

2.3 (c) *Effect of Strong Tail Wind*

Winds from tail are not desirable for aircraft operation. AGARDograph (RTO, 2003) brings out the following in this respect:- "Taking into consideration the presence of obstacles near the flight deck, strong tail-wind conditions (Area D in Figure 7) can create a hazardous situation. Moreover, such wind conditions result in large helicopter pitch-up angles reducing pilots view over the flight deck. Since the freedom of naval ships to manoeuvre is normally often limited by operational constraints, helicopter may be forced to take off or land in non-ideal conditions with respect to relative wind conditions. For these reasons strong tail-winds (above 10kts) should be tested with extreme caution."

2.3 (d) *Effect of Horizontal Gust*

Effect of Horizontal Gusts on rolling moment on rotor have also been discussed in (Whitbread & Coleman, 2000). It is documented that a medium sized rotor helicopter would be expected to be rolled over about 20^o in 3 seconds in response to a 5 m/s side gust. In the vicinity of a helodeck, the potential for large and abrupt changes in horizontal velocity depends on the design of the super structures. Shear layers springing from sharp vertical edges of bluff structures can present an effective horizontal gust to a transitioning helicopter. Turbulent air motions containing gusts with horizontal components having a high value are possible with mean winds of 10m/s and higher. A pilot flying a helicopter into a region with horizontal disturbances can therefore expect the aircraft to experience the largest perturbations in the angular motions, particularly for roll motions.

2.3 (e) *Effect of Vertical Gust*

Effect of vertical gusts have, for long, been a limiting criteria for helodeck design for offshore structures. Till recently, CAP 437 imposed a limitation of vertical mean wind speed (downdraught) of ±0.9 m/s for a wind speeds of upto 25m/s for airwake on the helodeck of offshore structures (This equates to a wind vector slope of 2 degrees). It is brought out in CAA 99004 (Whitbread & Coleman, 2000) that "Irrespective of the velocity gradients, if a helicopter does not have the available thrust margin to hover in, say, 4 m/s downdraught then the pilot will not be able to avoid being pushed onto the deck. But it has also been shown that, regardless of the thrust margin, with such a strong gust, the pilot needs to take counter action fairly quickly to avoid a dangerous situation". In another conclusion of the analysis, the document brings out the following:- "It has been shown that aircraft with hover thrust margins about 3% can withstand effects of the 0.9m/s vertical gust. Linear analysis predicts the requirement for a 14% thrust margin to withstand the effects of a 4m/s vertical downdraught. Alternatively, irrespective of the thrust margin, an aircraft would hit the deck with a velocity of 2m/s from a hover height of 2m in just 2 seconds without pilot intervention, after flying into such a gust".

As an illustration of the powerful nature of airwake effects, the CAA paper (Whitbread & Coleman, 2000) shows the results of air wake plots of downdraughts on a Type 23 Frigate (Figure 8), where the wind over deck is 30knots from 30^o starboard.

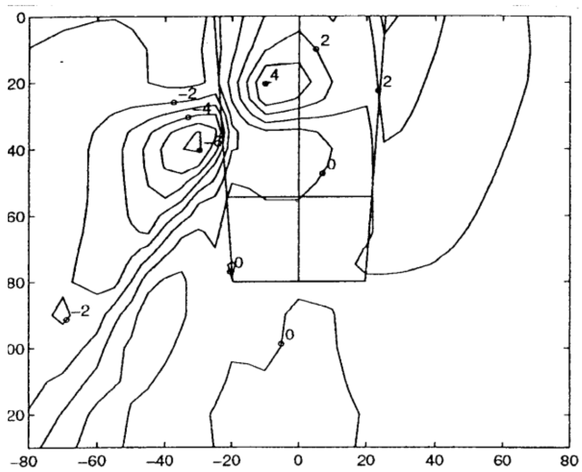

Figure 8. Contour plots of vertical wind component on Type 23 Frigate for 30knots WOD from 30^o starboard (Whitbread & Coleman, 2000)

In one standard approach path (e.g for a seaking helo), the helicopter approaches from the port side, side steps over the deck through the area of strong downdraught and station keeps over the landing spot until a suitable quiescent period when it is safe to touch down and engage the deck lock. The region of strong vertical flow gradient on the port edge of the deck represents the greatest hazard to safe helicopter operations in this case. As helo traverses through this region, the rotor will initially experience a downdraught peaking at 6m/s, followed by an upwash peaking at 4m/s.

With regards to differentiating downdraught (mean of vertical velocity component) from time-varying turbulence (measured as the standard deviation of the vertical velocity component), CAA 2004/03 (CAA, 2004) brings out the following:- "The simulator trials are focussed on assessing the workload resulting from time-varying turbulence as opposed to potential operating limits imposed by lack of power or torque margin. Such limits are typically caused by an aircraft with low torque/ power margins or for significant downdraft in the vicinity of the helodeck. Downdraft here is considered to be distinct from time-varying turbulence, although typically increased turbulence would accompany a large downdraft. Limitations on downdraft are currently expressed in CAP 437 by way of the downdraft criterion. This criterion needs to be reviewed in the light of the new criterion for turbulence." Further, it has been brought out that the term downdraught in CAP 437 actually refers to a limiting vertical component of velocity rather than downdraught. However, between the downward component (downdraught) and the upward component (upwash), the former represents a more severe risk to the helicopter than the later. This owes to the fact that a downward component will reduce the angle of attack on the rotor blades thereby reducing lift generation whereas an upwash will tend to increase the lift (also undesirable since the same is an uncontrolled imposed environment) and may hasten stall.

Accordingly, in the latest publication of CAP 437 (CAP 437, 2010), the vertical gust limiting criteria has been replaced with a turbulence criteria (standard deviation of fluctuating vertical velocity component not to exceed 1.75m/s). The reasons for this review are brought out as follows:- "CAP 437 proposes a maximum vertical component over helodeck of 0.9m/s. Simple theory suggests that, in the absence of ground effect, a thrust margin of at least 3% would be required to overcome the effects of this magnitude of gust and maintain a hover over the deck in zero wind. However, it should be noted that it is unlikely that with current helodeck designs of offshore structures, a helicopter could ever experience a 0.9m/s downdraught in the absence of the beneficial effect on thrust margin of a significant horizontal wind component".

The above assumption will, however, not hold good for a naval helo operation where the helodeck has a hangar in front, which leads to a drastic reduction in the headwind speed and an increase in the downdraught. Towards this, CAA paper 2004/03 (CAA, 2004) brings out the following:- "As turbulence is primarily a problem in high winds when the available lift and power margin is increased, it is considered that torque and power limits are unlikely to influence workload due to turbulence. This assumption may not be valid in cases where there is either a large downdraft, or the rotor is shielded from the free stream flow by superstructure and thus operating in low air speed regime. In either scenario, the amount of power in hand will be reduced and may become an issue depending on the power margins of the helicopter being considered. In terms of applying appropriate criteria to measurements of the expected airwake, the combination of the existing downdraft criterion and the proposed new turbulence criterion, may suffice for those cases involving downdraft. Further, if it were intended to consider the relaxation of the 0.9m/s downdraft criterion following the establishment of a validated turbulence criterion, then it would be particularly important to ensure that the role of torque and power limits in combined downdraft and turbulence condition is fully understood for helicopter response."

2.3 (f) *Effect of Moving Helodeck*

AGARDograph (RTO, 2003) speaks about the limitations of the helo operations on a moving deck. It brings out that most helicopter manufacturers provide sloped landing limitations for take-off and landing operations outside unprepared helicopter landing sites. In most land-based operations, pilots can adjust the helicopter heading to land either up-slope, down-slope, or cross-slope depending on the safest option. Similarly, limitations may restrict helicopter ship-borne operations due to the relative geometric attitude of the helicopter to the ship. In the Netherlands, the Flight Deck Officer will launch & recover the helicopter during a quiescent motion period of the ship, with the deck in an almost horizontal position. It must be noted that before take-off and directly after the land-on, the helicopter is secured to the flight deck by means of a harpoon grid system (in some navies known as "Talon"-system). The system greatly increases the allowable ship motions. For those operators where the helicopter crew lacks the assistance of a Flight Deck Officer to launch and land the helicopter, the deck slope aspect is of great importance in order to avoid dynamic roll over.

2.3 (g) *Effect of Size of Helo on Response to Turbulence*

Venturing into the effect of type of aircraft on the handling qualities, CAA research paper 2004/03 (CAA, 2004) brings out the following:- "The general consensus was that there isn't a single helicopter type, currently used in European offshore operations, that stands out as being particularly poor for handling turbulence. However, the feel of various types is almost certainly different. For instance, a relatively large helicopter with a sluggish response will tend to smooth out many of the gust disturbances such that the pilot is less aware of the turbulence, and may tend to drift further from his intended flight path before it becomes apparent that compensatory inputs are required. The longer a disturbance is left unchecked then the larger is the input required to correct the drift and harder is the task is to re-establish the desired flight path. Conversely, for a relatively light and lively aircraft the majority of disturbances are felt immediately as sharp-edged gusts, and the pilot will make a large number of smaller inputs to compensate. Most disturbances are compensated for before any significant drift is allowed to build, however the overall impression is of a less comfortable ride." The study was inconclusive in deterministically pointing out the effect of aircraft type since the power and torque limits were not included in the model, which often plays an important role in deciding which aircraft types can and cannot operate in adverse environmental conditions. To this end, literature brings out the following (CAA, 2004):- "It will often be the case that shear and downdraught are experienced simultaneously with turbulence, and it is the presence of downdraught, and the availability of sufficient power and torque margins to overcome it, that may often be the determining factor in limiting operations, or in requiring payload to be reduced in order to increase the margins." Various Navies, classification societies and helicopter manufacturers have brought out guidelines for sizing of the helodeck and the related requirements for given helicopters in the form of manuals and standards (Ship Interface, 2001, NORSOK, 2004 and DNV, 2001). Makkar et al (2016), as part of ongoing efforts at IIT Delhi, have experimentally studied the effect of varying downwash velocities of the helo with respect to the ship speed and have recorded changes in the air flow structure on the helodeck.

2.3 (h) Effect of Ship's Exhaust

Kulkarni et al (2005a) have undertaken a detailed review of the smoke nuisance problem on ships. The authors have brought out that the performance of gas turbines of fixed and rotary aircrafts are very sensitive to ambient conditions. The risk of compressor stalling increases significantly with a momentary temperature rise of 3^0 C or more. The 3^0C isotherm should therefore be at least 15m higher than the helodeck. For ships where the exhaust is directed in such a way as to impinge on the landing/ take-off path of the helicopter, the effects of ship's exhaust gases need to be considered on Pilot Workload. The data from wind tunnel studies undertaken by Kulkarni et al. (2005b) provided the physical quantities that could directly be correlated to the results of the numerical simulations. The authors have also presented the results of a detailed parametric investigation using CFD for a total of 112 different cases for exhaust smoke interaction with the superstructure by studying four velocity ratios (K=1, 2, 3 and 4) (the ratio of exhaust velocity to the ambient wind over deck relative velocity), seven yaw angles (ψ) (0^0 to 30^0 in steps of 5^0) and four superstructure configurations (Kulkarni, 2007).

Vijayakumar et al (2008) have undertaken extensive studies on superstructure configuration of Naval ships towards optimising the funnel heights in order to avoid smoke nuisance on the ship superstructure. The authors have carried out CFD simulations for different funnel heights to mast height ratio ranging from 0.35 to 1 along with Gas Turbine intakes for wind directions (yaw angles) between -30^0 to 30^0 at interval of 5^0 and for three velocity ratios (K=0.5,1 and 1.5). The emphasis of the study was to provide guiding polar plots for the designer to choose the appropriate funnel height for the naval ships during the earliest stages of design. Vijayakumar et al (2014) have presented the comparison of CFD simulations with the published results for two cases, namely hot jet in a cross flow and hot exhaust with a cross flow on a generic frigate. Vijayakumar et al (2012) have presented the results of flow visualization studies undertaken in a wind tunnel over a simplified superstructure of a generic naval ship in order to understand the effect of various parameters like mast size and location, gas turbine intakes, and funnel-to-mast height ratios on the exhaust plume path. These investigations have been carried out at four velocity ratios for three configurations of simplified superstructure. The result of these flow visualization studies provides insight into the process of plume dispersion in the vicinity of the funnel and other structures on the topside of naval ships. Landsberg et.al (1996 & 1995) report carrying out 3-D unsteady smoke and temperature time history computations in the helicopter landing zone and the ingestion of smoke into the helicopter hangars. Landsberg and Sandberg (Camelli, et al, 2004, Landsberg, et al, 1996 and Landsberg, et al, 1993) report the use of the CFD code FAST3D to compute the unsteady air wake about the LHD aircraft carrier and compute the temperature profile of the hot exhaust plume from the DDG–51 destroyer for the US Navy.

2.4 INTEGRATION OF SIMULATION RESULTS WITH PILOTED FLIGHT SIMULATIONS TO QUANTIFY SHOL

On the lines similar to Offshore Industry, in recent times, few countries have channelled their efforts towards modelling and simulation of the ship–helicopter dynamic interface to augment the SHOL definition process (Forrest et al, 2012). A great deal of this effort has focused on improving the fidelity of piloted flight simulators such that the results from simulated SHOL trials are comparable to those from at-sea flight trials. Forrest et al (2012) bring out the potential benefits offered by the dynamic interface simulation, including the following:-

(a) Identification of Wind over Deck (WOD) “hot spots” before at-sea testing which can be used to inform the flight-test program.
(b) The ability to assess particular WOD conditions which may have been missed during at-sea testing in order to maximize the operational envelope.
(c) Investigation of flight deck aerodynamics while new ships are still at the design stage to identify potential improvements to superstructure design, landing spot locations and placement of equipment.
(d) A greater understanding of ship air-wake turbulence and the mechanisms which cause it.
(e) A realistic simulation environment in which to conduct pilot training exercises.

As part of a review of collaborative Dynamic Interface (DI) modelling activities under the auspices of TTCP, Wilkinson et al. (1999) has described the development of a ship–helicopter simulation facility based at the United Kingdom’s Defence Evaluation and Research Agency. The simulated air-wake module is based on the superposition of basic flow patterns, with turbulent fluctuations provided by scaled random velocity time histories. Because of the empirical nature of this air-wake database, the three-dimensional components of turbulence are not correlated.

In a study conducted by Lee et al. (2003), a dynamic interface simulation of the UH-60A helicopter operating off an LHA ship was developed with an objective of understanding the impact of a time-varying ship air-wake on the pilot control activity for an approach operation, and to develop a human pilot model for analyzing the pilot workload.

Forrest et al (2012) have presented the results for a series of piloted flight simulation trials in which an SH-60B Sea

Hawk helicopter has been flown to the deck of several different ships, under the influence of unsteady CFD-based ship air-wakes. The authors have indicated achieving the first fully simulated SHOL diagrams published in the literature by deriving pilot workload ratings. Given the complexity involved in quantifying the qualitative assessment of test pilots during the Dynamic Interface Testing, this route merits attention wherein the environment may be mathematically modelled and the qualitative assessment of the Test Pilots in making of SHOL through Dynamic Interface Testing is retained. In such a case also, all the problems presently associated with the process of Dynamic Interface can be alleviated.

3. FINDINGS

The various factors affecting Shipboard helicopter operations can be classified into the following categories:- The helicopter, the class of ship, the operational environment, crew and operator. Towards investigation of the problem in its entirety, the literature survey has made an attempt to understand each of the above aspects and their interplay. Based on the effect of various components of airwake on helo handling capability and pilot workload, flow parameters defining the helodeck environment, have been identified. The limited knowledge availability about application of criteria for marine helo operations have been understood. It is understood that, as on date, no attempt seems to have been made to evaluate a ship design against a set of criteria for ensuring efficient helo operations. In general the survey of literature leads to the following conclusions:-

a) High workloads due to turbulence increase the risk of a pilot making an error of judgement despite the high level of skill normally associated with helicopter flying.
b) The greatest risk to helicopter operations is judged to be the point where the helicopter arrives over the helodeck and is required to hover prior to touchdown.
c) Lower the standard deviation of vertical velocity on the planes of rotation of helicopter rotor, lower is the turbulence and hence the pilot workload. Since the length scales of turbulence behind a ship superstructure are of the order of rotor diameter, increased turbulence will contribute to increased pilot workload. Thus, any reduction in the turbulence intensities on the rotor planes must necessarily translate into reduction in the pilot workload.
d) As turbulence is primarily a problem in high winds when the available lift and power margin is increased, it is considered that torque and power limits are unlikely to influence workload due to turbulence for helo operations on offshore structures which generally have very less obstructions. This assumption is not valid in case of ship helodeck, where there is either a large downdraft, or the rotor is shielded from the free stream flow by superstructure and thus operating in low air speed regime. In either scenario, the amount of power in hand will be reduced and may become an issue depending on the power margins of the helicopter being considered. In terms of applying appropriate criteria to measurements of the expected airwake, the combination of a downdraft criterion and a turbulence criterion, may be examined.
e) Levels of turbulence encountered in offshore installations are likely to be less than those associated with naval operations due, both to the better exposure of offshore helodecks, and the fact that wind speeds over naval helodecks are generally increased by the forward speed of the ship.
f) A good headwind component gives additional forward airspeed to provide a margin for recovery in the event of an engine failure. Relative wind conditions where very heavy turbulence exists (high wind speeds from ahead), in combination with spray nuisance and rather large ship amplitudes, especially in pitch, have to be avoided.
g) High engine power is needed at low relative wind speed and at high helicopter mass. Furthermore, at low relative wind speed the down-wash of the rotor generates spray, which is most bothersome when the helicopter hovers alongside the flight deck.
h) Winds from tail are not desirable for aircraft operation and are generally avoided during ship borne operations. Similarly, out of wind components are not generally preferred for use by helicopter pilots.
i) If a helicopter does not have the available thrust margin to hover in downdraught, then the pilot will not be able to avoid being pushed onto the deck. Downdraft here is considered to be distinct from time-varying turbulence, although typically increased turbulence would accompany a large downdraft. Downdraught is generally considered a function of helodeck aerodynamics.
j) Between the downward component (downdraught) and the upward component (upwash), the former represents a more severe risk to the helicopter than the later. This owes to the fact that a downward component will reduce the angle of attack on the rotor blades thereby reducing lift generation whereas an upwash will tend to increase the lift (also undesirable since the same is an uncontrolled imposed environment) and may hasten stall.
k) The airwake obtained on the helodeck on the rotor planes in wind tunnel or in CFD can be represented/replaced with single statistical quantities assumed to be acting on the rotor hub. Statistical estimates for turbulence on helodeck, form the basis of present day practice of fixing criteria for design of marine environment for helo landing.
l) Although the real area of interest for helo operations on warships lie immediately downstream of the recirculation zone, any reduction in the extent of the recirculation zone is surely expected to lead to a greater envelope for safe helo operations on the deck.
m) Above a particular critical value of Reynolds number, the flow characteristics of the ship air-wake are independent of Reynolds number changes within the

range of wind speeds on full scale ships and the reattachment zones for 15 knots and 30 knots of wind speed will occur essentially at the same position.

n) To accurately resolve all the flow features: turbulence, boundary layer, flow separation and interaction of helicopter flow-field with the ship airwake, in a time accurate simulation is a big challenge. The magnitude of the unsteadiness demands long time records which, coupled with large grids associated with such geometries, require enormous computational power. Full-scale or wind tunnel experiments, on the other hand, can easily generate long time records of data, but the associated initial setup cost and time can be substantial. Taking into cognisance the need to provide quick solutions for an improved environment over helodeck for helo operations, and not so much towards capturing the intricate flow details, steady state CFD calculations can be used, with an understanding that the results of the flow improvement techniques with the steady state analysis will not change drastically even when used with unsteady analysis, as far as the steady state CFD model is validated against experimental results.

4. A ROADMAP FOR FUTURE INVESTIGATION OF SHIP-HELO INTERFACE

The phrase 'Pilot Workload' or 'Pilot Effort Scale' used for grading of the helodeck environment, is a qualitative assessment of a test pilot which involves several environmental factors interacting in a seemingly random manner. These factors acting together, put up a formidable challenge to the helo pilot for ensuring safe operations. As a first step, a graded approach is required to breakdown the complex problem into smaller parts and understand the effect of these components on the pilot workload in isolation. If, during the course of the research, the contribution of various components to the qualitative Pilot workload can be quantified in some manner, a range of problems faced presently with respect to on-site qualification processes adopted for ship-helo interaction, can be solved through experimental and numerical methods. While such a knowledge will help reduce the on-site evaluation efforts being employed presently through SHOL trials, it can also be employed for improving the helodeck environment for safer helo operations. Once a method for quantification is established for the various components, "benchmark minimum acceptable numeric values" can be established based on experimental/ numerical evaluation of a ship helo combination for which SHOL trial results have been established as acceptable. The efficacy of other geometries, with respect to the different components adding up to the Pilot workload, can then be assessed against these benchmarked values for acceptance.

Considering the airwake component, which has been taken up for the present analysis, it is understood that one of the most important gaps, as on date, is the absence of a criteria set to grade a particular combination of ship and helicopter for ensuring minimum standards of safe operations. Such a criteria-based approach (with numerical limits on flow parameters) has been established by civil aviation authorities, through years of research, for helo operations from offshore structures. Considering that the fields of helo operation on warship and on offshore structures are dissimilar and inherit their peculiar problems from their grossly different geometries and operating environment, informed choices can be made while drawing lessons from such literature, on setting up of a criteria set for helo operations from warships. Thus, while it is understood that the numeric limits used for offshore industry will not be directly applicable for warship helo operations, limited guidelines on selection of flow parameters (to form up the criteria set) can be adopted from them since the flow parameters affecting the Pilot Workload will remain same for both the fields. Accordingly, a criteria set comprising of the following parameters, is proposed for grading a particular design against competing configurations:-

a) As part of the turbulence criteria used for offshore helodeck design, the design guidance document CAP 437 (2010) places an upper limit on the standard deviation of instantaneous vertical velocity. Accordingly, the first criteria points towards a reduced value of Standard Deviation of Instantaneous Vertical Velocity component on rotor plane for reduced Pilot Workload. While working in the numerical environment, the endeavor should be to reduce the average Turbulence Intensity values.

b) Before arriving at the criteria for turbulence, the UK Civil Aviation Authority, for a long time, had stipulated a criteria for maximum limit on the mean of the vertical component of velocity on helodeck. This was termed as the *Downdraft Criteria*. Though this criteria has been abolished for offshore structures in the wake of the new turbulence criteria, literature brings out that this flow parameter can become very important for warship helo operations. Typically downdraft reduces power and torque margins that are available to the pilot for control of helo, by forcing changes to the lift generation by rotors. For a geometry like that of offshore helodecks (which has a very open architecture), both high turbulence and high downdrafts can be associated with higher winds. High winds mean availability of increased power and torque margins in the hands of pilot which allows the pilot to handle higher degree of control even with the presence of downdraft. Hence abolishing the downdraft criteria for offshore industry, in the wake of turbulence criteria, has been resorted to. However, the downstream of warship superstructure provides an environment on helodeck with low relative wind speeds, a high turbulence and a high downdraft due to the presence of the superstructure airwake. In such a scenario, literature suggests a combination of both turbulence and downdraft to be considered for setting criteria limits. Accordingly, for reducing pilot workload, the second criteria will be the Downdraft Criteria wherein the vertical component of velocities over the rotor plane should be reduced. The word downdraft here comprises of both upward and downward vertical velocity component and both are considered undesirable.

c) One of the conclusions of the literature survey indicated that a higher relative wind velocity is a favourable condition for a helo pilot because it increases the power and torque limits that are available to him for control of helo. Accordingly, the third candidate for the criteria set should ensure that the Relative Wind Velocity in the direction of fore and aft line of helicopter (akin to head wind for helo while operating ashore) for a given hangar configuration over the rotor plane should be increased for an improved environment for helo handling.

d) The length of recirculation, as a flow parameter on helodeck, has been extensively investigated in literature. Though the design and length of contemporary helodeck may ensure that the helo operations are undertaken outside the extent of recirculation zone, it can be expected that a reduction in the extent of recirculation zone (even when located outside the actual helo operating radius) will indirectly lead to an increase in the relative velocity on rotor planes by reducing the low momentum area behind the hangar. Also, a reduction in the length of recirculation is expected to increase the distance between the shear layer and the helo landing area which in turn should lead to reduction in turbulence on the rotor planes. Accordingly, the length of the recirculation zone should be minimised for an improved ship-borne helo operation.

e) The presence of the superstructure in front of the operating helo makes the relative velocity incident on to the rotor uneven. Such an unevenness will result in a resultant moment on the helo due to the uneven lift forces created by the rotor. Accordingly, the value of standard deviation of the relative velocity on the rotor plane, which represents the non-uniformity of the relative velocity incident onto the rotor, should tend to zero for a better incident flow environment for the helo.

An analysis with the above proposed criteria set can be used to undertake a comparative analysis between competing configurations within each flow parameter. Further ahead, research needs to be undertaken to establish the inter-se importance/ weightage of these flow parameters forming up this one airwake component, with respect to their contribution to the Pilot workload. It is possible that a particular flow parameter making up the criteria set, far out-weighs the others in its effect on pilot workload and this aspect accordingly needs further investigation. This will be necessary for making an overall assessment for the airwake component based on a configuration's performance for each of the flow parameters. Also, benchmark numeric values, as discussed above, need to be established for these parameters through experimental/ numerical assessment of a ship-helo combination for which SHOL trial results have been established as acceptable. Such benchmarks can then be used for acceptance of a newly proposed geometry for the component of airwake.

The quantification process for the various components and establishing their inter-se weightage towards Pilot workload, as proposed above, can be undertaken by effectively employing piloted flight simulations in a parametric investigation with known combinations of various components simulated for a ship helo configuration. In order to remove human error in the qualitative scales, multiple pilots should be made to undertake testing for the same ship-helo configurations. The Pilot effort scales thus generated can be studied in line with the variations of the defining parameters to decide on the inter-se weightage for these parameters. This knowledge can then be translated into fixing numerical limits for the flow parameters for qualifying the ship design for efficient helo operations.

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