Defence Science Journal, Vol. 71, No. 2, March 2021, pp. 296-303, DOI : 10.14429/dsj.71.15648

Investigation of the Effect of Ski Jump on the Flow Dynamics around Generic Aircraft Carrier

Rahul Thakur* and K. Vignesh Kumar

Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi - 110 016, India
**E-mail: shirgul33@gmail.com*

ABSTRACT

The landing operation on an aircraft carrier is a complicated and risky process. Unlike land-based operations, the landing area available on carriers is in continuous motion in all the six degrees of freedom. The ski jump, flight deck, hull, and superstructure of the carrier interact with the oncoming wind's flow-field which creates a turbulent airflow behind the carrier. This 'burble effect' is very dangerous and has caused various mishaps in the past. To complement the work being undertaken at IIT Delhi to study the flow dynamics in the carrier environment, the present study investigates the effect of ski jump and superstructure on the flow around the generic aircraft carrier (GAC). Computational fluid dynamics (CFD) studies are undertaken to simulate the airwake and establish a baseline with the ski jump. Subsequently, further studies are carried out to analyse the sensitivity of the wake to changes in carrier geometry. The introduction of the ski generates a major proportion of turbulence encountered in the aft by the approaching pilot. This is reduced significantly by optimising ski jump geometry in various ways.

Keywords: Burble effect; Aircraft carrier landing; Ship air dynamics; CFD; ANSYS fluent

NOMENCLATURE

v	Fluid velocity vector
ρ	Fluid density
υ	Kinematic viscosity
μ	Dynamic viscosity
P	Fluid pressure
∇^2	Laplacian operator
TKe	Turbulent Kinetic Energy (J/kg)
TP	Transverse plane
LP	Longitudinal plane
C_p	Normalised pressure coefficient
P_i	Local pressure
P_∞	Reference atmospheric pressure
$C_{pi\,(CFD)}$	Normalised local pressure coefficient obtained by CFD
$C_{pi\,(exp)}$	Normalised local pressure coefficient obtained by experiments
N	Total no of pressure points
$\overline{u'}$	Turbulent velocity component in the x-direction
$\overline{v'}$	Turbulent velocity component in the y-direction
$\overline{w'}$	Turbulent velocity component in the z-direction
GAC	Generic Aircraft Carrier
STOVL	Short Take-Off and Vertical Landing
CATOBAR	Catapult Assisted Take-Off but Arrested Recovery
STOBAR	Short Take-Off but Arrested Recovery
LHA	Landing Helicopter Assault
LHD	Landing Helicopter Dock

Received : 03 March 2020, Revised : 20 October 2020
Accepted : 09 November 2020, Online published : 10 March 2021

1. INTRODUCTION

The aircraft carrier is one of the largest assets of any navy and is the home of naval aviation. The carrier carries high-value aircraft which operate in a highly risky environment. The aircraft on-board a carrier attempts to land on an unsteady moving airstrip of a few hundred meters in length with the carrier moving at its speed. The aircraft lands at high speeds sufficient enough to take off again (called 'bolter') in case of missing all the arresting wires[1]. Approaching at such high speed leaves the pilot with very less reaction time to correct errors[2].

Flow dynamics in this environment, also adds to the pilot workload[3]. The movement of aircraft carrier creates a wake that is highly turbulent, separated, unsteady, and contains vortices[4]. This airwake presents a major threat to the landing aircraft which has to traverse through this disturbing flow before touch down. Additionally, due to the unsteady flow, the response of the aircraft may not be as predicted, and therefore the load on the pilot increases further as brought out by Nackali[5], *et al.*

Pilots have observed a slight downward plunge in the last mile of their approach as they attempt to land on the carrier and this effect has come to be known as 'The Burble Effect'[6]. This is caused due to the formation of a velocity deficit region behind the carrier, arising from the hull, superstructure interaction with the airflow. This reduces the lift over the wings of the incoming aircraft resulting in the reported sinking effect[4]. The pilot has to therefore give additional thrust and alter controls rapidly to maintain the intended approach path, glide slope, and achieve the targeted landing spot[2]. The mis-anticipation of this sinking along with limited reaction time and pressure to execute a precise landing may often lead to mishaps which can hamper the operation capability of the carrier. Almost 78% of the aircraft landing accidents on an aircraft carrier are caused due to error by the pilot[7].

The burble effect is one of the major reasons for a large number of carrier accidents[3] which primarily arises due to airwake created by large bluff structures such as ski jump, hull, and superstructure[3]. The pilot workload can thus be reduced by optimising the geometry of the major bluff bodies[8-9] such as the ski jump and the superstructure. One such study was carried out by Ringleb[10] wherein various geometric modifications were done on the superstructure to achieve a better airwake in the flight approach zone. However, very few studies have been carried out focussed on the ski jump which is one of the major contributors to the burble in-flight approach zone.

2. MOTIVATION

A comprehensive study of the burble necessitates the development of a representative aircraft carrier model to study the effect of flow dynamics in the carrier environment[11]. The Generic Aircraft Carrier (GAC) is a simplified geometric model developed in IIT Delhi for studying flow dynamics around an aircraft carrier by Kumar[11], *et al.* The GAC is modelled as a flat top carrier with an island structure (akin to a CATOBAR configuration). There exists a need to also investigate the other carrier configurations which remain relevant in the world today, such as the latest Queen Elizabeth class carriers. STOVL (Short Take-Off and Vertical Landing) carriers like Queen Elizabeth or STOBAR (Short Take-Off and Arrested Recovery) carriers operated by other navies differ from the CATOBAR (Catapult Assisted Take-Off and Arrested Recovery) GAC in one particular aspect which is the "ski jump", a ramp attached to the bow of the carrier to aid in short take-off of fighter aircraft.

The ski jump, in simplified terms, could be modelled as a wedge-shaped bluff body at the forward-most part of the carrier and is expected to disturb the flow downstream considerably. The STOVL configuration on such carriers requires the pilots to do vertical landing at various landing spots on the carrier and hence flow disturbances by the ski jump in its downstream region may interact with the landing spots of such vertical landing helicopters or other fixed-wing aircraft.

3. LITERATURE REVIEW

3.1 Experimental Studies

The effect of airflow of the carrier onto aircraft operations has been a major topic of interest since the early 19th century. The first set of experiments to study the burble was conducted around the 1960s where multiple studies on aircraft carriers were carried out on scaled models. Olenski & Dankworth[12], Kjellman & Colt[13], Hannegan & Badger[14], Oldmixon & Lieut[15] were among the few who started working on this issue. Then, Barnett and White[16] tried to analyse the airflow over different carriers. The idea here was to understand the effect of carrier geometry onto the flow pattern and subsequently use this to address the issue. Experiments were also conducted on other ship shapes similar to carriers, for instance, a scaled model of a Landing Helicopter Dock by Rajagopalan[17], *et al.*

Recently, Cherry & Constantino[4], conducted an experimental study to model the air wake behind the carrier generated by the flight deck and the superstructure and study its effect on the landing of aircraft. They found that superstructure generates a region of low flow velocity and creates a velocity deficit behind the carrier. The study quantifies the improvements achieved in the wake by imparting changes to the superstructure.

3.2 Empirical/Mathematical Models and Numerical Simulation Studies

Also, for burble, various models have been developed like Military Specifications, MIL-F-8785-C[18] empirical model for simulation of its effects. A fuzzy logic-based aircraft landing system was then proposed by Steinberg[19] using the above burble model. Using the experience of the pilots, The Department of Defence Handbook[20], then validated the MILSPEC burble model as a relevant model and it has been used for simulation of aircraft approach in flight test simulators. Polsky and Naylor[21], modelled the burble in CFD and they found that the stern had a major impact on the airwake behind the carrier.

In addition to carrier geometry, the ski jump also plays a major role in the airflow dynamics of the carrier. Bardera[22], *et al.* studied the effect of a ski jump on the flight deck and the introduction of passive flow control devices over the ski jump. And You-shi and Xiang[23] also worked on performance increase and key problems of the ramp of the carrier. Polsky and Czerwiec[24] on the other hand studied the effect of the addition of bow flap on the air dynamics of Landing Helicopter Assault (LHA) intending to mimic the rounded edge of the bow of Landing Helicopter Dock (LHD) class of ships. In 2018, Bardera[25], et al. studied the flow field in the vicinity of a ski-jump ramp by testing a 1: 100 scaled model of an aircraft carrier in a wind tunnel.

The review of published literature on the topic brings out clearly that although multiple studies have been undertaken to analyse the burble, the effect of the ski jump and its interaction with the flow downstream and the superstructure needs attention. The present study focuses on this aspect.

4. METHODOLOGY ADOPTED

The airflow around the carrier is simulated using the Navier-Stokes equation (Eqns (1-3)) with the help of CFD.

Continuity Equation $\nabla.\vec{V} = 0$ (1)

Momentum Equations $\rho\frac{D\vec{V}}{Dt} = -\Delta P + \rho\vec{g} + \mu\nabla^2\vec{V}$ (2)

where, $\frac{D\vec{V}}{Dt} = \frac{\partial V}{\partial t} + (\vec{V}.\nabla)\vec{V}$ (3)

The methodology adopted to systematically address the problem is outlined below:

(a) Establishment of the baseline for the study using the GAC as a benchmark model.
(b) Validation of CFD numerical model used in this study by comparing it against experimental data.
(c) Inclusion of the ski jump to develop the GACSKI

configuration and analysis of its effects compared to the baseline.
(d) Imparting parametric changes to the ski jump for comparison against baseline GACSKI.
(e) Suitable configuration which provides “desirable” flow characteristics across various regions along the carrier body and in its wake is presented and the final configuration is recommended for further studies in future designs.

4.1 Establishment of Baseline – GAC

The Generic Aircraft Model (GAC) shown in Fig. 1 is used for this study[11]. This acts as the baseline for the present research. This incorporates salient features and traits from most carriers in a simplified geometry that is amenable to numerical modelling and meshing.

4.2 CFD Geometry and Mesh Generation

The 3D geometry was modelled in ANSYS Design Modeler with the dimensions as shown in Fig. 1. The boundaries of the domain are modelled as walls of the wind tunnel with dimensions as shown in Table 1.

Given that the model is asymmetric about the centreline the entire model is used for computation, unlike other ship studies that generally use half models to exploit symmetry and garner computational savings. An unstructured mesh with a growth rate of 1.1 with approximately 15,000,000 cells was generated.

To capture the complicated behaviour of the flow near the wall, the concept of y^+ has been formulated. Since, in this case, we intend to resolve the effects near the wall i.e. in the viscous sublayer then the size of the mesh and should be small and dense enough near the wall so that almost all the effects are captured. The near-wall region is thus meshed using the calculated first cell height value with gradual growth in mesh so that effects are captured and avoiding overall heavy mesh count. The details of the Y+ and boundary layers are included in Table 2.

4.3 Fluent Model

The CFD package used for this study was ANSYS FLUENT, a commercially available numerical simulations tool. The options used for the computation of the model are given in Table 2.

4.4 Variants

To study the effect of the inclusion of ski jump onto the carrier environment various variants were developed with certain modifications to ski jump. The motivation behind the genesis of each configuration is explained in detail in subsequent sections and as shown in Figs. 2 and 3.

Table 1. Dimensions of Wind Tunnel relative to the position of the model

Cross section	0.75m x 0.45m
Inlet	1.1m forward of model fore (equal to the length of the model).
Outlet	3.3m aft of model aft (thrice the length of the model)

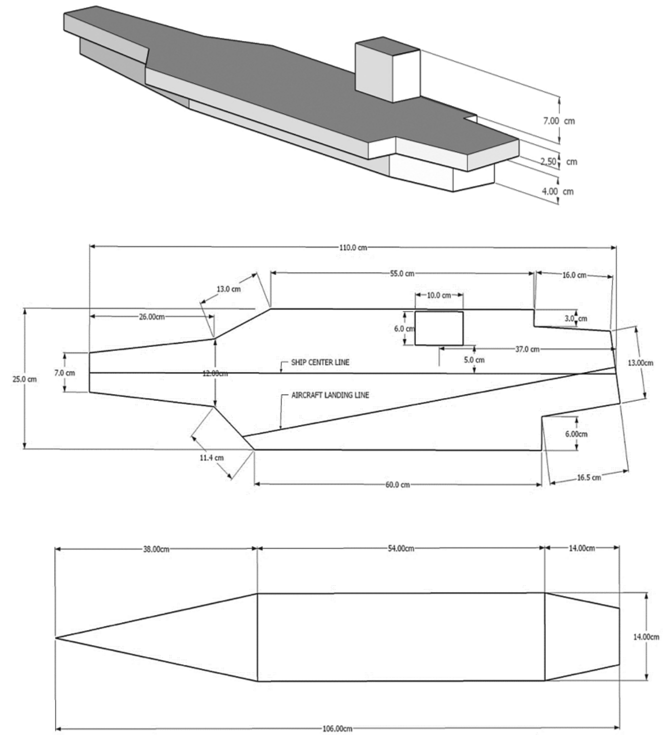

Figure 1. Details of generic aircraft carrier .

Table 2. Fluent model options

Viscous model	SST k-omega Model	Alpha*_inf = 1 Alpha_inf = 0.52 Beta*_inf = 0.09 a1 = 0.31 Beta_i (Inner) =0.075 Beta_i (Outer) =0.0828 TKe (Inner) Prandtl # = 0.075 TKe (Outer) Prandtl # = 2
Fluid	Air with density 1.225 kg/m^3 and viscosity 1.789X10^{-5} kg/ms	
Boundary conditions	Body surfaces Wind tunnel walls	No-slip condition
	WT Front	Velocity Inlet 15 m/s
	WT Aft	Pressure Outlet
Discretisation	Momentum TKE Turbulent dissipation rate	Second-order upwind
Pressure velocity coupling	Coupled	
Residuals	Continuity, u, v, w, k, omega	1X10^{-5}
y+ obtained	4	
Growth rate	1.02	
No of layers	18	

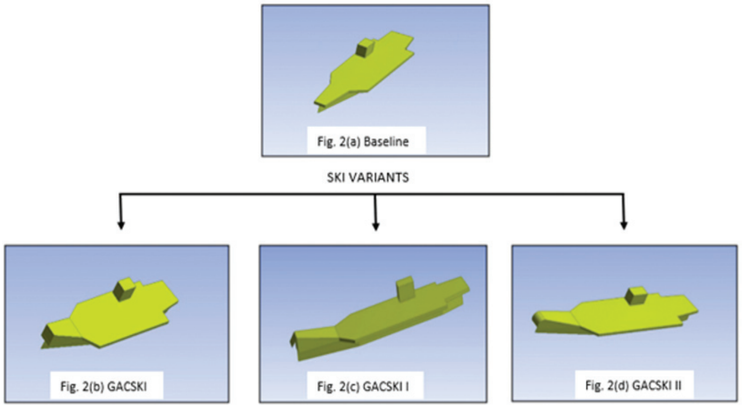

Figure 2. Variants of GAC.

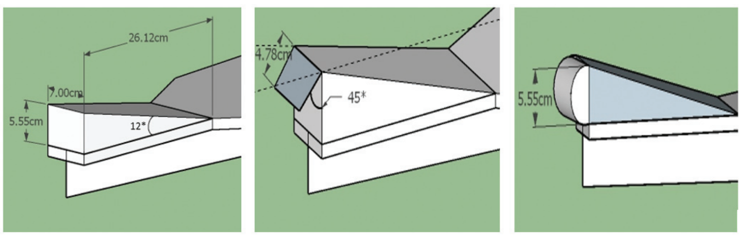

Figure 3. Dimension of variants.

(a) GAC (Baseline).
(b) GAC with wedge-shaped ski jump (GACSKI).
(c) GAC with bow flap at ski jump (GACSKI I)
(d) GAC with hemicylindrical ski jump (GACSKI II).

4.5 Validation

The first step in the study is to validate the CFD model of the Baseline geometry with the experimental data[11]. Data obtained from in house experiments conducted in IIT Delhi wind tunnel with a wooden model of the GAC was used to compare the pressure distribution over the deck of the GAC as a validation parameter[11]. The results obtained from the CFD model used in this study employing the k-omega SST turbulence model were found in agreement with the experimental results. The normalised pressure (Cp) (Defined by Eqn (4)) predicted by the present study was compared against the experimental results and showed cumulative error (defined as in Eqn (5)) was within 6%. A representative plot of the comparison along the centreline of the GAC model is presented in Fig. 4. The numerical setup using the SST k-omega turbulence model was therefore concluded as adequate to capture the flow physics within acceptable accuracy and has been used in the present study.

$$C_P = \frac{P_l - P_\infty}{\frac{1\rho v^2}{2}} \tag{4}$$

$$Error = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left(\frac{C_{Pi(CFD)} - C_{Pi(EXP)}}{C_{Pi(EXP)}}\right)^2} \tag{5}$$

4.6 Evaluation Parameters

For the pilot approaching to land on a carrier, the flow disturbances he encounters impress a direct effect on the workload. Flow parameters that are traditionally used to describe the flow conditions in the approach path are the streamwise velocity (u) and the turbulence in the flight path[26]. Any diminishment of *u* causes a loss in the lift of the aircraft and manifests as the sinking effect which pilots often report, while turbulent disturbances require constant control inputs to maintain glide slope[4].

The study conducted by Embry Riddle Aeronautical University[28] found that turbulence is a more important factor in assessing pilot workload than transverse velocity. It was observed that as the turbulent settings in the simulator were increased, performance tends to decrease linearly as shown in Fig. 5[28] while crosswinds do not contribute in any way to the pilot's workload.

Also, as quoted by Polsky in NAVAIR News Release[29],2007, "increased turbulence means the increased workload on pilot and hence increased risk". Hence, it can be inferred that the turbulence is more critical than transverse velocities. The scalar TKE defined in Eqn (6)[30], captures the cumulative effect of turbulence and has been used in the

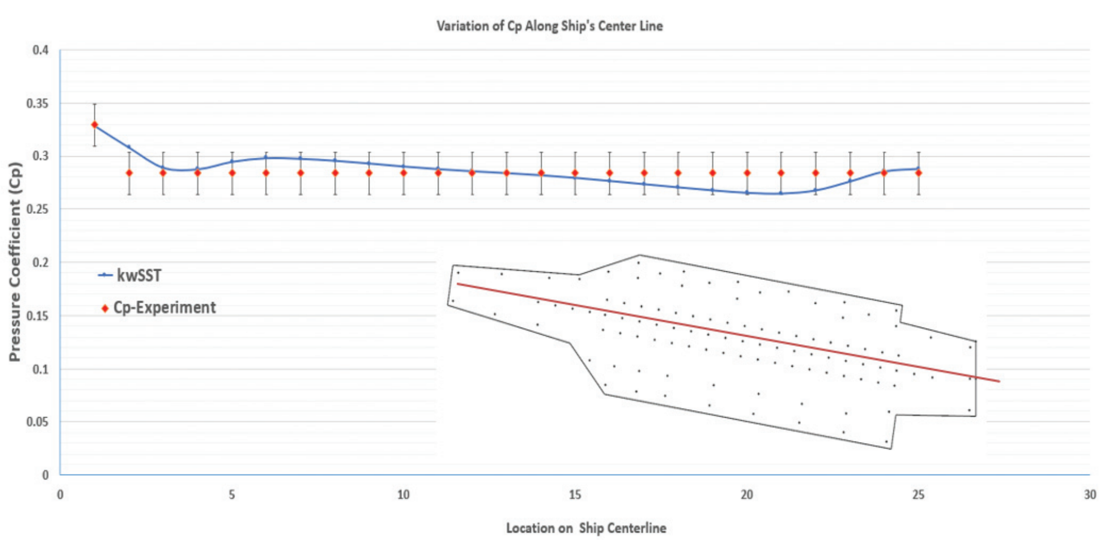

Figure 4. Comparison of experimental data with CFD Results on ship centreline.

present study as an indicator of the performance of various configurations explored, to evaluate their relative merit.

$$TKe = \frac{1}{2}\left[\left(\overline{u'}\right)^2 + \left(\overline{v'}\right)^2 + \left(\overline{w'}\right)^2\right] \qquad (6)$$

where turbulent velocity components are the difference between the instantaneous and average velocity.

The following definitions are pertinent to declare the regions of interest in this study.

(a) Approach line: This is the line along which the aircraft will make its landing approach towards the carrier. The line was chosen in accordance with standard landing procedures for aircraft carrier recovery following a 3-degree glide slope as shown in Fig. 5.

(b) Transverse Planes: Four YZ planes are taken to capture effect of ski at various landing zones. These are named as TP1, TP2, TP3 and TP4 whose locations are x= -0.82m, x= -0.25 m, x= 0 m, x= 0.5 m respectively (Fig. 5).

(c) Longitudinal Planes: Two XZ planes are taken to capture the effect along the ship's longitudinal axis. These are named LP1 and LP2 and are located at y= 0 m and y= 0.11 m (Fig. 5).

A baseline was established with the TKe parameter recorded for the original configuration. Each configuration was evaluated for the changes in TKe against the baseline in the specific regions of interest and a comparative study was carried out. The results are discussed in the following section.

4.7 Grid Independence

In addition, a study was carried out to determine an optimum point where a fairly accurate solution for the problem is found out at the expense of the least computational cost. The test results for a varying number of elements are compared in Fig 7 wherein it can be seen that beyond 1.5 crores elements there is no substantial increase in the accuracy of the results.

5. RESULTS AND DISCUSSION

Table 3 shows the value of TKe obtained for various Ski jump variants.

The various configurations analysed in the present study show the effects of changes in the shape of ski on the flow in the carrier environment. Several different factors needed to be studied to arrive at any conclusion. The contours of turbulent kinetic energy for each of the variant is compared in Figs. 7-10 and the summary of the results is tabulated in Table 4.

Firstly, considering the effect of the introduction of a ski jump on the GAC. The inclusion of a ski jump, a wedge-shaped bluff body causes increased turbulence and eddy generation along the flight deck of the aircraft carrier. However, as seen from Fig. 8 this increased turbulence is majorly felt close to the deck and decreases significantly aft of the carrier. The data along the approach line shows an increase of approximately 208% in turbulent kinetic energy as compared to the baseline configuration (without ski model) which will be felt by the pilot along his approach path.

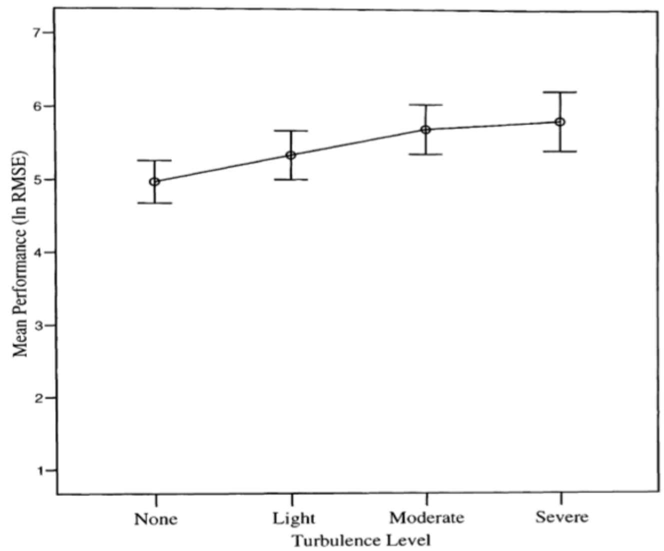

Figure 5. Average performance across turbulence level settings by Vivaldi[28].

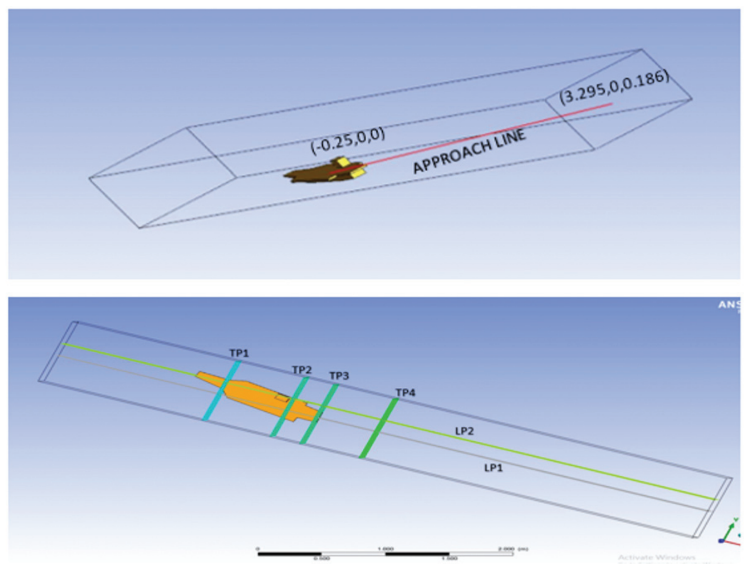

Figure 6. Evaluation parameters.

Table 3. TKe for SKI variants at evaluation parameters

Parameter Location	GAC (J/Kg)	GACSKI (J/Kg)	GACSKI I (J/Kg)	GACSKI II (J/Kg)
Approach line	7.39	22.79	18.574	10.491
TP 1	6651.03	16741.1	11058.2	5640.9
TP 2	12295	18483.7	12654.6	11958.7
TP 3	8962.46	13830.7	8387.02	8371.6
TP 4	2623.57	3200.5	3902.2	3509.25
∑TP	30532.06	52256	36002.02	29480.45
LP 1	31529.6	49789.6	36876.9	28782
LP 2	43917.2	69303.7	53976.6	40602

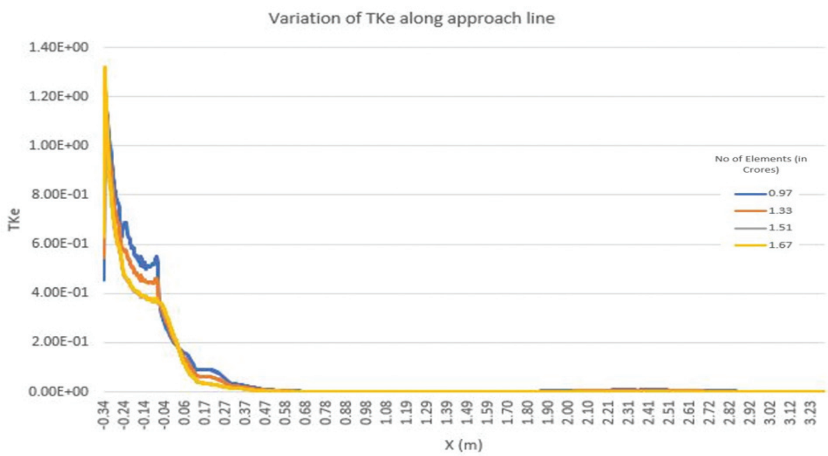

Figure 7. Grid independence.

One of the ways to reduce the pilot's workload and scope of error while landing at the aft of the carrier is to reduce the turbulence along the approach path. It is proposed that the ski jump can be geometrically optimised to reduce the turbulence generated from it. A modification was investigated to achieve this was a fitting an inclined flat plate at the bow of the carrier (Fig. 2). The flow here was found to report lesser turbulence after fitting the flap as seen in Fig. 9. As observed on TP1, the TKe reduced by approximately 34% whereas the TKe along the approach line reduced significantly by 18.5%.

On the further modification of ski by adding a hemicylindrical portion to ski to make it more streamlined (Fig. 2) and flow friendly, the reduction

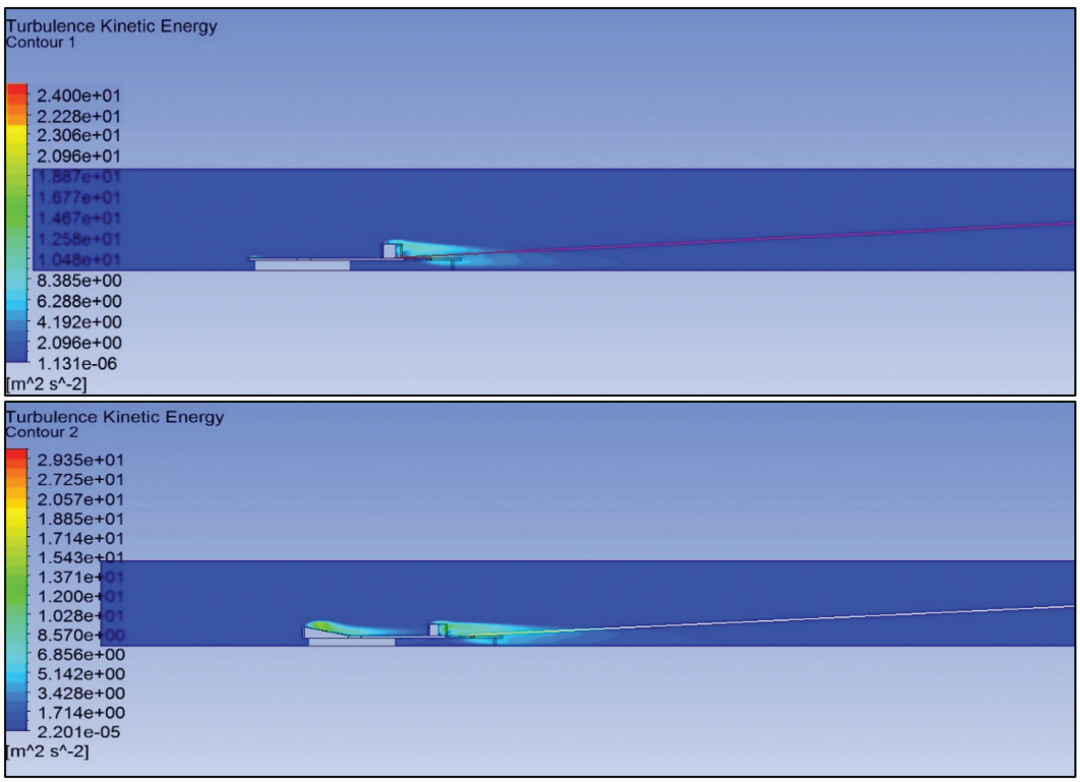

Figure 8. TKe Contour plot for GAC and GACSKI respectively.

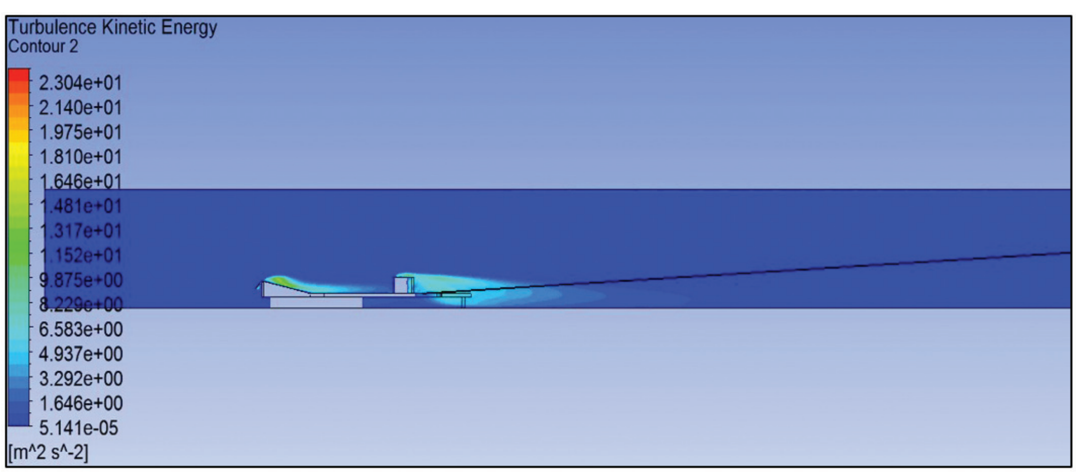

Figure 9. TKe Contour plot for GACSKI I.

Table 4. Comparison of TKe for variants

Case	Parameters				Objective
	Approach line (%)	TP ∑TKe (%)	LP1 (%)	LP2 (%)	
GAC vs GACSKI	208	71	58	58	Effect of ski on GAC
GACSKI vs GACSKI I	18.5	31	25	22	Effect of adding a bow flap to ski
GACSKI I vs GACSKI II	43.5	18	21	24	Effect of rounding the ski bow

Note: 'Red' numbers indicate an increase in value (undesirable) and 'Green' numbers indicate a decrease in values (desirable).

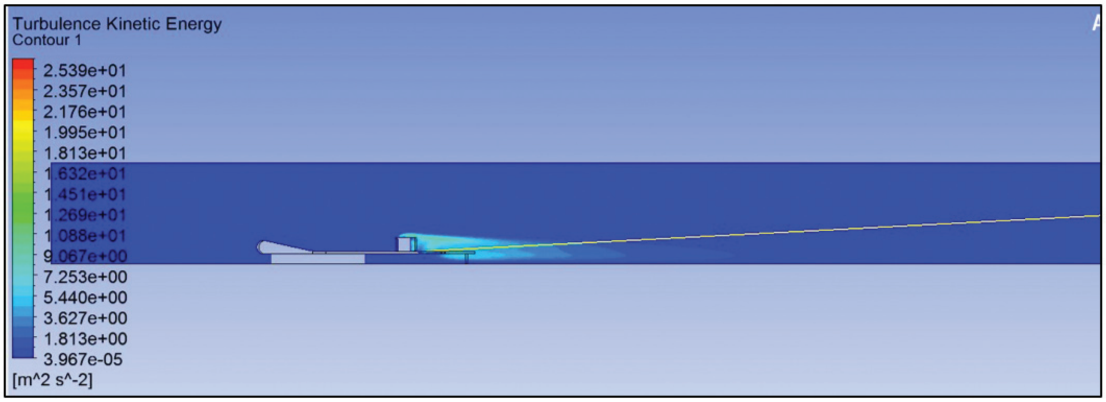

Figure 10. TKe contour plot for GACSKI II.

in turbulence due to modified ski is further down by the significant amount of 49% whereas, along the approach line, the TKe is found to reduce by a large amount of 43.5%.

As it emerges clearly, the GACSKI II configuration presents far reduced turbulence as compared to other variants as seen in Fig. 10. But the addition of an inclined flap plate is far simpler than a hemicylindrical shaped ski jump in terms of the retro fitment of existing aircraft carriers. The idea of GACSKI II can be incorporated in the upcoming carriers which reduces ski generated turbulence almost by half of GACSKI.

6. CONCLUSION

The effect of the ski jump on the flow in the aircraft carrier's environment has been studied and is summarised in Table 4. The disturbance in the flow field in regions of interest to the study is significantly reduced by the inclusion of a flap to the front edge of the ski jump which can be easily incorporated into the existing carrier by minor modifications. However, hemicylindrical bow shape rewards greater improvements to the flow and can be considered as one of the design innovations for upcoming future carriers.

REFERENCES

1. OPNAV Instruction 3710.7T US Navy, Feb 2009.
2. Frost, S. Aircraft Carrier study for predicting airflow dynamics with the increasing wind over deck velocities. Naval Air Engineering Centre, March 1968. doi: 10.21236/ADA020223
3. Guihua, Xia; Ran, Dong; Jiangtao, Xu & Qidan, Zhu. Linearized model of carrier-based aircraft dynamics in final-approach air condition. *Journal of Aircraft*, 2015, **53**(1),1-15. doi: 10.2514/1.C033175
4. Cherry, B. and Constantino, M. The Burble Effect: Superstructure and Flight Deck Effects on Carrier Air Wake. United States Naval Academy, Annapolis, MD, 21412, 2010.
5. Nacakli, Y.; Landman, D. and Doane, S. Investigation of Backward-Facing-Step Flow Field for Dynamic Interface Application. *J. Am. Helicopter Society*, 2009*,* **57**(3), 1-9. doi: 10.4050/JAHS.57.032005
6. Rudowsky, T.; Cook, S.; Hynes, M.; Heffley, R.; Luter, M.; Lawrence, T.; Niewoehner, R.; Bollman, D.; Senn, P.; Durham, W.; Beaufrere, H.; Yokell, M.; Sonntag, A. Review of the Carrier Approach Criteria For Carrier-Based Aircraft – Phase I; Final. Naval Air Warfare Center Aircraft Division, Rept. NAWCADPAX/TR-2002/71, Patuxent River, Oct 2002. doi: 10.21236/ADA411068
7. Brictson, C.A.; Pitrella, F.B.; and Wulfeck J.W. Analysis of Aircraft Carrier Landing Accidents (1965-1969). Dunlap and Associates, ONE, Washington, D.C., November 1969,.
8. Kääriä, C.H.; Wang, Y.; White, M.D. & Owen, I. An experimental technique for evaluating the aerodynamic impact of ship superstructures on helicopter operations. *Ocean Engineering,* 2013, **61**, 97-108. doi: 10.1016/j.oceaneng.2012.12.052
9. Maslov, L.A.; Valuev, N. O & Zharinov, A.V. The experience of aerodynamic disturbances research behind an aircraft-carrier ship with elements for the safe operation of ship-based aircraft. RTO Meeting Proceedings, 1999.
10. Ringleb, O.F. Air Flow Control Arrangements for Aircraft Carriers. United States Pat. 3362368, 1968, pp. 1–4.
11. Kumar, K.V.; Mathew, M.P.; Singh, S.N.; Sinha, S.S & Vijaykumar, R. Experimental investigation of flow over the flight deck of a Generic Aircraft Carrier. Procurement of Future Surface Vessels 2018, Warship 2018.

12. Olenski, J.J. & Dankworth, T.P. Carrier Crosswind Launching and Landing Operations with Current Navy Airplanes. Ft 35-093, Navy Air Test Centre, Patuxent River, August 1958.
13. Kjellman, T.K. & Colt, R.B. Survey Report of Wind Direction and Speed Across Flight Deck USS Ranger CVA 61(CVA 50 Class). Index NS 681-026-03, Contract No 72137, Bendix Aviation Corporation, Frietz Instrument Division, Baltimore, April 1958.
14. Hannegan, E.A. & Badger, H.J. Optimum Wind Over Deck for Shipboard Recovery Operations with Carrier-Based Planes. PTR-RSSH-31003, Naval Air Test Center, Patuxent River, Maryland,1 February 1961.
15. Oldmixon & Lieut, W.J. Acquisition, Reduction, and Analysis of Turbulence Data Associated with PA Configuration Approaches to Carrier Landings. Princeton, University Report #653, Dept of Aeronautical Engineering, Princeton, July 1963.
doi: 10.21236/AD0419101
16. Barnett, W.F. & White, H.E. Comparison of the Airflow Characteristics of Several Aircraft Carriers. David Taylor Model Basin, 1963.
doi: 10.21236/AD0491448
17. Rajagopalan, G.; Schaller, D.; Wadcock, A.J.; Yamauchi, G.K.; Heinneck, J.T.; Silva, M.J. Experimental and Computational Simulation of a Model Ship in a Wind Tunnel. AIAA Paper No. 2005-1347, Presented at the AIAA 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005,
doi: 10.2514/6.2005-1347
18. Moorhouse, D.J. & Woodcock, R. J. Background Information and User Guide for MIL 8785-C. Military Specification-Flying Qualities of Piloted Airplanes, 1982.
19. Steinberg, M. A Fuzzy Logic-based Aircraft Landing System. Lehigh University, 1991.
20. Department of Defence Handbook- Flying Qualities of Piloted Aircraft. MIL-HDBK-1797 19, December 1997.
21. Polsky, S. & Naylor. CVN Airwake Modelling and Integration: Initial Steps in the Creation and Implementation of a Virtual Burble for F-18 Carrier Landing Simulations. AIAA Modeling and Simulation Technologies Conference and Exhibit, 2005.
doi: 10.2514/6.2005-6298
22. Bardara, M.; Barcala, M. & Sevillano, A.R. Passive flow control over the ski jump of aircraft carriers. *Ocean Engineering,* 2016, **114**, 134-141.
doi: 10.1016/j.oceaneng.2016.01.019
23. You-shi & Xiang, Q.U. Performance increase and key problems of the carrier-based aircraft ramp/ catapult synthesised take off. School of Aeronautics Science and Technology, Beijing 100083, China.
24. Crezwiec R & Polsky S. A. LHA Airwake wind tunnel and CFD comparison with and without bow flap. *In* 22nd Applied Aerodynamics Conference and Exhibit, Aug 2004.
doi: 10.2514/6.2004-4832
25. Bardera, R.; Calero, M.L. & Sevillano, A.A.R. Experimental investigation of the aerodynamic flow in the aircraft carrier Ski-jump by means of PIV. *J. Mathematics Syst. Sci.*, 2017, **7**(12).
doi: 10.17265/2159-5291/2017.12.003
26. Owen, I.; White, M.; Scott, P.; Mateer, R. & Kelly, M. Modelling and Simulation at The University of Liverpool in Support of UK Naval Aviation. Univ. Liverpool, UK, 2015.
27. Mora, R.B. Wind flow investigation over an aircraft carrier deck by PIV. *Ocean Engineering*, 2019, **178**, 476–483.
doi: 10.1016/j.oceaneng.2019.03.020
28. Bruno, Vivaldi E. The Effect of Crosswind and Turbulence in Mental Workload and Pilot Tracking Performance. Embry-Riddle Aeronautical University - Daytona Beach, 2004.
29. Airwake Analysis Keeps Navy Ships Safe for Aviation, NAVAIR News Release, August 2007.
30. Pope, S.B. Turbulent Flows. Cambridge University, 2000.
doi: 10.1017/CBO9780511840531

CONTRIBUTORS

Lt. Rahul Thakur is a post graduate in Naval Construction from Indian Institute of Technology, Delhi and MTech in Ocean Engineering from Indian Institute of Technology, Kharagpur. The author's major contribution comes in form of establishing the analytical model of the problem.
The author's experience and knowledge in the field of design of aircraft carriers helped to come up with the idea of geometrically modifying the ski jump to reduce the effects of burble.

Cmdre. K. Vignesh Kumar is a post graduate in Naval Construction from Indian Institute of Technology, Delhi and M Tech in Ocean Engineering from Indian Institute of Technology, Kharagpur.
The author's vast knowledge and expertise in the field of fluid and ship dynamics helped to formulate conclusions of the present study.