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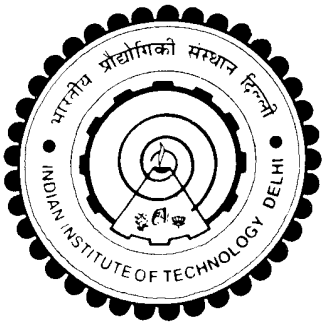

DEPARTMENT OF APPLIED MECHANICS
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STUDY OF THE SHIP AIRWAKE AND HELICOPTER DOWNWASH CHARACTERISTICS FOR SAFE HELO OPERATIONS

by

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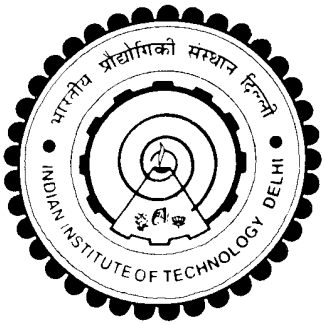
Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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I would like to dedicate this thesis to my loving Parents, my sister, Nidhi, and my brother, Yugraj

CERTIFICATE

This is to certify that the thesis titled " **Study of the Ship Airwake and Helicopter Downwash Characteristics for Safe Helo Operations**" being submitted by **Shrish Shukla,** is report of bonafide research work carried out by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of Indian Institute of Technology, New Delhi, India. We further certify that the thesis has attained a standard required for a Ph. D. degree of the Institute. The research reported and results presented in the thesis have not been submitted, in part or full to any other Institute or University for the award of any degree or diploma.

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Shrish Shukla

Date:

Place: New Delhi

ABSTRACT

The operation of helicopters at ships on-board has always been a very complex task owing to the presence of ship air wakes, high velocity gradients, widely varying turbulence length scales as well as the bluff shape ship superstructures. Further, this complexity increases with the addition of helicopter downwash during landing/take off. In addition, these difficulties are more critical for small category frigate class ships. This is mainly due to (i) compactness in shape and size along with fixed design considerations, (ii) the sea-keeping motions encountered in high seas provide a non-stationary oscillating platform, and (iii) the visual cues reduce drastically due to sea spray. Further, the onboard landing deck area is limited (typically twenty percent the entire ship top deck area) due to the vessel stability constraint. In essence, the above-mentioned constraints lead to shipborne helicopter operation being one of the most challenging and difficult tasks in every naval organisation. Hence, an early assessment of the resultant flow environment over the ship helodeck for at early design stage is very crucial to minimise the risk associated with the shipborne helicopter operation.

The study is thus aimed to seek a suitable cost-effective early stage preliminary design tool to evaluate the essential flow features of coupled ship-helo airwake and overcome the complexities associated with shipborne helicopter operations. The study utilises the available experimental and numerical resources to understand the combined ship-helo airwakes characteristics on helodeck contributing to influence the helicopter aerodynamics, and explore solutions for economical early stage approach in order to improve the safe ship-helo operations margin. The ship airwakes and their effect over the flow characteristics of the flight deck region has been analyzed experimentally and computationally. An outstanding problem is to operate a helicopter in the regions of coherent, high-amplitude/less-frequency turbulence flow, which

develop from the sharp edges and additional bluff bodies on the ship superstructure. Therefore, in order to gain insight into the ship airwake characteristics, the experiments have been undertaken on internationally accepted Simplified Frigate Ship (SFS2) along with the helicopter fuselage (ROBIN) at initial stage of investigations. The experimental investigations have been undertaken into two stages. In the first stage, the isolated ship airwake case have been studied experimentally. The combined ship-helo configurations have been extensively investigated with respect to the flight approach path followed on onboard helicopter operations over the helodeck in the second stage of experimental study. Subsequently, the steady flow investigations have been undertaken in order to establish a suitable numerical methodology to reasonably capture the flow characteristics of the experimental studies in the third stage of study.

Subsequently, the fourth stage of study presents a conceptual method to gain insight into the combined ship-helo flow phenomena over a helodeck. One of the prime objectives of this study is to develop an economical design tool employing both experimental as well as computational techniques to simulate the ship-helicopter coupled environment regime at early design stages reasonably well, so as to ease the burden of expensive and risky sea trials. For this purpose, a simplified dynamic interface (SDI) model is proposed to investigate the coupled effects of ship airwake and helicopter downwash. The study reports a parametric analysis to investigate the coupled ship-helo airwake behaviour and its impact on helicopter fuselage over the ship helodeck for different ship speed regimes by the proposed SDI model. The study also reports the influence of 'In Ground Effect' over the helodeck under different downwash conditions.

Further, an attempt has been made to setup preliminary single statistical value-based design criteria to grade the ship-helicopter interface for ensuring minimum standards of safe helo-

operations. The proposed approach is limited to the identification of some dominant resultant coupled ship-helo airwake flow features which influence the helicopter aerodynamics. Results discuss the efficacy of the present approach by highlighting the impact of the coupled flow dynamics in terms of induced fuselage drag, cross-flow characteristics, rotor plane wake and velocity gradients that exist over the helodeck region.'

In the last stage of study, an unsteady flow analysis has been undertaken on isolated ship (SFS2) to established a suitable unsteady approach for the ship airwake investigations. The overarching aim of this study was to reasonably capture the dominated energy frequency range which affect the onboard helicopter operations. This study provides some insights into the unsteady ship airwake characteristics. Results obtained using three modelling approaches for unsteady ship airwake characteristics namely, Unsteady Reynolds Averaged Navier Stokes (URANS) simulation, Scale Adaptive Simulation (SAS) and Detached Eddy Simulation (DES) discuss the effectiveness of the approaches. The study also attempts to compare mean flow quantities between the unsteady flow approach and steady flow approach

Finally, the proposals for further research have been laid out which are expected to aid in the endeavour towards a complete numerical assessment of the ship-helo interaction problem in future and creation of ship helo operating envelopes (presently created through rigorous First-Of-Class Flying Trials: FOCFT) within the realms of a laboratory.

Keywords: Ship-Helicopter Airwake, Simplified Dynamic Interface (SDI), Helicopter Downwash, Turbulent Flow.

सारांश

जहाजों पर हेलीकाप्टरों का संचालन हमेशा जहाज की हवा की लहरों, उच्च वेग ग्रेडिएंट्स, व्यापक रूप से बदलते हुए एयर टर्बुलेन्स की उपस्थिति और बड़े आकार के जहाज सुपरस्ट्रक्चर के कारण एक बहुत ही जटिल कार्य रहा है। इसके अलावा, लैंडिंग / टेक ऑफ के दौरान हेलीकॉप्टर के डाउनवाश के साथ यह जटिलता काफी बढ़ जाती है। यह कार्य छोटे वर्ग के फ्रिगेट श्रेणी के जहाजों के लिए अत्यधिक जटिल होती है। यह जटिलता मुख्य रूप से (i) जहाज के निश्चित डिजाइन के कारण होता है, (ii) उच्च समुद्र में सामना किए जाने वाले समुद्रीर्य लहरों की गति के कारण गैर-स्थिर प्लेटफ़ॉर्म प्रदान करती है, और (iii) समुद्रीर्य लहरों के कारण दृश्य संकेत में भारी गिरावट के कारण होती है। इसके अलावा, जहाज की स्थिरता की कमी के कारण ऑनबोर्ड लैंडिंग डेक क्षेत्र सीमित होता है (आमतौर पर पूरे जहाज के क्षेत्र का सिर्फ बीस प्रतिशत)। संक्षेप में, उपर्युक्त बाधाएं शिपबॉर्न हेलिकॉप्टर ऑपरेशन को जटिल करती हैं जोकी हर नौसेना संगठन में सबसे चुनौतीपूर्ण और कठिन कार्यों में से एक है। इसलिए, शुरुआती डिजाइन चरण के लिए जहाज के हेलोडेक पर परिणामी वायु प्रवाह वातावरण का प्रारंभिक मूल्यांकन शिपबॉर्न हेलिकॉप्टर ऑपरेशन से जुड़े जोखिम को कम करने के लिए बहुत महत्वपूर्ण है।

अतः इस अध्ययन का उद्देश्य युग्मित जहाज-हेलो एयरवेक की आवश्यक प्रवाह विशेषताओं का मूल्यांकन करने और शिपबॉर्न हेलिकॉप्टर संचालन से जुड़ी जटिलताओं को दूर करने के लिए एक उपयुक्त लागत प्रभावी प्रारंभिक प्रारंभिक प्रारंभिक उपकरण की तलाश करना है। हेलिकॉप्टर एयरोडायनामिक्स को प्रभावित करने में योगदान देने वाले हेलोडेक पर संयुक्त जहाज-हीलो एयरवेक विशेषताओं को समझने और सुरक्षित जहाज-हेलो परिचालन मार्जिन में सुधार के लिए किफायती प्रारंभिक चरण दृष्टिकोण के समाधान का पता लगाने के लिए अध्ययन उपलब्ध प्रयोगात्मक और संख्यात्मक संसाधनों का उपयोग करता है। जहाज एयरवेक और उड़ान डेक क्षेत्र की प्रवाह विशेषताओं पर उनके प्रभाव का प्रयोगात्मक और कम्प्यूटेशनल रूप से विश्लेषण किया गया है। एक बकाया समस्या सुसंगत, उच्च-आयाम / कम-

आवृत्ति अशांति प्रवाह के क्षेत्रों में एक हेलीकॉप्टर को संचालित करना है, जो कि जहाज के सुपरस्ट्रक्चर पर तेज किनारों और अतिरिक्त ब्लफ निकायों से विकसित होती है। इसलिए, जहाज एयरवेक विशेषताओं में अंतर्दृष्टि प्राप्त करने के लिए, जांच के प्रारंभिक चरण में हेलीकाप्टर बॉडी (रोबिन) के साथ अंतरराष्ट्रीय स्तर पर स्वीकृत सरलीकृत फ्रिगेट शिप (एसएफएस 2) पर प्रयोग किए गए हैं। प्रायोगिक जाँच दो चरणों में की गई है। पहले चरण में, पृथक जहाज एयरवेक मामले का प्रयोगात्मक रूप से अध्ययन किया गया है। प्रायोगिक अध्ययन के दूसरे चरण में हेलोडेक पर जहाज पर हेलीकॉप्टर संचालन के बाद उड़ान दृष्टिकोण पथ के संबंध में संयुक्त जहाज-हलो विन्यास की बड़े पैमाने पर जांच की गई है। इसके बाद, अध्ययन के तीसरे चरण में प्रयोगात्मक अध्ययन के प्रवाह विशेषताओं को यथोचित रूप से पकड़ने के लिए एक उपयुक्त संख्यात्मक पद्धति स्थापित करने के लिए स्थिर प्रवाह जांच की गई है।

इसके बाद, अध्ययन का चौथा चरण एक हेलोडेक पर संयुक्त जहाज-हेलो प्रवाह घटना में अंतर्दृष्टि प्राप्त करने के लिए एक वैचारिक विधि प्रस्तुत करता है। इस अध्ययन के प्रमुख उद्देश्यों में से एक है प्रायोगिक डिजाइन टूल का विकास करना, जिसमें प्रायोगिक तकनीकों के साथ-साथ कम्प्यूटेशनल तकनीकों को नियोजित करना, ताकि जहाज-हेलीकाप्टर युग्मित पर्यावरण शासन को प्रारंभिक रूप से अच्छी तरह से डिजाइन किया जा सके, ताकि महंगे और जोखिम भरे टेस्टिंग प्रणाली को सरल किया जा सके। इस परीक्षणों के लिए, जहाज एयरवेक और हेलीकाप्टर डाउनवॉश के युग्मित प्रभावों की जांच करने के लिए एक सरलीकृत गतिशील इंटरफ़ेस (एसडीआई) मॉडल प्रस्तावित है। यह अध्ययन प्रस्तावित एसडीआई मॉडल द्वारा विभिन्न जहाज गति शासनों के लिए जहाज हेलोडेक पर हेलीकॉप्टर पर इसके जहाज-हेलो एयरवेक व्यवहार और इसके प्रभाव की जांच के लिए एक पैरामीट्रिक विश्लेषण की रिपोर्ट करता है। अध्ययन में अलग-अलग डाउनवॉश स्थितियों के तहत हेलोडेक पर 'इन ग्राउंड इफेक्ट 'के प्रभाव की भी दर्शया गया है। इसके साथ-साथ, सुरक्षित हेलो-संचालन के न्यूनतम मानकों को सुनिश्चित करने के लिए जहाज-हेलीकॉप्टर इंटरफ़ेस को ग्रेड करने के लिए प्रारंभिक एकल सांख्यिकीय मूल्य-आधारित डिज़ाइन मानदंड स्थापित करने का प्रयास किया गया है। प्रस्तावित दृष्टिकोण कुछ प्रमुख परिणामी युग्मित जहाज-

हीलो एयरवेक प्रवाह सुविधाओं की पहचान तक सीमित है जो हेलीकॉप्टर वायुगतिकी को प्रभावित करते हैं। परिणाम प्रेरित हेलीकॉप्टपर बॉडी ड्रैग, क्रॉस-फ्लो विशेषताओं, रोटरप्लेन वेक और हेलोडेक क्षेत्र में मौजूद वेग गति के संदर्भ में युग्मित प्रवाह की गतिशीलता के प्रभाव को उजागर करके वर्तमान दृष्टिकोण की प्रभावकारिता पर चर्चा करते हैं।

अध्ययन के अंतिम चरण में, जहाज एयरवेक जांच के लिए एक उपयुक्त अस्थिर दृष्टिकोण स्थापित करने के लिए पृथक जहाज (सफस 2) पर एक अस्थिर प्रवाह विश्लेषण किया गया है। इस अध्ययन का व्यापक उद्देश्य वर्चस्व वाली ऊर्जा आवृत्ति रेंज पर केंद्रित है, जो जहाज पर हेलीकॉप्टर संचालन को प्रभावित करते हैं। यह अध्ययन अस्थिर जहाज एयरवेक विशेषताओं में कुछ अंतर्दृष्टि प्रदान करता है। अस्थिर जहाज एयरवेक विशेषताओं के लिए तीन मॉडलिंग दृष्टिकोणों का उपयोग करके प्राप्त किए गए परिणाम, अनस्टेडी रेनॉल्ड्स एवरेज्ड नावियर स्टोक्स (URANS) सिमुलेशन, स्केल एडेप्टिव सिमुलेशन (SAS) और पृथकएडी सिमुलेशन (DES) ने दृष्टिकोण की प्रभावशीलता पर चर्चा की। अध्ययन भी अस्थिर प्रवाह दृष्टिकोण और स्थिर प्रवाह दृष्टिकोण के बीच औसत प्रवाह मात्रा की तुलना करने का प्रयास करता है। अंत में, भावी शोध के प्रस्तावों को निर्धारित किया गया है, जो भविष्य में जहाज-हीलो समस्या के पूर्ण संख्यात्मक मूल्यांकन और जहाज के संचालन के नक्शे के निर्माण की दिशा में सहायता करने की उम्मीद करते है।

महत्वपूर्ण शब्दावली: शिप-हेलिकॉप्टर एयरवेक, सरलीकृत डायनामिक इंटरफ़ेस (एसडीआई), हेलीकाप्टर डाउनवॉश, टर्बुलेंट फ्लो।

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NOMENCLATURE

X, Y, Z	Longitudinal (streamwise), Transverse (spanwise) and Vertical co-ordinate direction
x/X	Normalized streamwise coordinate
y/Y	Normalized cross flow coordinate
z/Z	Normalized spanwise coordinate
u/U	Normalized streamwise velocity
v/V	Normalized cross flow velocity
w/W	Normalized vertical (spanwise) velocity
CTS	Convective Time Scale, defined as L/U_∞ (average time required for a fluid particle to pass the ship)
t*	Non-dimensional time (t/CTS), in CTS units
t	Physical time (sec)
Δt	Time-step (sec)
Δt^*	Non-dimensional time step ($\Delta t/CTS$)
V_s	Ship velocity
V_a	Atmospheric wind velocity
l	Reference length of the ship
U_∞	Free-stream velocity
V_{ro}	Rotor downwash velocity
V_r	Relative wind velocity, defined as (V_s- V_a)
α	Yaw angle of fuselage
β	Velocity ratio (U_∞/U_0)
Ψ	Wind over deck angle (degree)
l_{HDK}	Length of helodeck (m)
h_{HGR}	Height of helo-hangar

L_s, W_s H_s	Ship length, width, and height
L_d, W_d, H_d	Domain length, width, and height
r_d	Domain radius
Δ	Grid Scaling factor
Δ_0	Grid spacing in the region of interest
τ_w	Wall shear stress
υ_t	Eddy viscosity
μ_t	Dynamic eddy-viscosity
I	Turbulence intensity
k	Turbulent Kinetic Energy
ε	Turbulent dissipation rate
ω	Specific turbulent dissipation rate
St	Strouhal number
f	Natural shedding frequency (Hz)
y^+	Non-dimensional wall length
k	Turbulent kinetic energy (m^2/s^2)
ρ	Density of air (kg/m^3)
P	Mean pressure
Re	Reynolds Number
μ_t	Eddy viscosity
U_∞	Free-stream crossflow velocity (m/s)
U_o	Downwash velocity (m/s)
V_{id}	Induced Velocity (m/s)
u, v, w	Velocity components in x, y, z direction (m/s)
V	Resultant velocity ($\sqrt{u^2 + v^2 + w^2}$)

V_{ref}	Reference velocity ($\sqrt{U_\infty^2 + U_0^2}$)
V_n	Normalized resultant velocity (V/V_{ref})
V_{id}	Induced velocity at rotor plane (m/s)
D_r	Rotor diameter (m)
d_0	SRD diameter (m)
T	Rotor thrust (mg)
m	Gross weight of helicopter
g	Acceleration of gravity (m/s^2)
A	Rotor blade swept area ()
L_s	Length of ship (m)
L_f	Length of helicopter fuselage (m)
W_b	Ship beam (m)
W_f	Fuselage width (m)
H_f	Fuselage height (m)
l_{re}	Flow recirculation length (m)
W	Normalized recirculation length (l_{re}/l_{HDK})
L	Normalized rotor size (D_r/W_b)
R	Fuselage length (m)
y^+	Non-dimensional wall distance
I	Turbulent intensity (%)
k	Turbulent kinetic energy (m^2/s^{-2})
ω	Specific turbulent dissipation rate (s^{-1})
h_0	Rotor height from ground
l_{srd}	Projection length of SRD

Subscripts

i, j, k	Tensor notation
0	Initial conditions
T	Turbulent quantities
i	Inlet
o	Outlet
max	Maximum
min	Minimum

Abbreviations

ABL	Atmospheric Boundary Layer
CFL	Courant-Friedrichs-Lewy number
DDA	Digital Differential Analyzer
D-DES	Delayed Detached Eddy Simulation
DES	Detached Eddy Simulation
DI	Dynamic Interface
DIPES	Deck Interface Pilot Effort Scale
DNS	Direct Numerical Simulation
ETP	Experimental Test Pilot
FOCFT	First-Of-Class Flying Trials
I-LES	Implicit Large Eddy Simulation
POD	Proper Orthogonal Decomposition
PSD	Power Spectral Density
ROBIN	ROtor Body INteraction Fuselage
ROM	Reduced Order Modelling
SAS	Scale Adaptive Simulation

SFS	Simplified Frigate Ship
SHOL	Ship Helicopter Operating Limit
TNT	Turbulent/Non-Turbulent
TTCP	The Technical Cooperation Program
VTOL	Vertical Take-Off and Landing
X-LES	eXtra-Large Eddy Simulation