STUDY OF FLOW CHARACTERISTICS ON HELODECK OF A SHIP MODEL WITH MODELLED ROTOR DOWNWASH

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STUDY OF FLOW CHARACTERISTICS ON HELODECK OF A SHIP MODEL WITH MODELLED ROTOR DOWNWASH

by

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Dedicated to

My wife Shabnam, sons Ayaan and Zayden.

The helicopter is probably the most versatile instrument ever invented by man. It approaches closer than any other to fulfillment of mankind's ancient dreams of the flying horse and the magic carpet.

- *Igor Sikorsky*

CERTIFICATE

This is to certify that the thesis titled **"Study of flow characteristics on helodeck of a ship model with modelled rotor downwash"**, being submitted by **Ishaq Sayed Makkar** to the Indian Institute of Technology Delhi for the award of the degree Doctor of Philosophy, is a 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. 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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ABSTRACT

The research is intended to provide a pragmatic early-stage design methodology for evaluation of shipborne helo operations and a better understanding of the complex flow physics due to the interaction of the ship airwake with a simplified modelled rotor downwash near the helo deck, with available experimental and computational resources. The primary motivation factors for the study have been limited to coupled ship-helo flow dynamics studies and non-availability of a pragmatic procedure for evaluation maritime helo operations during early design stages.

The research includes both conventional literature review and a study of the extant ship geometries alongwith operational procedures (international frigates and destroyers - identification of critical superstructure geometry parameters). The research work involves both experimental and numerical studies undertaken on a coupled ship airwake with a simplified/modelled rotor downwash (SRD).

The experimental studies comprise of both quantitative *Experimental Flow Measurements (EFM)* and qualitative *Experimental Flow Visualisation (EFV)* studies on a Simplified Frigate Ship (SFS 2) and SRD model, in a wind tunnel. These studies have provided invaluable authentic in-house data for subsequent numerical model validation, followed by parametric numerical studies. Detailed mapping of the flowfield on multiple planes using five-hole probe measurements at a fixed SRD location and constant advance velocity ratio, $\alpha = 1$ have been undertaken in the *EFM* studies. Where α is the ratio of ship velocity (V_S) to the resultant of ship velocity and SRD velocity (V_R). Analyses of the flow field on the planes using contour plots, vector plots and wiremesh diagrams of the relevant flow velocity components from

the measured data (steady flow parameters: velocity components and planar velocity in all three directions), provides detailed insight into the flow structure. The *EFV* studies involves 98 smoke seeding based parametric cases in the wind tunnel. The sub-studies include identification of critical Reynolds number for flow similarity, Isolated ship airwake topology analysis, SRD variation studies for coupled ship and downwash conditions (advance velocity ratios, positions, landing/take-off trajectories), effect of flow modification either passive(hangar geometry) or active (rotating cylinder). A large volume of experimental data has been generated in terms of recordings and still frames from these studies. Three primary zones of interaction based on the advance velocity ratio (α) with their potential influence on the pilot workload has been a critical output of this study.

The numerical studies have been undertaken using the commercial CFD tool - ANSYS FLUENT. This includes detailed validation studies of the numerical technique against in-house experimental results (*EFM and EFV*). Subsequently, parametric CFD investigation with varying ship-helo combinations are studied. These cases include spatial/velocity ratio based SRD variation for: landing location, landing/take-off trajectory studies and flow modifications. The analysis includes quantitative statistical value-based approach for comparison of the flow variables (planar values on rotor planes), alongwith probable effects on pilot workload.

The final results of the study comprises of recommended safe windows for coupled ship airwake/SRD configuration with possible low pilot workload in terms of: Safe advance velocity ratio, Overall landing spot recommendation, suggested landing/take-off trajectory, turbulence intensities variation effects, flow improvement device effectiveness (active and passive) etc. A major contribution has been the validation of simplified SRD-based methodology (with combination of wind tunnel experiments and CFD simulations) for an early-stage ship/helo configuration design. Finally, suggestions for possible future research on the topic have also been enumerated.

सारांश

इस अनुशंधान का उदेश्य शिप बोर्न हेलो आपरेशन के मूल्यांकन एवं प्रारम्भिक चरण डिजाइन पद्धति प्रदान करना एवं हेलो डेक के पास एक सरलीकृत मोडेल्ड रोटर डाउन वाश के साथ शिप एयर वेक की संचार के कारण जटिल प्रवाह भौतिकी एवं उपलब्ध प्रयोगात्मक व कंप्युटेशनल संसाधन की बेहतर समझ है। प्राथमिक अध्ययन यूग्गिमत शिप-हेलोहवा के बहाव डायनेमिक्स के लिए अध्ययन और प्रारम्भिक डिजाइन चरणो के दौरान समुद्री हेलिकाप्टर संचालन के मूल्यांकन के लिए उपयोगी प्रक्रिया की अनुप्ल्ब्ध्द्ता तक सीमित है।

अनुसंधान में पारंपरिक साहित्य और परिचालन प्रक्रियाओं के साथ–साथ वर्तमान जहाज ज्यामिति (अंतरराष्ट्रीय फ्रीगेट और विंध्वंसक-महत्वपूर्ण सुपर स्ट्रेक्चर ज्यामिति मापदण्डों की पहचान) का समीक्षा अध्ययन शामिल है। शोध कार्य में एक सरिलीकृत मॉडल रोटर डाउन वाश (एस आर डी) के साथ युगग्मित शिप एयरवेक पर किए गए प्रयोगात्मक और संख्यात्मक/कंप्युटेशनल दोनों अध्ययन शामिल है।

प्रयोगिक अध्ययनो में वायु सुरंग में एक सरलीकृत फ्रीगेट शिप (एस एफ एस 2) और एस आर डी मॉडल पर मात्रात्मक प्रयोगिक प्रवाह माप (ई एफ एम)और गुणात्मक प्रयोगिक प्रवाह विजुयालाइजेशन (ई एफ वी) दोनों अध्ययन शामिल है। इन अध्ययनों ने संख्यातमक मॉडल सत्यापन के लिए इन हाउस डेटा प्रदान किया है। इसके बाद पैरामैट्रिक संख्यात्मक अध्ययन किया गया है। ई एफ एम अध्यनों में एक निश्चित एस आर डी स्थान और निरंतर एडवांस वेग अनुपात, α =1 पर पाँच-छेद जांच मॉप का उपयोग करते हुए कई समतलों पर फ्लोफील्ड/कंपुटेशनल का विस्तृत मानचित्रण किया गया है। जहां α जहाज के वेग (Vs) और जहाज के वेग एवं एस आर डी वेग (VR)के परिणाम

का अनुपात है। माप डेटा (स्थिर प्रवाह पैरामीटर: वेग घटक और तीनों दिशाओं में प्लानर वेग) से संबन्धित प्रवाह वेग घटकों के समोच्च क्षेत्र, वेक्टर क्षत्रों और वायर मेश आरेख का उपयोग करके समतलों पर प्रवाह क्षेत्र का विवरण प्रदान करता है।

ई एफ वी अध्ययन में वायु सुरंग में 98 धुआं बिखेरने पर आधारित पैरामैट्रिक मामले शामिल है। उप अध्ययनों में प्रवाह समानता के लिए महत्वपूर्ण रेनल्ड्स संख्या की पहचान पृथक जहाज एयरवेक आकार विश्लेषण, युग्मित जहाज और डाउन वाश स्थितियों के लिए एस आर डी भिन्नता अध्ययन (अग्रिम वेग अनुपात, स्थिति, लैंडिंग/टेक-आफ मार्ग), प्रवाह शांशोधन निष्क्रियता (हैंगर ज्यामिति) या सक्रिय (घूर्णन सिलेन्डर)शामिल है। इन अध्ययनों से रिकॉर्डिंग और स्थिर फ्रेम से संबंध में बड़ी मात्रा में प्रयोगात्मक डेटा उत्पन्न किया गया । पायलट कार्य भार पर उनके संभावित प्रभाव के साथ अग्रिम वेग अनुपात (α) पर मिश्रण बातचीत के तीन प्राथमिक क्षेत्र की पहचान इस अध्ययन का महत्वपूर्ण परिणाम रहा है।

संख्यात्मक सी एफ डी टूल –एंसिस फ्लुएंट का उपयोग करके संख्यातमक/कंप्युटेशनल अध्ययन किया गया इसमें आंतरिक प्रयोगात्मक परिणामों (ई एफ एम और ईफ वी) के संख्यातमक/कंप्युटेशनल तकनीक का विस्तृत सत्यापन अध्ययन शामिल है तत्पश्चात अलग-अलग शिप हॉलों संयोजकों के साथ पैरामैट्रिक सी एफ डी जांच का अध्ययन किया गया। इन मामलों में स्थानिक/वेग अनुपात आधारित एस आर डी भिन्नता शामिल है। जैसे लैंडिंग स्थान, लेंडिंग टेक-आफ मार्ग अध्ययन व प्रवाह संशोधन। इस विश्लेषण में पाइलट कार्य भार पर संभावित प्रभावों के साथ-साथ अस्थाई प्रवाह (रोटर संतलों पर तलीय मान) की तुलना के लिए मात्रात्मक सांखिकीय मूल्य आधारित द्रीष्टिकोण शामिल है।

अध्ययन के अंतिम परिणामों में संभावित पायलट निम्न वर्कलोड के साथ युगीमित जहाज एयरवेक/ एसआर डी के लिए सुरक्षित सीमाओं की सिफारिश की जाती है। जैसे सुरक्षित अग्रिम वेग अनुपात, समग्र लैंडिंग स्पॉट अनुशंसा, लैंडिंग टेक-आफ मार्ग अनुशंसा टार्बुलेन्स ईंटेंसिटी भिन्नता प्रभाव ,प्रवाह सुधार उपकरण प्रभावशीलता (सक्रिय और निष्क्रिय) इत्यादि। इस प्रारम्भिक चरण के जहाज/हेलो विन्यास डिजाइन के लिए सरलीकृत एसआरडी आधारित पद्धति (वायु सुरंग प्रयोगों और सी एफ डी सिम्युलेशन के साथ) सत्यापन, का प्रमुख योगदान रहा है । अंत मे इस विषय पर संभावित भविष्य में शोध किए जाने के सुझावों का भी उल्लेख किया गया है।

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ABL	Atmospheric Boundary Layer
ABS	American Bureau of Shipping
ADV	Acoustic Doppler Velocimeters
AFS	Advanced Flight Simulator
AGL	Above Ground Level
ALH	Advanced Light Helicopter
BAE	British Aerospace, UK
BFS	Backward Facing Step
ASW	Anti-Submarine Warfare
CAA	Civil Aviation Authority, UK
CAP	Civil Air Publication
CCG	Canadian Coast Guard
CFD	Computational Fluid Dynamics
CFDRC	CFD Research Corporation, Alabama, USA
COMREL	Communication Relay
CPF	Canadian Patrol Frigate
CRFM	Computational Rotor Aeroelastic Performance Prediction Code – Developed by DERA, UK
CVN	Aircraft Carrier (Nuclear Propulsion)
DERA	Defence Evaluation and Research Agency, UK
DDG	Guided missile Destroyers, NATO Classification
DES	Detached Eddy Simulation
DI	Dynamic Interface
DIPES	Deck Interface Pilot Effort Scale
DNS	Direct Numerical Simulation
DNV-GL	Det Norske Veritas - Germinischer Lloyd - Classification Society
DSTO	Defence Science and Technology Organisation, Australia

EFM	Experimental Flow Measurements
EFV	Experimental Flow Visualisation
EW	Electronic Warfare
ESM	Electronic Support Measures
ECM	Electronic Counter Measures
ECCM	Electronic Counter Counter Measures
ETP	Experimental Test Pilot
FE	Finite Element
FOCFT	First of the Class Flight Trials
FTE	Flight Test Engineer
fps	Frames per second
GASR	Group of Aerodrome Safety Regulators, CAA, UK -
GW	Gross Weight
HADR	Humanitarian and Disaster Relief
HAL	Hindustan Aeronautic Limited
Helo	Helicopter
Helodeck	Helicopter Deck
HIFR	Helicopter In-Flight Refuelling
HOSTAC	Helicopter Operations from Ships other than Aircraft Carriers
IACS	International Association of Classification Societies
IGE	In Ground Effect
JSHIP	Joint Shipboard Integration Process
LC	Least Count
LBM	Lattice Boltzmann Methods
LDA	Laser Doppler Anemometry
LDV	Laser Doppler Velocimetry
LES	Large Eddy Simulations
LHA	Landing Helicopter Assault
LMAR	Low Momentum Area Ratio
LPD	Landing Platform Decks
LPH	Landing Platform Helicopters
LSO	Landing Safety Officer

LUH	Light Utility Helicopters
MATCH	Medium Altitude Torpedo Carrying Helicopter
MCM	Mine Counter Measure
MEDEVAC	Medical Evacuation
MIF	Motion Induced Fatigue
MII	Motion Induced Interruptions
NAO	Naval Air Operations
NASA	National Aeronautics and Space Administration, USA
NATF	Naval Aerodynamic Test Facility, USA
NATO	North Atlantic Treaty Organisation
NATOPS	Naval Air Training and Operating Procedures Standardization, USN
NAVAIR	Naval Air Systems Command, USA
NAWC	Naval Air Warfare Centre, USA
NLR	National Aerospace Laboratory, Netherlands
NLDE	Non Linear Disturbance Equations
NHUH	Naval Heavy Utility Helicopters
NLUH	Naval Light Utility Helicopters
NMUH	Naval Medium Utility Helicopters
NPS	Naval Postgraduate School, USA
NRC-IAR/AL	National Research Council-Institute for Aerospace Research/ Aerodynamics Laboratory, Canada
NSWC	Naval Surface Warfare Center, USA
NVD	Night Vision Device
OGE	Out of Ground Effect
ONERA	French Office National d'études et de Recherches Aérospatiales - French Aerospace Lab (Lille), France
OP	Orifice Plate
OPV	Offshore Patrol Vessels
PANS	Partially-Averaged Navier-Stokes
PIV	Particle Image Velocimetry
PTP	Production Tests Pilots

RADAS	Rotorcraft Aero Dynamics and Aeroacoustics Solver
RAS	Replenishment at Sea
RANS	Reynolds Averaged Navier Stokes Equations
RAO	Response Amplitude Operator
RAS	Replenishment at Sea
RAST	Recovery, Assist, Secure and Traverse
RCS	Radar Cross Section
RC	Remotely Controlled
RLR	Recirculation Length Ratio
RN	Royal Navy
RPM	Rotations per minute
RSM	Reynolds Stress Model
RTO	Research and Technology Organisation, NATO
SAIF	Ship/Air Interface Framework, Royal Navy
SAFEDI	Safe Dynamic Interface Program, US Navy
SALTS	Shipboard Aircraft LIDAR Turbulence Sensor
SAMS	Ship Airwake Measurement System
SAR	Search and Rescue
SGS	Sub Grid Scale
SHOL	Ship Helicopter Operating Limits
SIR	SRD Influence Ratio
SME	Subject Matter Expert
SRM	Steady Rotor Model
SS	Warship Super Structures
TTCP	The Technical Cooperation Program
UAV	Unmanned Aerial Vehicle
URANS	Unsteady Reynolds Averaged Navier-Stokes
URM	Unsteady Rotor Model
USCG	United States Coast Guard
USN	United States Navy

USNA	United States Naval Academy
VERTREP	Vertical Replenishment
VFD	Variable Frequency Drive
WOD	Wind Over Deck

NOMENCLATURE

A_{LM}	Area of low momentum /high smoke density area on helodeck
A_{HDK}	Area of helodeck
B	Breadth of hangar
b	Half-breadth of hangar
Calibration Function Q_p	$\frac{P_5 - P_m}{\frac{1}{2}\rho V^2}$
Calibration Function S_p	$\frac{H - P_5}{P_5 - P_m}$
Calibration function $f(\theta)$	$\frac{P_3 - P_1}{P_5 - P_m}$
Calibration function $f(\psi)$	$\frac{P_2 - P_4}{P_5 - P_m}$
C_{OP}	Discharge coefficient of Orifice Plate
D	Diameter of the cylinder on model
D_{OP}	Pipe diameter connected to Orifice Plate
D/h	Normalised diameter of cylinder
D_r	Indicative diameter of Helo/SRD rotor
D_r/ L_{HDK}	Normalised indicative diameter of Helo rotor
d_{OP}	Diameter of the orifice hole
F_α	Area factor for thermal expansion of Orifice Plate
f_{SLF}	Shear Layer Flapping Frequency
G	Gap between Inclined plate and the hangar at the edge of hangar top
h	Height of hangar
H	Total Pressure
H_{BFS}	Height of Step in BFS
kts	Knots
LMAR	Low Momentum Area Ratio, A_{LM}/A_{HDK}

L_{HDK}	Length of Helodeck
L_N	Length of notch in Hangar shapes
L_R	Ratio of the length of recirculation to the height of the hangar, RLR, (l_R/h)
L_{SS}	Length of Superstructure
L_S	Length of Ship model
L1	Tapping point position prior OP from OP centreline
L2	Tapping point position post OP from OP centreline
l_R	Length of recirculation on helodeck
l_{SI}	Length of forward tip of smoke inception from hangar
P, P_{stat}	Static Pressure
P_1, P_2, P_3, P_4, P_5	Pressures sensed by 5-hole probe
P_m	$\frac{P_1 + P_2 + P_3 + P_4}{4}$
p_1	Upstream absolute pressure on Orifice Plate
Q_m	Mass flow rate across the Orifice Plate
Q_{OP}	Volume-based flow rate across the Orifice Plate
Re	Reynolds number
R_{eS}	Local Reynolds number of ship velocity
R_{eR}	Local Reynolds number of SRD downwash velocity
R_{eOP}	Local Reynolds number in OP
SFS	Simplified Frigate Ship
SIR	SRD Influence ratio on recirculation, Ratio of the length of forward tip of smoke inception from hangar to the height of the hangar, l_{SI}/h
SRD	Simplified Rotor Downwash
TI	Turbulence Intensity
t_{OP}	Orifice plate thickness
U_{ref}	Reference Velocity in BFS
V	Total velocity vector at a point, $\sqrt{(V_x)^2 + (V_y)^2 + (V_z)^2}$
V_{mag}'	Normalised total velocity vector at a point

V_S	Velocity vector of ship motion
V_r	Velocity vector of downwash through SRD
V_R	Resultant velocity of ship velocity and SRD downwash velocity, $\sqrt{(V_S)^2 + (V_r)^2}$
V_w	$\lvert V_{wod} \rvert$, Free stream velocity in wind tunnel
V_{wind}	Velocity vector of Wind
V_{wod} , WOD	Velocity vector of Wind Over Deck
V_x'	Normalised velocity component in x direction
V_x, u	Velocity component in x direction
$\overline{V_x}$	Mean of normalised x component of velocity
V_{xy}	Tangential velocity vector on x-y plane, $\sqrt{(V_x)^2 + \left(V_y\right)^2}$
V_{xy}'	Normalised tangential velocity vector on x-y plane
V_{xz}	Tangential velocity vector on x-z plane, $\sqrt{(V_x)^2 + (V_z)^2}$
V_{xz}'	Normalised tangential velocity vector on x-z plane
V_y'	Normalised velocity component in y direction
V_y, v	Velocity component in y direction
V_{yz}	Tangential velocity vector on y-z plane, $\sqrt{\left(V_y\right)^2 + (V_z)^2}$
V_{yz}'	Normalised tangential velocity vector on y-z plane
V_z'	Normalised vertical component of velocity (in z direction)
V_z, w	Vertical Component of velocity (in z direction)
$\overline{V_z}$	Mean of normalised vertical component of velocity
$\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$	Diagonal components of Reynolds stresses in terms of velocity fluctuations in x, y and z directions respectively
WOPWOD	Without Pipe Without Downwash (Only Ship)
WPWOD	With Pipe Without Downwash (Ship with SRD switched off)
WPWD	With Pipe With Downwash (Ship with SRD switched on)
X direction	Longitudinal direction along length of ship

x', x/L_{HDK}	Normalised x coordinate
Y direction	Transverse / Athwartship direction
y', y/b	Normalised y coordinate
Z direction	Vertical Direction
z', z/h	Normalised z coordinate
α	Advance Velocity Ratio, (V_S/ V_R)
β_{OP}	Diameter ratio of Orifice Plate, $(d/D)_{OP}$
β	Ratio of the tangential velocity of the cylinder circumference to the free stream velocity
γ	Ratio of Reynolds number of Ship and SRD velocity, R_{eS}/R_{eR}
ε	Turbulent dissipation rate
ε_{OP}	Expansibility factor in OP flow
$\bar{k}$, k	Turbulent Kinetic Energy
μ_t	Turbulent viscosity
ρ	Density of air
ρ_1	Density of the fluid at the upstream condition of OP
θ	Pitch Angle of wind over deck at a given point
Ψ	Yaw Angle of the wind over deck at a point
ω	Specific dissipation rate
∆h	Manometer pressure head
∆p	Pressure differential across Orifice Plate