INVESTIGATIONS ON TRANSIENT FLOW IN DRAFT TUBE OF A FRANCIS TURBINE DURING LOAD VARIATION

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by

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Dedicated to

The abiding memory of my beloved grandfather - late Saif-Ud-Din Saifi, my first teacher and the most affectionate person I have ever met.

Mom and Dad.
At their feet lies my existence; in their service my life finds purpose.

Certificate

This is to certify that the thesis entitled **"Investigations on Transient Flow in Draft Tube of a Francis Turbine During Load Variation"**, submitted by **Mr. Faiz Azhar Masoodi** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Energy Science and Engineering, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

Prof. Rahul Goyal
Assosiate Professor
Department of Energy Science and Engineering,
Indian Institute of Technology Delhi.

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"I can no other answer make but thanks,
And thanks; and ever thanks"
– William Shakespeare, *The Twelfth Night*.

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Faiz Azhar Masoodi
21/08/2025

Abstract

Off-design and transient operations of hydraulic turbines is contemporarily frequented for balancing the grid power intermittence introduced by variable renewable energy. Steady state operation is characterized by a constant discharge and varied conditions of load such as the best efficiency point, part load, deep part load, high load and full load. Load change, and start/stop events are the regimes of transient operation and involve a time varying flow rate. An adverse consequence of off-design/transient turbine operations is development of vortex breakdown phenomenon. Vortex breakdown in draft tubes manifests as a rotating vortex rope at part load operation and enlarged vortex core at high load operation. Development of vortex breakdown causes a complete disorganization of the flow with development of unfavourable pressure fluctuation leading to loss of turbine efficiency.

This thesis encapsulates thorough numerical investigations on the formation and elimination of the enlarged vortex core and rotating vortex rope consequent to load changes on the turbine. Steady state turbine operation at best efficiency point, high load and part load conditions as well as transient operations between these operating points are simulated. Initially, a detailed assessment of the applicability of URANS-based standard $k-\epsilon$ and SST $k-\omega$ turbulence models for the characterization of a part load vortex rope is carried out. Simulations are performed at part load using the commercially available ANSYS CFX software. Obtained axial and radial velocity fields are compared with results from the experiment. A detailed spectral analysis is carried out using Fast Fourier Transforms to identify the dominant frequencies of pressure fluctuation in numerical and experimental data. A mismatch between experiment and simulation is identified and quantified to evaluate the utility of URANS models for investigations on vortex breakdown. It is discerned that more advanced turbulence models are required for an accurate flow field prediction.

Subsequent simulations of steady state turbine operation at best efficiency point, high load and part load, as well as transient operations between these operating points, are conducted using OpenFOAM open-source software. Turbulence closure is attained using the scale adaptive simulations - shear stress transport turbulence model. Dynamic meshing based on a Laplacian smoothing scheme is used to account for mesh deformation arising from guide vane motion during load change.

The pressure and velocity fields have been determined and analyzed to elucidate the physics of vortex breakdown, the phenomenon underlying the formation of the enlarged vortex core and rotating vortex rope. At best efficiency point, a close agreement between numerical and experimental velocity profiles is seen. However, at high load and part load, while the numerical results agree satisfactorily with experiment toward the peripheral region, a slightly increased deviation is seen in the central region due to the presence of vortex breakdown.

Vortex breakdown in the draft tube occurs due to exceedance of the swirl magnitude beyond a critical value. Transient operations of the turbine from best efficiency point to off-design conditions lead to an exceeded magnitude of swirl in the flow exiting the runner. Consequently, vortex breakdown occurs in the draft tube causing an unusual flow pattern. The vortex core significantly swells up toward high load. A central axial flow stagnation commences centrally near 50% of the transient sequence duration. Subsequently, flow is separated into a nearly stagnant, expanded central vortex core, and a high-speed outflow surrounding it. A steep axial velocity change is observed radially across the interface of outflow and vortex core earmarking strong shear layers, which roll up to form a compact spiral structure. Flow reversals within the enlarged vortex core are seen to be intermittent. Reverse transition from high load to best efficiency point results in a gradual reorganization of the velocity field, purging main features of the vortex breakdown such as flow reversals and stagnation, within 50% of the time of load change. Onward, the flow is gradually restored to a form characteristic of the best efficiency point.

In the best efficiency point to part load transient sequence the changes in velocity field are noticeable after about 30% of the time of transient operation has elapsed. VB commences with a central flow stagnation in the draft tube. The flow separates about a stagnation point leading to development of a stagnation region that dilates radially in time. Post 50% of the transient operation intermittent flow reversals are observed within the stagnation region. The flow at PL is stabilized after completion of the transient sequence. A wavy boundary of the stagnation region earmarks the strong radial gradients of axial velocity representing strong interfacial shear layers between the stagnation region and surrounding outflow. The shear layers roll up leading to formation of rotating vortex rope. The flow morphology depicts a spiral type vortex breakdown.

सारांश

हाइड्रोलिक टरबाइन का ऑफ-डिज़ाइन और क्षणिक (transient) संचालन आजकल अक्सर उस ग्रिड पावर अस्थिरता को संतुलित करने के लिए किया जाता है, जो परिवर्तनीय नवीकरणीय ऊर्जा स्रोतों से उत्पन्न होती है। स्थिर अवस्था (steady state) संचालन को एक स्थिर प्रवाह दर और विभिन्न भार स्थितियों – जैसे कि सर्वश्रेष्ठ दक्षता बिंदु, आंशिक भार, गहरे आंशिक भार, उच्च भार और पूर्ण भार – से परिभाषित किया जाता है। भार परिवर्तन तथा स्टार्ट/स्टॉप जैसी घटनाएँ क्षणिक संचालन के अंतर्गत आती हैं, जहाँ प्रवाह दर समय के साथ बदलती है। ऑफ-डिज़ाइन/क्षणिक टरबाइन संचालन का एक प्रतिकूल परिणाम वॉर्टेक्स ब्रेकडाउन (vortex breakdown) की उत्पत्ति है। ड्राफ्ट ट्यूब में वॉर्टेक्स ब्रेकडाउन आंशिक भार पर घूमते हुए वॉर्टेक्स रोप (rotating vortex rope) और उच्च भार पर विस्तारित वॉर्टेक्स कोर के रूप में प्रकट होता है। वॉर्टेक्स ब्रेकडाउन का विकास प्रवाह को असंगठित कर देता है और अवांछित दाब उतार-चढ़ाव पैदा करता है, जिससे टरबाइन दक्षता घट जाती है।

यह शोध प्रबंध टरबाइन पर भार परिवर्तन के परिणामस्वरूप विकसित होने वाले विस्तारित वॉर्टेक्स कोर और घूमते वॉर्टेक्स रोप की उत्पत्ति एवं उनके निराकरण पर गहन संख्यात्मक जाँच प्रस्तुत करता है। स्थिर अवस्था में टरबाइन संचालन को सर्वश्रेष्ठ दक्षता बिंदु, उच्च भार और आंशिक भार स्थितियों पर तथा इन बिंदुओं के बीच क्षणिक संचालन को भी सिमुलेट किया गया है। प्रारंभ में, आंशिक भार वॉर्टेक्स रोप के लक्षण निर्धारण हेतु URANS आधारित मानक $k-\epsilon$ और SST $k-\omega$ टर्बुलेंस मॉडल की प्रयोज्यता का विस्तृत मूल्यांकन किया गया। आंशिक भार पर सिमुलेशन ANSYS CFX वाणिज्यिक सॉफ़्टवेयर का उपयोग करके किए गए और प्राप्त अक्षीय व रेडियल वेग क्षेत्रों की तुलना प्रायोगिक परिणामों से की गई। प्रेशर उतार-चढ़ाव की प्रमुख आवृत्तियों को पहचानने हेतु FFT आधारित विस्तृत स्पेक्ट्रल विश्लेषण किया गया। प्रयोग और सिमुलेशन के बीच अंतर का मूल्यांकन कर यह स्पष्ट किया गया कि वॉर्टेक्स ब्रेकडाउन की सटीक भविष्यवाणी के लिए और अधिक उन्नत टर्बुलेंस मॉडलों की आवश्यकता है।

इसके बाद, स्थिर अवस्था (सर्वश्रेष्ठ दक्षता बिंदु, उच्च भार, आंशिक भार) और इन अवस्थाओं के बीच क्षणिक संचालन के सिमुलेशन OpenFOAM ओपन-सोर्स सॉफ़्टवेयर में किए गए। इसमें Scale Adaptive Simulation – Shear Stress Transport (SAS-SST) टर्बुलेंस मॉडल का उपयोग किया गया और लोड परिवर्तन के दौरान गाइड वेन की गति से उत्पन्न जाल (mesh) विकृति को समायोजित करने के लिए Laplacian smoothing आधारित डायनामिक मेसिंग का उपयोग हुआ। दबाव और वेग क्षेत्रों का विश्लेषण कर वॉर्टेक्स ब्रेकडाउन की भौतिकी, विशेषकर विस्तारित वॉर्टेक्स कोर और घूमते वॉर्टेक्स रोप की उत्पत्ति, स्पष्ट की गई। सर्वश्रेष्ठ दक्षता बिंदु पर संख्यात्मक और प्रायोगिक वेग प्रोफाइल में निकटतम सामंजस्य पाया गया। किंतु उच्च और

आंशिक भार पर, परिधीय क्षेत्र में तो परिणाम संतोषजनक थे, परंतु केंद्रीय क्षेत्र में वॉर्टेक्स ब्रेकडाउन की उपस्थिति के कारण कुछ विचलन पाया गया।

ड्राफ्ट ट्यूब में वॉर्टेक्स ब्रेकडाउन तब होता है जब स्वर्ल की परिमाण (swirl magnitude) एक निर्णायक सीमा से अधिक हो जाता है। टरबाइन का क्षणिक संचालन, सर्वश्रेष्ठ दक्षता बिंदु से ऑफ-डिज़ाइन स्थितियों की ओर जाते समय, रनर से निकलने वाले प्रवाह में स्वर्ल को अत्यधिक बढ़ा देता है। फलस्वरूप, ड्राफ्ट ट्यूब में वॉर्टेक्स ब्रेकडाउन उत्पन्न होता है और असामान्य प्रवाह संरचना बनती है। उच्च भार पर वॉर्टेक्स कोर का आकार काफी बढ़ जाता है। लगभग 50% क्षणिक क्रम की अवधि में केंद्रीय अक्षीय प्रवाह स्थगन (stagnation) आरंभ हो जाता है। इसके बाद प्रवाह एक लगभग स्थिर, विस्तारित केंद्रीय वॉर्टेक्स कोर और उसके चारों ओर उच्च वेग वाले आउटफ़्लो में विभाजित हो जाता है। इस इंटरफेस पर तेज अक्षीय वेग परिवर्तन देखा गया, जो प्रबल शियर लेयर्स बनाता है और अंततः एक कॉम्पैक्ट सर्पिल संरचना में लिपट जाता है। विस्तारित वॉर्टेक्स कोर के भीतर प्रवाह का उलटना (flow reversal) रुक-रुक कर होता है। उच्च भार से सर्वश्रेष्ठ दक्षता बिंदु की ओर उलटे संक्रमण के दौरान लगभग 50% समय में प्रवाह क्षेत्र पुनर्गठित हो जाता है और वॉर्टेक्स ब्रेकडाउन की मुख्य विशेषताएँ जैसे प्रवाह उलटना और स्थगन समाप्त हो जाती हैं। इसके बाद प्रवाह धीरे-धीरे सर्वश्रेष्ठ दक्षता बिंदु की विशेषता वाले रूप में लौट आता है।

सर्वश्रेष्ठ दक्षता बिंदु से आंशिक भार की क्षणिक क्रमावली में, प्रवाह वेग क्षेत्र में परिवर्तन लगभग 30% समय बीत जाने के बाद स्पष्ट दिखाई देते हैं। VB ड्राफ्ट ट्यूब में केंद्रीय प्रवाह स्थगन से आरंभ होता है। प्रवाह एक स्थगन बिंदु के चारों ओर विभाजित हो जाता है, जिससे एक स्थगन क्षेत्र विकसित होता है जो समय के साथ रेडियल रूप से फैलता है। 50% समय के बाद इस स्थगन क्षेत्र में रुक-रुक कर प्रवाह उलटना देखा गया। आंशिक भार पर प्रवाह क्षणिक क्रम पूरा होने के बाद स्थिर हो जाता है। स्थगन क्षेत्र की लहरदार सीमा, अक्षीय वेग के तीव्र रेडियल प्रवणताओं को दर्शाती है, जो स्थगन क्षेत्र और उसके चारों ओर के आउटफ़्लो के बीच मजबूत इंटरफ़ेस शियर लेयर का प्रतिनिधित्व करती है। ये शियर लेयर्स लिपट कर घूमते वॉर्टेक्स रोप का निर्माण करती हैं। प्रवाह संरचना सर्पिल प्रकार के वॉर्टेक्स ब्रेकडाउन को प्रदर्शित करती है।

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Abbreviations

AMI	**A**rbitrary **M**esh **I**nterface
APG	**A**dverse **P**ressure **G**radient
BEP	**B**est **E**fficiency **P**oint
CFD	**C**omputational **F**luid **D**ynamics
CRIO	**C**ompact **R**econfigurable **I**nput/**O**utput
DNS	**D**irect **N**umerical **S**imulation
EVC	**E**nlarged **V**ortex **C**ore
GV	**G**uide **V**ane
HL	**H**igh **L**oad
HPC	**H**igh **P**erformance **C**omputer
IDC	**I**nner **C**ore **D**iameter
LES	**L**arge **E**ddy **S**imulation
LEVM	**L**inear **E**ddy **V**iscosity **M**odel
Nd:YAG	**N**eodymium-**d**oped **Y**ttrium **A**luminum **G**arnet
PISO	**P**ressure **I**mplicit with **S**plitting of **O**perator
PIV	**P**article **I**mage **V**elocimetry
PL	**P**art **L**oad
PVC	**P**recessing **V**ortex **C**ore
RANS	**R**eynolds-**A**veraged **N**avier–**S**tokes
RVR	**R**otating **V**ortex **R**ope
SIMPLE	**S**emi-**I**mplicit **M**ethod for **P**ressure-**L**inked **E**quations
URANS	**U**nsteady **R**eynolds-**A**veraged **N**avier–**S**tokes
VB	**V**ortex **B**reakdown

Symbols

f_n	Runner frequency (Hz)
k	Turbulent kinetic energy (J)
n_s	Specific speed (-)
I	Turbulence intensity
T_G	Generator torque
U	Horizontal component of velocity within numerical plane (m/s)
U_x	Velocity x-component (m/s)
U_y	Velocity y-component (m/s)
U_z	Velocity z-component (m/s)
U^*	Normalized horizontal component of velocity within numerical plane (-)
V^*	Normalized velocity component normal to numerical plane (-)
W	Axial component of velocity within numerical plane (m/s)
W^*	Normalized axial component of velocity within numerical plane (-)
x^*	Normalized radial distance from draft tube central axis
α	Guide vane angle ($\circ$)
ϵ	Turbulence dissipation rate (m^2/s^3)
ν	Kinematic viscosity (m^2/s)
ν_t	Turbulent or eddy viscosity (m^2/s)
v_p	Planar velocity within central xz plane(m/s)
ω_{gv}	Guide vane angular speed ($^\circ$/s)