

**STUDIES ON DIRECTION FINDING AND
MOTION STATE ESTIMATION OF
MANEUVERING AERIAL VEHICLE FROM ITS
ACOUSTIC EMISSION**

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**CENTRE FOR APPLIED RESEARCH IN ELECTRONICS
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ACOUSTIC EMISSION**

by

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CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

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Dedicated to

My parents and my wife

Certificate

This is to certify that the thesis entitled “**Studies on direction finding and motion state estimation of maneuvering aerial vehicle from its acoustic emission**” being submitted by **Mr. Sunil Kumar Sinha** to the Centre for Applied Research in Electronics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Abstract

Aerial vehicles perform a crucial role in both commercial and military applications. Low flying aerial vehicles or aircrafts are also used for illegal activities across territorial borders due to difficulty in detecting the air vehicles by radar. Tracking of low altitude aircraft through radar systems is ineffective and costly in comparison with tracking via acoustic signature. Ground based sensors used for measuring acoustic signals of aircraft can be applied to detect and distinguish targets. This thesis presents the development of an acoustic attenuation simulation model, that estimates the attenuation observed by the acoustic signal emitted by the aerial vehicle during its in-air propagation. Field experiments are conducted to analyze the efficacy of the model. Directivity pattern measurement results in azimuth and elevation show very close to omni-directional pattern for both the frequency bands and hence, have negligible effect on transmission loss. It is concluded that results from the acoustic attenuation simulation models are comparable with measured acoustic attenuation when an acoustic source is moving with varying speed and altitude. Sensitivity analysis of total transmission loss with environmental parameters is also done in this chapter. The effect on total transmission loss by variation of environmental parameters like temperature, pressure and relative humidity is considered for analysis. The detailed analysis about contribution of environmental parameter variation towards transmission loss estimation can be used in providing uncertainty bounds due to imperfect environmental parameter knowledge, for motion parameter estimation of aerial vehicles.

An acoustic vector sensor is also designed and fabricated to estimate the direction of arrival of the aerial vehicle. A p-p based acoustic vector sensor is developed and the design aspect of the same is described in this thesis. Various base mounting structures

for the acoustic vector sensor are considered for suitable use in field. The same is used in the field experiments. The directivity pattern of the developed sensor is measured. An almost omnidirectional pattern is observed in both azimuth and elevation. The mathematical expressions for the estimation of elevation and azimuth angles in terms of the cross power spectrum density are given. Numerical simulation is performed for the direction of arrival (DOA) estimation of a single-frequency acoustic source with varying signal to noise ratio (SNR) and microphone separation distance. The results show that the absolute elevation angle error increases with an increase in microphone separation distance from the central microphone. Other results are also presented in the thesis.

The thesis also presents the study of a method to estimate the azimuth and elevation angles of maneuvering in-air tonal source and quadcopter by using an acoustic vector sensor. Field experiments are also conducted where a quadcopter is flown and its direction of arrival is estimated from the acoustic signal emitted by the quadcopter. The estimated results are compared with reference azimuth and elevation angles measured from Global Positioning System (GPS) values. An algorithm for DOA estimation of maneuvering tonal source and quadcopter's acoustic signature is also developed. The thesis also presents an estimator of a quadcopter's all motion states. A time-frequency analysis is performed from the received acoustic signal and the present motion state of quadcopter is estimated. Field experiments are conducted, where a quadcopter is flown in different motion states and the acoustic signal emitted by the quadcopter is analysed for motion state estimation.

An estimator is developed for the state of the quadcopter during flight. A motion state estimation table is prepared for the estimation of quadcopter's states. The attenuation of the acoustic signal during its propagation is modeled and its results are further used to estimate the flight state of the aerial vehicle. The sensor positioned on the ground estimates the DOA and motion state of the quadcopter. Knowledge of estimated parameters enables users at ground to make inferences about aerial vehicles. The efficacy of the state estimator is also tested by flying the quadcopter in simulation mode in two modes i.e. in stationary or hover state and in forward motion state.

सार

विमान वाणिज्यिक और सैन्य अनुप्रयोगों दोनों में महत्वपूर्ण भूमिका निभाते हैं। रडार द्वारा कम उंचाई पर उड़ने वाले हवाई वाहनों का पता लगाने में कठिनाई के कारण क्षेत्रीय सीमाओं के पार अवैध गतिविधियों में भी विमानों का उपयोग किया जाता है। ध्वनिक हस्ताक्षर के माध्यम से ट्रैकिंग की तुलना में रडार सिस्टम के माध्यम से कम उंचाई वाले विमानों की ट्रैकिंग अप्रभावी और महंगी है। विमान के ध्वनिक संकेतों को मापने के लिए उपयोग किए जाने वाले ग्राउंड आधारित सेंसर का उपयोग लक्ष्य का पता लगाने और भेद करने के लिए किया जा सकता है।

यह थीसिस एक ध्वनिक क्षीणन सिमुलेशन मॉडल के विकास को प्रस्तुत करती है, जो विमान के इन-एयर प्रचार के दौरान उत्सर्जित ध्वनिक सिग्नल द्वारा देखे गए क्षीणन का अनुमान लगाती है। मॉडल की प्रभावकारिता का विश्लेषण करने के लिए फील्ड प्रयोग किए गए हैं। डायरेक्टिविटी पैटर्न मापन के परिणाम दिगंश और उंचाई दोनों आवृत्ति बैंडों के लिए ओमनी-दिशात्मक पैटर्न के बहुत करीब दिखाते हैं और इसलिए, संचरण हानि पर नगण्य प्रभाव पड़ता है। यह निष्कर्ष निकाला गया है कि ध्वनिक क्षीणन सिमुलेशन मॉडल के परिणाम मापा ध्वनिक क्षीणन के साथ तुलनीय होते हैं जब एक ध्वनिक स्रोत अलग-अलग गति और उंचाई के साथ आगे बढ़ रहा होता है। इस अध्याय में पर्यावरणीय मापदंडों के साथ कुल संचरण हानि का संवेदनशीलता विश्लेषण भी किया गया है। तापमान, दबाव और सापेक्ष आर्द्रता जैसे पर्यावरणीय मापदंडों में बदलाव से कुल संचरण हानि पर प्रभाव विश्लेषण के लिए माना जाता है। हवाई वाहनों के गति पैरामीटर आकलन के लिए, अपूर्ण पर्यावरणीय पैरामीटर ज्ञान के कारण अनिश्चितता सीमा प्रदान करने में संचरण हानि अनुमान के लिए पर्यावरणीय पैरामीटर भिन्नता के योगदान के बारे में विस्तृत विश्लेषण का उपयोग किया जा सकता है।

विमान के आगमन की दिशा का अनुमान लगाने के लिए एक ध्वनिक वेक्टर सेंसर भी डिजाइन और निर्मित किया गया है। एक पी-पी आधारित ध्वनिक वेक्टर सेंसर विकसित किया गया है और इस थीसिस में उसी के डिजाइन पहलू का वर्णन किया गया है। क्षेत्र में उपयुक्त उपयोग के लिए ध्वनिक वेक्टर सेंसर के लिए विभिन्न आधार बढ़ते संरचनाओं पर विचार किया जाता है। फील्ड प्रयोगों में भी यही प्रयोग किया गया है। विकसित सेंसर के डायरेक्टिविटी पैटर्न को मापा गया है। दिगंश और उंचाई दोनों में लगभग सर्वदिशात्मक पैटर्न देखा जाता है। क्रॉस पावर स्पेक्ट्रम घनत्व के संदर्भ में उंचाई और दिगंश कोणों के आकलन के लिए गणितीय अभिव्यक्तियाँ दी गई हैं। शोर अनुपात (एसएनआर) और माइक्रोफोन पृथक्करण दूरी के अलग-अलग सिग्नल के

साथ एकल-आवृत्ति ध्वनिक स्रोत के आगमन की दिशा (डीओए) के आकलन के लिए संख्यात्मक सिमुलेशन किया जाता है। परिणाम बताते हैं कि केंद्रीय माइक्रोफोन से माइक्रोफोन पृथक्करण दूरी में वृद्धि के साथ पूर्ण उन्नयन कोण त्रुटि बढ़ जाती है। अन्य परिणाम भी थीसिस में प्रस्तुत किए गए हैं।

थीसिस एक ध्वनिक वेक्टर सेंसर का उपयोग करके इन-एयर टोनल स्रोत और क्वाड्रॉप्टर के मोशन के दिगंश और उन्नयन कोणों का अनुमान लगाने के लिए एक विधि का अध्ययन भी प्रस्तुत करता है। फील्ड प्रयोग भी आयोजित किए जाते हैं जहां क्वाड्रॉप्टर उड़ाया जाता है और क्वाड्रॉप्टर द्वारा उत्सर्जित ध्वनिक सिग्नल से इसके आगमन की दिशा का अनुमान लगाया जाता है। अनुमानित परिणामों की तुलना ग्लोबल पोजिशनिंग सिस्टम (जीपीएस) मूल्यों से मापे गए संदर्भ दिगंश और उन्नयन कोणों से की गई है। टोनल स्रोत और क्वाड्रॉप्टर के ध्वनिक हस्ताक्षर के डीओए आकलन के लिए एक एल्गोरिदम भी विकसित किया गया है। थीसिस क्वाड्रॉप्टर की गति की सभी अवस्थाओं का अनुमानक भी प्रस्तुत करती है। प्राप्त ध्वनिक संकेत से एक समय-आवृत्ति विश्लेषण किया जाता है और क्वाड्रॉप्टर की वर्तमान गति स्थिति का अनुमान लगाया जाता है। फील्ड प्रयोग आयोजित किए गए हैं, जहां एक क्वाड्रॉप्टर को अलग-अलग मोशन स्टेट्स में प्रवाहित किया जाता है और क्वाड्रॉप्टर द्वारा उत्सर्जित ध्वनिक सिग्नल का गति अवस्था के आकलन के लिए विश्लेषण किया जाता है।

उड़ान के दौरान क्वाड्रॉप्टर की स्थिति के लिए एक अनुमानक विकसित किया गया है। क्वाड्रॉप्टर की अवस्थाओं के आकलन के लिए एक मोशन स्टेट एस्टीमेशन टेबल तैयार की जाती है। इसके प्रसार के दौरान ध्वनिक संकेत के क्षीणन को प्रतिरूपित किया जाता है और इसके परिणामों का उपयोग हवाई वाहन की उड़ान स्थिति का अनुमान लगाने के लिए किया जाता है। जमीन पर स्थित सेंसर क्वाड्रॉप्टर के डीओए और गति की स्थिति का अनुमान लगाता है। अनुमानित मापदंडों का ज्ञान जमीन पर उपयोगकर्ताओं को हवाई वाहनों के बारे में अनुमान लगाने में सक्षम बनाता है। राज्य अनुमानक की प्रभावकारिता का परीक्षण क्वाड्रॉप्टर को सिमुलेशन मोड में दो मोड में यानी स्थिर या होवर अवस्था में और आगे की गति की स्थिति में उड़ाकर भी किया जाता है।

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Abbreviations

AAE	absolute angular error
AATMAV	acoustic attenuation model for aerial vehicle
ADC	analog-to-digital converter
AE	angular error
AVS	acoustic vector sensor
AV	aerial vehicle
CPSD	cross power spectral density
DOA	direction of arrival
EO	electro optic
GPS	global positioning system
MUSIC	multiple signal classification
p-p	pressure-pressure
p-u	pressure-particle velocity
p-a	pressure-particle acceleration
u-u	particle velocity-particle velocity
RF	radio frequency
RMSAE	root mean square angular error
RSS	received signal strength
RH	relative humidity
SNR	signal to noise ratio
STFT	short time fourier transform
TDOA	time difference of arrival

T-F	time-frequency
TL	transmission loss
UAV	unmanned aerial vehicle
ULA	uniform linear array