STUDIES ON UNDERWATER DIRECTIONAL ACOUSTIC SENSOR

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

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Submitted

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Dedicated to

Mother India

Certificate

This is to certify that the thesis entitled **"Studies on Underwater Directional Acoustic Sensor"** being submitted by **Mr. Bipin Kumar** 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 bonafide research work carried out by him under my supervision. In my 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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Bipin Kumar

Abstract

Acoustic sensors that preferentially detect sound from a given direction over other directions are known as directional acoustic sensors. Several underwater directional acoustic sensors have been investigated in the thesis. Analytical, simulation and experimental studies have been conducted, and prototypes of first-order and second-order directional acoustic sensors have been developed. Additionally, an analytical expression has been derived to determine the weights of 8 and 10-channel receivers of third-order directional acoustic sensors to achieve the desired directivity index.

A first-order directional acoustic sensor is also known as an Acoustic Vector Sensor (AVS). We have done a comparative study of various types of underwater AVS in the form of analytical, computer simulation, and experimental studies for the underwater environment (by drawing on previous research). Analytical approaches are utilised to compare the P-P, P-U, and PAGE-based AVS in Signal-to-Self Noise Ratio (SSNR) and SNR. We also derive an analytical expression for the SNR of particle velocity in the presence of correlated and uncorrelated ambient noise scenarios for various inter-element spacings.

We investigate the design parameters for a P-U based directional acoustic sensor using Finite Element Method (FEM) modelling and experimental work to acquire a more in-depth comprehension of its capabilities. We have built a prototype of AVS at the Indian Institute of Technology, Delhi and carried out experimental research at the National Institute of Ocean Technology (NIOT), Chennai. We have shown the beampattern in addition to the DoA estimation utilising a hydrophone array and the P-U based AVS.

A second-order directional acoustic sensor estimates pressure, particle velocity, and particle velocity gradient along three orthogonal axes. FEM analysis demonstrates the influence of mutual coupling and investigates the effect of misalignment of the sensitive axis of accelerometers on the beampattern. By adjusting the intersensor distance between the accelerometers along the sensitive axis, we examine the variation in the directivity index. We have also developed the prototype of a second-order directional acoustic sensor and tested it in an underwater tank at NIOT Chennai. We also obtained the beampattern and Directivity Index (DI).

A third-order directional acoustic sensor estimates the pressure, particle velocity, particle velocity gradient, and second-order velocity gradient along three orthogonal axes. We have derived the DI of a third-order directional acoustic sensor along with the weights of different channels for optimum DI. The DI of a third-order directional acoustic sensor varies from 7.7 dB to 12 dB. We also test the DI by varying the inter-sensor distance between the accelerometers positioned along the axis. We have also done a sensor misalignment study and found that the beampattern of second and third-order directional acoustic sensors highly depends on it. We also present various methods that can be used to make a third-order directional acoustic sensor by using hydrophones and accelerometers.

प्रस्तावना

विशेष दिशा में अन्य दिशाओं से आवाज़ को प्राथमिकता से डिटेक्ट करने वाले ध्वनिक ग्राहकों को दिशात्मक ध्वनिक ग्राहक कहा जाता है। थीसिस में कई उपकरणों के लिए निर्धारित ध्वनिक ग्राहकों के लिए अध्ययन किया गया है। विश्लेषणात्मक, सिमुलेशन और प्रायोगिक अध्ययन किए गए हैं, और प्रथम क्रम और द्वितीय क्रम के ध्वनिक ग्राहकों के प्रोटोटाइप विकसित किए गए हैं। साथ ही, तृतीय क्रम के ध्वनिक ग्राहकों के 8 और 10 चैनल रिसीवर के वेट्स का निर्धारण करने के लिए एक विश्लेषणात्मक संकेत भी निकाला गया है जो वांछित प्रत्यक्षता सूचकांक प्राप्त करने के लिए है।

प्रथम क्रम के ध्वनिक ग्राहक को एकांतर ध्वनिग्राही (एकूस) भी कहते हैं। हमने उपकरणों के तले पानी के वातावरण के लिए विभिन्न प्रकार के एकूस के तुलनात्मक अध्ययन किए हैं (पूर्व अनुसंधान पर आधारित)। सिग्नल-टू-सेल्फ नॉइज अनुपात (एसएसएनआर) और एसएनआर में पूर्वगणित विधियों के माध्यम से प्रेजर-प्रेजर, प्रेजर-यू और पेज-आधारित एकूस को तुलनात्मक विश्लेषण के लिए विश्लेषणात्मक दृष्टिकोन उपयोग किए गए हैं। हम अभिकंट तत्व विधि (एफईएम) मॉडलिंग का उपयोग करके प्रेस-यू आधारित ध्वनिक ग्राहक के डिज़ाइन पैरामीटर्स का अध्ययन करते हैं और इसकी क्षमता को और अधिगम करने के लिए प्रायोगिक काम किया है। हमने भारतीय प्रौद्योगिकी संस्थान, दिल्ली में एक एकूस के प्रोटोटाइप का निर्माण किया है और नेशनल इंस्टीट्यूट ऑफ़ ओसियन टेक्नोलॉजी (एनआईओटी), चेन्नई में प्रायोगिक अनुसंधान किया है। हमने हाइड्रोफोन एरे और प्रेस-यू आधारित एकूस का उपयोग करके बीमपैटर्न और डायरेक्टिविटी इंडेक्स (डीआई) का भी अनुमान लगाया है। द्वितीय क्रम के ध्वनिक ग्राहक तीन अपरोक्ष ध्वनि मापी, अणु वेग और अणु वेग ग्रेडिएंट को तीन अनुपातिक ध्वनि मापियों के माध्यम से आंकता करते हैं। एफईएम विश्लेषण द्वारा भौतिक संयोजन के प्रभाव की प्रदर्शनी और मानव बिगृधियों के असंबद्धता के प्रभाव की जाँच की गई है। संवेदकों के बीच अंतर-संवेदक दूरी को संवेदकों के संवेदनशील अक्ष के अलगाव से समीकरण करके, हम दृष्टिकोन इंडेक्स में परिवर्तन की जांच करते हैं। हमने द्वितीय क्रम के ध्वनिक ग्राहक के प्रोटोटाइप का भी विकास किया है और इसे नेशनल इंस्टीट्यूट ऑफ़ ओसियन टेक्नोलॉजी, चेन्नई में एक अधोदर टैंक में परीक्षण किया गया है। हमने बीमपैटर्न और डायरेक्टिविटी इंडेक्स (डीआई) की भी प्राप्ति की।

तृतीय क्रम के ध्वनिक ग्राहक में दबाव, अणु वेग, अणु वेग ग्रेडिएंट और द्वितीय क्रम के वेग ग्रेडिएंट का अनुमान लगाया जाता है जो तीन अनुपातिक ध्वनि मापियों के माध्यम से किया जाता है। हमने तृतीय क्रम के ध्वनिक ग्राहक

के डायरेक्टिविटी इंडेक्स (डीआई) को भी निकाला है साथ ही, विभिन्न चैनलों के वेट्स का निर्धारण करने के लिए विभिन्न तरीके प्रस्तुत किए हैं ताकि आवश्यक डीआई प्राप्त किया जा सके। तृतीय क्रम के ध्वनिक ग्राहक के डीआई विभिन्न अंतर-संवेदक दूरी को बदलकर भी टेस्ट किया गया है जो अक्ष के संवेदकों के अलगाव पर निर्भर करता है। हमने संवेदक असंबद्धता अध्ययन भी किया है और पाया है कि द्वितीय और तृतीय क्रम के ध्वनिक ग्राहक के बीमपैटर्न पर इसका अधिक निर्भर करता है। हम भी विभिन्न तरीकों को प्रस्तुत करते हैं जिनका उपयोग हाइड्रोफोन और एकूस का उपयोग करके तृतीय क्रम के ध्वनिक ग्राहक बनाने के लिए किया जा सकता है।

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Abbreviations

AVS	Acoustic Vector Sensor
PAGE	Phase and Amplitude Gradient
HDAVS	Highly directional Acoustic Vector Sensor
FEM	Finite Element Method
AE	Absolute Error
AAE	Absolute Angular Error
IBP	Ideal Beampattern
EBP	Estimated Beampattern
RMSE	Root Mean Square Error
NIOT	National Institute of Ocean Technology
HPBW	Half Power Beamwidth
DIFAR	Directional Frequency Analysis and Recording
DoA	Direction of Arrival
MSAE	Mean Square Angular Error
SNR	Signal to Noise Ratio
SSNR	Signal to Self Noise Ratio
MF	Microflown
WiMUST	Widely Scaled Mobile Underwater Sonar Technology
DAVS	Dual Accelerometer Vector Sensor
PML	Perfectly Matched Layer
PDF	Probability Density Function
DI	Directivity Index

List of Symbols

The next list describes several symbols that will be later used within the body of the document

$B(\theta, \phi)$ Beampattern

α Absorption coefficient

β Specific gravity

$\boldsymbol{a(t)}$ Acceleration vector in time domain

$\boldsymbol{I(t)}$ Intensity vector in time domain

$\boldsymbol{r}$ Position vector

$\boldsymbol{u(t)}$ Velocity vector in time domain

$\boldsymbol{U}$ Velocity vector in frequency domain

Γ Reflection coefficient

λ Wavelength

$\nabla P(\omega)$ Amplitude of pressure gradient

$\nabla \Phi$ Phase gradient

ω Radian frequency

ϕ Declination angle

ρ Medium density

$\sigma^2_{AN}(\omega)$ Power spectral density of of ambient noise

$\sigma^2_{SN}(\omega)$ Power of spectral density of self noise

$\sigma^2_{TN}(\omega)$ Power spectral density of total noise

τ Time delay

θ Azimuth angle

$a(\theta, \phi)$ Directional cosine of along x-axis

$a_1(\theta, \phi)$ Approximated directional cosine along x-axis

$a_2(\theta, \phi)$ Approximated directional cosine-square along x-axis

$a_3(\theta, \phi)$ Approximated directional cosine-cube along x-axis

$b(\theta, \phi)$ Directional cosine along y-axis

$b_1(\theta, \phi)$ Approximated directional cosine along y-axis

$b_2(\theta, \phi)$ Approximated directional cosine-square along y-axis

$b_3(\theta, \phi)$ Approximated directional cosine-cube along y-axis

$c(\theta, \phi)$ Directional cosine along z-axis

c Speed of sound

$c_1(\theta, \phi)$ Approximated directional cosine along z-axis

$c_2(\theta, \phi)$ Approximated directional cosine-square along z-axis

$c_3(\theta, \phi)$ Approximated directional cosine-cube along z-axis

d Inter-element spacing

$E_{coupled}$ Energy of coupled signal

$E_{Incident}$ Incident signal energy

k Wave number

$n(t)$ Noise

$p(t)$ Acoustic pressure in time domain

$p_i(t)$ Incident pressure wave in time domain

$p_r(t)$ Reflected pressure wave in time domain

S_a Sensitivity factor of accelerometer in mv/g

S_P Sensitivity factor of pressure sensor in $dBre1V\ \mu Pa$

$U_0(\omega)$ Particle velocity along x-axis in frequency domain

$u_0(t)$ Particle velocity along x-axis in time domain

$U_1(\omega)$ Velocity gradient along x-axis in frequency domain

$u_1(t)$ Velocity gradient along x-axis in time domain

$U_2(\omega)$ Gradient of $U_1(\omega)$ along x-axis in frequency domain

$u_2(t)$ Gradient of $u_1(t)$ along x-axis in time domain

$U_i(\omega)$ i^{th} partial derivative of particle velocity along x-axis with respect to x in frequency domain

$u_i(t)$ i^{th} partial derivative of particle velocity along x-axis with respect to x in time domain

$V_0(\omega)$ Particle velocity along y-axis in frequency domain

$v_0(t)$ Particle velocity along y-axis in time domain

$V_1(\omega)$ Velocity gradient along y-axis in frequency domain

$v_1(t)$ Velocity gradient along y-axis in time domain

$V_2(\omega)$ Gradient of $V_1(\omega)$ y-axis in frequency domain

$v_2(t)$ Gradient of $v_1(t)$ along y-axis in time domain

$V_i(\omega)$ i^{th} partial derivative of particle velocity along y-axis with respect to y in frequency domain

$v_i(t)$ i^{th} partial derivative of particle velocity along y-axis with respect to y in time domain

$W_0(\omega)$ Particle velocity along z-axis in frequency domain

$w_0(t)$ Particle velocity along z-axis in time domain

$W_1(\omega)$ Velocity gradient along z-axis in frequency domain

$w_1(t)$ Velocity gradient along z-axis in time domain

$W_2(\omega)$ Gradient of $W_1(\omega)$ z-axis in frequency domain

$w_2(t)$ Gradient of $w_1(t)$ along z-axis in time domain

$W_i(\omega)$ i^{th} partial derivative of particle velocity along z-axis with respect to z in frequency domain

$w_i(t)$ i^{th} partial derivative of particle velocity along z-axis with respect to z in time domain

$y_c(t)$ Particle velocity along y-axis in time domain

$y_o(t)$ Pressure signal in time domain

$y_s(t)$ Particle velocity along z-axis in time domain

z Acoustic impedance