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Reduced-order model for underwater target identification using proper orthogonal decomposition

Sai Sudha Ramesh [a,*], Kian Meng Lim [b]

[a] Temasek Laboratories, National University of Singapore, Singapore 117411, Singapore
[b] Department of Mechanical Engineering, National University of Singapore, Singapore 119260, Singapore

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A B S T R A C T

Research on underwater acoustics has seen major development over the past decade due to its widespread applications in domains such as underwater communication/navigation (SONAR), seismic exploration and oceanography. In particular, acoustic signatures from partially or fully buried targets can be used in the identification of buried mines for mine counter measures (MCM). Although there exist several techniques to identify target properties based on SONAR images and acoustic signatures, these methods first employ a feature extraction method to represent the dominant characteristics of a data set, followed by the use of an appropriate classifier based on neural networks or the relevance vector machine. The aim of the present study is to demonstrate the applications of proper orthogonal decomposition (POD) technique in capturing dominant features of a set of scattered pressure signals, and subsequent use of the POD modes and coefficients in the identification of partially buried underwater target parameters such as its location, size and material density. Several numerical examples are presented to demonstrate the performance of the system identification method based on POD. Although the present study is based on 2D acoustic model, the method can be easily extended to 3D models and thereby enables cost-effective representations of large-scale data.

1. Introduction

The field of underwater acoustics has seen enormous development over the past decades due to its extensive applications in underwater communication/navigation (SONAR), seismic exploration, oceanography and marine biology. The study of acoustic scattering from underwater objects is an important part of mine detection and classification. In particular, such acoustic signatures can be used in the identification of buried mines for mine counter measures (MCM). In practice, most target identification strategies are devised based on ensemble data collected from two approaches, namely (1) Image-based SONAR data and (2) Non-image based SONAR data which comprise of target's acoustic-structural response to a specific incoming pulse. The common functional attributes of any target identification method are (a) representation of ensemble data in an appropriate form such that they contain the most dominant features, and (b) implementation of an appropriate classifier based on trained neural networks, the relevance vector machine (RVM) /kernel methods. The classifiers are designed to predict target parameters in a given underwater scenario.

* Correspondence to: Temasek Laboratories, National University of Singapore, T-Lab Building, 5A, Engineering Drive 1, #09-02, Singapore 117411, Singapore.

E-mail address: tslssr@nus.edu.sg (S.S. Ramesh).

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Target identification based on image-based SONAR data can be found in references [1–5]. Mahmood et al. [1] have developed a feature extraction scheme based on electro-optical imagery data collected from a laser line scan (LLS) to distinguish underwater targets in the presence of clutter and distortion. They have used Zernike moments to represent the shape-dependent features and a back-propagation neural network (BPNN) as target classifier. Ye et al. [2] use a combination of the optimum trade-off maximum average correlation height (OT-MACH) filter and neural network (NN) for effective target recognition. The OT-MACH filter operates in Fourier domain, finding correlations in the image that contain likely positions of targets. Once the OT-MACH filter has detected the likely regions of interest (ROI) that contain the target, the ROI can go through further image processing and feature extraction to serve as inputs to a neural network for verification. Langner et al.[3] presented some theoretical considerations about the resolution required for detection, classification, and identification of objects in side scan SONAR images. Overviews of various image processing algorithms that can be used to identify ROIs are presented. They employ a probabilistic neural network (PNN) classifier to identify the final target features. Unlike other image-based identification methods that classify targets based on shape and size, Bazeille et al.[4] use a colour criterion to identify underwater targets. Their method follows the Beer-Lambert law that describes the exponential decrease of light intensity with distance. Each colour has a set of compatible colours depending on the distance travelled by light through water. Their identification process is based on principal component analysis (PCA) which is used to estimate the compatibility / attenuation line for target classification. Sherin and Supriya [5] presented a brief review of target classification algorithms, in particular the support vector machines (SVM) which is claimed to have higher classification accuracy compared to other methods like genetic algorithm (GA) and particle swarm optimization (PSO). Other applications of image based target identification models can be found in the works of Wilcox and Fletcher [6] and Driggers et al. [7].

Target classification based on non-image based SONAR data can be seen in references [8–12]. The research works of Goo [8–10] are primarily based on target detection using natural resonance and resonant scattering theory. In references [8,9], Goo's work mimics a dolphin's approach to target detection and recognition. A transmitted pulse similar to a dolphin's pulse, which is a very short sinusoidal pulse consisting of a broadband signal centered at 120 kHz, is considered. The acoustic signatures from various targets are transformed using the G-Transform (which is a triple forward Fourier transform of time signal). These transformed target signatures are then used as inputs to a trained neural network for further target identification. Goo [10] also applied the above technique to identify ‘silent’ targets based on ambient noise data recordings which contain correlated target signals. Bucaro et al. [11] explored the feasibility and advantages of using a structural-acoustic feature-based technique to detect and identify unexploded ordnance (UXO). The scattered echoes in the structural-acoustic regime are related to the dynamic vibrations of the target, and hence their time-frequency features can be utilized to uniquely identify buried underwater targets. A recent research by Ou et al. [12] employs pseudo Wigner distribution (PWD) function to represent target features contained in the scattered acoustic waves. The resulting target signatures are analysed in the time-frequency plane. The redundant target features are then eliminated and the useful information is represented by a fuzzy C-Means (FCM) method.

The aforementioned research strongly indicates the use of acoustic signatures in target classification. While image-based classifications (usually operating at higher frequencies) furnish details regarding the shape/size of a target, the non-image based classifications using acoustic signatures encompass a wide range of frequencies (low to high) whose wavelengths are comparable to the target dimensions. This allows for sound waves to penetrate the target material and the scattered acoustic waves may contain unique information about the target's material composition. The fact that acoustic ‘fingerprint’ from targets can be used to predict their material compositions is quite remarkable, especially in the elimination of false positive targets or in the estimation of amount of explosives contained in the shell.

The present study is based on target identification and classification using scattered acoustic waves. While a majority of the research studies have focused on target feature identification, studies on target material type classification have been less active. Therefore the present research is targeted at the development of a fast and real-time system for identification/classification of underwater objects that is crucial for mission critical scenarios. The scattered sound field data necessary for target identification is obtained by running several offline full scale numerical simulations for various target parameters (namely size, location with respect to the seabed and material properties). A full-scale numerical model normally takes a long time to run in order to obtain a complete simulation with simplifying assumptions. To address this issue, a reduced-order model based on the proper orthogonal decomposition technique (POD) is employed in companion to the full-scale model to achieve the speed needed for real-time applications.

The model-order reduction (MOR) technique is a systematic approach to obtain smaller and faster models to capture most (typically about 80% to 90%) of the physics/response of the large scale system while keeping a small number of degrees of freedom. It is a robust technique that enables cost effective representations of the large scale system. The system response is projected onto a reduced space basis thereby yielding a low-order system that is very efficient for real-time simulation and prediction. By constructing an appropriate basis, the low order system is able to capture the dynamics of the high fidelity system reasonably well. There are several methods to determine the projection basis, such as Krylov subspace methods [13,14], balanced truncation [15–17], reduced-basis method [18] and the proper orthogonal decomposition methods [19,20].

The proper orthogonal decomposition (POD) method, which is also known as Karhunen-Loéve decomposition [21] and principal component analysis (PCA) [22], has a desirable feature of extracting the most dominant modes for constructing the basis. The POD basis functions are optimal in that the error between the original and low-order representation of the snapshot data is minimized for a given size of the basis. The POD method encompasses a wide range of applications such as