Learning Eigenstructure of Underwater Acoustic Propagation Using Computational Intelligence: A Study on the VTUAD Dataset

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Abstract - This study proposes a computational-intelligence-based framework for analysing the spectral eigenstructure of underwater acoustic observations in the VTUAD dataset in order to investigate the separation of source-related vessel characteristics and propagation-related channel effects through eigendecomposition, unsupervised clustering, and genetic-algorithm-based modal selection.

Keywords - underwater acoustics, computational intelligence, eigenstructure analysis, spectral decomposition, propagation operators, vessel classification, VTUAD dataset, genetic algorithms, modal analysis, acoustic propagation, unsupervised clustering, hydroacoustics

I. Introduction

The present study investigates whether the spectral eigenstructure of underwater acoustic recordings can be used to distinguish between vessel-dependent source information and propagation-dependent channel effects. The analysis is based on the VTUAD dataset, which contains underwater audio recordings organised by vessel type and distance-related acquisition scenarios. The dataset includes several vessel categories. These metadata make it possible to relate acoustic observations not only to the nominal vessel class but also to the physical conditions under which the signal was acquired.

Consequently, the signal recorded by a hydrophone represents not only the acoustic characteristics of the source, but also the propagation dynamics of the ocean acoustic channel. The observed acoustic field is therefore shaped by both vessel-dependent and environment-dependent mechanisms. A direct supervised classification of vessel types may consequently conflate source-related and propagation-related effects. This study proposes to investigate whether the eigenstructure learned from spectral representations of underwater acoustic recordings can reveal propagation-related organisation of the observed acoustic field[1].

Within this framework, computational intelligence methods are not used merely as predictive tools, but as mechanisms for discovering latent organisation within the learned acoustic eigenstructure.

II. Eigenvalues Separation in Hydroacoustics

For each audio fragment, a time–frequency representation is first computed using the short-time Fourier transform.

Based on this spectrogram, a frequency–frequency covariance-like matrix is constructed. This matrix characterises how the energy associated with different frequency components changes together over time. In other words, it captures statistical relationships between frequency bands and summarises dominant spectral-energy patterns present in the recording. The resulting matrix may therefore be interpreted as an empirical operator describing the observed acoustic structure of the signal and its propagation-dependent spectral organisation.

The next step consists of computing the eigendecomposition of this operator. This procedure produces a set of eigenvalues and corresponding eigenvectors. The extracted eigenstructure should therefore be interpreted as an empirical spectral representation of the observed propagation field rather than as a direct physical normal-mode decomposition of the ocean environment. Nevertheless, the learned modal organisation may still reflect important propagation-related characteristics of the underwater acoustic channel. Since the observed spectral structure is influenced by both the acoustic source and the propagation environment, the resulting eigenstructure is expected to contain mixed information associated with source characteristics, propagation conditions, and their interaction.

III. Methods for Feature Separation

The purpose of the proposed experiments is to investigate whether source-related and propagation-related components can be partially separated or interpreted through modal selection and clustering.

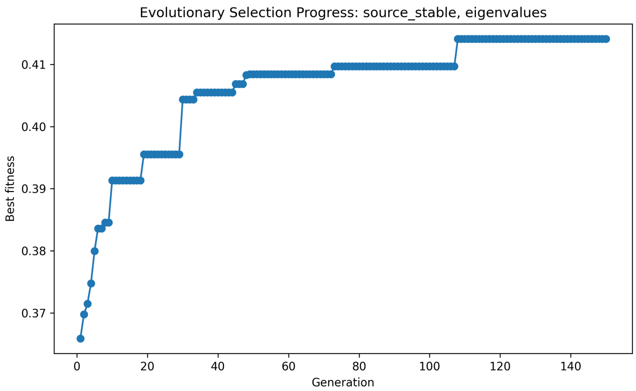
The first hypothesis is that the eigenvalue spectrum contains information about vessel type. If this is true, then recordings from the same vessel category should exhibit similar eigenvalue distributions, even across different distance scenarios. In such a case, clustering or classification based on eigenvalue-derived modal features should align more strongly with vessel labels than with propagation-distance labels. This would suggest that the empirical operator retains source-dependent structure [2].

The second hypothesis is that some eigenmodes are sensitive to the propagation scenario. Such a result would indicate that the spectral operator captures channel-dependent distortions or modal filtering effects induced by the underwater environment [3].

The third and most realistic hypothesis is that the eigenstructure reflects a source–channel interaction. Clusters or selected modal features may correspond to combinations such as “cargo vessel at shorter distance”, “tugboat at longer distance”, or “background under a specific propagation regime”. Consequently, the broader objective of the study is to determine which components of the eigenstructure remain relatively stable for a given vessel type and which components are more strongly influenced by propagation conditions and observation geometry.

IV. Genetic Algorithm for Feature Selection

To test these hypotheses, a genetic algorithm is used for modal selection. The algorithm evolves a population of such masks through tournament selection, crossover, and mutation. The optimisation process is intended not only to improve predictive performance but also to identify compact subsets of eigenmodes that are most informative for characterising the underlying acoustic propagation mechanisms.

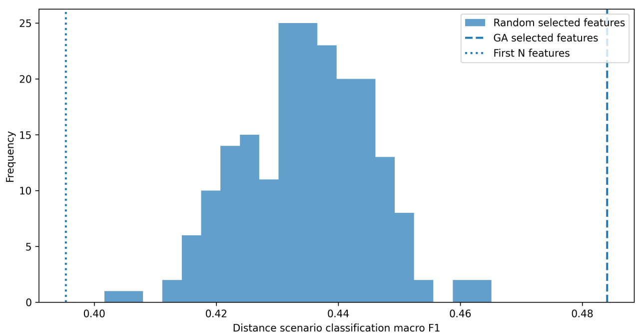


Two optimisation regimes are considered. In the source-stable regime, the genetic algorithm maximises vessel classification performance while penalising excessive sensitivity to the distance scenario and penalising overly complex modal subsets. This regime searches for eigenmodes that are informative about vessel type and relatively stable across propagation conditions.

In the propagation-sensitive regime, the genetic algorithm maximises distance-scenario classification performance and favours modal features whose behaviour varies across scenarios. This regime searches for eigenmodes that are more strongly associated with propagation effects than with vessel identity.

The selected modal features are then compared against several baselines: the first leading modes, all available modes, and randomly selected mode subsets of the same dimensionality as the genetic-algorithm-selected subset. This comparison is essential. If the selected modes outperform the first leading modes, then the informative propagation-related structures are not simply the most energetic ones. If they outperform random subsets, then the optimisation process has identified a non-trivial modal organisation.

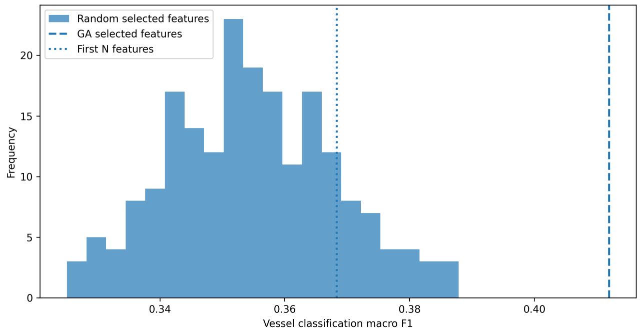
V. Results of Statistical Testing



Scenario classification

The proposed framework provides a systematic way to move beyond direct vessel classification. Instead of treating the acoustic recording as a simple input for supervised learning, the proposed method analyses the empirical spectral operator induced by the recording. Its eigenvalues and eigenvectors serve as interpretable intermediate representations describing the organisation of the observed propagation field.

The selected modal subsets are analysed statistically in terms of vessel-type separability, propagation-scenario sensitivity, and cluster organisation in the learned eigenspace. The comparison with baseline modal subsets enables assessment of whether the discovered eigenmodes represent statistically significant propagation-related structures rather than arbitrary or energy-dominant components of the acoustic spectrum. Unsupervised clustering methods are applied to investigate whether the extracted eigenstructure is organised primarily according to vessel identity, propagation distance, or coupled source–channel interaction patterns.



Vessel classification

The statistical testing stage therefore evaluates whether the dominant modal organisation of the observed acoustic field is governed primarily by source characteristics, propagation conditions, or their interaction.

VI. Conclusion

This study proposes a computational-intelligence-based framework for analysing underwater acoustic observations through spectral eigenstructure learning. Rather than using underwater acoustic recordings solely for direct vessel classification, the proposed approach investigates the latent modal organisation induced by acoustic propagation and source–channel interaction.

The framework combines spectral eigendecomposition, unsupervised clustering, and evolutionary optimisation in order to identify propagation-sensitive and source-stable modal structures. The proposed methodology enables investigation of whether the dominant organisation of the observed acoustic field is governed primarily by vessel characteristics, propagation conditions, or coupled source–channel effects.

The proposed approach therefore provides a basis for future research on interpretable underwater acoustic representation learning, propagation-aware computational intelligence, and data-driven modelling of underwater acoustic observation systems.

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