Extraction of complex natural resonances of ships acoustic signals using Matrix Pencil Method

1st Daniel Chaparro-Arce
Universidad Nacional de Colombia
Bogotá, Colombia
dafchaparroar@unal.edu.co

2nd Sergio Gutierrez
Universidad de San Buenaventura
Bogotá, Colombia
sgutierrez@usbbog.edu.co

3rd Andrés Gallego
Universidad Nacional de Colombia
Bogotá, Colombia
ajgallegog@unal.edu.co

4th Carlos Gutierrez
Escuela Naval de Cadetes "Almirante Padilla"
Cartagena, Colombia
cagm.enap@gmail.com

5th Felix Vega
Universidad Nacional de Colombia
Bogotá, Colombia
jfvegas@unal.edu.co

6th Cesar Pedraza
Universidad Nacional de Colombia
Bogotá, Colombia
capedrazab@unal.edu.co

***Abstract*—In the field of naval operations, the traffic control and the location of unregulated vehicles are of vital importance to the traffic of ports, governments and naval military forces, among others this helps to control the security and sovereignty of certain areas. Processing the underwater acoustic signals using methods such as MPM for its complex natural resonance extraction can be an effective but challenging way for identification of these ships. In this paper, we show that in the presence of a stable medium, it is possible to determine the principal frequency components related ships in a classification process. The analysis was developed using 30 signals of a cargo vessel ship, 66 of a frigate and 69 of a subchaser. Results show that the total averages of the poles of the ships are in specific regions of the plane, however, the analysis of the imaginary quantities of the complex natural resonances may bring a better insight for the identification process.**

***Index Terms*—Matrix Pencil Method, cargo vessel, acoustic submarine signals, poles, ships.**

I. Introduction

MPM is a particular implementation of the Singularity Expansion Method (SEM), developed by Baum (1976) [1]. The main objective of MPM is the extraction of the natural complex resonances typical of a determined signal in the time domain. Through the interpretation provided by MPM, it is possible to perform a mathematical model of a signal that can be used in information reduction processes used for sending data by wireless communication. Also, can be used identification of physical characteristics of a given phenomenon, or even location of targets [3].

Currently, many of the vehicle control processes of maritime areas rely on visual inspection, which greatly limits sweeping of large distances. Commercially, the location of ships in bays and ports is done using GPS devices. However, for this process to take place, it is necessary that all boats have a receiver, which is not the case with irregular boats [4].

This work aims to show an analysis of the implementation of MPM in three different vessels, in order to verify the differences between them for a subsequent location process. In principle, the concept and mathematical procedure of the MPM implementation will be introduced. Then, the analyzes performed in the comparison of the data of the ships and the diffusion for future works.

II. Matrix Pencil Method

MPM is an implementation of SEM used in time-domain signal. The principal main of this procedure is to provide a mathematical approximation of a signal based in its principal complex natural resonances. This method implements the **Singular Value Decomposition** (SVD) to find the values of the first M complex coefficients (s_i) and residues (R_i) to the form $(R_1 e^{s_1 \lambda}, R_2 e^{s_2 \lambda}, ..., R_M e^{s_M \lambda})$ [1].
The continuous function g_p can be expressed as a discrete sum using the information of sample frequency ($F_m = \frac{1}{\Delta t}$), so that:

$$g_p = f_p(p\Delta t), p = 0, 1, 2, ..., N \tag{1}$$

Here N is the quantity of points in the signal. With this information, we can obtain a mathematical model that could be used in analyzing data providing a trustworthy signal reconstruction.The approximation can be expressed like a summary (f_p) of the form:

$$f_p = \sum_{i=1}^{M} R_i e^{s_i p \Delta t}, p = 1, 2, 3, ..., N \tag{2}$$

Here, M is the number of singularities that we want to get and $M \leq N$. According to the Fourier theory, the accuracy of the approximation depends on the number of M. The principal steps in the process to find that singularities are described below [2].

First, we need to define the *Pencil Parameter* (L) used to find a balance between the accuracy of the method and the computational load (as the linear prediction matrix size changes according to this). That value could be in the range of $\frac{N}{3} < L \leq \frac{N}{2}$ to facilitate the calculation of the SVD in the MPM process. After defining L we can construct the *Hankel Matrix* (Y) to the form:

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$$Y = \begin{bmatrix} f_0 & f_1 & . & . & f_L \\ f_1 & f_2 & . & . & f_{L+1} \\ . & . & . & . & . \\ . & . & . & . & . \\ f_{N-L-1} & f_{N-L} & . & . & f_{N-1} \end{bmatrix} \quad (3)$$

After obtaining have the Y matrix, we define the Y_1 matrix by removing the last row of Y, and the Y_2 matrix by removing the first row of Y. The poles $\lambda_i = e^{s_i \Delta t}$ are the eigenvalues, where (4) is singular.

$$[Y_2]^H - \lambda [Y_1]^H \quad (4)$$

Here H denotes the *Hermitian Conjugate* of a matrix. The computing to solve the eigenvalues problem of (4) is impossible to treat using traditional methods. A solution to this problem is reducing the complexity using the SVD, thus we can decompose the Y matrix obtaining:

$$Y = USV^H \quad (5)$$

Then, we define the number of M. For this step, we can use different processes described in [2] [7]. Once we choose this value, we can define V' as the first M rows of V. After that, we create V_1 and V_2 as the matrix V' without the last and the first columns deleted, respectively. At this point, the problem of eigenvalues is reduced to find the eigenvalues, where (6) is singular.

$$[V_2]^H - \lambda [V_1]^H \quad (6)$$

This problem also is intractable with computational techniques, thus it is necessary to reduce the complexity with the SVD again. As a result, we can obtain.

$$[V_1]^H = U_v S_v V_v^H \quad (7)$$

The problem can be solved by finding the eigenvalues of the matrix defined as $[V_1]^+[V_2^H]$ (where "+" denotes the Moore Penrose pseudo-inverse). This is possible using the next interpretation.

$$[V_1]^+[V_2^H] = V_v S_v' U_v^H [V_2^H] \quad (8)$$

We can compute the poles λ_i using traditional numerical methods. After that, the coefficients s_i can be defined as:

$$s_i = \frac{1}{\Delta t} log(\lambda_i), i = 1, 2, 3, ..., M \quad (9)$$

Now, we need to find the values of the residues R_i. For this step, we need information about the poles and the original function. We define the Vandermonde matrix as:

$$V_{an} = \begin{bmatrix} 1 & 1 & . & . & 1 \\ \lambda_1 & \lambda_2 & . & . & \lambda_M \\ . & . & . & . & . \\ . & . & . & . & . \\ \lambda_1^{N-1} & \lambda_2^{N-1} & . & . & \lambda_M^{N-1} \end{bmatrix} \quad (10)$$

After defining this matrix, the residues R_i can be defined by solving the underdetermined linear system described next:

$$\begin{bmatrix} 1 & 1 & . & . & 1 \\ \lambda_1 & \lambda_2 & . & . & \lambda_M \\ . & . & . & . & . \\ . & . & . & . & . \\ \lambda_1^{N-1} & \lambda_2^{N-1} & . & . & \lambda_M^{N-1} \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ . \\ . \\ R_M \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ . \\ . \\ f_{N-1} \end{bmatrix} \quad (11)$$

With the complex values of s_i and R_i, we can rebuild the signal using the summary presented in (2) with the same number of N [8].

III. Implementation of MPM in ships signals

The information presented throughout this work is the result of processing data from 30 signals to cargo vessel ship, 66 to a frigate and 69 of a subchaser ship. The purpose of performing the MPM process on these signals is to verify the accuracy of the method applied to different signals from the same source, recognizing patterns in the singularities of the ship and comparing the information with the poles of other targets.

In [3], MPM in acoustic signals from ships was implemented ensuring that the reconstruction provided by this method is successful. Thus, taking into account the variable number of poles calculated based on the number of components in frequency of the signal, a test can be carried out to determine the repeatability of the method in the implementation in this type of signals.

First, we calculate the 26 most significant poles in every signal in each ship. These singularities are related to the 13 principal frequencies components in the signal (every frequency has its conjugate complex) and contain the vast majority of the signal energy (above of 90%). The number of singularities was chosen considering the average correlation coefficient in each signal [3].

After applying MPM in every signal, we found in each ship the average value of each of the 26 poles in the order given by the development of the method. As the order of the singularities in the MPM process has direct relation with the quantity of energy associated with the pole. Once these values are calculated, it is possible to carry out a density analysis related to the dispersion of the poles along the imag/real plane [5].

For this, it is possible to establish a region for each ship in which the greatest possible number of poles is enclosed within a specific area where the highest density of singularities is found. This region depends on the characteristics of the signal and could give tools in the identification targets process. Figure 1 shows the average poles and the delimited region for each ship.

After calculating the average of the poles using the information of all signal in each ship, we found standard deviations in the axis. So we got values of 823.825, 899.02 and 731.932 in the imaginary axis of cargo vessel, frigate and subchaser, respectively and 7.688, 33.521 and 22.948 in the real axis. Although it is possible to generate specific regions for each

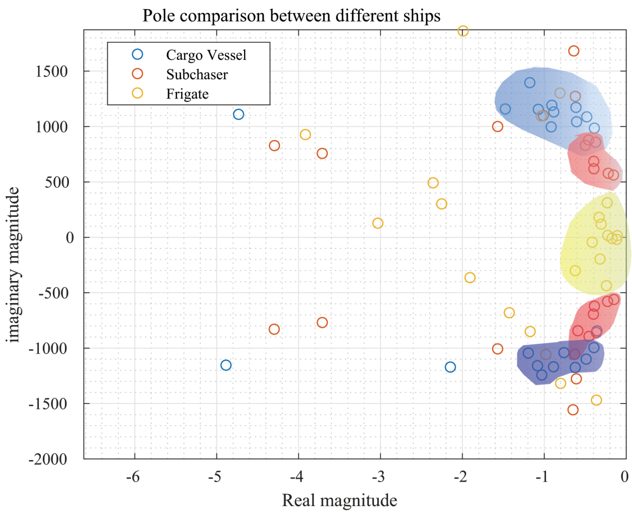

Fig. 1. Pole distribution graph for three ships

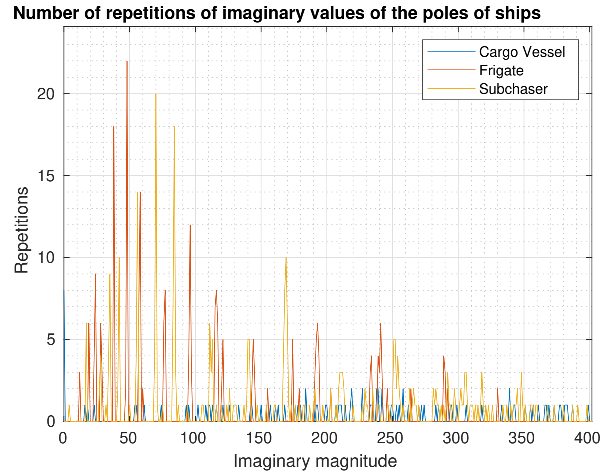

Fig. 2. Main frequencies in ship signals.

ship, based on the location of the poles in the real/imag plane. It is evident from the standard deviation values that there is a large dispersion between the singularities, which could put at risk the processes of location.

One of the reasons why these results are presented could be because the order in which MPM calculates the poles depends on the amount of energy present in each frequency. Thus, the order in which the fundamental frequencies of the ships are calculated can vary, for example, depending on the ambient noise and the place in which the boat is located.

Although Figure 1 evidences the differentiation of the dispersion of the poles in the three processed samples, the presence of singularities is evident away from the regions of each ship, mainly on the real axis. The real part in the pole corresponds to the damping factor of the singularity and this value could also change due to different factors like the distance and the speed of the ship.

In order to improve these results, we opted to focus on the information provided by the imaginary magnitude of the poles, which corresponds to the frequency information of the pole. For this purpose, we take all signals in each ship and apply MPM, searching the main 26 singularities. We focused directly on the positive values of the imaginary part of all poles, thus ruling out the damping factor (real part of the pole) and the negative frequencies, related to the conjugated complexes of the positive quantities.

With this information, we performed a count of frequency repetitions in all the signals, with the aim of finding the most representative frequencies of each boat. This count allows to generate a function where the domain represents the imaginary value of the pole, and the range is determined by the number of repetitions in the processed signals of each ship. The function is shown in Figure 2 .

The information provided by the signals from the cargo vessel ship is not enough to determine the main characteristics of this boat, this indicates the need to use as many signals as possible for good analysis. In the case of the frigate and the subchaser, the highest number of findings was found below the values of 350, therefore, the data analysis was restricted to these values. Likewise, common concordances are presented for both vessels, such as 58 and 28. This can give us clues about the information related to the medium and these values could be discarded for further analysis.

With the information obtained up to this point, after discarding the common values, it is possible to determine the main imaginary components in the frigate as 48 (with 22 repetitions) and 38 (18 repetitions). In the case of subchaser we have values of 70 (20 repetitions) and 84 (18repetitions). These data could be processed for the process of identifying targets in real environments, having variables such as the characterization of the environment, the distance and the speed at which the ship is located. For this, we could use methods like neural networks, machine learning, etc.

IV. Conclusions

The analysis of identification and classification of signals using MPM can be reduced to the processing of information provided by the positive imaginary component of the poles calculated by the method. These data contain information related to the fundamental frequencies specific to each ship. With this, it is possible to generate a library in which the information of known ship signals is contained with the purpose of to compare with unknown boat signals in a later implementation stage. However, in order to perform this process properly, the presence of a large number of previous ship signals that you want to include in the library is necessary.

One of the advantages of using this method with signals of different sources is that it is possible to determine the pattern of the medium by comparing the common components in signals of different types of ships, which could be used in noise reduction processes. However, a stable medium is required because this characterization could be affected in the case that the medium changes its physical characteristics as a function of time, thus affecting the previously calculated imaginary values.

The mathematical abstraction obtained with MPM can be used to identify the characteristics of certain signals and give guidance on target identification processes, not only limited to naval operations. As future works, we can talk about the implementation of methods such as machine learning and neural networks to optimize the classification process of ships using their underwater acoustic signals. Once a library has been generated with the information of the poles of various ships it is possible to implement these methods to carry out the comparison process and to make the feedback of the data within it. These information analysis processes could also be used in signals from other sources and for other types of applications that are considered relevant.

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