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Intelligent PSR Estimator for Feature Extraction of a Passive Sonar Target

Hyun-Sik Kim and Doheon Lee

Abstract: In real-time sonar classification, the propeller shaft rate (PSR) estimator for a feature extraction of the passive sonar target has the following problems: it requires an accurate and efficient performance due to the difficulty of distinguishing the harmonic family composed of the PSR fundamental and its harmonics from multiple spectral lines in the frequency spectrum, and it requires an easy design procedure in terms of structure and parameters. To solve these problems, an intelligent PSR estimator (IPSRE) using expert knowledge and the evolution strategy (ES) is proposed here. Simulation results show that the proposed algorithm effectively solves sonar classification problems in real-time.

Keywords: Evolution strategy, feature extraction, passive sonar target, PSR estimation.

1. INTRODUCTION

The frequency spectrum resulting from the detection and tracking of a target detected by a long-range passive sonar has various frequency components [1,2]. Among them, the narrowband (NB) components due to mechanical devices are dominant for classifying a passive sonar target and they form harmonic families composed of fundamentals and their harmonics. This means that it is essential and difficult to distinguish the harmonic family from multiple spectral lines in the frequency spectrum.

In particular, the propeller shaft rate (PSR) [3,4], which is among the speed-related NB components, is used to extract the order set of the harmonic family as a feature of the target and enables the speed-dependant feature database (DB) to be used effectively for classification because it is used to estimate the target speed. Furthermore, the PSR enables the effective extraction of other features by decreasing the number of valid features as it can be used to help eliminate the harmonic family from the multiple spectral lines in advance. Therefore, PSR estimation is the basic and core element in feature extraction and classification of the passive sonar target.

In many post-processing sonar systems, such as land-based and shipboard systems, a human operator usually utilizes the harmonic cursor for PSR estimation, which is a set of auxiliary graphic lines representing a harmonic family candidate. Although this method is an accurate and verified PSR estimation method in real sonar systems because it is based on the knowledge and experience of the well-trained expert, it is not a real-time method and can only be applied to a stable graphic area that has straight frequency lines in a frequency diagram expressed with respect to frequency and time. Therefore, an advanced PSR estimation method requires accurate performance in terms of real-time and non-graphical PSR estimation.

To solve these problems, various algorithms have been suggested. Zhou and Giannakis [5,6] proposed an algorithm that extracts the harmonic families. Although it performs well, it does not have an easy design procedure in terms of structure and parameters. Also, Kummert [3] proposed an algorithm that utilizes the minimum distances between all frequency components and each PSR candidate. Although it performs well and has an easy design procedure, it requires improved performance in terms of accuracy and efficiency.

These mean that the issues of accuracy, efficiency, and simplicity in real-time PSR estimation have not yet been solved completely.

To resolve these problems, an intelligent PSR estimator (IPSRE) using expert knowledge and the evolution strategy (ES) is proposed. Although Kim [7] has already proposed this algorithm, more simulation studies as well as detailed descriptions were required. The main idea of the proposed method is to develop a harmonic cursor-based graphical method of the post-processing sonar system, which is an accurate and verified PSR estimation method, by substituting the ES-optimization for the operator tuning of the harmonic cursor maintaining the design simplicity.

The ship-radiated noise model is introduced in Section 2. The design of the IPSRE is described in Section 3, and the simulation results of the IPSRE in the feature extraction of the passive sonar target are presented in Section 4. Finally, the conclusions are summarized in Section 5.

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2. SHIP-RADIATED NOISE MODEL

Passive sonar systems use the noise radiated by a potential target, such as surface vessels or submarines, to detect it in among the background of ambient noise. The modified generic spectrum of ship-radiated noise in the 10–1,000 Hz frequency band is shown in [7].

The noise level of the frequency is derived using the following equation [1]:

$$NL(f) = NL_{1k} - 20\log\left(f/1{,}000\right), \tag{1}$$

where NL_{1k} is the noise level at 1 kHz and f is the frequency.

The sources of the ship-radiated noise can be divided into five noise types: propeller, flow, machine, submarine transient, and activity [1,2]:

Rotating propellers generate spectral lines at very low frequencies. The frequencies of these lines depend upon the rotation speed of the propeller and its geometry. The depressions induced by the movements of the blades create some cavitation, causing a characteristic broadband noise. The cavitation noise level depends upon the rotation speed of the propeller.

Turbulence is generated by the flow of water on the hull of the ship or on the active face of the acoustic transducer or its protection. This type of noise depends upon the ship speed, frequency, and shape and emplacement of the transducer's protection.

Many noisy machines such as generators, hydraulic machinery, and winches are installed on ships. The machine noise is generally independent of the ship's speed. It is therefore felt more keenly when the ship is at low speed and it is masked at high speed by the flow and cavitation noise. The main frequencies of this noise are usually accompanied by their harmonics.

The acoustic stealth of a submarine can be degraded by exceptional transmission of short transient noise, lasting from a few milliseconds to a few seconds. The causes are often impossible to avoid and include opening a torpedo launch tube, steering maneuvers, starting mechanical or hydraulic machinery, and so on.

Some activities of civilian ships are very noisy, such as seismic surveys, drilling, trawling, towing, and the deployment of submersibles.

Of the noise sources mentioned above, the propeller noise includes the PSR as a speed-related NB component of the frequency spectrum for the passive sonar target.

3. DESIGN OF IPSRE

3.1. Definition of the reference harmonic model

In many post-processing sonar systems, such as land-based and shipboard systems, a human operator effectively utilizes the harmonic cursor for the PSR estimation: the harmonic cursor is a set of auxiliary graphic lines that represent a harmonic family candidate. While the three frequency lines seems to be a harmonic family without the six-order harmonic cursor in Fig. 1, the fact that only two frequency lines meet the auxiliary graphic lines of the 2nd and the 5th order and thus are the members of the harmonic family is easily shown by employing the harmonic cursor.

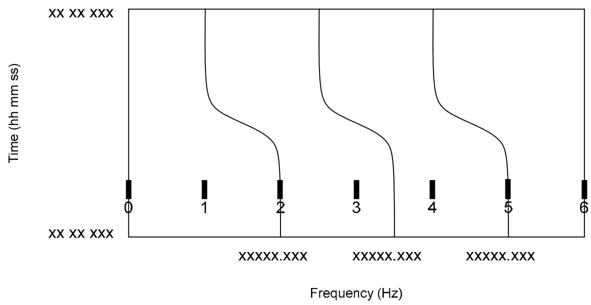

Fig. 1. Harmonic cursor-based graphical method.

As an input of the PSR estimator, the tonal vector that equals frequency components on the frequency spectrum is defined as

$$\boldsymbol{f} = \left[f_1 \quad f_2 \quad \cdots \quad f_n\right]^T, \tag{2}$$

where $n = 1,\ldots,N$, N is the number of tonal frequencies that comprise the tonal set. Based upon the tonal vector definition, the reference vector expressing the harmonic cursor of the post-processing sonar system is defined as

$$\boldsymbol{f_M} = \left[f_M \quad 2f_M \quad \cdots \quad hf_M\right]^T, \tag{3}$$

where $h = 1,\ldots,H$, H is the highest order of the harmonics.

When considering the harmonic cursor-based graphical method to be used by the expert in terms of (2) and (3), this is considered as a minimization problem because the PSR expressed by f_s is estimated by finding the f_M minimizing the distance $\left\|\boldsymbol{f} - \boldsymbol{f_M}\right\|$. In this estimation, the $\boldsymbol{f_M}$ that satisfies the condition $f_M = f_s$ can be found when the tonal vector has no noise, and the $\boldsymbol{f_M}$ that satisfies the condition $f_M \approx f_s$ can be found when the tonal vector has noise due to the detection and tracking error. Here, the expert does not use the direct method comparing each tonal of the tonal vector directly, but uses the indirect method comparing the tonal vector with the reference vector. In addition, the expert does not use the micro method focused on information of each individual frequency, but uses the macro method focused on information of a frequency set. These are the reasons why the harmonic cursor-based graphical method has an accurate performance.

Although this method is an accurate and verified PSR estimation method in real sonar systems because it is based upon the knowledge and experience of a well-trained expert, it is not a real-time method and can only be applied to a stable graphic area that has straight frequency lines in the frequency diagram expressed with respect to frequency and time. Therefore, advanced methods require accurate performance in terms of real-time and non-graphic PSR estimation. From this point of view, the design of the IPSRE is equal to a real-time and non-graphic harmonic cursor.

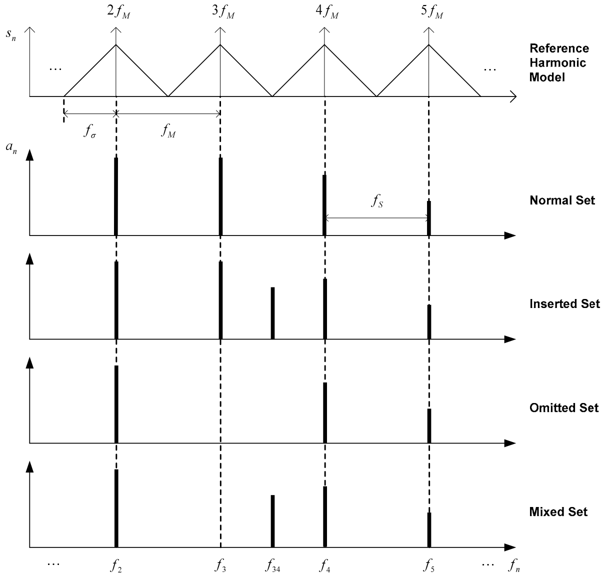

Fig. 2. Reference harmonic model and possible sets.

To implement a real-time and non-graphic harmonic cursor by developing the reference vector as expert knowledge, a reference harmonic model is proposed.

The reference harmonic model does not have bell-shaped membership functions [8,9], but has triangular membership functions [8] with the same width f_σ and different centers. This model is shown in Fig. 2. Here, each triangular membership function has no cross-section in order to guarantee frequency separation ability; i.e., a tonal f_{34} can be eliminated from the harmonic family of the normal set because it has a zero membership value. This justifies the triangular membership functions and the design parameter f_σ is easily determined by $f_\sigma \le f_M/2$.

The design parameter H is also easily determined by

$$H = round\left(\frac{f_N}{f_M}\right), \tag{4}$$

where $round(\cdot)$ is the function of the nearest integer value. This means that the proposed case where the parameter is determined by (5) is more efficient than the human-operated case where the parameter is determined by the width of the displayed spectrum in the sonar system.

Consequently, the reference harmonic model is expressed by

$$Reference\ Harmonic\ Model = f(f_M, f_\sigma, H). \tag{5}$$

By using this model, the effect of the noise due to the detection and tracking error can be reduced and the incompleteness of tonal vectors due to the acoustic environment can be ignored because it is an indirect and macro method. In addition, by using it, the design procedure becomes easy because the computational complexity is nearly decreased to $2N$ and the number of design parameters is small. Note that the reference harmonic model addresses simplicity as well as accuracy for real-time PSR estimation.

3.2. Optimization of the reference harmonic model

For optimizing the proposed reference harmonic model, the possible tonal sets that equal the NB frequency spectrum of tonal frequencies are divided into four sets for the case study: the normal set is composed of the harmonic family; the inserted set is composed of the harmonic family and other tonal frequencies; the omitted set is composed of part of the harmonic family; and the mixed set is a combined case of the inserted and the omitted set. These are shown in Fig. 2.

Finding $\hat{f}_s = f_M \in [f_{res}, \Delta f_{\max}]$ that minimizes the distance $\|\boldsymbol{f} - \boldsymbol{f_M}\|$ when f_{res} and $\Delta f_{\max}$ are respectively the frequency resolution and the maximum change in frequency width is considered the maximizing problem for the following fitness function $J \in [0,1]$:

$$J = \left(\sum_{n=1}^{N} s_n\right)\left(\frac{1}{N} + \frac{1}{H}\right)\Big/2, \tag{6}$$

where $s_n \in [0,1]$ is the score of an n-th tonal frequency used as input for the reference harmonic model. The N-related term is to prevent the case that each of $f_M = 2f_s, 4f_s, 8f, \cdots$ is selected as the solution; i.e., the values of the fitness function with only s_n are the same when $f_M = 2f_s, 4f_s, 8f, \cdots$. In addition, the H-related term is to prevent the case that each of $f_M = f_s/2, f_s/4, f_s/8, \cdots$ is selected as the solution; i.e., the values of the fitness function with only s_n are the same when $f_M = f_s/2,\ f_s/4, f_s/8, \cdots$.

In order to efficiently maximize the fitness function in (6), the ES is modified for this paper. ES imitating the principles of natural evolution as a method for solving parameter optimization problems has the following characteristics: there are no constraints such as continuity or derivativeness of the objective function in (6), and it is an asexual reproduction method that uses only a mutation operator with Gaussian random variables, compared to the genetic algorithm (GA) which is a sexual reproduction method [10,11].

The mutation operator of the modified-ES for finding f_M is defined as

$$f_{M_{offspring}}(g+1) = f_{M_{parent}}(g) + N(0,\sigma), \tag{7}$$

where g is generation number and σ is the standard deviation of the random variables.

In this paper, the $(\mu + \lambda)$-ES that selects the best μ out of $\mu + \lambda$ individuals in the next generation when μ parents generate λ offspring is considered in the case of $\mu = 1$ and the mutation operator is modified to improve the search efficiency as follows:

$$\sigma = \begin{cases} 0, & if \;\; p = 1 \\ f_{res}, & if \;\; p < C_p \\ \Delta f_{\max}, & otherwise, \end{cases} \tag{8}$$

where p is the number of individuals and C_p is the population constant. The first row means that this method uses elitism. The second row means that this method has local search ability. The third row means that this method also has global search ability.

By using this ES, the optimization of the reference harmonic model can be efficient because it has both local and global search abilities. In addition, by using it, the design procedure can be easy because the number of design parameters is small. Note that the modified-ES addresses the problems of simplicity as well as efficiency for real-time PSR estimation.

Consequently, the IPSRE has an easy design procedure as well as an accurate and efficient performance for real-time PSR estimation. The block diagram of the proposed intelligent PSR estimation system including the modified-ES is presented in [7].

4. SIMULATION RESULTS

The IPSRE performance was verified with the PSR estimation problem that the revolution velocity of the propeller shaft is time-varying, based upon the frequency spectrum produced from tracking [12] the passive sonar target. Although this simulation and verification has been previously studied in [7], this case study was more concrete because it had a greater variety in conditions and results.

For the original target and tracking filter, the scenarios, the models, and the parameters were given in [7,13] when the state vector is defined as

$$\boldsymbol{x}(k) = \left[f_s \;\; \dot{f}_s \;\; \ddot{f}_s \right]^T. \tag{9}$$

For the reference harmonic model, the width of the triangular membership functions was determined by $f_\sigma = f_{res}/2$ satisfying the condition $f_\sigma \le f_M/2$. The parameters for ES were also given in [7]. In determining ES parameters, $f_{res} < \sigma_w$ was given by the operator of the passive sonar system, and $\Delta f_{\max}$ was determined by the acceleration rate a and measurement noise σ_w that are already known through the design procedure of the tracking filter. g and $\mu + \lambda$ were determined by f_{res} and $\Delta f_{\max}$, and they were required to be increased in the case that f_{res} was small and $\Delta f_{\max}$ is large. Consequently, determining parameters was very easy.

The validity of the proposed fitness function was shown when the full search $f_M \in [0.1, 50]$ is executed by the step f_{res} with respect to $f_s = 10$. Obviously, the results show that the proposed fitness function is well defined and the PSR estimation problem has a discontinuous fitness function [7].

Fig. 3 shows that the results of the PSR estimation for a normal set. The top plot shows the frequency spectrum in the latest time. The middle plot shows the frequency diagram expressing the frequency spectrum in terms of frequency and time. As a human operator estimates the PSR using the harmonic cursor on this diagram, estimation is not easy in this case because the frequency lines are unstable during time 1−100 seconds while stable during time 100−150 seconds. Obviously, the proposed estimator acts well at all times. The bottom plot shows the real-time estimated PSR by the proposed algorithm. This means that the proposed algorithm has accurate performance irrespective of the stability of the frequency lines.

Figs. 5, 7 and 9 show the results of PSR estimation for the inserted, omitted, and mixed sets from Fig. 3. These mean that the proposed algorithm has accurate performance in general.

Fig. 11 shows the PSR estimation results for the mixed set that has no fundamental. This means that the proposed algorithm has accurate performance irrespective of the existence of the fundamental.

Figs. 4, 6, 8, 10 and 12 show that the trends of best fitness value related to the results of Figs. 3, 5, 7, 9 and 11 respectively. The five generations equal one sampling period for each figure. Their trends have increased or decreased forms despite the elitism because of the time-

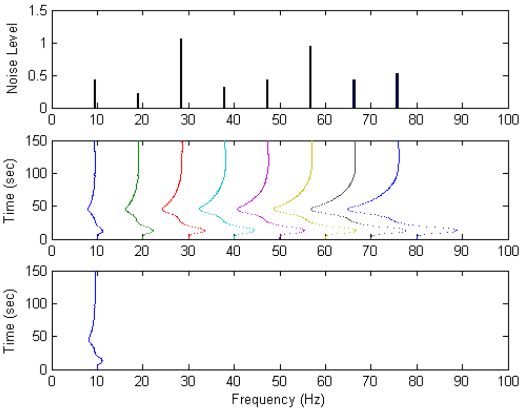

Fig. 3. Results of PSR estimation (normal set).

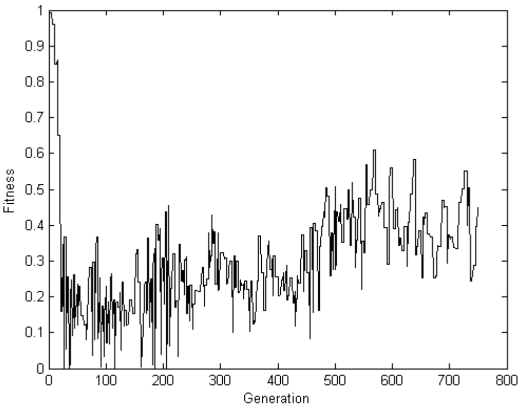

Fig. 4. Trend of best fitness (normal set).

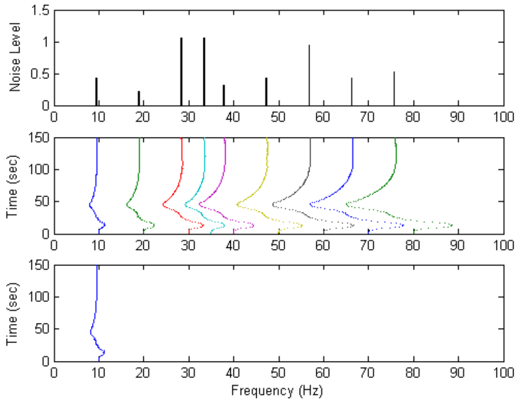

Fig. 5. Results of PSR estimation (inserted set).

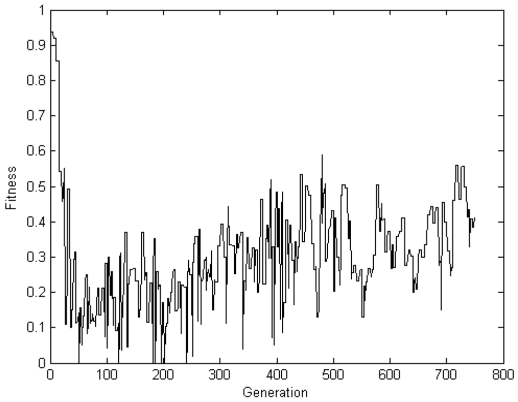

Fig. 6. Trend of best fitness (inserted set).

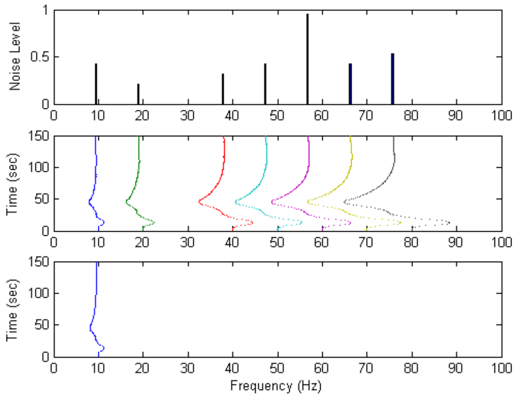

Fig. 7. Results of PSR estimation (omitted set).

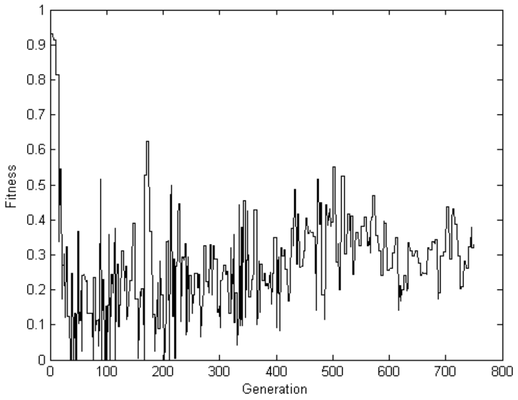

Fig. 8. Trend of best fitness (omitted set).

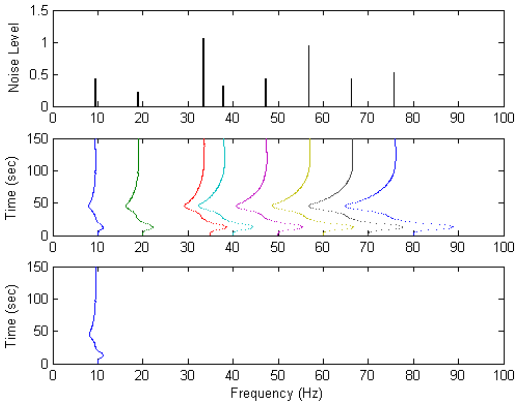

Fig. 9. Results of PSR estimation (mixed set 1).

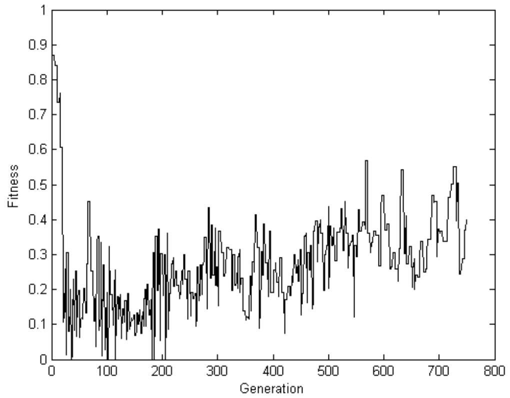

Fig. 10. Trend of best fitness (mixed set 1).

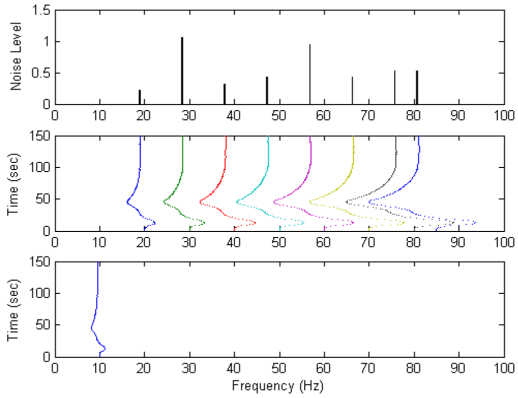

Fig. 11. Results of PSR estimation (mixed set 2).

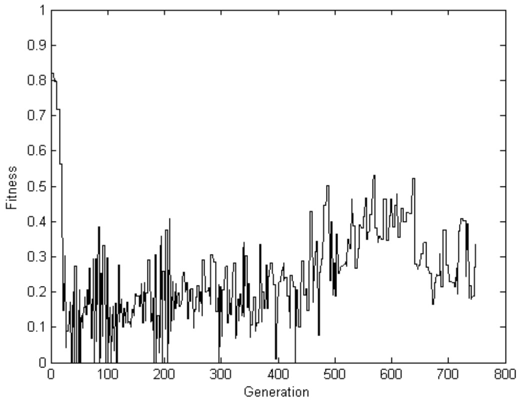

Fig. 12. Trend of best fitness (mixed set 2).

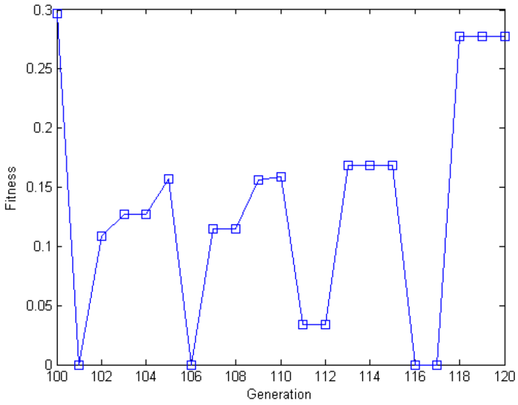

Fig. 13. Trend of best fitness (mixed set 2, focused on 100−120 generations).

varying PSR, i.e., the best individual in previous generation is not the best in current generation because of the time-varying PSR. However, Fig. 13 focuses on the 100−120 generations in Fig. 12 and shows the trend has an improved or saturated form. This means that the proposed algorithm performs efficiently for the difficult problem of the discontinuous fitness function.

From these results, the IPSRE is proven to have meaningful terms for real-time PSR estimation of a passive sonar target.

5. CONCLUSIONS

In this paper, an IPSRE using expert knowledge and the ES has been proposed to address all problems regarding accuracy, simplicity, and efficiency in real-time PSR estimation. The issue of simplicity as well as accuracy was resolved by using the reference harmonic model, and the issue of simplicity as well as efficiency was solved by using the modified-ES.

The proposed algorithm has three major advantages: 1) it has accurate and efficient performance for real-time PSR estimation 2) it has an easy design procedure because it has a simple structure and a small number of parameters, and 3) it can be applied to a real-time sonar system as well as a post-processing sonar system. These mean that the proposed algorithm is very practical for sonar classification systems.

To verify the performance of the proposed algorithm, a PSR estimation of a passive sonar target was performed. The simulation results showed that the proposed algorithm effectively solves the problems for real-time sonar classification. Through this, a PSR estimator as the basic and core element in feature extraction and further classification of the passive sonar target has been established.

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