Analysis of methods to optimize control systems for power supply of marine vessels using fuzzy logic and fractal analysis

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Abstract. The paper considers the features of promising methods to optimize the control systems for power supply of marine vessels using fuzzy logic and fractal analysis. In order to design an effective control contour for the power supply system (PSS), it is proposed to use synergistic mechatronic systems based on intelligent technologies with fundamentally new properties that allow for a more effective solution of control problems using fractal analysis of time series to increase the adequacy of forecasting through in-depth analysis of the causes of emergency situations. The synergistic effect SE of the control within such systems is a set of effects obtained as a result of their combination and synchronization in time and space. Practical aspects of fractal analysis are considered on the example of a two-cycle engine with supercharging and air cooling. In the study of fractal processes, a method is proposed for identifying and eliminating the short-term dependence of the value of the time series of the process \( S(t) \), which is characteristic of autoregressive processes, using regression with respect to \( S(t-1) \) and conducting the \( R/S \) analysis of the remainder \( X(t) \). Short-term dependence is eliminated provided that long-term dependence is maintained. Autoregressive AR(1) differences are analyzed at a certain time interval for various engine operating modes. The results of the \( R/S \) analysis of the engine operation and the determination of the Hurst exponent are used to increase the efficiency of forecasting and control of the PSS in the period of the detected chaotic behavior of the time series.

1. Introduction

The problem of managing the dynamic objects under uncertainty, that is the problem of constructing variable control systems, is one of the urgent problems in modern theory and practice, the solution of which is discussed in the works by Josiney A Souza, Keighobadi Jafar, Shi Wenrui, Dong Hairong, Shi Jiasheng, Pavlova N.G., Sevinov Zh.U., Mishchenko A.V., Pilyugina A.V.

At the same time, the analysis of scientific papers on this topic showed that in practice the existing methods and techniques for the PSS management encounter certain difficulties. For example, mathematical models for predicting the stability of the operation of main machines at low rotational speed must take into account a priori information about the pressure of the working cycle and injection, compression ratio, propulsion efficiency, and the useful thrust of the propeller, which are difficult to describe mathematically.

All this necessitates the development of new approaches and mechanisms to simulate and predict complex dependencies accompanied by fuzzy formalized problems.
Based on the above, the paper aims to consider the features of promising methods to optimize control systems for PSS using fuzzy logic and fractal analysis.

2. Materials and methods

The design and development of advanced control systems for modern PSS is a complex task that includes research and design work in mechanics, hydrodynamics, control and power engineering. Such PSS characteristics as dimensions (mechanics) are largely determined by the parameters of energy sources and converters (power engineering) and affect the processes of motion in water (hydrodynamics). The control system of the PSS should take into account the impact of the environment (resistance to the vessel motion, meteorological conditions, propeller thrust) and, as far as possible, provide for the system response to internal and external changes.

These issues are updated in the context of a number of international requirements and restrictions. For example, according to the resolution of the Marine Environment Protection Committee MEPC.213 (63), each vessel has to develop and apply an energy efficiency management plan. In addition, the above resolution of technical and operational measures to reduce greenhouse gas emissions include the development and use of ship energy efficiency management plans (SEEMP) for all types of ships, both new and existing, with a preliminary development of the energy efficiency design index EEDI [1].

It should be noted that due to specific technological features, the PSS is one of the striking examples of systems with distributed parameters that operate in dynamic modes. The processes occurring in the PSS are described by partial differential equations system. In turn, the mathematical models for managing the PSS are characterized by a significant amount of information necessary for their description, a high order and a large number of parameters, and nonlinearity of optimization criteria and constraints.

2.1 Description of methods

PSS managing requires special information technologies to create or improve control systems based on intelligent technologies such as fuzzy logic. The latest advances in science and technology indicate that it is advisable to use fractal dimension as an effective tool for managing complex dynamic systems of the PSS type rather than standard deviations characterizing the variability of random phenomena, which is logically integrated into models based on fuzzy logic. Based on the fact that the decision-making process regarding the management of complex dynamic systems is characterized by a significant degree of uncertainty and volatility, a new approach should employ various classes of fractals, fractal analysis, which confirms the importance and relevance of the chosen topic.

It is known that PSS operation is a non-stationary stochastic-chaotic process that develops in time [2]. Accordingly, various data are received in the control loop of the ESS in the form of an ensemble of time series: \( x(t) = \{x_j(t)\}, j = 1,2,\ldots,n; \ t \in T \), where \( T \) is the observation time.

Since the main characteristics of the PSS change in time, forecasting these time series is associated with certain difficulties, thus, a number of scientists suggest using adaptive control systems for the PSS.

In comparison to traditional approaches, adaptive control systems use an additional self-tuning loop, which is an obvious advantage. In this case, the main disadvantage of adaptive control systems is that they do not always allow implementing robust control. It should be noted that adaptation algorithms are developed in the absence of uncontrolled disturbances and, accordingly, do not establish the object characteristics during the identification process. These algorithms are quite difficult to implement and are efficient only in the absence of randomly occurring disturbances. In addition, the hypothesis of the quasi-stationarity of the control object should be fulfilled throughout the entire period of the controller adjustment [3].

In this regard, it is advisable to use intelligent control systems based on fuzzy logic to control the PSS, since they allow the design of synergistic mechatronic systems with fundamentally new properties. The synergistic effect \( SE \) of the control within such systems is a set of effects obtained as a
result of their combination and synchronization in time and space, and it can be achieved only if it belongs to the system-synergetic combination of these effects:

\[
SE = E_{\text{EMK}} \cap E_{\text{HE}} \cap E_{\text{IT}} \cap E_{\text{CAK}}
\]

where \(E_{\text{EMK}}\) is the effect of introduction of electromechanical control tools;
\(E_{\text{HE}}\) is the effect of using advanced microprocessor technology and power electronics;
\(E_{\text{CAK}}\) is the effect of using modern ICT technologies and introducing automated systems into the control loop;
\(E_{\text{IT}}\) is the effect of using intelligent technologies in the control system.

2.2 Basic data

On a practical example, let us consider the features of the construction and functioning of an intelligent control system of the PSS, which is based on fuzzy logic. In this case, the methodological apparatus for solving the problems posed is fractal analysis, which makes it possible to determine the persistence levels of chaotic information flows in the control system.

A two-cycle engine with supercharging and air cooling is used as an experimental setup for modeling.

When constructing a model, it is necessary to solve the following problems:

- combine a set of methods for fractal analysis of time series into a single methodology;
- analyze the fractal dimension and the Hurst exponent based on the sequential R/S analysis;
- evaluate the autocorrelation effect of the previous values of time series on the next values and determine future trends;
- determine the spatial dimensions of the dynamic processes achieved.

Consider the trend characteristics of the following time series \(A(t), B(t), C(t), D(t)\), where \(A(t)\) is the average effective pressure, \(B(t)\) is the specific indicator fuel consumption, \(C(t)\) is the amount of air for combustion of 1 kg of fuel, and \(D(t)\) is the amount of exhaust gases.

The discretization of the time series was performed with a step of \(\Delta t = 0.84\) s, which was determined on the basis of the Shannon-Kotelnikov theorem.

To process the data obtained, the programs and applications developed in the Matlab software. To search for the mathematical expectation, variance, standard deviation, standard functions were calculated: \(\mathbb{E} = \text{mean}(T)\) – mathematical expectation; \(\text{Var} = \text{std}(T)\) – average deviation; \(\text{Dv} = (\text{Var})^2\) – variance.

The results obtained are shown in Table 1.

| Studied indicator | Mathematical expectation | Variance | Mean-square deviation |
|-------------------|--------------------------|----------|----------------------|
| \(A(t)\)          | 115.403                  | 7.332    | 2.840                |
| \(B(t)\)          | 157.334                  | 57.646   | 7.951                |
| \(C(t)\)          | 258.061                  | 6.511    | 2.665                |
| \(D(t)\)          | 0.602                    | 0.125    | 0.372                |

At the next stage, for the investigated time series, the Hurst index \(H\) was calculated. To determine the fractal dimension \(D\), the spatial dimension \(n\) of the dynamic process of engine operation, as well as the correlation measure \(C\), the following formulas were used:

\[
D = \lim_{d \to 0} \frac{\log N(d)}{\log \left( \frac{d}{2} \right)}, \quad N(d) \approx \frac{1}{d^D}, \quad \text{when} \quad d \to 0: N \cdot d^D = 1 \quad \text{and} \quad C = 2^{2H-1} - 1
\]

Table 2 summarizes the calculation results.
Table 2. Calculation results of chaotic indicators of time series

| Investigated time series | Hurst exponent $H$ | Fractal dimension $D$ | Spatial dimension $n$ | Correlation measure $C$ |
|--------------------------|-------------------|----------------------|----------------------|------------------------|
| $A(t)$                   | 0.711             | 1.489                | 2                    | 0.246                  |
| $B(t)$                   | 0.955             | 1.245                | 2                    | 0.733                  |
| $C(t)$                   | 0.833             | 1.367                | 2                    | 0.471                  |
| $D(t)$                   | 0.816             | 1.384                | 2                    | 0.439                  |

Table 2 shows that the Hurst exponent $H$ for all signals is greater than 0.5. Thus, the time series has a certain chaos, but the dynamics of these signals will not change and develop in the previous direction. With regard to the peculiarities of the two-cycle engine operation, this enables solution of the problems of forecasting and early detection of possible changes in the operating conditions of the PSS through the calculation of the Hurst index $H$ in real time.

The chaotic nature of the engine operation is evidenced by the fact that the fractal dimension $D$ for all the studied parameters is not an integer. However, since $D \in [1.0; 2.0]$ and $D < 1.55$, such chaos can be controlled. The value of the spatial dimension $n = 2$ indicates the number of factors involved in the dynamic process. The advantage of the results obtained in the study of the levels of persistence of parameters and indicators of the engine operation process is that the fractal and spatial dimensions of each time series can be determined. The Hurst exponent indicates such an important property for the engine operation as trend. This indicator is universal and applicable for any time series, even with unknown divisions.

The identification and elimination of the short-term dependence characteristic of autoregressive processes are of particular relevance in the study of fractal processes. Linear dependence increases the Hurst exponent and shows the effect of long-term memory. To eliminate the short-term dependence, it is necessary to regress the value of the time series of the process $S(t)$ as a dependent variable relative to $S(t-1)$. After that, find a linear relationship between them and conduct the $R/S$ analysis of the remainder $X(t) = S(t) - [(a + bS(t-1)]$. If the original series had a long-term memory, the relationship is preserved, while the short-term dependence is eliminated.

3. Results

Let us analyze the autoregressive $AR(1)$ differences for the engine operation modes at a certain time interval. These differences are used to eliminate or minimize the linear relationship. Linear dependence can shift the Hurst exponent and make it significant (with no long-term trends), that is cause a type I error. Autoregressive $AR(1)$ differences will minimize the bias. This process is called pre-bleaching or de-trending [4]. In the $R/S$ analysis, the removal of trends will remove the serial correlation.

The procedure for finding the first difference is similar to removing the autoregressive dependence and the linear trend. This often makes it possible to obtain a stationary series that is investigated for stationarity using the criteria of series, inversions, etc.

Figure 1 shows time behavior of the $R/S$ trajectory that indicates the chaotic behavior of the time series (average effective pressure), which corresponds to white noise characterized by a frequent change in the trend of the engine operation.
Figure 1. Result of R/S-analysis of the engine operation graph (mean effective pressure)

The results of the R/S analysis of the engine operation graphs and the determination of the Hurst exponent increase the efficiency of forecasting and control of the PSS in the period of the detected chaotic behavior of the time series [5]. This, in turn, requires a special approach and attention to ensuring an optimal and stable thermal state of engine parts and assemblies, timely scavenging and cleaning of cylinders from exhaust gases.

4. Conclusion

The study is relevant due to the fact that the revealed features of the fractal with respect to retrospective information about PSS operation and the fuzzy logic can be used to determine the periods of the unstable state of the system for an adequate forecast of its reliable operation and effective management in the future [6–9].

Thus, the results of the study yield the following conclusions. In practice, traditional methods of predicting the behavior of the PSS encounter certain difficulties when the behavior of time series is chaotic, since the mathematical models of the process must consider numerous factors that affect its dynamics. Intelligent control systems based on fuzzy logic are aimed to design synergetic mechantronic systems with fundamentally new properties in order to more effectively solve control problems using fractal analysis of time series, which contributes to the increased adequacy of forecasting through in-depth analysis of the causes of emergency situations.

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