The hierarchical fuzzy model of hydro acoustic activity for underwater vehicles

V E Bolnokin¹, S A Sorokin², V I Storozhev³, Duong Minh Hai⁴ and A A Shcheka⁵

¹Mechanical Engineering Research Institute of the Russian Academy of Sciences, 4, Maliy Haritonievsky all., Moscow, 101000, Russian Federation
²M.A. Kartsev Computing System Research and Development Institute (NIIVK, JSC), 108, Profsoyuznaya str., Moscow, 117437, Russian Federation
³Donetsk National University, 24 Universitetskaya str., Donetsk, 83001, DPR, Ukraine
⁴Naval Technical Institute, 9, Mac Quyet Str, Hai Phong City, Duong Kinh Dist, Viet Nam
⁵Vladimir State University named after Alexander and Nikolay Stoletovs, 87, Gorky str., Vladimir, 600000, Russian Federation

E-mail: vitalybolnokin@yandex.ru

Abstract. The description of the basic equations and numerical-analytical methods of analysis of the theoretical model of functioning and structural-parametric optimization of hydro acoustic screens of underwater vehicles. The technique is based on a hierarchical fuzzy model of hydro acoustic activity underwater vehicles.

1. Introduction

One of the most important aspects of scientific and technical problems in the field of design and operation of various categories of underwater vehicles (UWV) was and still is the problem of their acoustic fields. The task of reducing the level of acoustic activity UWV in the general context is due to the requirements of reducing the degree of sonar "noise" as a factor of negative impact on the ecological situation and the state of the environment, on the processes of marine fishing, on sonar and underwater communication technologies. For special purpose UWV the problem of hydro acoustic protection consists in reducing the possibility of their passive detection and identification based on generated acoustic signals of various nature, level and spectrum; in reducing the probability of reaching the levels of hydro acoustic sensitivity for anti-submarine weapons systems; in reducing the intensity and contrast levels reflected from the surface of the ship UWV of signals in active sonar sensing technologies. For UWV high levels of intrinsic hydro acoustic radiation and diffractive fields of hydro acoustic waves complicate the functioning and reduce the quality of operation of hydro acoustic devices for deep-sea installation, location and positioning. So, the proper acoustic fields are UWV causes problems for both generating and receiving signals by sonar systems. In such a situation, the key tasks are to ensure effective directional radiation of "noiseless" hydro acoustic signals, energy-efficient contrast reception, filtering and signal processing.

Theoretical models of the functioning of structural elements of hydro acoustic shielding of vibration emitters and hydro acoustic antennas have been the subject of research in an extensive number of
publications, summarized in [1-4]. The analysis of a number of models of multilayer hydro acoustic screens with anisotropic functional gradient components is presented in publications [5-12]. As a follow-up to these studies, this paper presents a method for analyzing the functioning model and structural and parametric optimization of sound-proof properties of multilayer screens.

2. Fuzzy hierarchical model of the generalized index of hydro acoustic activity of underwater vehicles

A separate specific class of scientific and technical problems from the field under consideration is the problem of hydro acoustic shielding of such classes of devices UWV, such as sonar emitters and sonar antennas.

Multi-factor nature of the acoustic activity phenomenon UWV with elements of uncertainty and fuzziness in the quantitative description of the degree of influence of these factors is the basis for setting the problem of forming a fuzzy generalized indicator for an integral assessment of acoustic activity UWV. As a variant of its solution, the concept of generalized fuzzy estimation of the analyzed phenomenon is proposed [5, 7, 12, 13, 14] based on the introduction of the Index of potential acoustic activity IPAA (Index of Potentially Acoustic Activity), determined using a multi-level branched fuzzy hierarchical model for accounting for partial factors of acoustic activity UWV.

The proposed private version of the IPAA formation methodology is based on a branched hierarchical instrumental expert model of causal relationships between acoustic activity factors and the structure shown in figure 1. Linguistic and quantitative estimates of the relative importance of the individual criteria being compared shown in table 1.

These alternatives consist in using numerical estimates of comparisons by one expert, forming a matrix of clear numbers; in using interval estimates of comparisons by one expert, forming a matrix of clear intervals; in using numerical estimates of comparisons by a group of experts, transformed into a matrix of fuzzy intervals with membership functions $\mu_{a_{ij}}$.

Table 1. Linguistic and quantitative estimates of the relative importance of the individual criteria being compared.

| Qualitative assessment of the comparison of particular criteria | Quantitative assessment $a_{ij}$ |
|--------------------------------------------------------------|---------------------------------|
| Strictly equivalent (identical)                              | 1                               |
| Weakly preferable                                           | 3                               |
| Somewhat preferable                                         | 5                               |
| Much preferable                                              | 7                               |
| Strictly preferable                                          | 9                               |
| Intermediate values of importance                           | 2, 4, 6, 8                      |

The $a_{ij}$ score of comparing criterion j with criterion i has the inverse of $a_{ij}$.

3. Solving the problem

In the first case, the normalized ranks $\alpha_i$ (i=1…n) for each group of partial criteria of the initial level are determined based on the solution of the optimization problem [14]:

$$ S = \sum_{i=1}^{n} \sum_{j=1}^{n} (a_{ij}\alpha_j - \alpha_i)^2 \rightarrow \min; \sum_{i=1}^{n} \alpha_i = 1 $$

by the method of indefinite Lagrange multipliers. When introducing the Lagrange function for the optimization problem under consideration in the form

$$ L = \sum_{i=1}^{n} \sum_{j=1}^{n} (a_{ij}\alpha_j - \alpha_i)^2 + \lambda \left( \sum_{i=1}^{n} \alpha_i - 1 \right) $$
and the formulation of optimality conditions

\[ \frac{\partial L}{\partial \alpha_i} = 0 \text{ (i = 1, n)}, \]

**Figure 1.** Structure of the tool-expert hierarchical model for the formation of the IPAA indicator.
the determination of rank sets in groups of partial criteria $S_{ij}, S_{ij}, S_i$ is carried out on the basis of solving systems of linear algebraic equations of the form

$$
\alpha_i = \alpha_i^* / \sum_{i=1}^{n} \alpha_i^*, \quad \alpha_i^* = \left( \prod_{j=1}^{n} \alpha_{ji} \right)^{1/n}.
$$

A fundamentally important indicator of the degree of reliability of determining the components of the normalized rank vector is the consistency index of the matrix of paired comparisons [14]. This index is calculated as a result of an approximate estimate of the maximum value of the matrix $\| a_{ij} \|$.

The determination of rank sets in groups of partial criteria is controlled based on the analysis of consistency indices $\delta_c$ and indicators of consistency relations $\gamma_c$ of the corresponding matrices of paired comparisons $\| a_{ij} \|$ dimension comparisons $n$ calculated [14] using the formulas

$$
\delta_c = (\lambda_{\text{max}} - n) / (n - 1), \quad \gamma_c = \delta_c / \gamma_n
$$

where $\lambda_{\text{max}}$ are the values of the maximum eigenvalues of the pair comparison matrices $\| a_{ij} \|$, $\gamma_n$ — and are the consistency values of random matrices of given orders, represented for a certain range of dimensions of the pair comparison matrices in table 2. An approximate value of the consistency index for $\| a_{ij} \|$ the dimension matrix $n$ can also be obtained [14] in the form

$$
\delta_c = \left( \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_i a_{ij} - n \right) / (n - 1).
$$

**Table 2.** Values of consistency indicators for random matrices of varying dimensions.

| The dimension of the matrix | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Indicator $\gamma_n$       | 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|
The consistency of expert assessments for sets of paired comparisons of particular criteria is considered acceptable if the values $\gamma_c$ do not exceed 0.1-0.2.

Aggregation of partial criteria of various levels in each of the selected subsets $S_{ijk}$, $S_i$, $S_j$ after determining the normalized ranks of criteria within groups, based on the relations

$$
\mu_{S_{ij}}(x) = \alpha_{1(S_{ij})} \mu_{S_{ij1}}(x) + \alpha_{2(S_{ij})} \mu_{S_{ij2}}(x) + ... + \alpha_{N(S_{ij})} \mu_{S_{ijN}}(x),
$$

$$
\mu_{S_i}(x) = \alpha_{1(S_i)} \mu_{S_{i1}}(x) + \alpha_{2(S_i)} \mu_{S_{i2}}(x) + ... + \alpha_{N(S_i)} \mu_{S_{iN}}(x),
$$

$$
\mu_{IPAA}(x) = \alpha_{1(Si)} \mu_{K_{i1}}(x) + \alpha_{2(Si)} \mu_{K_{i2}}(x) + ... + \alpha_{7(Si)} \mu_{K_{i7}}(x),
$$

in which $N_{ij}$, $N_i$ – respectively, the number of fuzzy partial criteria in the corresponding group, $x$ - vector characteristic of fuzzy alternatives.

If it is necessary to obtain strict pessimistic estimates of the impact on the IPAA, a multiplicative convolution of particular criteria is used

$$
\mu_{S_{ij}}(x) = \alpha_{1(S_{ij})} \mu_{S_{ij1}}(x) \cdot \alpha_{2(S_{ij})} \mu_{S_{ij2}}(x) \cdot ... \cdot \alpha_{N(S_{ij})} \mu_{S_{ijN}}(x),
$$

$$
\mu_{S_i}(x) = \alpha_{1(S_i)} \mu_{S_{i1}}(x) \cdot \alpha_{2(S_i)} \mu_{S_{i2}}(x) \cdot ... \cdot \alpha_{N(S_i)} \mu_{S_{iN}}(x),
$$

$$
\mu_{IPAA}(x) = \alpha_{1(Si)} \mu_{K_{i1}}(x) \cdot \alpha_{2(Si)} \mu_{K_{i2}}(x) \cdot ... \cdot \alpha_{7(Si)} \mu_{K_{i7}}(x).
$$

The criteria are formalized by introducing fuzzy trapezoidal intervals of variation of acceptable values of the corresponding parameters.

The formalization of particular criteria using an expert curve of the degree of severity of the expected effect, an example of which is described in figure 2.

![Figure 2. Structure of expert curve of the severity of the expected effect on the qualitative linguistic level (X1 – not expressed ($\mu=0$); x2 is a very weak ($\mu=0.1$); X3 – weak ($\mu=0.25$); X4 – moderately expressed ($\mu=0.5$); X5 is strongly expressed ($\mu=0.75$ mm); X6 – it is highly expressed($\mu=0.9$); X7 – fully expressed ($\mu=1$)).](image)

**4. Conclusion**

The developed fuzzy hierarchical model of the generalized index of hydro acoustical activity of underwater transport environments used obtain indicative estimates in cases of possible variation in the degree of application of certain mechanisms for reducing acoustic activity taken into account in it, after which alternatives are analyzed to develop a rational design solution.
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