APPLICATION OF TAGUCHI METHOD FOR PARAMETRIC STUDIES OF A FUNNEL SHAPED STRUCTURE USED FOR NOISE REFLECTION WITH SOURCE ON THE CENTER

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ABSTRACT

In this paper, attempt has been made to minimize sound reflection from the wall by using Taguchi's method and to find optimal structure for the suggested test-section inside the cavitation tunnel. The suggested structure which was added to the test-section is funnel-shaped with a performance like a check valve. In order to obtain approximate values of five independent parameters, three levels were taken into account for each parameter. By combining parameters of different levels, 27 tests were designed using Taguchi's method and Minitab Software. Different acoustic analyses were conducted in COMSOL Multiphysics software, and defined parameter of general reflection coefficient was obtained for 21 observer points. Applying the general reflection coefficients to Minitab Software and drawing the SNR graph, approximate values of the parameters were obtained. However, these values did not produce enough accuracy to design the optimal structure. For this reason, five levels around optimal values, obtained from the previous analysis, were considered for each parameter. Same steps were repeated again for the parameters at five levels and optimal values were obtained. Optimal structure was modelled and analyzed. Consequently, appropriate defined parameters of general and local reflection coefficients were extracted which represented an optimal structure for the intended test section.

KEYWORDS

Acoustic Propagation; Cavitation Tunnel; Test Section; Funnel shape; Propeller; Transient Analysis; Gaussian pulse; COMSOL Multiphysics

1. INTRODUCTION

Underwater acoustic issues are among controversial scientific subjects of study which are used in shipping and seismology. Tests related to the sound are among the most expensive tests, but with the help of powerful software, they can be run with minimized costs. By using software modeling, parametric studies can be conducted for different types of situations and under different boundary conditions with relatively low cost. Cavitation tunnel is made of some parts with test-section being its most important part. Cavitation tunnel includes different test sections with special laboratory applications and in every examination its related test section will be

installed in the tunnel. One of the main tests carried out in cavitation tunnel is testing the noise resulting from marine propellers. This type of test can be considered as one of the most critical tests in examining and designing the propeller for a better performance. Test-section, which is used to accomplish this task, should have a certain structure. It should be designed in a way that can have the least sound reflection, when the noise emanating from the propeller hits the wall.

Main aim of the current study is to examine and suggest an optimum structure for the test-section, which has the best capability of scattering the propagated sound. A survey of articles, which have focused on the behavior of different structures in scattering the sound, is presented next.

Aboudi [1] studied extraction of sound wave in uniformly rotating systems. He showed the scattering amplitude for the rotating cylinder and examined the effect of certain speeds on the angles of incidence. Abrahams [2] examined the scattered sound field when fluid-plate is large and solved the governing equation by matched asymptotic expansions method. Schleicher and Howe [3] studied sound incidence to an annular aperture in mean flow duct. In their analysis, they examined incidence of sound with long wavelength and a thin rigid disc whose cross-section is axi-symmetric. Dong et al. [4] studied sound scattering feature for double-layered sphere particles, on the basis of ultrasonic resonance. Godinho et al. [5] investigated three dimensional sound scattering by rigid barriers around high buildings. They used various numbers and evaluated the SPL attenuation near the building façade. Gennaretti et al. [6] examined the scattered sound field by an elastic moving object. They started their work by Ffowcs Williams and Hawkings formula and obtained integral boundary formula for sound propagation.

On the other hand, Lethuillier et al. [7, 8] studied theoretically and experimentally the multiple scattering of acoustic waves from a grating of two immersed in cylindrical shells. Falou et al. [9] solved problem of ultrasound scattering by spherical structures of wave propagation using COMSOL Multiphysics. Scattering of incident plane wave was predicted by moving body with the surface of finite impedance by Wang and Yang [10]. Martina and Maurel [11] considered scattering sound by random sets of identical circular cylinders. Ouis [12] studied scattering of a spherical wave by a thin hard barrier on a hard plane. Prospathopoulos et al. [13] investigated the scattering of sound wave from a radially layered cylindrical obstacle on a 3D ocean waveguide. The results were used for general problem of 3D acoustic scattering from axisymmetric inhomogeneities in ocean low frequency waves.

2. METHODOLOGY

The main equation which is solved in transient solution in COMSOL Multiphysics software is

$$\frac{1}{\rho_0 c_s^2} \frac{\partial^2 P}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0} (\nabla P - q) \right) = Q \quad (1)$$

Where $P = P(r, t)$ is acoustic pressure, c_s is sound speed, ρ_0 is density of the balanced fluid, and q and Q are determinants of dipole and monopole sources. Various boundary conditions can be modeled in COMSOL Multiphysics software but here Neumann boundary condition is used on the basis of Eq.2. This boundary condition is applied on the walls and is defined as sound hard wall in the software [14].

$$\mathbf{n} \cdot \left(\frac{1}{\rho_0} (\nabla p - \mathbf{q}) \right) = 0 \quad (2)$$

As shown in Fig.1, point O is the source of sound propagation and point A is the observer point on which the results are read. To determine the quality of sound reflection and the effect of structure on the sound reflection, two important parameters should be defined. First criteria, is the local sound reflection coefficient. As seen in Fig.1, a sound pulse is propagated from the source (blue field) and after passing the observer point at A, depending on its structure, scatters to different fields. It is clear from this figure that it is divided into two yellow and brown fields. These wave fields, due to superposition principle, can weaken or strengthen each other.

Fig.1. Schematic of an observer point A (green) and O source (red).

If SPL diagram is drawn when the problem is solved at the observer point, a diagram similar to Fig.2 is obtained. If first maximum sound in this graph is called local initial sound and maximum sound of the remaining time is called return maximum sound, then local reflection sound coefficient is defines as follows:

$$\text{local sound reflection coefficient} = \frac{\text{return maximum sound}}{\text{local Initial sound}} \quad (3)$$

Another coefficient that must be defined as a second criterion is general sound reflection coefficient. This coefficient specifies how much of the total propagated sound from source O is reflected to the desire point. Definition of this coefficient is the same as local sound reflection coefficient except for the fact that the denominator is the initially propagated sound from the source.

$$\text{General sound reflection Coefficient} = \frac{\text{return maximum sound}}{\text{propagated initial sound from source}} \quad (4)$$

In all of the analyses, an initial sound source type of Gaussian pulse with 0.01 m²/s amplitude and frequency of 60 kHz is considered and test-section was filled with water of 1000 kg/m³

density and the sound propagation speed is considered to be 1600 m/s. Also, the investigated areas are shown in Fig.3 with blue color. Based on order of the points, it is expected that there will be a suitable statistical population of all points inside the test section.

Fig.2. Diagram of measuring the passing sound through an arbitrary point.

As mentioned earlier, results are read at the observer points. These points are shown in Fig.3 with their exact coordinates. Bearing in mind that the figure is symmetrical, it seems like these 21 points are appropriate approximations of all the points located on the cross-section of the study.

Fig.3. Coordinates of the point from which the results are extracted.

In this study, the structures are considered as rigid wall so that optimal values for effective parameters are specified. It should be noted that outer test section has 450 millimeter length and sound source characteristics are the same as in the previous analysis. To obtain an optimal design for the structure, 5 parameters are defined as: L (Distance to wall), k (aperture length), d (internal aperture), D (external aperture) and t (Thickness).

Fig.4. Funnel-shaped structure added to the test section.

a. Taguchi Method

Design of Experiments (DOE) is an effective statistical method that can study several parameters at the same time. By applying this method, engineers, scientists, and researchers can reduce the test and this reduction will be the cause of more researches [15]. In Taguchi's method [15], various orthogonal arrays, depending on the selected parameters and the related levels, are used as experiments matrices. In this method, changes are introduced by a variable called signal to noise ratio (S/N ratio). The experimental condition which has the highest value of signal to noise ratio is chosen as an optimal condition [16]. To design the structure optimally and determine the exact value of each parameter, Taguchi's method is used. Minitab software has facilitated the use of Taguchi's method. Using this software, tests are designed and the exact level of each parameter is determined according to the type of output.

In Taguchi designs, a measure of robustness is used to identify control factors that reduce variability in a product or process by minimizing the effects of uncontrollable factors (noise factors). Taguchi experiments often use a 2-step optimization process. In step 1, the signal-to-noise ratio is used to identify those control factors that reduce variability. In step 2, control factors are identified that move the mean to the target and have a small or no effect on the signal-to-noise ratio. The signal-to-noise ratio measures how the response varies relative to the nominal or target value under different noise conditions. Data sequence for the general reflection coefficients which are higher-the-better performance characteristic are pre-processed based on equation (5).

$$S/N = -10 \times \log (\sum(1/Y^2)/n) \quad (5)$$

3. VERIFICATION AND VALIDATION

In order to make sure that method of study is appropriate and accurate, practical results of numerical modeling in COMSOL Multiphysics software are verified in this section. Data used for verification are taken from Yamaguchi et al.'s [17] paper. Their research is one of the most valid on studying the propagated noise in test-section of cavitation tunnel, which has been used as a source of validation by many researchers. This test was conducted in Tokyo University with a test-section having a square cross-section of 45 centimeter and with the capability of testing a

propeller of 20 to 22 centimeter diameter. Structure and size of the test-section is shown in Fig.5. The mentioned paper examines the noise propagated by single-frequency source in the center. The modeling was done according to what is shown in Fig.5. Problem was modeled by applying common boundary conditions in COMSOL Multiphysics software and solved with good accuracy, compared to experimental data.

Fig.5. Cross section of test section in the cavitation tunnel, Tokyo University.

Acoustic pressure is plotted in vertical direction along the tunnel in Fig.6. Decrease in acoustic pressure inside the air fluid is quite evident. As observed in Fig.6s, two graphs; one related to the results of the current paper and the other related to the Yamaguchi's et al.'s research, are compared which are very similar to each other, but have some trivial differences.

Fig.6. Computed acoustic pressure distribution in cross section of test section in vertical direction compared with experimental data.

4. RESULTS AND DISCUSSION

Applying Taguchi's method by assuming presented values of table 1 and using Minitab statistical software, 27 tests are designed. All 27 tests are modeled by combination of parameters in different levels in AutoCAD Software. Subsequently, geometrical model is inserted in the COMSOL Multiphysics software to be analyzed. By applying boundary conditions, domain values, certain frequencies for the source located on the center of cross-section, and the conditions of sound propagation environment which will be explained thoroughly later, the analyses are carried out. After analyzing the tests in COMSOL Multiphysics software, general reflection coefficient values for 21 mentioned points in Fig.3 are obtained. Mean of general reflection coefficient values for 27 tests are displayed in Fig.7.

Table 1. Parameter levels for primary design (in mm).

Parameters Levels	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
1	20	15	6	8	2
2	30	30	12	16	4
3	40	60	24	32	6

Fig.7. Mean of general reflection coefficients in 27 tests.

By analyzing the data using Minitab software, 27 tests are achieved which are the combination of 5 parameters in 3 levels. After modeling and tests analyses and presenting the results to Minitab software, plots of Fig.8 are obtained. These plots indicate optimal values of parameters and their effects on one another. The exact amount

of SN ratios referred in Figure 8, are also listed in Table 2. The larger the value of SN, the better performance is indicated.

Fig.8. Left: Plot of SN ratio for 27 tests for primary design; optimal levels are shown with red circles. Right: Plot of Means for 27 tests for primary design.

Table 2. The exact amount of SNR for the parameters shown in Fig.8.

Parameters Levels	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
1	1.0551	1.064	1.068	1.0551	1.0481
2	1.0494	1.0539	1.044	1.0573	1.0636
3	1.0570	1.0444	1.0509	1.0483	1.0486

As seen in Fig.8, optimal values occur when SNR values are maximum and Means are minimum. These values are presented in table 3.

Table 3. Optimal values of 5 parameters in 3 levels of 27 tests.

Parameters	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
Levels	3	1	1	2	2
Size (mm)	40	15	6	16	4

To make sure about design and accuracy of the obtained optimum results, effective parameters were investigated in 5 levels around optimal points. These values are shown in table 4. Twenty five tests were designed for 5 parameters and 5 levels using Minitab software. After modeling and analyzing the tests, general reflection coefficients were found. Total general reflection coefficients were obtained from the mean of extracted general reflection coefficients of 21 points illustrated in Fig.3. Mean of total general reflection coefficients obtained from 25 tests are shown in Fig.9.

Table 4. Applied values for 5 parameters around the obtained optimal points.

Parameters Levels	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
1	36	9	2	12	3
2	38	11	4	14	3.5
3	40	13	6	16	4
4	42	15	8	18	4.5
5	44	17	10	20	5

By inputting values in Minitab software, the output is obtained which is presented in Fig.10. The exact amounts of SNR are displayed in Table 5. Figure 10 shows the behavior of 5 parameters in 5 levels. As seen in Fig.10, the optimal values occur when SNR values are maximum and means are minimum. These optimal values are demonstrated in table 6.

Table 5. The exact amount of SNR for parameters shown in Fig.10; larger is better.

Parameters Levels	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
1	1.0994	1.0882	1.0942	1.0798	1.0995
2	1.0986	1.0924	1.0903	1.0953	1.1028
3	1.0827	1.0882	1.0806	1.0967	1.0848
4	1.0867	1.0981	1.1	1.0911	1.0882
5	1.0884	1.0883	1.0895	1.0931	1.08

Fig.9. Mean value of general reflection coefficients in 25 tests.

Fig.10. Left: Plot of SN ratio for 25 tests for detailed design, Right: Plot of Mean values for 25 tests for detailed design.

Table 6. The obtained optimal values from 5 parameters in 5 levels of 25 tests.

Parameters	k (Aperture length)	L (Distance to wall)	D (External aperture)	d (Internal aperture)	t (Thickness)
Levels	1	4	4	3	2
Size (mm)	36	15	8	16	3.5

It is obvious that distance to the wall and values of internal aperture are exactly the same as in the previous tests. In the meantime, the obtained values of thickness (t) by the taguchi's tests do not differ much from the previous cases in which thickness was aprior assigned. After modeling the new geometry using optimized parameters, the resulting structure is produced and illustrated in Fig.11.

Fig.11. Shape of optimal structure for the test section.

Therefore, by analysis of the optimal model, general reflection coefficient and local reflection coefficient are found to be 0.8776 and 0.9843, respectively. Local reflection coefficient contours for final optimal structure are shown in Fig.12. To better visualize the behavior of optimal structure, pressure contours at different times are shown in Fig.13. The obtained value for optimal design of the test-section are based on general reflection coefficient, but local reflection coefficient is another important parameter which, despite of being ineffective on the main design, can determine the positions on which the noise is more concentrated.

Fig.12. Local reflection coefficient contours for final optimal structure.

Fig.13. Pressure contours at different times for optimal test section.

5. CONCLUSIONS

In this study, a geometrical structure is suggested for reducing the propagated noise in test-section of a cavitation tunnel, which is doubled by hitting the walls. The suggested structure is funnel shaped which acts like a check valve. When the sound is propagated in the test-section and reaches the suggested structure, major part of it can easily enter the space between the wall and the structure. Sound, by hitting the structure and the wall several times, loses its energy and is drastically weakened. The structure is considered to have 5 independent parameters including aperture length, distance to the wall, internal aperture, external aperture and thickness. At first stage of the experiment, 3 levels were defined for the parameters and 27 tests were carried out. After analyzing these tests in COMSOL Multiphysics Software, optimal value for each parameter was obtained. To obtain more accurate values for each parameter, same parameter was again defined in 5 levels and by combining these levels, 25 new tests were designed. Modeling and analyzing the new results, optimum values of 36 cm for aperture length, 15 cm for distance to the wall, 16 cm for internal aperture, and 8 cm for external aperture and 3.5 cm for external wall thickness were obtained. Finally, considering the acquired optimum values, average values of defined parameters of general reflection coefficient and local reflection coefficient were found to be 0.8776 and 0.9843, respectively, which compared to all the computed coefficients for the previous case studies, can be considered the most optimal coefficients representing an optimum structure.

REFERENCES

- [1] Aboudi, J., Scattering of sound waves by rotating cylinders and spheres, *Journal of Sound and Vibration*, 19 (4), 437-444, 1971.
- [2] Abrahams, I. D., Scattering of sound by an elastic plate with flow, *Journal of Sound and Vibration*, 89 (2), 213-231, 1983.
- [3] Schleicher, R.M., Howe, M.S., on the interaction of sound with an annular aperture in a mean flow duct, *Journal of Sound and Vibration* 332 5594–5605, 2013.
- [4] Dong, X., Mingxu, S., Xiaoshu C., Resonance scattering characteristics of double-layer spherical particles, *Particuology* 10 117– 126, 2012.
- [5] Godinho, L., Antnio, J., Tadeu, A., The scattering of 3D sound sources by rigid barriers in the vicinity of tall buildings, *Engineering Analysis with Boundary Elements* 26 781–787, 2002.
- [6] Gennaretti, M., Testa, C., boundary integral formulation for sound scattered by elastic moving bodies, *Journal of Sound and Vibration* 314 (2008) 712–737, 2008.
- [7] Lethuillier, S., Pareige, P., Izbicki, J.L., Conoir, J.M., Scattering by two adjacent immersed shells: theory and experiment. In: *Proceedings of the fourth european conference on underwater acoustics*. Rome, Italy; 1998. p. 837–42.
- [8] Lethuillier, S., Pareige, P., Conoir, J.M., Izbicki, J.L., Scattering by two very close immersed shells: numerical results. In: *Proceedings of the IEEE international ultrasonics symposium*. Nevada, USA; 1999. p. 837–42.
- [9] Falou, O., Kumaradas, J. C., & Kolios, M. C. (2006). Modeling acoustic wave scattering from cells and microbubbles. In *Proceedings of the COMSOL users conference 2006 Boston, USA*.
- [10] Wang, T.Q., Yang, Z.G., Scattering of plane wave from moving body underwater with finite impedance surface, *Journal of Sound and Vibration*, Volume 273, Issues 4–5, 21 June 2004, Pages 969–987.
- [11] Martina, P.A., Maurel, A., Multiple scattering by random configurations of circular cylinders: Weak scattering without closure assumptions, *Journal of Wave Motion*, Volume 45, Issues 7–8, September 2008, Pages 865–880.
- [12] Ouis, D., Scattering of a spherical wave by a thin hard barrier on a reflecting plane, *Journal of Applied Acoustics*, Volume 59, Issue 1, January 2000, Pages 19–66.

- [13] Prospathopoulou, A.M., Athanassoulis, G.A., Belibassakis, K.A., Underwater acoustic scattering from a radially layered cylindrical obstacle in a 3D ocean waveguide, *Journal of Sound and Vibration*, Volume 319, Issues 3–5, 23 January 2009, Pages 1285–1300.
- [14] Introduction to COMSOL Multiphysics, <http://www.comsol.com/shared/downloads/IntroductionToCOMSOLMultiphysics.pdf>, May 2013.
- [15] Nutek Inc, Design of Experiments (DOE) Using the Taguchi Approach, Bloomfield Hills, MI. USA.
- [16] Roy, R.K., A Primer on the Taguchi Method, 2nd ed., Society of Manufacturing Engineers, 2010.
- [17] Yamaguchi, H., Kato, H., Matsuda, K., Measurement and computation of the acoustic field in a cavitation tunnel, *Journal of Marine Science and Technology*, 1996.