Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 8249245, 7 pages
https://doi.org/10.1155/2018/8249245

Research Article

Parametric Underwater Transmission Based on Pattern Time Delay Shift Coding System

Yue Cheng,[1,2,3] Anbang Zhao ,[1,2,3,4] Juan Hui ,[1,2,3] Tiansi An,[5] and Bin Zhou[6]

[1] *Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China*
[2] *Key Laboratory of Marine Information Acquisition and Security (Harbin Engineering University), China*
[3] *College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China*
[4] *National Key Laboratory of Science and Technology on Underwater Acoustic Antagonizing, China*
[5] *Dalian Scientific Test & Control Technology Institute, Dalian, 116000, China*
[6] *Key Laboratory of Science and Technology, Hangzhou 310000, China*

Correspondence should be addressed to Anbang Zhao; zhaoanbang@hrbeu.edu.cn

Received 5 August 2018; Accepted 13 December 2018; Published 26 December 2018

Academic Editor: Nazrul Islam

The technique of pattern time delay shift coding (PDS) underwater acoustic (UWA) communication based on parametric array is presented in this paper, which is easy to be implemented and robust in the spatiotemporal variable ocean environment. The parametric array can generate low-frequency, broadband, and high-directivity beam with small-aperture. The high directivity reduces the impact of time variant characteristics of UWA channel especially multipath effects and improves the reuse rate of underwater acoustic channel at the same time. The wide bandwidth allows high rate communications. The sea trial results show that it can be employed to combat multipath propagation in shallow water and achieve very low bit error rate (BER). The theoretical research and sea trial verify the feasibility and effectiveness of the proposed UWA method.

1. Introduction

Underwater acoustic communication (UWA) is one of the fast developing areas in acoustic research. It is also an important method to achieve underwater information perception and interaction. High performance of UWA communication requires high data rates and reliability at the same time [1]. However, UWA channel is one of the most complex wireless channels. There are still many difficulties in high-speed UWA communication, such as multipath interference, low carrier frequency, high background noise, and limited bandwidth. People have been studying all kinds of UWA communication systems [2, 3], starting early with frequency shift keying (FSK). As the representative of incoherent modulation technology, it is robust but low data rate, unable to carry out high-speed communications. Coherent modulation technology has greatly improved the data rate, but because of the channel influence, it requires complex equipment platform to achieve low error communications, with low spectrum efficiency.

UWA channels are randomly temporal and spatial varying [4]. Reflection at the boundaries and ray bending lead to multipath formation. The intersymbol interference (ISI) caused by the multipath channel is one of the most important obstacles to UWA communication. In order to achieve stable low-frequency communication at low bit error rate (BER), efficient techniques must be used to reduce the ISI. Pattern time delay shift coding (PDS) scheme [5, 6], which belongs to pulse position coding, makes use of time delay shift values of the pattern to encode information. The duty cycle is small so that it can economize the system power. The PDS scheme adopts code division and each information code has the ability to mitigate the ISI and overcome multipath fading and noise interference.

After the related theory of parametric emission derived by Berktay, the parametric array has been applied in the fields of underwater sound detection and communication extensively and deeply. Parametric emission method and its relationship with the underwater environment are discussed

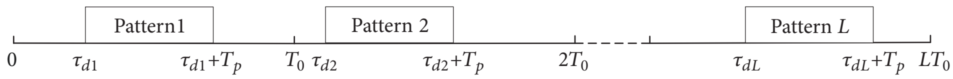

Figure 1: Pattern time delay shift coding scheme.

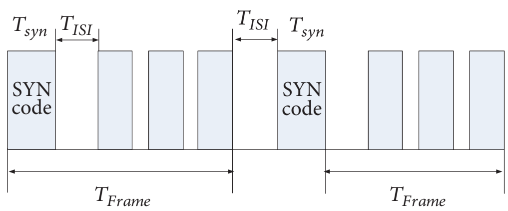

Figure 2: Communication frame structure.

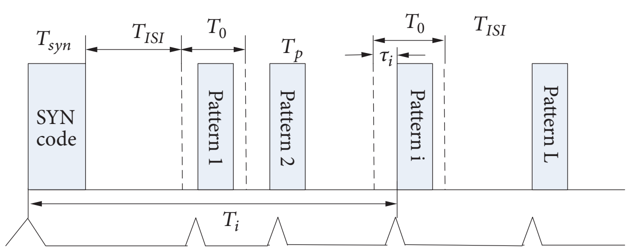

Figure 3: Regular decoding scheme.

in [7, 8]. Subsequently, the parametric array was used in medical inspections [9], marine biological exploration [10], target tracking [11], and buried object detection [12]. The emission issue of broadband difference frequency signal was studied in [13]. In [14, 15], parametric communication has gradually become one of the hot topics in nonlinear acoustics.

In this paper, we study the parametric underwater transmission based on pattern time delay shift coding system. The performance of the system is studied in detail. Finally, the feasibility, availability, and robustness of the communication system are verified by the sea trial results.

2. The PDS Scheme and Parametric Array

2.1. Coding Principle. Pattern time delay shift coding [16] communication system is a kind of pulse position modulation, which is proposed by Harbin Engineering University in the 1990s. The information and channel coding technology are combined into the symbol design; thus every basic code has anti-multipath ability. The information transmission is reliable, and with small duty cycle the PDS scheme can economize the system power. Therefore, the PDS communication system has great advantages in the application of UWA communication. Its information is not in the symbol waveform but on the time delay where the pattern code appears, and different information is represented by the different time delays. Figure 1 is a schematic diagram of a set of symbols structure containing L pattern codes. τ_{di} represents the time delay of the i-th pattern code, where i =1,2,. . .,L; T_p is the length of pattern code; T_0 is symbol width; the encoding time is $T_c = T_0 - T_p$; the duty cycle $\eta = T_c/T_p$.

Assume each symbol carries n bits of information, the encoding time T_c is evenly divided into $(2^n - 1)$ parts, and the quantization unit of the time delay shift is $\Delta\tau = T_c/(2^n - 1)$; the time delay shift value is $\tau_d = k\Delta\tau$, where $k = 0, 1, \ldots, 2^n - 1$. Different time delays represent different information; for example, each symbol carries $n = 4$ bits of information, and the encoding time T_c is divided into 15 parts. If $k = 0$, digital information "0000" is represented. If $k = 11$, "1011" is represented.

Pattern time delay shift coding scheme makes use of the time delay shift values of the pattern to code the information. The PDS communication rate is given as follows.

$$v = \frac{\log_2 \left(T_c/\Delta\tau + 1\right)}{T_0} = \frac{n}{T_0} \quad (1)$$

From (1), when the symbol width T_0 is constant, the communication rate is associated with the information number n of each code element. The larger the n, the smaller the coding quantization interval, and the higher the communication rate.

2.2. Decoding Principle. Copy-correlation of delay estimation method [5] is used to decode on the receiving end. The copy of the emission signal is used as reference signal, functioning as a matched filter in performances. The frame data structure of the PDS communication scheme is shown in Figure 2.

In order to suppress multipath interference, a section of time slot T_{ISI} (more than the extended time of the multipath) is inserted between the synchronous-code and the information code and also between the frames. Frame length depends on the channel time variation, and it should be shorter than the relatively stable time of channel.

Linear Frequency-Modulated (LFM) signal is used as the synchronous-code. The synchronous-code in the data will give the time base of decoding window, so we can determine the moment when strongest signal arrives. On receiving end, the correlation peak obtained from the correlator is corresponding to time, and it is the synchronization reference of decoding window. This moment is the arrival time of the strongest multipath.

After determining the synchronization time, the copy correlator will make the correlation with local pattern, so we can obtain the pattern correlation peak. As we can see from Figure 3, the time difference between the i-th pattern correlation peak and the synchronous correlation peak is

$$T_i = T_{syn} + T_{ISI} + (i - 1)\,T_0 + \tau_i \quad (2)$$

where T_i is the time difference of two correlation peaks; T_{syn} represents the time of the synchronous-code; T_0 is pulse cycle; τ_i is the i-th time delay difference of the pattern code. From (2),

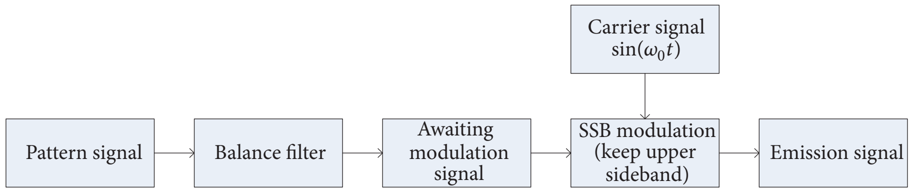

Figure 4: Transmitter of PDS system with parametric array.

$$\tau_i = T_i - T_{syn} - T_{ISI} - (i-1)\,T_0 \quad (3)$$

and the time delay of the pattern code will be determined, so we can decode.

2.3. Parametric Array. Parametric array [17] is a sound transmitting device which can generate difference frequency, sum frequency, and other second harmonics sound waves. The difference frequency signal is low-frequency wideband signal and has a high directivity with no side lobe. As sound absorption coefficient is proportional to the square of frequency, during the wave propagation, the sum frequency wave and the primary wave decay fast because of their high frequency. Beyond a certain distance, only low-frequency difference frequency wave remains.

A wideband signal and a single-frequency signal are used as the primary wave, and then a new wideband difference signal will be produced. The properties of this difference signal depend on the primary wideband signal's envelope, and its sound pressure is [18, 19]

$$p(\tau) = \frac{\beta p_0 S}{8\pi \rho_0 c_0 z \alpha_0} \frac{\partial^2}{\partial t^2} E^2(\tau) \quad (4)$$

where β is nonlinear coefficient; p_0 is sound pressure amplitude of the primary wave; S is area of the sound source; ρ_0 is medium density; z is propagation distance; $E(\tau)$ represents modulated envelope function (primary wave signal which has been modulated); $\tau = t - z/c_0$ represents time delay. From (4), we know that the sound pressure $p(\tau)$ which is self-modulated from parametric array is proportional to the second derivative of $E(\tau)$ when the primary signal is wideband signal.

The most significant advantage is the fact that high directivity is achieved by means of a physically small transmit transducer. In practical applications of the parametric array, one of the main problems is to improve its conversion efficiency; the conversion efficiency here is the ratio of power needed for producing the same difference frequency signal by nondirectional emission to the total power of primary frequency signal. It represents the transition effect of primary high frequency wave producing sound pressure of the directional low-frequency wave.

Suppose that the low-frequency sound wave is nondirectional radiation, the sound pressure obtained at R_0 distance from the sound source is equal to the sound pressure p_d on the axial direction, and then radiated sound power of the low-frequency wave should be

$$W_{ed} = \frac{\omega_d{}^4 \beta^2 W_1 W_2}{2\pi \rho_0 c_0{}^7 \gamma^2} \quad (5)$$

where W_1 and W_2 is the radiated sound power of primary wave. $\gamma = \alpha_1 + \alpha_2 - \alpha$ where α_1, α_2, and α are the coefficient of sound absorption of primary wave and difference frequency wave.

Suppose$W_1 = W_2$, and total power $W = W_1 + W_2 = 2W_1 = 2W_2$; (5) will be converted to

$$\frac{W_{ed}}{W} = \frac{2\pi^3 \beta^2 f_d{}^4 W}{\rho_0 c_0{}^7 \gamma^2} \quad (6)$$

where f and f_d are frequency of primary signal and difference frequency signal, respectively.

According to [13], absorption coefficient of freshwater is $\alpha/f \approx 1.73 \times 10^{-14} Np/m \cdot s^2$. When $f_d \le f_1$, $\gamma \approx 2\alpha_1 = 3.46 \times 10^{-14} f^2 N_p/m$ and nonlinear parameter $B/A = 5$, $\beta = 1 + B/2A = 3.5$; we will get the following.

$$\frac{W_{ed}}{W} = \frac{2\pi^3 \times (3.5)^2}{(1.48)^7 \times 10^{24}} \cdot \frac{1}{(3.46)^2 \times 10^{-28}} \cdot \left(\frac{f_d}{f}\right)^4 W \approx 4.1 \times 10^4 \left(\frac{f_d}{f}\right)^4 W \quad (7)$$

As for seawater, there is no relaxation absorption; when the temperature is 5°, conversion efficiency is as follows.

$$\frac{W_{ed}}{W} = 8.25 \left(\frac{f_d}{f}\right)^4 W \quad (8)$$

As can be seen, increasing the power of the primary wave radiation can directly improve the conversion efficiency in the same medium. However, overlarge power will lead to finite amplitude effect. When propagation medium and total radiation power is constant, the conversion efficiency is proportional to the fourth power of ratio of difference frequency and primary frequency. Therefore it is possible to improve conversion efficiency by increasing difference frequency or reducing primary frequency. However, increasing the difference frequency will increase the transmission loss and reduce propagation distance, and reducing primary frequency will impact on directivity. Therefore, to achieve the best conversion efficiency, we should consider both of them in practice.

3. System of PDS Based on Parametric Array

A new UWA communication system with parametric array and PDS scheme is shown in Figure 4. Parametric array and

Table 1: Related parameters and processing results.

Pattern data	L/m	Fs/Hz	n/bit	Tp/ms	BER	v /kbps
3k~8kHz	300	200k	6	8	0	0.3
4k~6kHz	300	200k	6	8	0	0.3
4k~8kHz	300	200k	6	8	0	0.3
4k~8kHz	300	200k	6	8	0	0.3
4k~8kHz	300	200k	8	8	0	0.4
6k~8kHz	300	200k	6	8	0	0.3

[1]Note: the bit error rate is 0, which means there is no error in the statistical range.

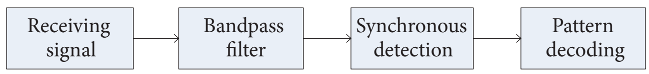

Figure 5: Processing flow of the receiving end.

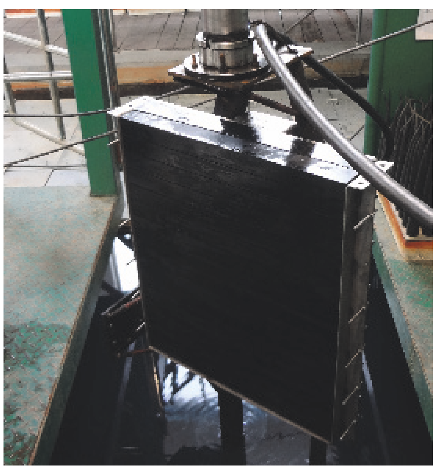

Figure 6: Acoustic parametric array.

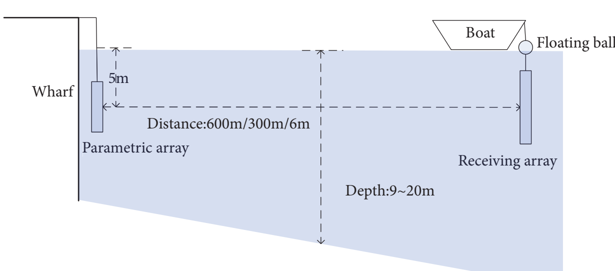

Figure 7: Structural scheme of sea trial devices.

PDS scheme are combined together; in other words, a new UWA communication system is put forward. When pattern encoding is complete, send the pattern signal to a balance filter. A balance filter is used; since the conversion efficiency is proportional to the fourth power of ratio of difference frequency and primary frequency, the signal amplitude in the lower frequency portion is smaller. For this reason, before the SSB modulation, we design a balanced filter to equalize the signal attenuation which is caused by conversion efficiency of parametric array. Filter order is 1024. According to the array used in this paper, set 6 dB drop per octave within the pattern's band range. After SSB modulation of pattern signal, Single Side Band modulation of the balanced pattern signal is realized, and a bandpass filter is used to keep the upper sideband, which is put as primary wave of the parametric array together with the carrier signal.

Processing flow of the receiving end is shown in Figure 5. On the receiving end the received signal go through a bandpass filter first. The filter's order is 1024 and frequency range is the pattern band range in the experiment. Finally, decode the pattern signal.

The parametric array used in the sea trial is in Figure 6. This array is one kind of plane piston transducer, and its size is $0.625m \times 0.52m$. In horizontal direction the parametric array is composed of linear array which has 16 channels, with 16×14 vibrators. There is no grating lobe in the range of $\pm 15^{\circ}$. The weight of the parametric array is about 180 kg (without cables). Its -3dB main lobe width is 4.80°.

4. Sea Trial Data Processing

In order to verify the communication effect of the system based on parametric array in actual marine environment, the system was set up as Figure 7. As transmitting device, the parametric array was installed on pier wall. A boat from a distance was the reception point, and acoustic signal was received by an underwater vertical array.

Three experiments were carried out and the source level of primary frequency wave was about 225 dB. Communication distance of the first experiment was 600 meters. Random numbers were transmitted. The related parameters are shown as follows: coding band of pattern, $4k \sim 8kHz$; quantification bit, 4 bits; length of pattern, 8 ms. On the basis of transmitted rate 0.2kbps, no errors were present. Figures 8–11 are, respectively, the waveform of the random number before and after pattern coding, emission signal, receiving signal after band filtering, and the correlation peaks location of received signal after decoding.

The distance of the second experiment was 300 meters. The related parameters and processing results are shown in Table 1, where L is distance; F_s is sampling frequency; n

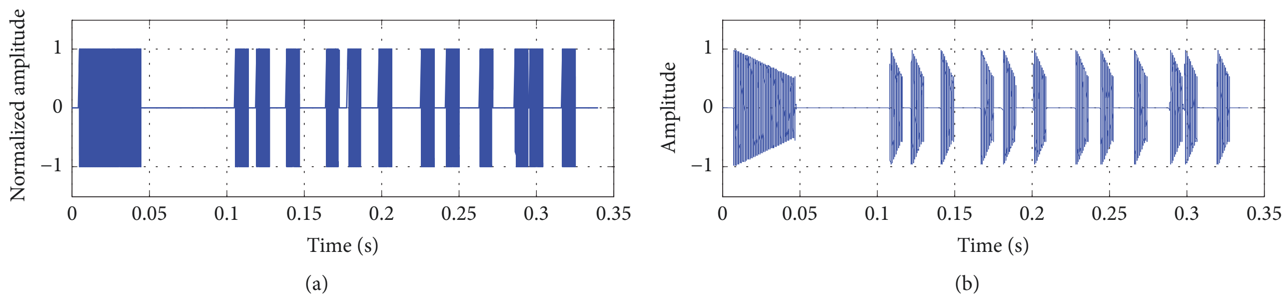

FIGURE 8: Time domain waveform of pattern signal. (a) Before balance. (b) After balance.

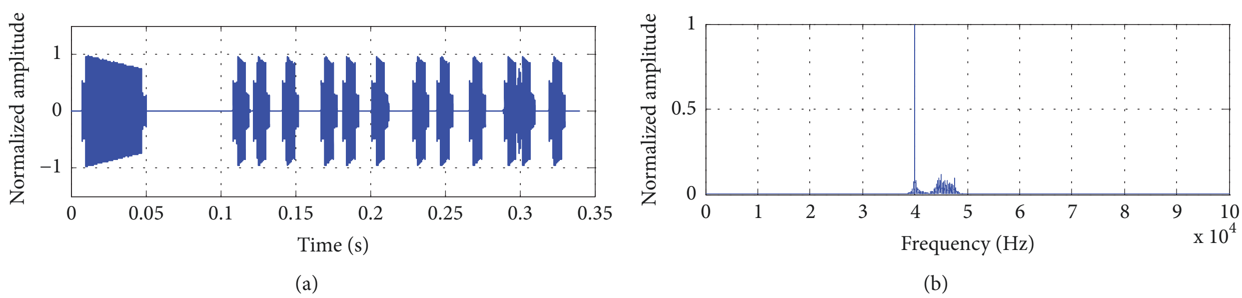

FIGURE 9: Emission signal. (a) Time domain. (b) Frequency domain.

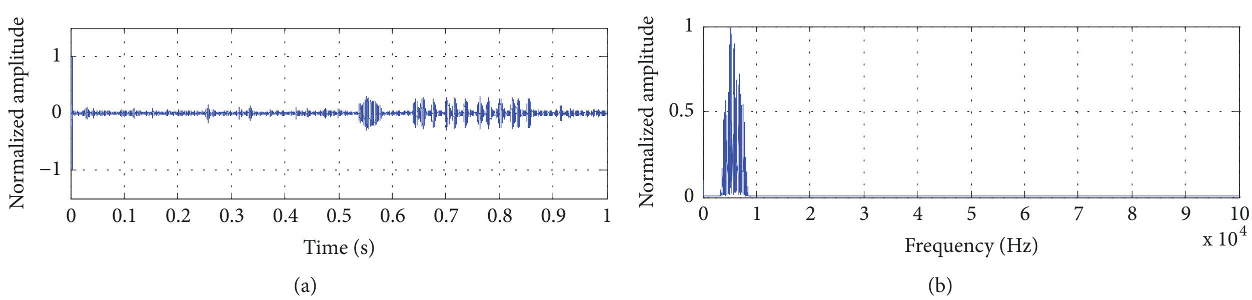

FIGURE 10: Receiving signal after band filtering.

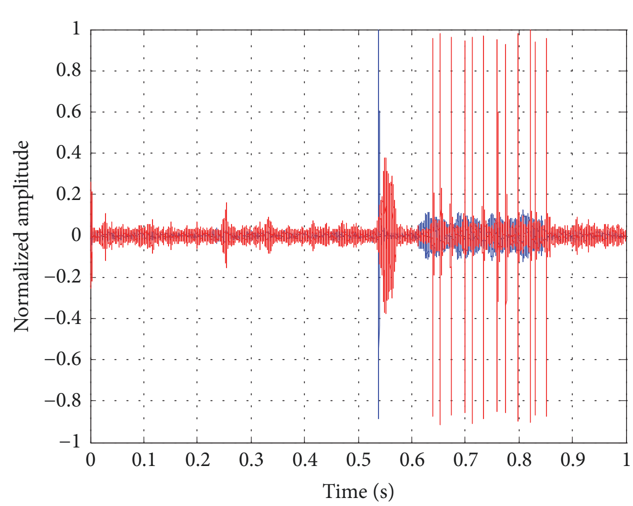

FIGURE 11: Correlation peaks location.

Table 2: Related parameters and processing results.

Pattern data	L/m	Fs/Hz	n/bit	Tp/ms	BER	v /kbps
3k~8kHz	6	500k	6	8	0	0.3
4k~6kHz	6	500k	6	8	0	0.3
4k~8kHz	6	500k	6	6	0	0.3
4k~8kHz	6	500k	6	8	0	0.3
4k~8kHz	6	500k	8	8	0	0.4
6k~8kHz	6	500k	6	8	0	0.3

[2]Note: the bit error rate is 0, which means there is no error in the statistical range.

is quantification bit; T_p is length of pattern code; v is the communication rate; SSB carrier frequency is 40 kHz.

The distance of the third experiment was 6 meters. The related parameters and processing results are shown in Table 2.

5. Conclusions

The PDS underwater acoustic communication system based on parametric array is presented in this paper. Parametric array generates low-frequency waves with high directivity in small size, almost without side lobe, which can reduce the reflection in the horizontal direction and improve the reuse rate of the underwater acoustic channel. The sharp directivity of the difference signal can reduce the multipath interference in the vertical direction of the waveguide. The processing result of the sea trial data shows advantages of the combination of the PDS scheme and parametric array. It has the ability to achieve reliable remote acoustic communications in underwater environment. Better applications are hoped in engineering.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work is supported by National Natural Science Foundation of China under Grants No. 11374072, 61501061, and 61371171; Open Foundation of National Key Laboratory of Science and Technology on Underwater Acoustic Antagonizing (SSDKKFJJ-2017-02-01); and Acoustic Science and Technology Laboratory Stable Support Project (SSJSWDZC2018002).

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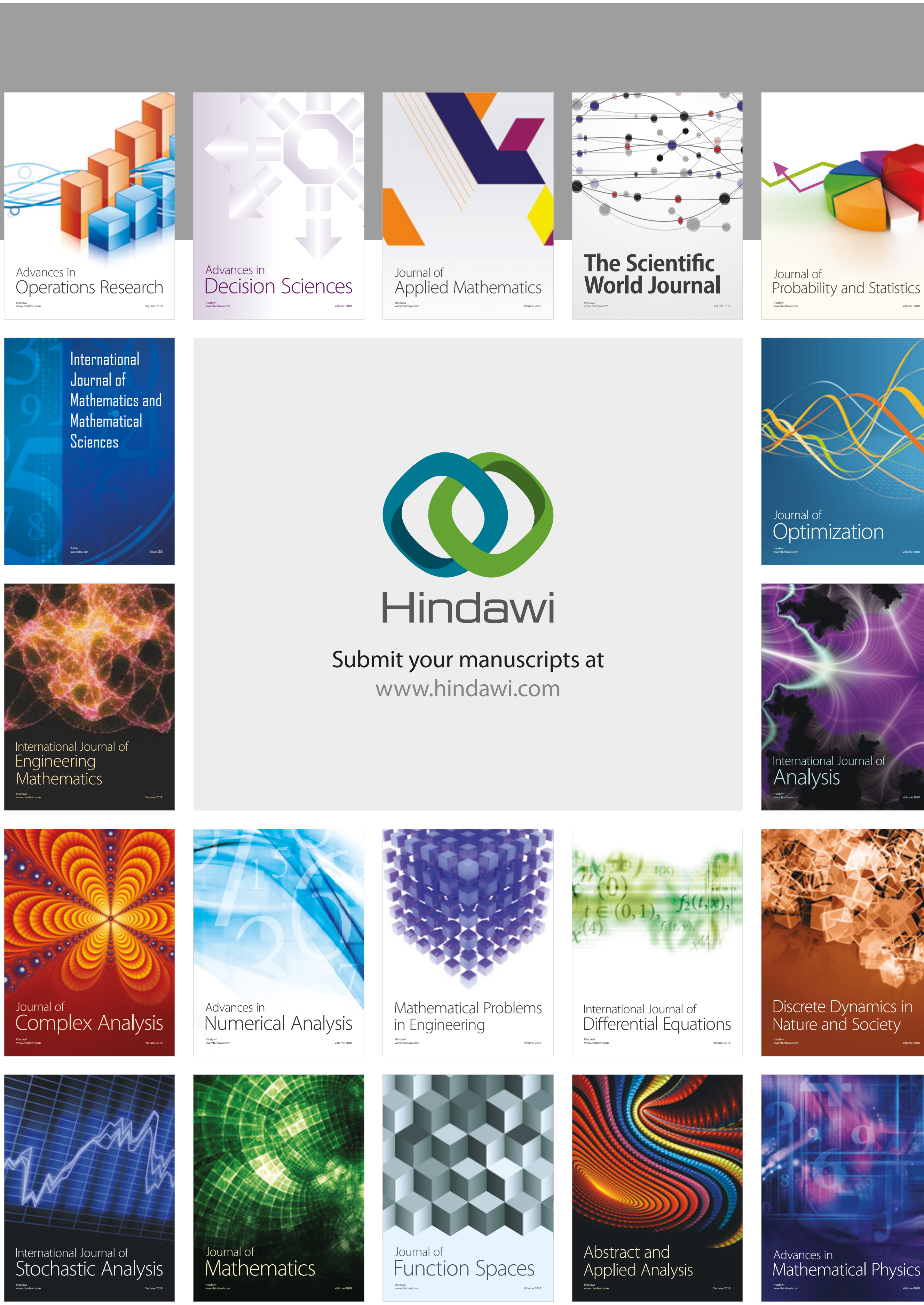
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