Hindawi Publishing Corporation
Modelling and Simulation in Engineering
Volume 2014, Article ID 426718, 7 pages
http://dx.doi.org/10.1155/2014/426718

Research Article

Electrical Discharge Machining of Al (6351)-5% SiC-10% B_4C Hybrid Composite: A Grey Relational Approach

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Received 26 February 2014; Accepted 2 May 2014; Published 13 May 2014

Academic Editor: Azah Mohamed

The goal of the present experimental work is to optimize the electrical discharge machining (EDM) parameters of aluminum alloy (Al 6351) matrix reinforced with 5 wt.% silicon carbide (SiC) and 10 wt.% boron carbide (B_4C) particles fabricated through the stir casting route. Multiresponse optimization was carried out through grey relational analysis (GRA) with an objective to minimize the machining characteristics, namely electrode wear ratio (EWR), surface roughness (SR) and power consumption (PC). The optimal combination of input parameters is identified, which shows the significant enhancement in process characteristics. Contributions of each machining parameter to the responses are calculated using analysis of variance (ANOVA). The result shows that the pulse current contributes more (83.94%) to affecting the combined output responses.

1. Introduction

In the past few years, research work in materials has shifted towards composite materials to meet the requirements of modern industry like higher strength, low weight, high hardness, low density, and less wear. Aluminum metal matrix composites (MMCs) are appropriate material for any industry, which satisfies these requirements. They are preferred to have high thermal conductivity, higher strength, good damping properties, and lower density and are used in several applications such as cylinder block liners, vehicle drive shafts, automotive pistons, and bicycle frames [1, 2]. In several such kinds of applications, nontraditional machining process, like electric discharge machining, is being employed for easy machining of aluminum based metal matrix composite [3, 4]. In EDM process, machining parameters such as pulse current, pulse duty factor, gap voltage, and pulse duration have influences more on the output responses like material removal rate (MRR), electrode wear rate, and surface roughness [5].

Obtaining maximum material removal with minimum electrode wear ratio is the demand of manufacturing industry. On the other hand, electrode wear should be minimized to reduce the product cost. Optimum combination of process parameters is required to meet the customer requirements. Karthikeyan et al. [6] investigated the effect of the pulse current and pulse duration on EWR, MRR, and SR and also framed a mathematical model and concluded that the current affects the MRR and EWR proportionally, whereas an increase in the pulse duration reduces both MRR and EWR. J. L. Lin and C. L. Lin [7] studied the machining parameters, namely, work piece polarity, pulse on time, duty factor, open discharge voltage, discharge current, and dielectric fluid and optimized the multiple performance characteristics including material removal rate, surface roughness, and electrode wear ratio through GRA.

The surface texture of the machined surface has to be measured in order to improve the quality. Few researchers have worked with the composite materials with an objective to reduce the surface roughness. Singh et al. [8] carried out an experimental work with Al-SiC composite with the combined objective to optimize the process parameters on output responses such as surface roughness, tool wear rate, and radial overcut by using the grey relational analysis. Mohan et al. [9] investigated the machinability study of the Al-SiC composite with an objective to determine the influence of the electrical parameters, content of the SiC particle, and electrode material on the surface roughness. The result shows that the roughness value decreases with an increase in the current and with less SiC particles in the composite.

Power consumed during machining process is to be minimized because it directly influences the product cost. Very few research works address minimization of the power consumption in CNC machining process [10–12]. However, no relevant work has been reported in EDM till date.

In this work, an investigation has been made to identify the optimal combination of input parameters of EDM machining on Al (6351)-SiC-B_4C hybrid composite using grey relational analysis. The major input parameters selected to evaluate the process are electrode wear ratio, surface roughness, and power consumption, and the corresponding machining parameters are pulse current, pulse on time, pulse duty factor, and voltage. Further, ANOVA analysis was carried out to find the contribution of each parameter. Finally, the results are validated through the confirmation experiment.

2. Experimental Work

2.1. Fabrication and Testing of the Composite. The composite material consists cast aluminum alloy as a matrix material and SiC and B_4C are the reinforcements. Al 6351 cast material was preheated in a resistance furnace at 450°C about 3 to 4 hours before melting. The SiC and B_4C reinforcement particles were also preheated at about 1,000°C to 1,200°C to make their surface oxidized [13]. The average size of the SiC and B_4C particles was found to be 69 μm and 149 μm, respectively. The preheated aluminum was heated beyond its liquidus temperature to melt it completely. The preheated reinforcements were added manually and mechanical mixing was carried out for about 10–15 minutes to disperse them uniformly in the matrix. The final temperature of the melt was controlled to be in the range of 730°C ± 10°C, and the pouring temperature is maintained at 720°C. After proper stirring, the melt was poured into the mold having diameter and thickness of 100 mm and 50 mm, respectively, and was also allowed to cool at room temperature. The tensile strength and yield strength of the fabricated composites are determined as per ASTM B557M-10 standard and the values are shown in Table 1. The prepared composite material is presented in Figure 1 and the dispersion of the reinforcements in the matrix is ensured by the optical microscopic image as shown in Figure 2.

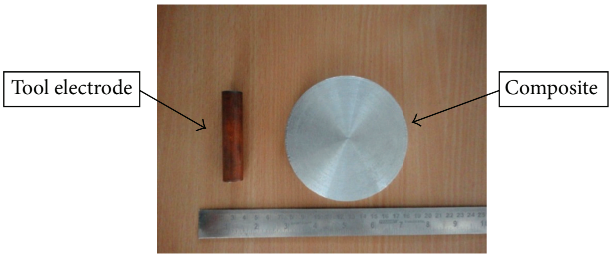

Figure 1: Prepared composite material.

Table 1: Mechanical properties of the composite.

Composite	Tensile strength (N/mm^2)	Yield strength (N/mm^2)	Density (kg/m^3)	Hardness (HB)
Al—5 wt.% SiC—10 wt.% B_4C	132.48	107.43	2705	76.78

Table 2: Machining parameters and their levels.

Parameters	Unit	Levels		
		1	2	3
Pulse current (I)	Ampere	5	10	15
Pulse on time (T_{on})	μs	50	75	100
Pulse duty factor (τ)	—	4	6	8
Gap voltage (V)	Volt	40	45	50

2.2. Experimental Facility. The electrical discharge machining was carried out on a die sinking EDM (EDM-SMART ZNC machine, make: M/S Electronica, Pune, India) powered with 3-phase servostabilizer. Copper rod of a 16 mm diameter was used as an electrode and the experimental work was conducted in the dielectric medium having viscosity of 2.6 cs at 40°C and flushing pressure of 1.5 kg/cm^2. A constant depth of 2 mm was maintained throughout the experiments.

Electrode wear ratio is calculated from tool wear rate and material removal rate. Tool wear was calculated by the difference in weight obtained before and after the machining process. A high precision Shimatzu weighing balance AUX120 (max. capacity of 210 g and accuracy of 0.1 mg) was used to calculate the weight loss. Surface roughness for all the experiments is measured by Mitutoyo Surftest SJ301 (measuring range: 350 μm and measuring speed: 0.25 mm/s). The transverse length of each measurement was set to 5 mm and the average roughness value was noted. Electrical power consumed during the machining process was measured by using power harmonic analyzer (max. range—current: 2000 A and voltage: 600 V) from the 3-phase power supply with an aid of two probes which is presented as Figure 3.

2.3. Design of Experiments. To predict the number of experiments to be conducted, first the total degrees of freedom (DOF) should be known. Each factor takes two DOF; thus the total DOF is eight for four factors. The number of experiments to be conducted should be always above the selected DOF. Thus, based on the Taguchi's design of experiments, L27 orthogonal array was chosen. Table 2 shows the machining parameters and their ranges for the experiments and the experimental results are presented in Table 3.

Table 3: Experimental results.

Exp. number	Pulse current (A)	Pulse on time (μs)	Pulse duty factor	Gap voltage (V)	Electrode wear ratio (%)	Surface roughness (μm)	Power consumed (kW)
1	5	50	4	40	0.24	5.49	2.66
2	5	50	6	45	0.25	4.54	2.13
3	5	50	8	50	0.29	6.48	2.30
4	5	75	4	45	0.46	5.83	2.70
5	5	75	6	50	0.51	5.88	2.80
6	5	75	8	40	0.40	6.19	2.18
7	5	100	4	50	0.24	5.34	2.56
8	5	100	6	40	0.14	6.38	2.55
9	5	100	8	45	0.19	6.61	1.72
10	10	50	4	40	2.58	8.21	1.66
11	10	50	6	45	2.45	7.79	2.12
12	10	50	8	50	2.21	6.91	2.14
13	10	75	4	45	1.89	7.93	1.98
14	10	75	6	50	1.71	9.11	2.04
15	10	75	8	40	1.74	7.83	2.01
16	10	100	4	50	1.13	7.69	1.85
17	10	100	6	40	0.88	9.52	1.87
18	10	100	8	45	0.95	8.31	1.63
19	15	50	4	40	3.18	8.48	1.75
20	15	50	6	45	3.00	8.56	1.64
21	15	50	8	50	2.63	8.81	1.35
22	15	75	4	45	2.50	10.03	1.47
23	15	75	6	50	2.17	9.27	1.49
24	15	75	8	40	2.21	9.74	1.40
25	15	100	4	50	1.94	8.95	1.36
26	15	100	6	40	1.85	12.82	1.12
27	15	100	8	45	1.82	13.33	0.85

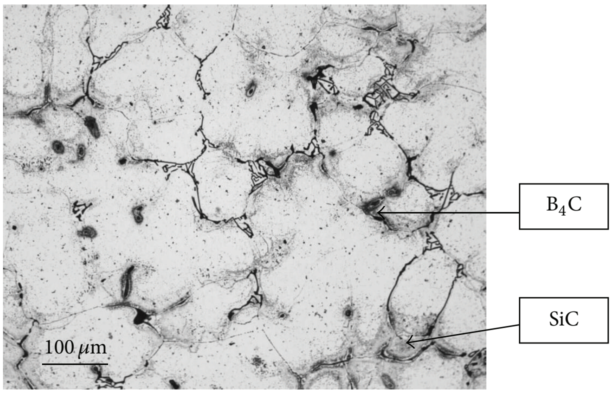

Figure 2: Microstructure of the composite.

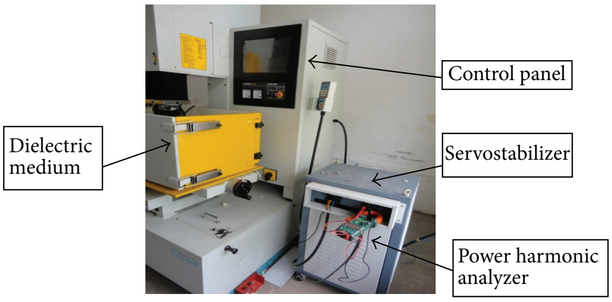

Figure 3: The experimental facility.

3. Grey Relational Analysis

The grey relational analysis is a multiobjective optimization process used to determine the optimum combination of the input parameters and also to determine the influence of each machining parameter on the machining characteristics. This analysis needs a sample of limited size with discrete chronological data to facilitate reliable modeling and estimation of system behavior. The following steps are carried out during GRA:

Step 1 (S/N ratio calculation). Since the machining characteristics such as electrode wear ratio, surface roughness, and power consumption are to be minimized, the smaller-the-better characteristic is selected. The signal to noise ratio can be calculated by using (1). This is appropriate for a problem where minimization of the quality characteristics is anticipated. Consider

$$S/N\ \text{ratio} = -10\log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_{ij}, \qquad (1)$$

where n = number of replications; y_{ij} = observed response, $i = 1, 2, \dots, n$; $j = 1, 2, \dots, k$.

Step 2 (normalization). It is essential to normalize the values before analyzing them with the grey relation theory [14]. Here normalization of the experimental result for the responses is done and rated between 0 and 1. The normalization of the experimental result was calculated by using

$$z_{ij} = \frac{\max\left(y_{ij},\ i = 1, 2, \dots n\right) - y_{ij}}{\max\left(y_{ij},\ i = 1, 2, \dots n\right) - \min\left(y_{ij},\ i = 1, 2, \dots n\right)}, \qquad (2)$$

where y_{ij} is the jth performance characteristic in the ith experiment, and max y_{ij} and min y_{ij} are the maximum and minimum values of the jth performance characteristic for alternative ith experiment.

Step 3 (grey relational coefficient). The grey relational coefficients for the output responses from the normalized values can be determined by using

$$\left(y_0(k), y_i(k)\right) = \frac{\Delta \min + \xi \Delta \max}{\Delta_{0j}(k) + \xi \Delta \max}, \qquad (3)$$

where,

(i) $j = 1, 2, \dots, n$; $k = 1, 2, \dots, m$, n is the number of experimental data items and m is the number of responses;

(ii) $y_0(k)$ is the reference sequence ($y_0(k) = 1$, $k = 1, 2, \dots, m$); $y_j(k)$ is the specific comparison sequence;

(iii) $\Delta_{0j} = \|y_0(k) - y_j(k)\|$ is the absolute value of the difference between $y_0(k)$ and $y_j(k)$;

(iv) $\Delta \min = \min \min \|y_0(k) - y_j(k)\|$ is the smallest value of $y_j(k)$;

(v) $\Delta \max = \max \max \|y_0(k) - y_j(k)\|$ is the largest value of $y_j(k)$;

(vi) ξ is the distinguishing coefficient, which is defined in the range $0 \le \xi \le 1$.

Step 4 (grey relational grade). The grey relational grade for combined objectives can be calculated from the grey relational coefficient of all the responses and it is ranked in order. Evaluation of the performance measures is based on this grade and it is calculated from

$$\delta_j = \frac{1}{k}\sum_{i=1}^{m} y_{ij}, \qquad (4)$$

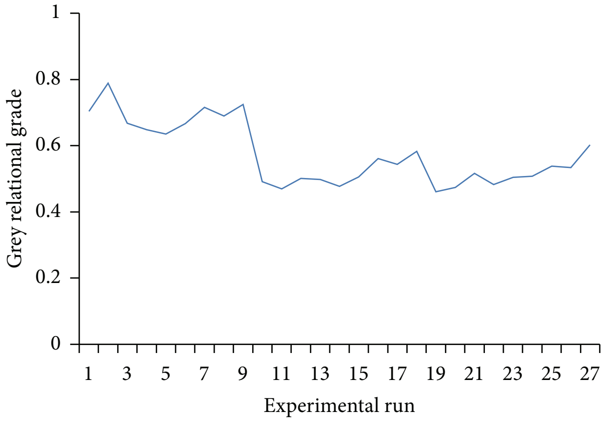

Figure 4: Grey relational grade.

where δ_j is the grey relational grade for the jth experiment and k is the number of performance characteristics.

4. Result and Discussion

The signal-to-noise ratio was calculated for all the output variables by considering the smaller-the-better characteristics. Further, normalization was done to rate the values between 0 and 1. Finally, grey relational coefficient was calculated for all the responses by assuming the coefficient constant $\xi = 0.5$. Table 4 shows the grey relational grade, which was determined from the combined objectives of the coefficient value.

From Figure 4, it is observed that experiment number 2 shows a higher grey relational grade (0.78), which indicates a better combination of process parameters for the multiobjective optimization process (pulse current = 5 A, pulse on time = 50 μs, pulse duty factor = 6, and voltage = 45 V) with an objective to minimize the electrode wear ratio, surface roughness, and power consumed for the machining.

ANOVA is the application of a statistical method to determine the influence of each factor on the responses. The single objective experimental method cannot find the influence of each parameter on the entire process. ANOVA has been applied to determine the contribution of each input parameter on the combined multiperformance characteristics. From Table 5, it is understood that the pulse current contributes more (Q = 83.94%) on the multiple performance characteristics followed by the pulse on time (Q = 10.99%), pulse duty factor (Q = 2.20%), and gap voltage (Q = 2.07%). Figure 5 represents the bar chart for the contribution of each factor on the output responses. The F-test was conducted at 95% confidence level. It was found that all the F-test values were greater than $F_{0.05,2,26} = 3.37$ which represents the statistical and physical influence of all the input parameters affecting the output characteristics simultaneously.

Increased pulse current produces high discharge of electrical spark between the two electrodes, which may cause greater tool erosion and increased electrode wear ratio. Pulse current also increases the bombarding forces between the electrode and the material. This will result in formation of

Table 4: Grey relational analysis.

Ex. number	S/N ratio (EWR)	S/N ratio (SR)	S/N ratio (PC)	Normalized value (EWR)	Normalized value (SR)	Normalized value (PC)	GRC (EWR)	GRC (SR)	GRC (PC)	GRG
1	12.43	−14.79	−8.49	0.96	0.89	0.07	0.93	0.82	0.35	0.70
2	12.10	−13.14	−6.56	0.96	1.00	0.34	0.93	1.00	0.43	0.78
3	10.62	−16.23	−7.23	0.94	0.77	0.25	0.90	0.69	0.40	0.66
4	6.75	−15.31	−8.62	0.89	0.85	0.05	0.82	0.77	0.34	0.64
5	5.92	−15.38	−8.94	0.87	0.84	0.00	0.80	0.76	0.33	0.63
6	7.86	−15.83	−6.76	0.91	0.81	0.31	0.85	0.72	0.42	0.66
7	12.43	−14.55	−8.16	0.96	0.90	0.12	0.93	0.84	0.36	0.71
8	17.20	−16.09	−8.13	1.00	0.79	0.12	1.00	0.70	0.36	0.68
9	14.28	−16.40	−4.71	0.98	0.76	0.55	0.96	0.67	0.52	0.72
10	−8.24	−18.28	−4.40	0.19	0.58	0.58	0.38	0.54	0.54	0.49
11	−7.76	−17.83	−6.52	0.24	0.63	0.34	0.39	0.57	0.43	0.46
12	−6.87	−16.78	−6.60	0.32	0.73	0.33	0.42	0.64	0.43	0.50
13	−5.54	−17.98	−5.93	0.42	0.61	0.42	0.46	0.56	0.46	0.49
14	−4.65	−19.19	−6.19	0.48	0.48	0.38	0.49	0.49	0.45	0.47
15	−4.79	−17.87	−6.06	0.47	0.62	0.40	0.48	0.57	0.45	0.50
16	−1.06	−17.71	−5.34	0.67	0.64	0.48	0.60	0.58	0.49	0.56
17	1.08	−19.57	−5.43	0.75	0.43	0.47	0.67	0.46	0.48	0.54
18	0.47	−18.39	−4.24	0.73	0.57	0.60	0.65	0.53	0.55	0.58
19	−10.05	−18.56	−4.86	0.00	0.55	0.53	0.33	0.52	0.52	0.46
20	−9.53	−18.64	−4.29	0.06	0.54	0.59	0.34	0.52	0.55	0.47
21	−8.39	−18.89	−2.60	0.18	0.51	0.74	0.37	0.50	0.66	0.51
22	−7.96	−20.02	−3.34	0.22	0.37	0.68	0.39	0.44	0.61	0.48
23	−6.72	−19.34	−3.46	0.33	0.46	0.67	0.42	0.48	0.60	0.50
24	−6.87	−19.77	−2.92	0.32	0.40	0.71	0.42	0.45	0.63	0.50
25	−5.75	−19.03	−2.67	0.40	0.49	0.73	0.45	0.49	0.65	0.53
26	−5.33	−22.15	−0.98	0.43	0.05	0.86	0.47	0.34	0.78	0.53
27	−5.20	−22.49	1.41	0.44	0.00	1.00	0.47	0.33	1.00	0.60

Table 5: Results of ANOVA.

Input parameters	DOF	Sum of squares (SS)	Mean sum of squares (MS)	Contribution (%)	F-ratio
Pulse current	2	0.05634	0.02817	83.94	948.31
Pulse on time	2	0.00737	0.00368	10.99	124.14
Pulse duty factor	2	0.00147	0.00073	2.20	24.85
Voltage	2	0.00139	0.00069	2.07	23.43
Error	18	0.00053	0.00003	0.80	
Total	**26**	**0.06713**			

craters on the machined surfaces and produces poor surface finish. Dvivedi et al. [15] conducted experiments with Al 6063 material and concluded that the pulse current influences more the output response than other parameters. Nikalje et al. [16] conducted experiments with MDN 300 steel and noticed similar observations.

Finally, the confirmation test was conducted to verify the optimal levels and to determine the improvement in grey relational grade. According to Table 6, an improvement in performance was noticed when the optimal conditions were used in EDM process.

5. Conclusion

Aluminum alloy (6351) reinforced with 5 wt.% SiC and 10 wt.% B_4C hybrid composite was fabricated through the stir casting route successfully and the following observations were made through electrical discharge machining.

(i) Grey relational analysis was successfully used to predict the optimum input parameters for achieving lower electrode wear ratio, surface roughness, and power consumption.

Table 6: Confirmation test.

Level	Output response Initial $I = 10$ A, $T_{\text{on}} = 50\,\mu$s, $\tau = 4$, $V = 40$ V	 Predicted $I = 5$ A, $T_{\text{on}} = 50\,\mu$s, $\tau = 6$, $V = 45$ V	 Experimental $I = 5$ A, $T_{\text{on}} = 50\,\mu$s, $\tau = 6$, $V = 45$ V
Grey relational grade	0.49	0.75	0.78
Improvement in grade	—	0.26	0.29

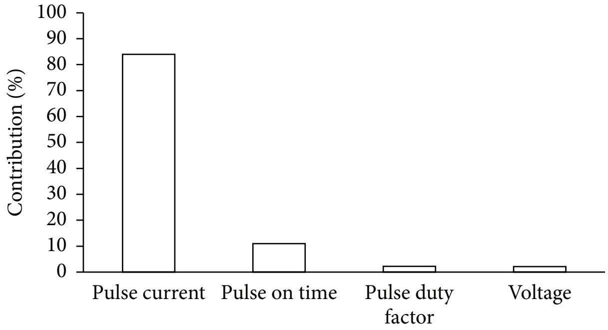

Figure 5: Contribution of each factor.

(ii) The optimal machining parameter (pulse current = 5 A, pulse on time = 50 μs, pulse duty factor = 6, and voltage = 45 V) was found through grey relational grade.

(iii) The pulse current is the most significant parameter for affecting the output response ($Q = 83.94\%$) followed by pulse on time ($Q = 10.99\%$), pulse duty factor ($Q = 2.20\%$), and voltage ($Q = 2.07\%$).

(iv) Increase in pulse current increased the discharge energy of electrical spark and produced poor surface finish.

(v) The result of F-test shows that all the input parameters have a significant influence on affecting the output characteristics simultaneously.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors express their thanks to DAE-BRNS, Mumbai, for providing fund to carry out this work (no. 2012/34/39/BRNS). The authors also thank the Centre for Advanced Machining, Kalasalingam University, for the support to carry out this work.

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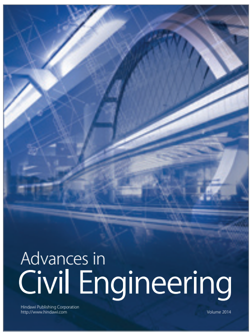
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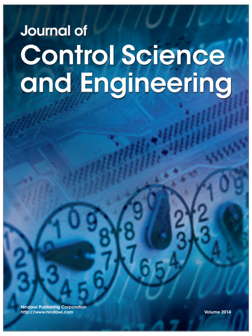
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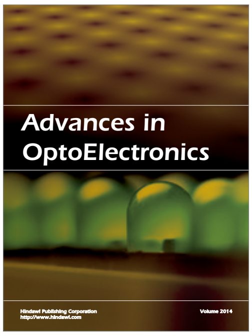
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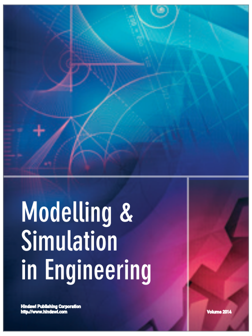
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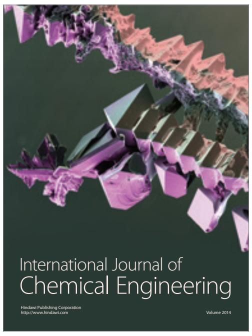
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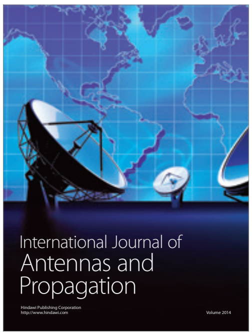
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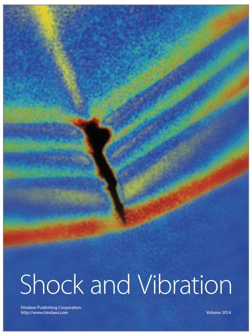
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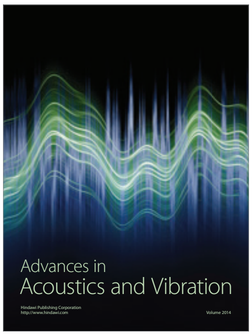
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