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Research Article

Thermal Life of Carbon Structures: From the Earth to after the Titan

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With the increasing of consumption of sources and the population of mankind on Earth, scientists are looking for an alternative planet in the solar system that can establish the second home for mankind. Previously, Mars has been the center of attention by scientists due to the closer distance to Earth and being similar to that in many aspects. Recently, scientists discovered that there may be a better alternative. Titan, despite its great distance from the Earth, seems like a better planet for the mankind colonization due to its atmosphere that create a shield against the radiation in comparison to Mars' atmosphere that is thin and is not capable to create an adequate shield against radiation. In the previous work, the thermal life of carbon structures on Mars was approximately estimated. The aim of this research is to provide a method to estimate the thermal life of carbon structures on Titan. Carbon structures are currently used in space structures due to their lightweight and strength.

1. Introduction

In the previous research [1], thermal life of unidirectional carbon fiber/epoxy composite (UD CF/EP) on Mars was evaluated because Mars is one of the closest and most similar planet to Earth in the solar system. Hence, one-way human mission to Mars is proposed [2].

The presence of water [3] and its characteristics were the motivations for scientists to select Mars as the second home for mankind in the solar system. As a result, it seemed necessary to evaluate the thermal life of carbon structures on Mars because it is one of the best materials that can be used in making space structures [4].

Unfortunately, Mars' atmosphere is very thin [5]. Thus, it is not capable to diminish the radiation. Hence, it can be considered as a health risk for mankind. Recently, scientists are attracted to Titan, Saturn's moon. The reason is, in spite of its great distance from the Earth, Titan is similar to Earth [6]. The most important feature of Titan is its atmosphere that is a very good shield against cosmic radiation [6]. Hence, there is no danger for human health regarding radiation. Therefore, Titan appears to be the best candidate for the second human home in the solar system.

Nevertheless, with the comparison of the Titan's temperature with Mars' temperature, it appears that minimum temperature on Titan is −183°C [7], but in Mars is −123°C [5]. Consequently, with this extreme cold temperature on Titan, it seems necessary to analyze the thermal life of carbon structures on Titan for the upcoming possible space missions to Titan.

In the previous works [1, 8], methods to obtain the thermal life of UD CF/EP due to the application of this material in space structures' industry in low Earth orbit (LEO) and Mars were developed.

It seems that up to this time, there is no research related to the thermal life estimation of UD CF/EP or other carbon structures on space mission from the Earth to Titan and after that. Thus, in this study, it is tried to estimate the thermal life of carbon structures for Titan mission.

The results of the present study may contribute to predict the thermal life of space structures containing carbon nanotube (CNT) and UD CF/EP in the space mission to

Titan. Therefore, these results will contribute to make the space structures safer and prevent from thermal failure due to thermal fatigue and extreme cold temperature.

In the present research, by using an analytical method, and extension of the relations from the previous research [1, 8], relations are obtained to estimate the thermal life of carbon structures in Titan mission.

2. Carbon Structures

"Advanced carbon fiber-reinforced composite laminates have been widely used in satellite structures, where the advantages of these materials—their high specific stiffness, near-zero coefficients of thermal expansion (CTE), and dimensional stabilities—make them uniquely suitable for applications in a low-specific weight environment. However, since the beginning of composite structure applications, there has been a strong need to quantify the environmental effects on the composite materials based on the coupon-level laminate test data. Recent studies have shown that the environmental conditions that are the most representative of space and that tend to degrade the properties of composite laminates involve vacuum, thermal cycling atomic oxygen (AO), and micrometeoroid particles. In this respect, there is significant interest in the construction of an experimental database to capture the collective understanding of the degradation mechanisms of composite laminate in in-service environments. It is necessary to be able to predict the long-term durability of composite laminates with engineering accuracy to use these materials with confidence in critical load-bearing structures" [4].

3. Thermal Life Estimation

In the present study, carbon structures are UD CF/EP structures. It seems that it is significant to mention that based on the previous study [9], thermal life of CNT is at least 10% higher than that for UD CF/EP. Thus, in this study, by increasing 10% to the UD CF/EP thermal life, the thermal life of CNT can be achieved. Thermal life for carbon structures is the numbers of the temperature variations that carbon structures can last until their failure. As it is obvious, thermal cycles contain temperature variations. Hence, they are convertible to each other by some multiplication.

3.1. Steady-Linear Method. In the previous research [1], the steady-linear method (SLM) was developed to predict the thermal life of UD CF/EP material on Mars. The question is "how SLM can contribute to estimate the thermal life of UD CF/EP on Titan?"

By analyzing the SLM, it can be realized that this method has been developed to estimate the thermal life of UD CF/EP for 100 K temperature variation for each cycle on Mars. Each cycle represents day temperature to night temperature and back to day temperature which is 100 K. This is due to the fact that temperature variation between each day and night on Mars is approximately 50 K [5]. Fortunately, it seems that the temperature variation on Titan is approximately the same as of Mars [7]. This information confirms the thermal cycle of 100 K on Titan. As a result, it appears that temperature variation in each thermal cycle on Mars can be equal to that on Titan. Nevertheless, the minimum temperature on Mars is about −123°C [5]. On the other hand, in Titan the minimum temperature is about −183°C [7].

The minimum temperature is the main cause of fracture in UD CF/EP because the stress-free temperature in UD CF/EP is 23°C [4]. Thus, as the difference temperature between the environment and stress-free temperature increases, the interlaminar shear stress (Ilss) in UD CF/EP increases. As a result, with the stress increase, the thermal life will decrease because of crack propagation and breaking bonds between carbon fiber and epoxy. On Mars, the difference between UD CF/EP stress-free temperature (23°C) and coldest temperature (−123°C) is equal to 146°C. On the other hand, on Titan, the difference between UD CF/EP stress-free temperature (23°C) and coldest temperature (−183°C) is equal to 206°C. Consequently, Ilss is higher. This result in breaking more bonds between carbon fibers and epoxy and earlier fracture due to higher stress. In the following equation, it has been tried to establish the best estimate for predicting the maximum Ilss ($\mathrm{Ilss}_{\max}$) [10].

$$\mathrm{ILss}_{\max} = \Delta\alpha_{\max} \cdot \Delta T_{\max} \cdot G_{\max}. \tag{1}$$

Equation (1) represents the $\mathrm{ILss}_{\max}$ in axial direction of fiber/matrix interface areas. In (1), α, T, and G are the coefficient of thermal expansion (CTE), temperature, and shear modulus, respectively. In order to maintain enough safety to calculate the $\mathrm{Ilss}_{\max}$, maximum values are substituted in the above equation. However, in order to employ this relation for estimating the thermal life of UD CF/EP, a few modifications seem necessary. The following equation can represent these modifications.

$$\mathrm{ILss}_{\max} = \left(|\alpha_{\mathrm{CFACTE}}| + \alpha_{\mathrm{epoxy}}\right) \cdot \left(|T_{\mathrm{coldest}}| + T_{\mathrm{s}}\right) \cdot G_{\mathrm{CFASM}}. \tag{2}$$

Additionally, (2) can be indicated as (3) because both (2) and (3) represent the highest possible Ilss in UD CF/EP and are the same value.

$$\mathrm{ILss}_{\max} = \left(\alpha_{\mathrm{epoxy}} - \alpha_{\mathrm{CFACTE}}\right) \cdot \left(T_{\mathrm{s}} - T_{\mathrm{coldest}}\right) \cdot G_{\mathrm{CFASM}}. \tag{3}$$

The above relations are provided by the substitution of (4), (5), and (6) into (1).

$$\Delta\alpha_{\max} = |\alpha_{\mathrm{CFACTE}}| + \alpha_{\mathrm{epoxy}} = \alpha_{\mathrm{epoxy}} - \alpha_{\mathrm{CFACTE}}, \tag{4}$$

$$\Delta T_{\max} = |T_{\mathrm{coldest}}| + T_{\mathrm{s}} = T_{\mathrm{s}} - T_{\mathrm{coldest}}, \tag{5}$$

$$G_{\mathrm{CFASM}} = G_{\max}. \tag{6}$$

In mentioned equations, $|\alpha_{\mathrm{CFACTE}}|$ is the magnitude (positive value) of carbon fiber's axial CTE (CFACTE). α_{epoxy} is the CTE for epoxy. $|T_{\mathrm{coldest}}|$ is the magnitude (positive value) of the coldest temperature on the planet, and T_{s} is the UD CF/EP stress-free temperature (23°C). In addition, G_{CFASM} is the carbon fiber's axial shear modulus (CFASM). Because carbon fiber's axial CTE and coldest temperature in Titan both have negative values, (4) and (5) can be written in two forms.

Furthermore, with the reference to Table 1, carbon fiber's axial shear modulus is higher than epoxy's axial shear modulus. Hence, in (2) and (3), carbon fiber's axial shear modulus is used to derive the maximum Ilss.

As a next step to calculate the thermal life of UD CF/EP on Titan, it seems enough to solve the relation ILSS = Ilss. It means that when interlaminar shear stress (Ilss) reaches the value of interlaminar shear strength (ILSS) in UD CF/EP, it will fracture due to breaking bonds between carbon fibers and epoxy.

Previously, ILSS relation is obtained for maximum thermal cycles equal to 100 K temperature variation on Mars [1]. Due to this fact that temperature variation on Titan is approximately the same value (100 K), this relation (obtained from SLM on Mars) can be employed to estimate the thermal life on Titan as well.

$$\mathrm{ILSS}(N) = -5.12712e-3(N) + 102.0698785. \tag{7}$$

The required relation (ILSS = Ilss) can be developed while (7) is equal to (2) or (3).

$$\begin{aligned} &-5.12712e-3(N) + 102.0698785 \\ &\quad = \left(\left|\alpha_{\mathrm{CFACTE}}\right| + \alpha_{\mathrm{epoxy}}\right) \cdot \left(\left|T_{\mathrm{coldest}}\right| + T_s\right) \cdot G_{\mathrm{CFASM}}. \end{aligned} \tag{8}$$

By substituting the values of Table 1 in (8), with T_{coldest} on Mars equal to −123°C and $T_{\mathrm{coldest}} = -183°\mathrm{C}$ on Titan, the cycle numbers to thermal failure on Mars and Titan can be obtained. The method to achieve the cycle numbers to failure by applying (8) is illustrated in Figure 1. Moreover, the cross section's dimensions and arrangement of UD CF/EP are illustrated in Figures 2(a) and 2(b), respectively. It is important to notice that in Figure 2, the diameter of carbon fibers' bundle embedded in epoxy is 0.5 mm. According to this cross section [8], the volume fraction of carbon fibers' bundles in UD CF/EP is 19.6%. Thus, the volume fraction of epoxy is equal to 80.4%.

The values for thermal life on Mars and Titan are 10,235 and 6261 cycles, respectively. The decrease in the numbers of thermal cycles on Titan is due to the lower temperature (−183°C) in comparison with Mars (−123°C).

3.2. Extended Convex Curves Method. In 2014, convex curves method [8] has been proposed to estimate the thermal fatigue life of UD CF/EP in Earth orbit for satellite structures rotating around the Earth. Each temperature cycle in Earth orbit can be defined as −175°C (solar eclipse) to 120°C (sun illumination) and back to −175°C [4]. Thus, each cycle in low Earth orbit (LEO) represents 590°C temperature variation.

The following relation represents the ILSS equation in LEO based on the convex curves method (CCM). The cycles on Mars and Titan contain 100 K temperature variation. On the other hand, each cycle in LEO contains 590°C temperature variation. Hence, each cycle in LEO is 5.9 times of each cycle on Titan and Mars. As a result, by substituting $N/5.9$ instead of N in CCM equation for ILSS, this relation transforms in a state that can be used to estimate the thermal life for Titan and Mars. This relation can be achieved with the mentioned procedure to obtain ILSS equation as follows:

Table 1: Material properties of UD CF/EP [4, 12].

Materials	Epoxy	Carbon fiber
Axial coefficient of thermal expansion (1/°C)	43.92e − 6	−0.83e − 6
Transverse coefficient of thermal expansion (1/°C)	43.92e − 6	6.84e − 6
Axial Poisson's ratio	0.37	0.2
Transverse Poisson's ratio	0.37	0.4
Axial elastic modulus (GPa)	4.35	377
Transverse elastic modulus (GPa)	4.35	6.21
Axial shear modulus (GPa)	1.59	7.59
Transverse shear modulus (GPa)	1.59	2.21
Volume fraction (%)	80.4	19.6

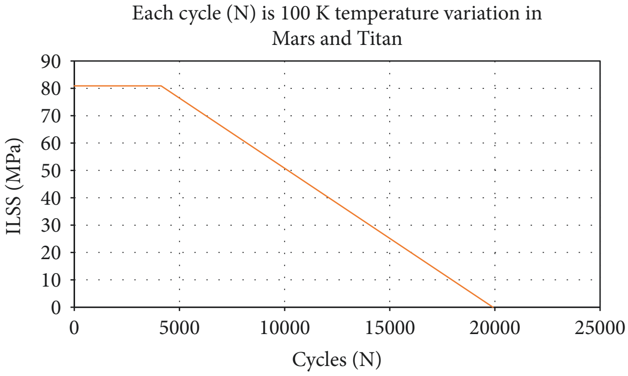


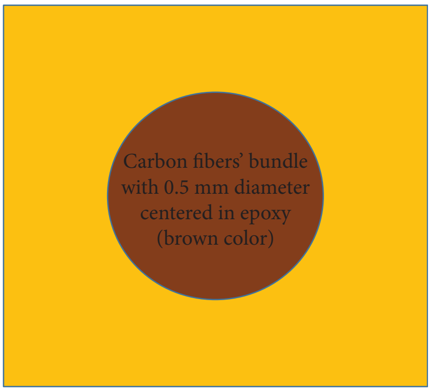
Figure 1: ILSS (MPa) (vertical axis) as a function of cycle numbers (horizontal axis) each with 100 K temperature variation for UD CF/EP, obtained by SLM [1].

$$\mathrm{ILSS}(N_{\mathrm{LEO}}) = (-1.05e-6) \cdot (N)^2 - (4.41e-3) \cdot (N) + 80.9, \tag{9}$$

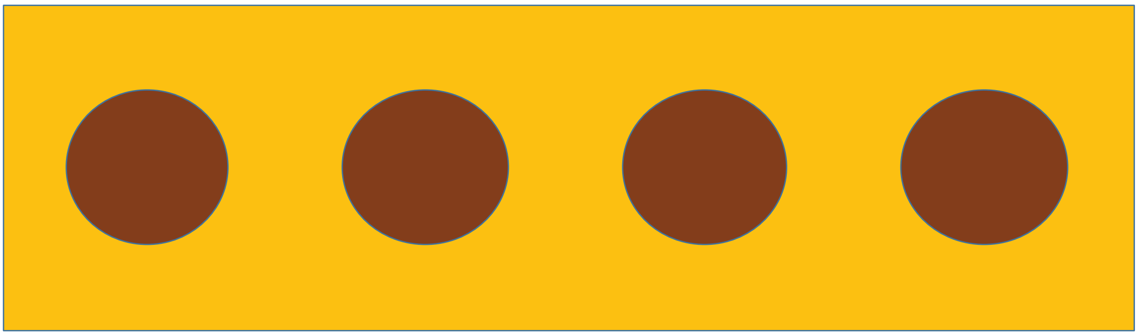
$$\begin{aligned} \mathrm{ILSS}(N_{\mathrm{Mars}}) = \mathrm{ILSS}(N_{\mathrm{Titan}}) &= (-1.05e-6) \cdot \left(\frac{N}{5.9}\right)^2 \\ &\quad - (4.41e-3) \cdot \frac{N}{5.9} + 80.9. \end{aligned} \tag{10}$$

This procedure can be named as extended convex curves method (ECCM). At this part, by solving ILSS (based on ECCM) while is equal to $\mathrm{Ilss}_{\max}$ ((2) or (3)) and obtaining N (cycle numbers to failure), cycle numbers to thermal failure on Titan and Mars can be achieved. These values are 10,316 and 22,135 cycles, respectively. Cycle numbers to failure for SLM are lower in comparison with ECCM. It means that SLM represents a higher conservative response. Thus, it involves more factor of safety.

3.2.1. From Earth to Titan. In this section of the manuscript, the application of ECCM to determine the thermal life of UD CF/EP from the departure from the Earth till landing on Titan and after that is described. However, this proposal that



(a) Epoxy with 1 ∗ 1 mm, cross section (yellow color)



(b) An example of arrangement of carbon fibers' bundles (brown color) in epoxy (yellow color)

Figure 2: Cross section of the UD CF/EP [8], dimensions (a) and arrangement (b), from up to down, respectively. (b) An example of arrangement of carbon fibers' bundles (brown color) in epoxy (yellow color).

ECCM is capable to estimate the thermal life from the Earth to Titan seems correct. The reason behind is that ECCM is capable to determine the thermal life of UD CF/EP based on the temperature variation and that is what needed to predict the thermal life in space environment. Following equation represents the ILSS based on the CCM.

$$\mathrm{ILSS}(N_{\mathrm{LEO}}) = (-1.05e-6)\cdot(N)^2 - (4.41e-3)\cdot(N) + 80.9. \tag{9}$$

By substituting N (cycle numbers in LEO equal to 590°C) with $(\sum_{i=1}^{n}\Delta T_i\cdot n_i)/590$, ECCM equation for thermal life from the Earth to Titan and even after that can be developed.

$$\mathrm{ILSS}\left(\sum_{i=1}^{n}\Delta T_i\cdot n_i\right) = (-1.05e-6)\cdot\left(\frac{\sum_{i=1}^{n}\Delta T_i\cdot n_i}{590}\right)^2 - (4.41e-3)\cdot\left(\frac{\sum_{i=1}^{n}\Delta T_i\cdot n_i}{590}\right) + 80.9. \tag{11}$$

In order to determine the term $\sum_{i=1}^{n}\Delta T_i\cdot n_i$, first it is needed to consider the space environment and its effect on temperature variation of UD CF/EP space structure.

The elements that may cause temperature variation in UD CF/EP space structure from the Earth to Titan are as follows (Vincent, 2016; Alan, 1995):

(1) Escape from Earth (EFE)
(2) Solar eclipse (SE)
(3) Sun illumination (SI)
(4) Debris friction (DF)
(5) Micrometeorite friction (MMF)
(6) Radiation
(7) Spacecraft propulsion (SP)
(8) Entrance to planet (ETP)
(9) Each day and night (EDAN)

In the following relation, each of these terms can be presented as n subtitle. The relation that can be substituted into ECCM equation for determining ILSS in space is as follows:

$$\sum_{i=1}^{n}\Delta T_i\cdot n_i = \Delta T_{\mathrm{EFE}}\cdot n_1 + \Delta T_{\mathrm{SE}}\cdot n_2 + \Delta T_{\mathrm{SI}}\cdot n_3 + \Delta T_{\mathrm{DF}}\cdot n_4 + \Delta T_{\mathrm{MMF}}\cdot n_5 + \Delta T_{\mathrm{Radiation}}\cdot n_6 + \Delta T_{\mathrm{SCP}}\cdot n_7 + \Delta T_{\mathrm{ETP}}\cdot n_8 + \Delta T_{\mathrm{EDAN}}\cdot n_9. \tag{12}$$

However, even more terms can be added to this relation. Following this procedure, by substituting this relation in

ECCM equation for ILSS while it is equal to $\mathrm{ILss}_{\max}$, relation for predicting the total allowed temperature variation can be developed. This temperature variation is the critical temperature variation because it may cause thermal fatigue failure in UD CF/EP space structure. The following relation is simply (11) equals to (2) or (3), from left to right, respectively.

$$(-1.05e-6)\cdot\left(\frac{\sum_{i=1}^{n}\Delta T_i\cdot n_i}{590}\right)^2-(4.41e-3)\cdot\left(\frac{\sum_{i=1}^{n}\Delta T_i\cdot n_i}{590}\right)+80.9 = \left(|\alpha_{\mathrm{CFACTE}}|+\alpha_{\mathrm{epoxy}}\right)\cdot\left(|T_{\mathrm{coldest}}|+T_{\mathrm{s}}\right)\cdot G_{\mathrm{CFASM}}. \tag{13}$$

4. Conclusions

Cycle numbers to thermal failure for UD CF/EP on Titan and Mars based on SLM are less than those for ECCM. The reason for this is the nature of SLM that is developed for a higher factor of safety. Or it can be mentioned that the application of CCM or ECCM is without any safety factor due to the fact that these methods are obtained from the exact data for ILSS of UD CF/EP. It means that no margin of safety is added to ILSS equation for CCM and ECCM.

It is important to mention that the application of bidirectional carbon fiber/epoxy composite (BD CF/EP) is not recommended in space structures. The reason behind is that according to the previous research [11], the rate of crack growth due to temperature variation in BD CF/EP is about 170 times of that in UD CF/EP. Hence, the application of BD CF/EP in space structures may put the human lives and space structures' integrity in risk of failure. On the other hand, employing CNT in space structures may be recommended due to the results [9] that CNT thermal strength in the cases of temperature variations is approximately 10 percent higher than that for UD CF/EP. Consequently, it takes about 10 percent higher thermal cycle numbers to failure when compared to UD CF/EP.

In Titan's mission, further precautions must be taken in comparison to Mars' mission. Because the distance between Titan and Earth is much greater than the distance between Mars and Earth. Thus, the probability of failure due to radiation, micrometeorites, spacecraft propulsion, solar eclipse, sun illumination, debris, etc. may increases. Furthermore, the coldest temperature on Titan is extremely low (60 K lower than the coldest temperature on Mars). As a result, the probability of fracture due to thermal failure in carbon structures increases. This is due to the increase in $\mathrm{ILss}_{\max}$ in UD CF/EP.

In the present study, methods to predict the thermal life of UD CF/EP that is applied in carbon structures in space are developed and compared. In particular, these relations are used for Titan to determine the thermal failure cycles in its environment. Two methods have been used to determine the cycle numbers to failure on Titan and Mars: SLM and ECCM. Furthermore, it has been shown that ECCM can be used to predict the thermal failure from Earth departure to landing on Titan and even after that. The results have shown that SLM may estimate the thermal life with a higher factor of safety when compared to ECCM.

Symbols

ILSS:	Interlaminar shear strength
$\mathrm{ILss}_{\max}$:	Maximum interlaminar shear stress
$\Delta\alpha_{\max}$:	Maximum difference of axial coefficients of thermal expansion between carbon fiber and epoxy
$\Delta \mathrm{T}_{\max}$:	Maximum temperature variation between stress-free temperature and ambient temperature
$G_{\max}$:	Maximum shear modulus in axial direction
α_{CFACTE}:	Carbon fiber's axial coefficient of thermal expansion
α_{epoxy}:	Epoxy's axial coefficient of thermal expansion
T_{s}:	Stress-free temperature
T_{coldest}:	Coldest temperature
G_{CFASM}:	Carbon fiber's axial shear modulus
N:	Cycle numbers to failure
ΔT:	Temperature variation.

Data Availability

The (experimental and analytical) data used to support the findings of this study are included in [1, 4–9, 11, 12].

Conflicts of Interest

The author declares that there are no conflicts of interest.

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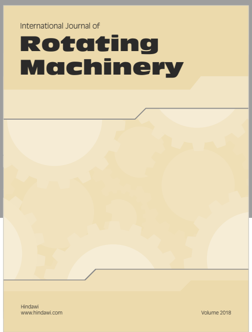
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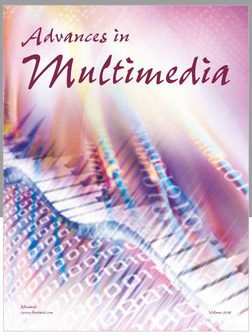
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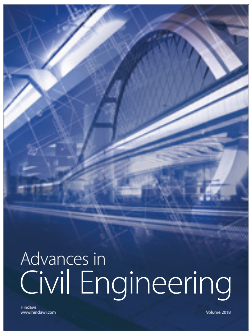
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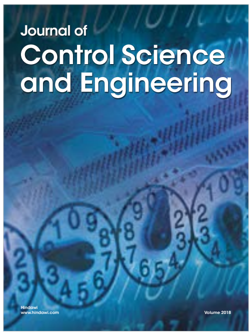
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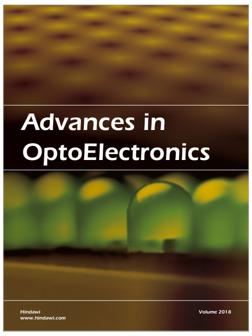
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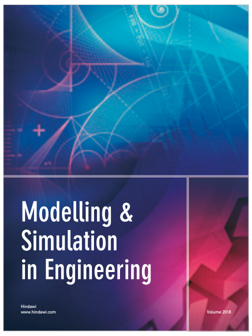
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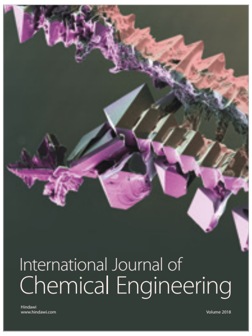
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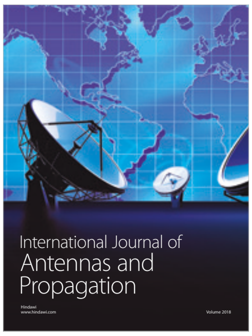
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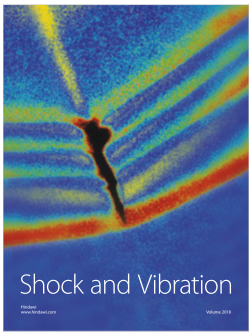
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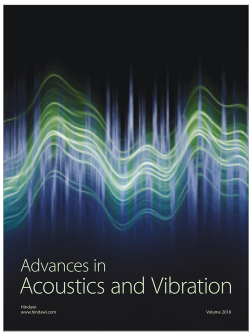
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