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Research Article

Direct Synthesis of Dual-Parameter Concentric Ring RA with Enhanced Bandwidth

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Reflectarray antennas (RAs) are nowadays a quite popular technology, used in several applications, due to a significant number of attractive properties, such as low cost, low weight, conformal deployment, and the possibility of introducing suitable reconfigurable capabilities. Unfortunately, they present also some intrinsic limitations and drawbacks compared with other solutions and, in particular, a relatively narrow bandwidth; that of course could be enlarged, but generally with a drastic increase of the structure complexity. The objective of this work is the design of a single-layer passive reflectarray, in which the reradiated elements have no conventional shape and enough degrees of freedom to compensate both the spatial and frequency phase variation of the reradiated field. In particular, here we focus on a reradiating element consisting in two concentric square rings in which two different and quite independent geometric parameters are varied.

1. Background and Aim of the Work

As it is well known, reflectarray (RA) antennas consist of one or more feed antennas illuminating a usually flat reflecting surface, whose electromagnetic reflecting performances have to be suitably designed in order to obtain the required performances of the whole radiating system. Reflectarray antennas have been first proposed in 1963 by Berry et al. [1], where the reflecting surface consisted of a planar array of variable length shorted waveguide components. So, the original reflectarray antenna was definitively not a low cost, easy to manage, light antenna, allowing foldability or any other of the interesting features that nowadays are typical properties of reflectarray solutions.

Probably this is the reason why for more than a decade this strange solution, without apparent advantages but with evident drawbacks compared, for example, with parabolic reflectors, has not been considered again, till 1975, when the feasibility of a reflectarray with scanning possibilities has been claimed in a US patent [2]. In this case a reflecting surface consisting of spiral antenna elements has been proposed, where each reradiating element uses a suitable set of diodes to manage properly the phase of the reflected wave allowing even some beam scanning of the whole system. So it is possible to say that, from the very beginning, the usual way of enhancing reflectarray antenna electromagnetic performances in order to introduce them in real life application is to exploit complexity at most.

The real breakthrough in reflectarray technology came when the evolution of printed circuit technology and high-frequency laminates synthesis allowed low-profile, lightweight implementations. In fact, even if the first reflectarray patent introducing a microstrip patch antenna-based reflecting surface has been published in 1977 [3], it is only from the late eighties that this kind of solution spread out.

Furthermore, in order to achieve good antenna performances, a very large array of patches has to be suitably designed exploiting in the proper way all the possible geometrical free parameters, requiring the adoption of numerical electromagnetic solvers, sophisticated numerical optimization tools, and in any case a significant numerical effort.

These, that is, the technology enablement and the numerical modeling tool availability, are the reasons why only nowadays printed reflectarrays technology became well assessed, and in the last years it substituted other technologies in many fields of applications, in particular where it is of paramount importance to fulfill constraints such as high gain, narrow beam with low side lobes, light weight and smaller volume, easiness of deployment, and foldability.

The main limitation now to a complete diffusion of this kind of solutions is due to the fact that the most recent antenna systems require a very large bandwidth, typically even the multiband operability or the possibility of beam steering, features that are still difficult goals to be achieved with a printed reflectarray.

In fact, for what concerns the bandwidth, it is intrinsically limited for two different orders of reasons: the poor bandwidth of printed radiating elements themselves, usually no larger than the 3–6%, and, most important, the frequency dependence of the phase delay of the incident field. In particular this second aspect is quite critical and becomes dominant in large RAs [4, 5], since it requires that the RA elements should be able to compensate different phase delays at different operating frequencies.

The usual assessed way to enhance the RA bandwidth is that of using radiating elements that consist in two or more stacked printed single radiators (see, for instance, [6–8]). However, this technique results in a heavier, bulkier, and quite complex reradiating structure, requiring a careful and expensive manufacturing and presenting some difficulties for its foldability.

Recently, alternative solutions have been proposed, in which the RA elements are single-layer printed patches of nonconventional shape [9–14], properly chosen in order to present more degrees of freedom with respect to the one usually adopted for multilayer stacked structures, which can be used to compensate the frequency variation of the phase, allowing the bandwidth enhancement. Among all the different types of patches that have been considered for this purpose, particular interest has been devoted to concentric rings of different shape, since this kind of choice looks promising as an effective compromise between a moderate increase of the complexity of the single patch geometry and its phase compensation capabilities. Furthermore, this type of radiating elements intrinsically possess different degrees of freedom, since the size and the width of the single rings could be varied independently; moreover it has a reduced resonance sizes and finally it has been seen that if such kind of elements are used in a multilayer structure, in which the elements of each layer work in a different frequency band, they do not affect each others, allowing the realization of a multilayer, multiband structure. Despite of the large number of degrees of freedom, in most of the RAs in which concentric rings are used, only one geometric parameter is independently varied [11–13], while the others are changed proportionally: in this way it is possible to easily enlarge the bandwidth but not enough to fulfill the requirements in several applications.

These are the reasons why, in the framework of this paper, we consider as radiating element a concentric double-square ring configuration, in which at least two geometrical parameters are varied. In this way, it is possible to compensate with one parameter the spatial phase shift and with the other the frequency variation of the incident field phase, so that the reradiated field remains almost the same in the whole bandwidth, overcoming the previously considered limitations. In other words, it means that each element of the array has to provide a phase contribution to the reradiated field that varies both with the element position and with the frequency. With the aim of validating the effectiveness of the such reradiating element, we considered different RAs with increasing size: the results of their full-wave analysis show that the proposed reradiating element is a good candidate for single-layer, large-bandwidth reflectarrays.

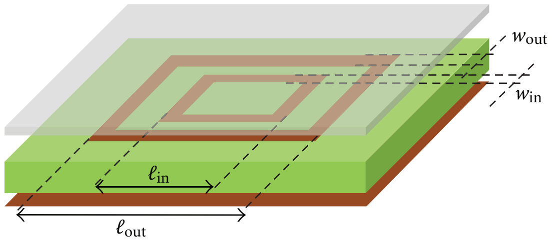

Figure 1: Geometry of the considered reradiating element.

2. RA Unit Cell

The RA reradiating element considered in this work is of the type sketched in Figure 1, and it consists of two square concentric rings, each one characterized by its side length ℓ, and width w. The structure in Figure 1 is therefore characterized by several degrees of freedom, that is, the two lengths, the two widths, and the aspect ratios, which are not completely independent: since the choice of which one of them has to be varied to control that the phase of the reradiated field is not electromagnetically equivalent, the first analysis carried out has been finalized to figure out which set of all the possible different geometrical parameters of a two concentric ring configuration may present the best phase variation.

In order to achieve this result, for all of them the variation of the reradiated field with a suitable set of different couples of geometrical parameters has been computed, considering the element embedded in an infinite periodic lattice and adopting a full-wave MoM approach. An example of the kind of obtained results is reported in Figure 2, where the phase variation provided is reported as a function of the size ℓ_{out} of the outermost ring and the aspect ratio p, which relates the size of the inner ring to that of the outer one; that is, $\ell_{\mathrm{in}} = p\ell_{\mathrm{out}}$; the two ring widths ($w_{\mathrm{out}}$, w_{in} in Figure 1) have been instead maintained proportional to the size of the relative ring. This couple of geometrical parameters is the one used to design the entire RAs, whose numerical results are shown in the next section.

Figures 3 and 4 report the phase variation due to the variation of the side length ℓ_{out}, for a fixed value of the aspect ratio p and due to the variation of p, fixed ℓ_{out}, respectively. The three curves in the two figures refer to different frequencies. From these figures, it is possible to conclude that all these phase curves present a significant phase range, more remarkable when ℓ_{out} is varied, running from around 300 to more than 600 degrees, and an important

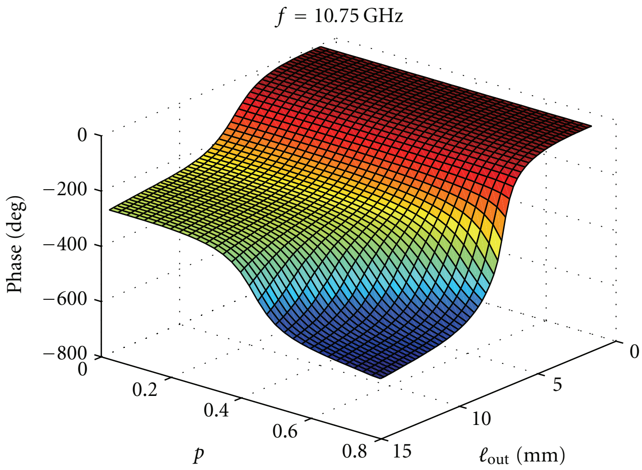

Figure 2: Phase variation provided at 10.75 GHz as a function of two geometrical parameters.

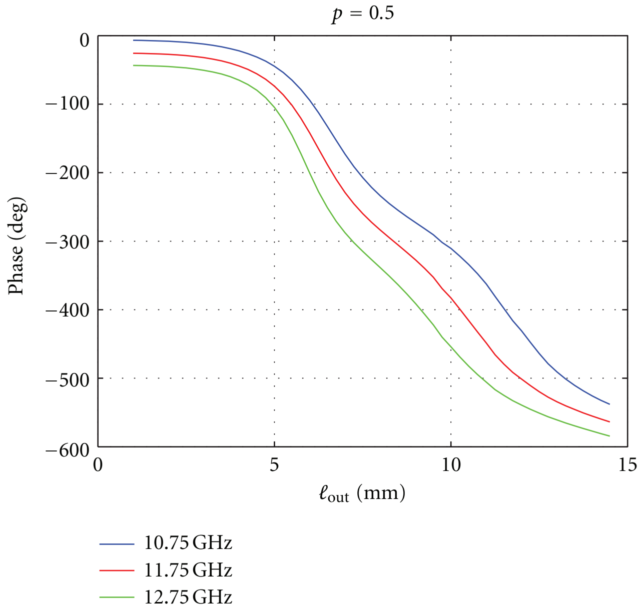

Figure 3: Phase variation provided a as a function of ℓ_{out}.

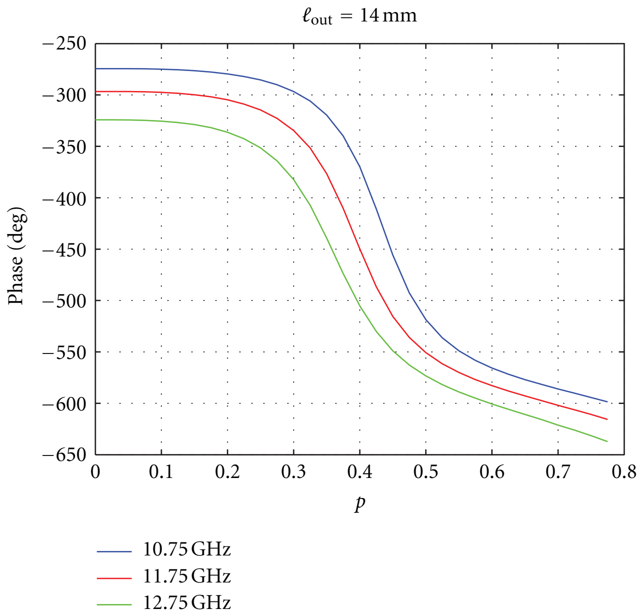

Figure 4: Phase variation provided as a function p.

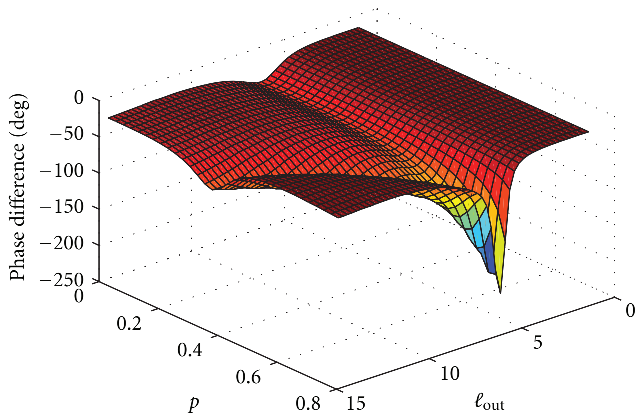

Figure 5: Difference between the phase at the central frequency and at one extreme of the band as a function of ℓ_{out} and p.

quasi-linear behavior: moreover, curves corresponding to different frequencies are almost parallel.

The design of each reradiating element in a RA, which implies the optimal choice of ℓ_{out} and p giving the proper phase value to compensate both the phase delay introduced by the distance between the feed and the element and the variation due to the frequency, requires not only the phase maps like the one shown in Figure 2, but also those like the one in Figure 5, reporting the difference between the curves of the phase variation with the two selected geometrical parameters computed at the central frequency and at an extreme of the band. Adopting the design procedure described in [14], it is therefore possible to find the proper values of ℓ_{out} guaranteeing the compensation of the phase delay introduced by the path between the feed and each element; then it is possible to act on p to assure the proper variation of this phase with frequency.

3. Numerical Results

In order to experimentally validate the synthesis design concepts previously detailed and, in particular, to prove the real possibility to enhance the bandwidth with the use of the introduced double parameters reradiating element, two reflectarray configurations of different size have been considered. Both of them are offset fed, since in that case the distances between the feeder and the lower and upper sides of the reflector are quite different and the frequency compensation of the introduced delays is more complex to achieve. The planar reflectors have been designed in such a way that the direction of maximum radiation is slanted with respect to the broadside: in this way it is possible to

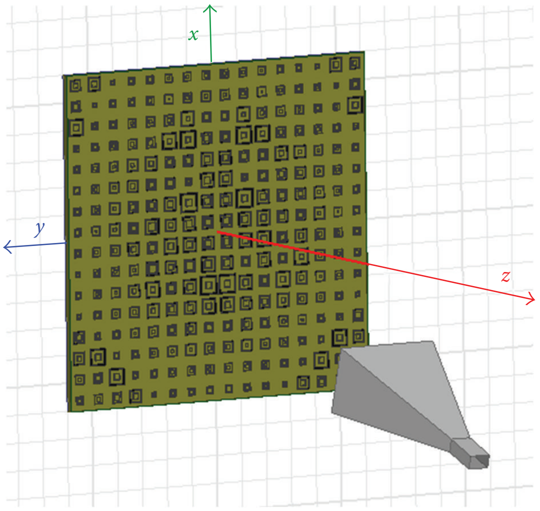

Figure 6: View of the designed 16 × 16 RA geometry.

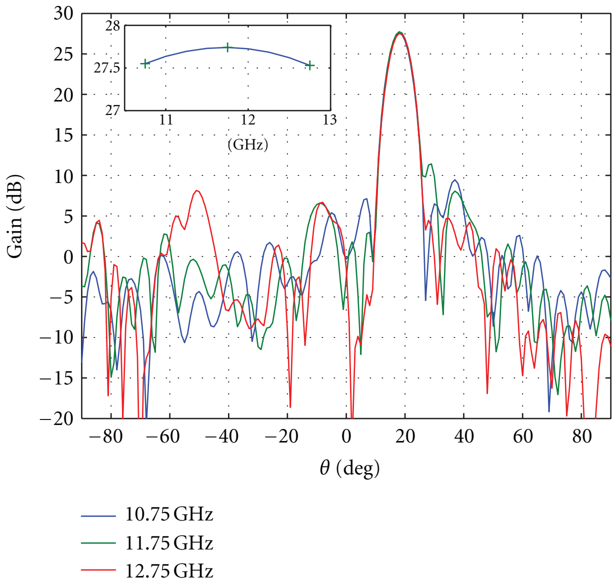

Figure 7: Radiation patterns of the 16 × 16 RA computed at three different frequencies in the plane $\phi = 0°$. Inset: gain frequency variation.

better control if the phase compensation introduced by the reradiating elements is effective at the different frequency, checking if the direction of maximum radiation remains constant. The first RA we considered is the configuration depicted in Figure 6, consisting in a 16 × 16 planar reflector fed by a rectangular horn located at a distance of 390 mm along the z-axis and of 125 mm along the x-axis from the center of the coordinate system, which is coincident with the central point of the reflector. To improve the reradiating elements performances, a two-layered dielectric structure has been used, consisting of a substrate characterized by height $h_1 = 5$ mm and relative dielectric constant $\epsilon_{r1} = 1.1$ and in a cover with $h_2 = 0.85$ mm and $\epsilon_{r2} = 2.5$.

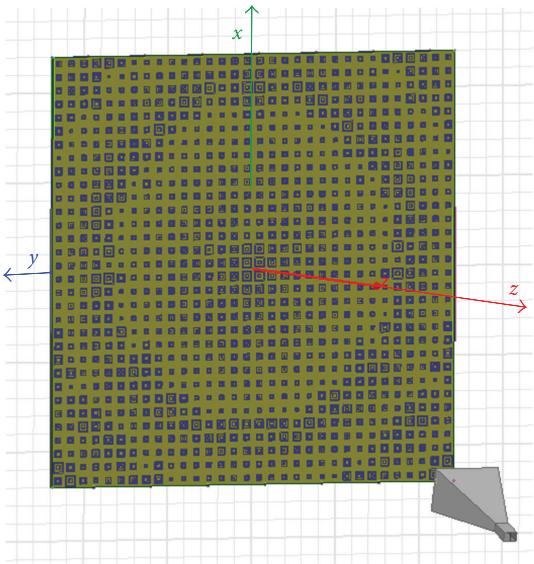

Figure 8: View of the designed 32 × 32 RA geometry.

The structure has been designed using the two degrees of freedom of the double-ring reradiating elements to obtain the maximum reradiation in a direction tilted of 18° with respect to the normal and to minimize the gain variation in the frequency range [10.75–12.75] GHz, as reported in Figure 7.

The entire RA has been analyzed using a commercial full-wave simulator [15], and the radiation patterns for different frequencies have been computed. In Figure 7 the radiation patterns in the plane $\phi = 0°$ computed at the extremes and at the center of the frequency band are shown: in this case, not only the gain variation is really small, lower than 0.5 dB in the entire band, but the side lobe level remains almost constant and below −18 dB with respect to the maximum.

The second considered configuration is the 32 × 32 planar reflector depicted in Figure 8. In this case the rectangular horn is located at a distance of 671 mm along the z-axis and of 217.5 mm along the x-axis from the center of the coordinate system, which is coincident with the central point of the reflector. As in the previous design, in order to improve the reradiating elements performances, the same two-layered dielectric structure has been used, consisting in a substrate characterized by height $h_1 = 5$ mm and relative dielectric constant $\epsilon_{r1} = 1.1$ and in a cover with $h_2 = 0.85$ mm and $\epsilon_{r2} = 2.5$. As in the previous case, the planar reflector has been optimized to work on the frequency band [10.75–12.75] GHz and to have a direction of maximum radiation tilted of 18° with respect to broadside.

In Figure 9 the 3D radiation pattern of the reflectarray, computed at the central frequency, is reported, showing the high directivity of the designed structure and the absence of unwanted high lobes apart from those around the maximum.

Finally, in Figure 10 the cuts in the vertical plain for three different frequency values are shown: the main lobe is almost coincident in the three cases, and no shift of the main beam occurs changing frequency. The side lobes

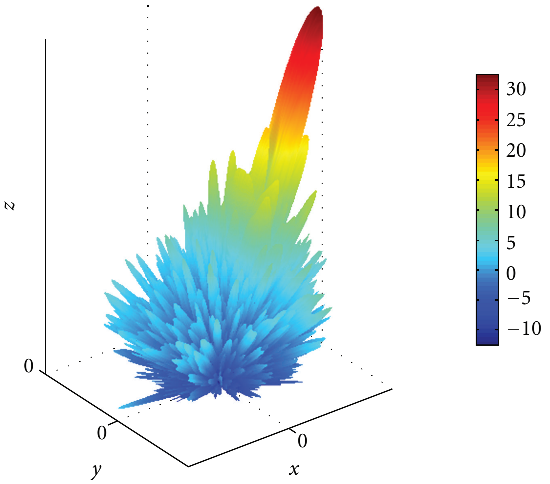

FIGURE 9: 3D radiation patterns of the 32 × 32 RA computed at the central frequency.

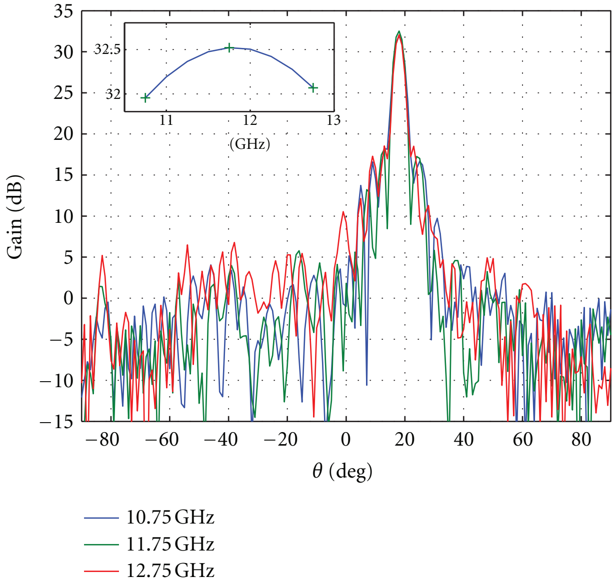

FIGURE 10: Radiation patterns of the 32 × 32 RA computed at three different frequencies in the plane $\phi = 0°$. Inset: gain frequency variation.

slightly increase with the frequency, but in any case they are well controlled. Finally, in the figure inset it is reported the frequency behavior of the gain, showing that also in this case it remains almost constant on the entire bandwidth.

4. Conclusions

In this paper we present the design of planar reflectarray antennas using concentric square rings as reradiating elements. In opposite to what already published, here two geometric parameters have been varied in order to better control both the spatial and frequency phase variation of the reradiated field and to overcome one of the main drawbacks of the RAs, that is, their narrow bandwidth. The full-wave numerical analyses, carried out on two sample antennas of 256 and 1024 elements, respectively, show a 1 dB gain bandwidth of almost the 17% and confirm the promising characteristics of such radiating elements.

Acknowledgment

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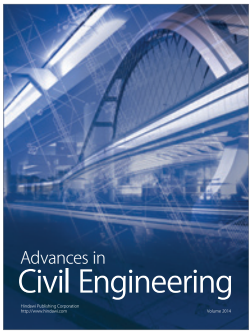
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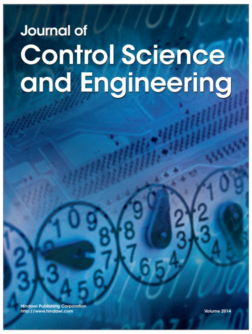
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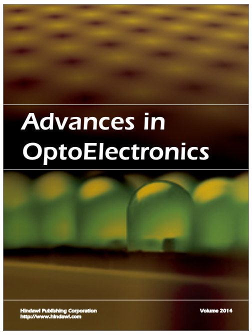
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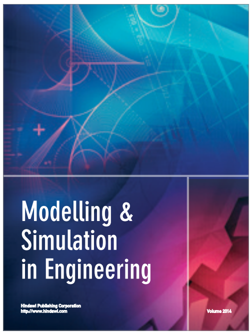
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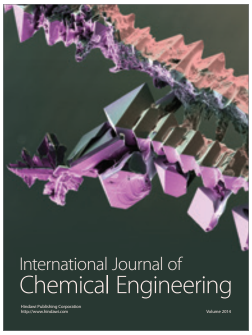
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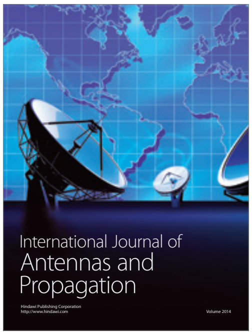
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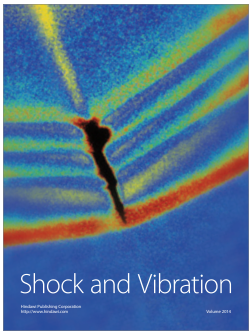
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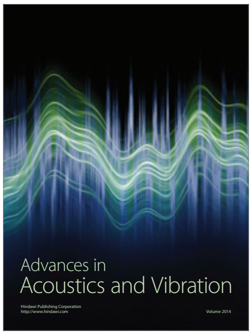
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