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Research Article

Study of Factors Making Space-Contaminated Optical System Unusable

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Molecular and particulate contamination of space optical surfaces can be extremely detrimental to optical system performance. In order to determine whether optical system is unusable, we must do a lot of tests. For reducing experimental effort, computational criterion for unusable space optical system is put forward, which is based on experimentation and calculation by 2D-FDTD (finite-difference time domain). And then factors making optical system unusable are studied when distribution of light intensity is consistent with the criterion. Results show that small particulate is more detrimental to optical system than big one for particle with high permittivity is. The distribution of particles making optical system unusable is also obtained.

1. Introduction

There are two types of contamination that affect optical performance: molecular and particulate contamination. Particulate contamination can occur through two phenomenons: obscuration and scattering effects. Particulate obscuration occurs when surface particles prevent light from reaching the underlying surface [1]. For particles with high permittivity, particulate obscuration plays a main role. Here, particulate with high permittivity is research subject.

Molecular and particulate contamination of spacecraft optical surfaces can be extremely detrimental to optical system performance [2]. Surface-deposited particles induce not only decreasing transmittance of optical system, but also reducing the image quality of optical system [3]. For system of space optical communication, contamination of optical surface can change the light intensity distribution [4].

As particles on optical surface accumulate, the space optical system will be unusable at last. Under what conditions the space optical system is unusable is concerned. As we know, particle size, the space between particles and absorbency of particles can influence quality of optical system. Then we should do a lot of experiments to ascertain whether optical system is unusable. In order to save money and time, a computational criterion for unusable space optical system is useful. In this paper, the criterion is put up. And then, for particle with high permittivity, factors making optical system unusable are studied.

2. The Criterion for Unusable Optical System

Kahnert [5] has analyzed some of the most widely used numerical techniques in detail. In these models, FDTD can resolve scattering by inhomogeneous, anisotropic, and arbitrarily shaped charged or uncharged particles [6], so that it has been applied to such diverse applications as antenna scattering [7], analysis of microstrip circuits [8], absorption in tissue [9], optical absorption by biology cellula [10–13] or scattering by atmospheric ice crystals [14], irregular aggregates [15], multifaceted concave and convex particles [16], spheres with nonspherical inclusions [17], hexagonal columns with air bubble and soot inclusions [18] or clusters of particles with or without inclusions [19], consistent and rigorous analysis of infinite graphene layers is developed [20], electrically thin dispersive layers [21], calculation of reflection coefficient for the plane wave incident on planar periodic structures [22], light scattering and absorption by nonspherical particles embedded in an absorbing dielectric medium [23], an arbitrary beam's interaction with an arbitrary dielectric surface [24], to name but a few examples. So FDTD is chosen. Because this calculation is only used to reduce experimental effort, rather than for exact simulation,

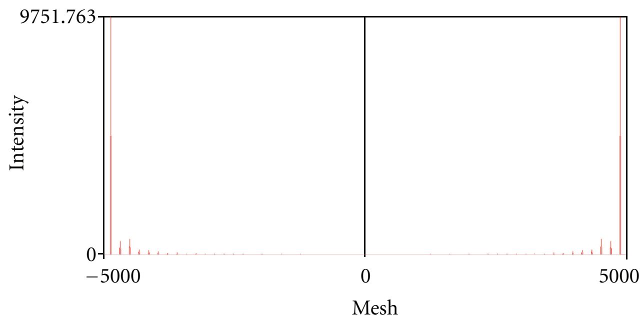

Figure 1: Distribution of transmitted light intensity while $2r = 0.3$ mm and $d = 0.4$ mm.

2D-FDTD is appropriate. And 2D-FDTD can also decrease calculation workload.

According to resolution test, when the diameter ($2r$) of particulates is 0.3 mm, the maximal space ($d_{\max}$) between particles, resulting in optical system being unusable, reaches 0.4 mm. In this case, far-field light intensity distribution calculated by 2D-FDTD is shown in Figure 1, and the relevant near-field distribution of light intensity is constant. Furthermore, light intensity distributions are also calculated when space between particles is less than 0.4 mm and diameter of particulates is more than 0.3 mm. Results show that both far-field light intensity distributionand near-field distribution are in accord with that of $2r = 0.3$ mm and $d = 0.4$ mm [25]. Then a criterion for unusable optical system is put forward. That is to say, optical system can be thought unusable once near-field distribution of light intensity is constant and far-field light intensity distribution is like Figure 1. In [25], the resolution power is obtained by software HYRes 3.1, which is written by Olympus Corporation.

3. Factors Making Optical System Unusable

As FDTD equations display, ε and C_s are factors. ε and C_s are different for different contaminants. That is to say, the kind of contaminant is a factor.

For the kind of contaminant (e.g., $\varepsilon = 1.5 + 5.0i$), both the size of particulates and the space between particles are factors. Here, when distribution of light intensity is consistent with the criterion, the relationship between the maximal particle space and radius of particles is research emphasis.

3.1. Relationship between Radius of Particles and the Maximal Particle Space. Here, relevant maximal space between particles ($d_{\max}$) is obtained, firstly, for unusable optical system, when radius of particulates varies from 0.0325 mm to 1.25 mm (error is less than 1 μm). See Figure 2.

From Figure 2, the relationship between radius of particles and maximal space between particles is linear on the whole, although there are some exceptions. That is to say, as radius of particulates increases, maximal space between particles increases linearly. This is reasonable because the diameter of the Airy disk varies inversely with the particle's radius, the smaller the particles are, the larger the Airy disk is.

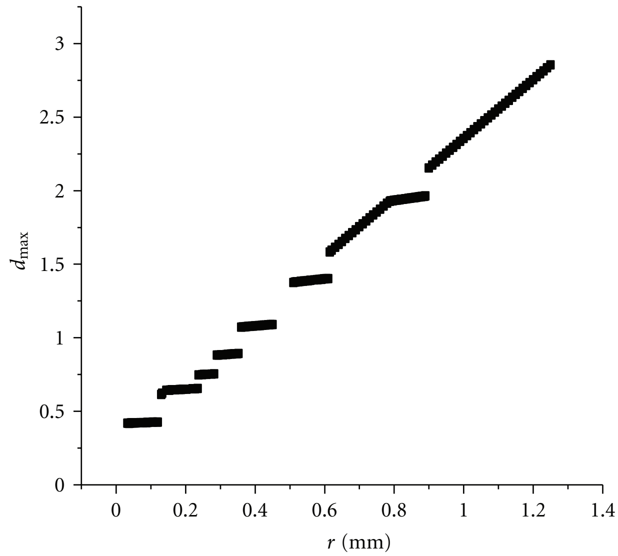

Figure 2: Relationship between radius of particles and maximal particle space.

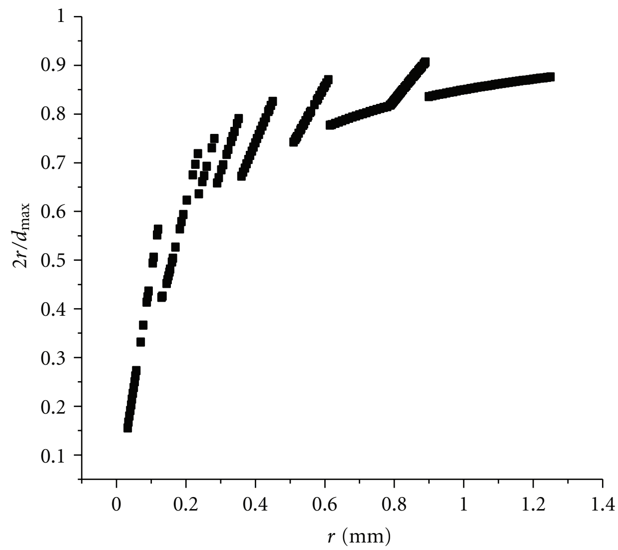

Figure 3: Relationship between r and $2r/d_{\max}$.

Then the change of light intensity overlap is less susceptible to the particle size. $d_{\max}$ in Figure 2 has smaller change with r. As the particle size becomes bigger, diffraction image of one particle becomes sharper. Then $d_{\max}$ changes with r rapidly.

From the linear relationship between $d_{\max}$ and r, it may be deduced that total coverage of contaminant, which causes the optical system to be unusable, is equal for all size particles. Therefore, ratio of opaque part to all is calculated when radius of particles is different.

3.2. Relationships between r and $2r/d_{\max}$. In order to study how total coverage of contaminant influences optical imaging system, $2r/d_{\max}$ is calculated when radius of particles, r, is different. See Figure 3.

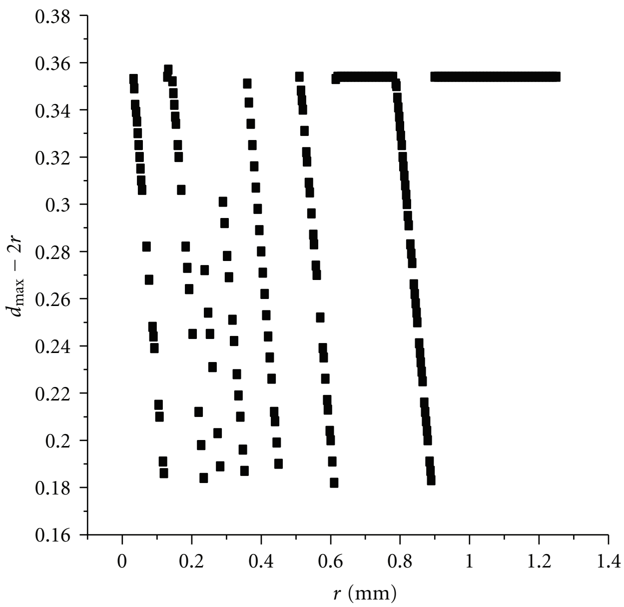

Figure 4: Relationship between r and $d_{max} - 2r$.

From Figure 3, total coverage of contaminant is not constant, which means total coverage of contaminant is not so important to imaging. It can also be seen from Figure 3 that the less radius of particles is, the less the quantity of contaminants which cause optical system to be unusable is. After r reaches a certain size, $2r/d_{max}$ moves up but slowly with the increasing of r. So a smaller quantity of smaller than larger particulates on optical surface can induce optical system to become unusable. In a word, small particulates are more detrimental to optical system than large particulates.

So the small particle's contamination prevention should be the most important of particle's contamination prevention.

3.3. Relationship between r and $d_{max} - 2r$. Because of particle's extinction, $d_{max} - 2r$ may be an important parameter for transmissivity of optical system. And then, $d_{max} - 2r$ is calculated correspondingly, when distribution of light intensity is consistent with the criterion. Results are plotted in Figure 4.

Result of Figure 4 is consistent with that of 3.1. Furthermore, there is an interesting fact in Figure 4, that is, $d_{max} - 2r$ is always less than 0.36 mm. This means that according to the criterion put up in this paper, it is possible to obtain an exact value of resolution power from HYRes 3.1 when the space between particles is more than 0.36 mm, although resolution power of optical system will decrease somewhat. However, it is not quite clear why this value is 0.36 mm.

4. Conclusions

In this paper, a criterion is put up based on test and calculation and it is used to determine whether optical system is usable or not in calculation. Then factors which may induce optical system unusable are studied. For particle with $\varepsilon = 1.5 + 5.0i$, the following results can be deduced when optical system is unusable: (1) maximum space between particles is linear with radius of particles approximately, (2) the smaller the radius of particles is, the smaller is the minimal coverage of particle, (3) small particles are more detrimental to optical system than large particles are, and (4) $d_{max} - 2r$ is always less than 0.36 mm.

In conclusion, when distribution of light intensity is consistent with the criterion, the smaller the size of particulates is, the smaller the maximum space between particles is. But this is not to say that optical system will be unusable so long as the coverage of particulates reaches a value, whether the particles on optical surface are large or small. In fact, the lesser radius of particle is, the less minimal coverage of particles is, when optical system becomes unusable. That is, small particulates are more detrimental to optical system than large particulates. From the above study, if $d_{max} - 2r$ is more than 0.36 mm, resolution power can be read out by HYRes 3.1.

The results are benefit to study relevant problem of similar structure, such as periodic arrays of left-handed metamaterials [26], monolayer and bilayer graphene deposited on a SiO_2/Si substrate [27], and multiwall carbon nanotubes [28]. And they may be of guidance for designs of some components, for example, design of graphene magnetic field sensors [29].

The paper presents that if near-field light intensity from FDTD is equal to the fixed value, optical system is hardly usable. However, the criterion is possibly not the best.

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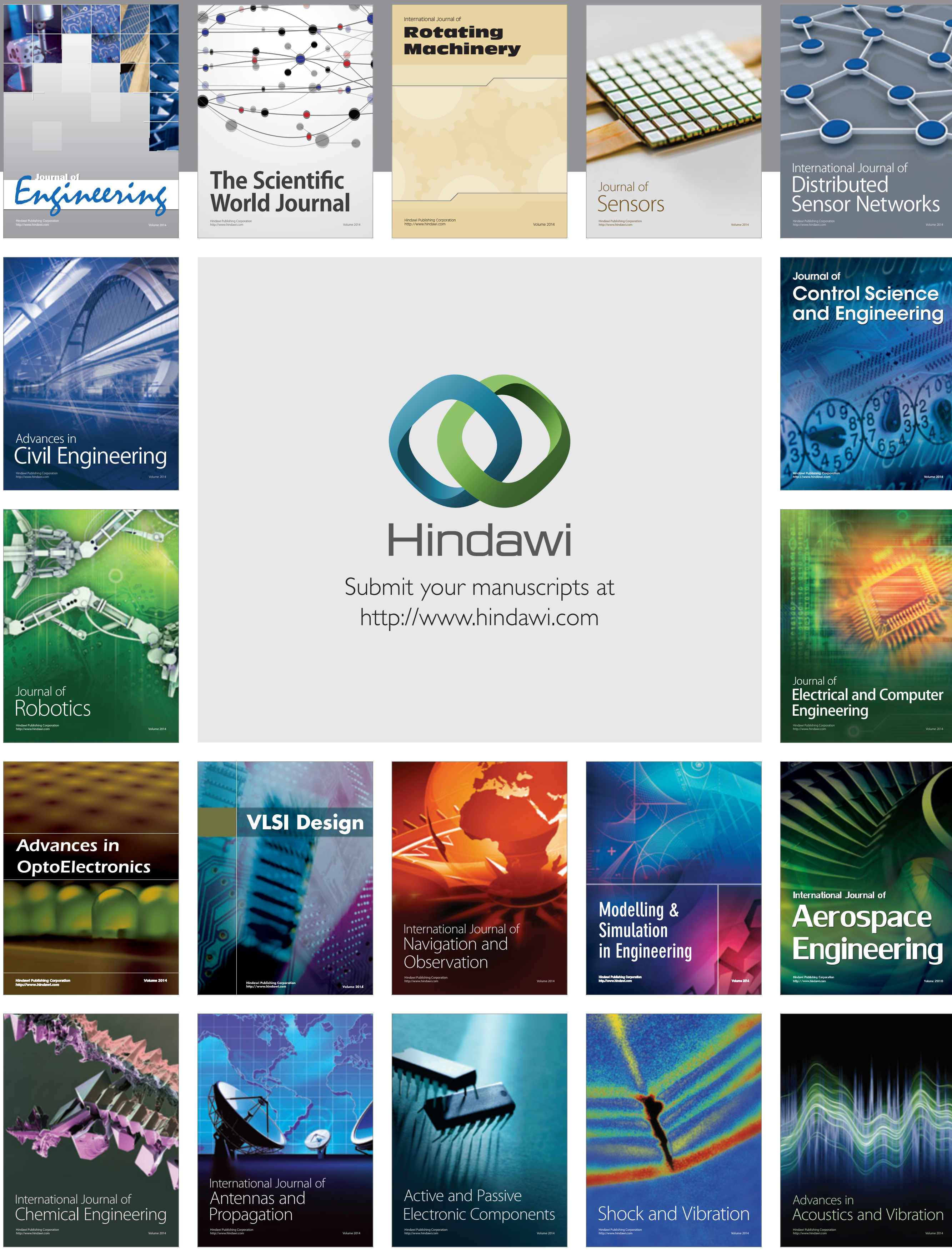
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