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by

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Application of Complex Ray Theory in EM Scattering and RCS Analysis

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Abstract: The complex ray theory provides a simple and useful approach for the analysis of the propagation and scattering of HF EM waves in various complicated environments. This paper deals with complex ray fields in free space, reflection and refraction at a single interface, multiple reflections and transmission through a layered medium, total reflection and critical reflection at a planar interface, diffraction at an edge, complex ray expansion and superposition, as well as RCS calculation by complex ray method. In addition, some numerical results are given. Keywords: Electromagnetic wave propagation; Electromagnetic wave reflections; High frequency. (...)

I. Complex Ray in Free Space[1–5]

Complex ray theory is a theory developed in the 70's to obtain an approximation solution to the high frequency wave field problems. In the 80's, due to the rapid progress in the computer technology, the theory of complex ray theory has received wide application in the electromagnetic-wave related fields such as laser, optical fiber, antenna, and microwave and the elastic wave fields such as water sound and earthquake wave. The purpose of this paper is to discuss the application of complex ray theory in the study of high frequency electromagnetic scattering and analysis of radar cross section.

According to analytical expansion principle of complex function, if the magnitude of the imaginary part of the coordinate of the waver source is given. the complex source point with complex coordinate can be obtained. These rays propagating in the complex space from the complex source and are called the complex rays. Following the traditional ray theory and methods, the trace of the complex rays can be followed and the ray field can be calculated.

In order to simplify the problem, the discussion in this paper was based on a two-dimensional structure ($\partial/\partial x = 0$). Figure 1 shows the free space. A wave vector b was defined at the source of the polarized linear electrical current $S(y_S, z_S)$ along the x direction. The parameter b was called the wave width parameter and the directional angle a_b was called the wave directional angle of the vector b (see figure 1). The coordinate of the complex source was defined as $\tilde{s}(\tilde{y}_S, \tilde{z}_S)$

$$\tilde{y}_s = y_s + jb\cos\alpha_b, \quad \tilde{z}_s = z_s + jb\sin\alpha_b \qquad (1)$$

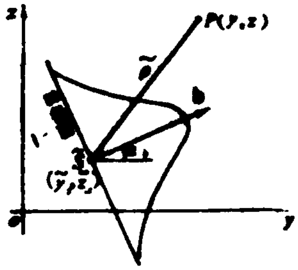
Using the cylindrical Bogarin function for expansion, the field expression at the observation point P(y,z) of the two-dimensional complex source (ignoring the time factor exp(-jwt)) is

$$\tilde{E} = -\frac{\omega\mu_0}{\sqrt{j8\pi k_0\tilde{\rho}}}e^{jk_0\tilde{\rho}}, \quad |k_0\tilde{\rho}| \gg 1 \qquad (2)$$

where the complex distance is

$$\tilde{\rho} = \sqrt{(y-\tilde{y}_s)^2 + (z-\tilde{z}_s)^2}, \quad \mathrm{Re}(\tilde{\rho}) > 0 \qquad (3)$$

In the real space, the plane that passes through S point and is perpendicular to the vector b is defined as the caliber plane of the complex source (see figure 1). On this caliber plane, the complex source point field has the uniform phase distribution and the Gaussian-type amplitude distribution and its remote radiation field is also a Gaussian-



Fiqure 1: Two-dimensional complex source point and its caliber field distribution

key: 1 - caliber circle

type fixed-directional radiation wave. Therefore, it is appropriate to use the complex source point field to simulate the concentrated waves such as the mono-pulse laser wave or the radar antenna major wave front. Based on the conclusion of the real-space ray optics and after simple analysis and expansion, the transmission and scattering of the wave field can be solved. Since the physical optical integration or the plane wave spectrum integration of the caliber field is avoided, the numerical process was made even simpler.

In this paper, we will briefly introduce the various methods of the complex ray theory, including the complex ray tracing method, the near-axis approximation method, the agglomeration ray method, the complex ray diffraction method, the complex ray expansion method, and the application of these methods in the calculation of the scattering field and analysis of the radar cross section.

II. Reflection and Refraction of Complex Rays [6,7]

Considering the two-dimensional random curved surface f(y,z)=0 shown in figure 2, for the complex source $\tilde{S}$ defined in equation (1) and the observation point P, a complex ray which passes through a point A on the curved surface and reaches point P can be obtained through iteration process. This ray should satisfy the complex space Feima principle with the complex light distance as the limit value

$$\frac{d[\tilde{L}_1(\tilde{a}) + \tilde{L}_2(\tilde{a})]}{d\tilde{a}} = 0 \tag{4}$$

where $\tilde{L}_1$ and $\tilde{L}_2$ are the complex distances for the incident and the reflected paths and $\tilde{a}$ is the complex reflected angle (see figure 2). Therefore, the field at point P can be written as

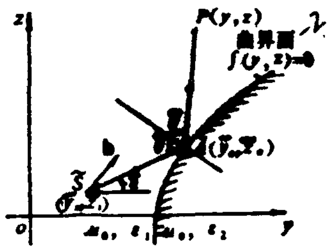


Figure 2: Reflection of complex ray

key: 2 - curved interface

$$\tilde{E} = -\frac{\omega\mu_0 \tilde{R}(\tilde{\theta})\tilde{D}(\tilde{\theta})}{\sqrt{j8\pi k_1(\tilde{L}_1+\tilde{L}_2)}} e^{jk_1(\tilde{L}_1+\tilde{L}_2)} \tag{5}$$

where $\tilde{R}(\tilde{\theta})$ and $\tilde{D}(\tilde{\theta})$ are the complex reflection and complex diffusion functions. These functions can be obtained by substituting the incident angle θ in the real space with the complex incident angle $\hat{\theta}$. The method which uses the iteration technique to trace the complex ray parameter (such as the complex reflected angle $\tilde{\theta}$) is called the complex ray tracing method. Obviously, tremendous computer time is required in the tracing process.

In order to simplify the numerical process, the near-axis approximation can be used.[6,7] It only requires the tracing of the real trace along the wave axial line, then the complex ray field $\tilde{E}_0$ at the axial observation point P_0 can be calculated approximately and then the complex ray field at the near-axis observation point P can be obtained through the micro-disturbance correction of complex phase and complex amplitude

$$\tilde{E} = \tilde{E}_0 e^{j\tilde{\delta}+\tilde{v}_R+\tilde{v}_D} \tag{6}$$

where

$$\tilde{E}_0 = -\frac{\omega\mu_0 R(\theta_0)\tilde{D}(\theta_0)}{\sqrt{j8\pi k_1(L_{10}+L_{20}-jb)}} e^{jk_1(L_{10}+L_{20}-jb)} \tag{7}$$

The $\hat{\delta}$ in equation (6) denotes the complex phase correction and $\tilde{v}_R$ and $\tilde{v}_D$ are the corrections for the reflection and diffusion functions. They are all functions of the near-axis distance d and can be expanded by Taylor's series. (In Taylor's series expansion, only the first term should be considered for approximation calculation.[6,7])

For the complex rays that penetrate through the interface and into another medium, the complex expansion should be based on the Snare's law

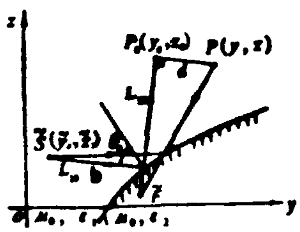


Figure 3: Near-axis approximation of complex rays

and the results of the refraction of complex rays should be similar to those of the reflection of complex rays.

III. Continuous Refraction and Multiple Reflection of Complex Rays [8-11]

In the layered homogeneous medium shown in figure 4, the complex rays can reach the observation point after multiple reflections and refractions. Therefore, the total field at point P should be the summation of all the possible complex ray fields

$$\tilde{E} = \sum_{M=0}^{\infty} \tilde{E}_M \qquad (8)$$

where $\tilde{E}_M$ denotes the complex ray field which reaches point P after M times of reflections between the two layers (see figure 4). The calculation can be proceeded with either complex ray tracing method or the near-axis approximation method[8]

$$\tilde{E}_M = -\frac{\omega\mu_0}{\sqrt{j8\pi k_0 L_0}} \tilde{T}\tilde{R}_M\tilde{D}_M e^{jk_0\tilde{\varphi}_M} \qquad (9)$$

where $\tilde{T}=\tilde{t}_1\tilde{t}_2$ is the coefficient of refraction of this double-refraction. $\tilde{R}_M = \prod_{m=1}^{2M} \tilde{r}_m$ is the total coefficient of reflection after M times of reflections. $\tilde{D}_M = \prod_{m=0}^{2M+1} \tilde{d}_m$ is the total diffusion coefficient, and $\tilde{\varphi}_M = L_0 + n_1 \prod_{m=1}^{2M+1} L_m + L_r$ is the total complex light distance. They can all be solved from the complex ray paths.[8-10]

In order to simplify the summation process of the infinite series in equation (8), the residual terms from the $\bar{M}$-th term can be treated together. If the thickness of these layers is uniform or if the incident ray is near the normal vector of the curved surface, then the residual terms can be expressed, after Fourier transformation and integration approximation calculation, as[11]

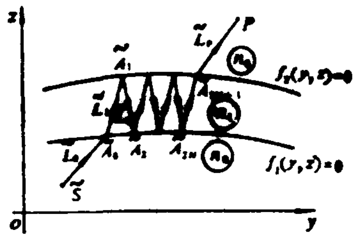


Figure 4: Multiple reflection and refraction of complex rays

$$\tilde{E}_c = \sum_{M=\bar{M}}^{\infty} \tilde{E}_M = -\frac{\omega\mu_0}{\sqrt{j8\pi k_0 L_0}} \tilde{T}_c \tilde{R}_{\bar{M}} \tilde{D}_{\bar{M}} e^{jk_0 \tilde{s}_{\bar{M}}} \tag{10}$$

Comparison of equations (8) and (10) shows that the summation of these residual terms can be regarded as the contribution from the $\bar{M}$-th complex ray. It would only require to replace the transmission coefficient $\tilde{T}$ in equation (8) by the transmission coefficient of the agglomeration of the rays $\tilde{T}_C$. Therefore, equation (8) can be re-written as the mixed-field structure of the ordinary rays and the agglomeration rays

$$\tilde{E} = \sum_{M=0}^{\bar{M}-1} \tilde{E}_M + \tilde{E}_c \tag{11}$$

The numerical results show that a satisfactory scattering field result, from a engineering standpoint, can be obtained with $\bar{M}$=0 (no ordinary rays, only the agglomeration rays) or $\bar{M}$=1 (one ordinary ray, and the agglomeration rays).

IV. Total Reflection and Critical Reflection of Complex Rays[12–14]

When the complex ray field with Gaussian wave front is incident from a optically less dense medium to an optically more dense medium and if on the interface (see figure 5, $\varepsilon_1 > \varepsilon_2$), the incident angle θ is less than the total reflection critical angle $\theta_c = \sin^{-1}\sqrt{\varepsilon_2/\varepsilon_1}$, then there exists only the geometrical optical reflection field $\tilde{E}_g$, which is the contribution from the complex ray field to the independent saddle point and is expressed in terms of the integration of the plane wave spectrum $\tilde{E}_S$

$$\tilde{E}_g = \tilde{E}_s = -\frac{\omega\mu_0}{\sqrt{j8\pi k_1 \tilde{s}_r}} \tilde{R}(\tilde{\xi}) e^{jk_1 \tilde{s}_r} \tag{12}$$

where

$$\tilde{s}_r = \sqrt{(y-\tilde{y}_0)^2 + (z+z_0)^2}, \mathrm{Re}(\tilde{s}_r) \geq 0 \tag{13}$$

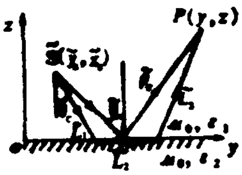


Figure 5: Total reflection and lateral waves of complex rays

When the incident angle is greater than the critical angle, the total reflection field of the complex ray should include both the contributions to the independent saddle point $\tilde{E}_s$ and to the independent supporting point $\tilde{E}_b$ [12-14] from the geometrical optical field $\tilde{E}_g$ and the complex lateral wave field $\tilde{E}_l$; namely

$$\tilde{E} = \tilde{E}_g + \tilde{E}_l = \tilde{E}_s + \tilde{E}_b \tag{14}$$

where

$$\tilde{E}_l = \tilde{E}_b = -\frac{\omega\mu_0}{\sqrt{2\pi}}\,tg^2\theta_c \cdot \frac{e^{j[k_1(\tilde{L}_1+\tilde{L}_3)+k_2\tilde{L}_2]}}{(jk_2\tilde{L}_2)^{3/2}} \tag{15}$$

where $\tilde{L}_1$, $\tilde{L}_2$, and $\tilde{L}_3$ denote the transmission paths of the lateral waves as shown in figure 5. Obviously, when $\tilde{\theta} \to \theta_c$, $\tilde{L}_2 \to 0$ and equation (15) gives the quantitative results of the spreading field and there exists a transition region of the complex ray reflection field. In order to make the singularity of the transition field smooth, a uniform equation which includes the transitional function should be used. In other words, the asymptotic contribution when the saddle point is close to the supporting point should be expressed as [12-14]

$$\tilde{E} = \tilde{E}'_g + \tilde{E}_t \tag{16}$$

where $\tilde{E}'_g$ is given by equation (12) with $\tilde{R}(\tilde{\theta})=1$, $\tilde{E}_t$ is the field of the transitional region

$$\tilde{E}_t = -\frac{\omega\mu_0}{\sqrt{j8\pi}} \frac{e^{jk_1\tilde{\rho}_1[\cos(\tilde{\theta}-\theta_c)+\ldots]}}{\sin\theta_c\cos^2\theta_c(-i2k_1\tilde{\rho}_1\tilde{\gamma})^{3/4}} D_{1/2}(\tilde{z}) \tag{17}$$

where

$$\tilde{\rho} = \frac{\sin(\theta_c - \tilde{\theta})}{\sin 2\theta_c} \tag{18}$$

$$\tilde{\gamma} = -\frac{1}{8}\left(\frac{\cos\tilde{\vartheta}}{\cos^3\theta_c} + \frac{\sin\tilde{\vartheta}}{\sin^3\theta_c}\right) \tag{19}$$

$$\tilde{x} = j\sqrt{j2k_1\tilde{\rho}_r\tilde{\gamma}}\,\frac{\tilde{\beta}}{2\tilde{\gamma}} \tag{20}$$

where $D_{1/2}(\tilde{x})$ is the 1/2 order parabolic column function of the complex parameter $\tilde{x}$. The range of the transitional region is determined by the magnitude of the complex parameter. Therefore, the parameter $\tilde{x}$ can be defined as the "numerical distance" of x and the numerical results show that x=2 is a criterion for the judgement:[12,13] when x>2 then the general equation (14) can be used and when x<2 then the uniform equation (16) should be used.

Besides the total reflection transitional region, singularities of the complex ray field also exist in the reflection interface, the shadow interface, the focus line, and the focus point regions. When this is the case, an appropriate special function should be used for the smoothing-calibration of the transitional function propagating field as described above.

V. Diffraction of Complex Rays[15]

Diffraction of complex rays occurs at the edge, tip, or smooth convex surfaces of the structure. Figure 6 shows a Gaussian wave incident upon an ideally conducting half-plane structure. If the complex source point field is used to express the Gaussian wave and if the extension of the applicability of the theoretical equations of geometrical diffraction of

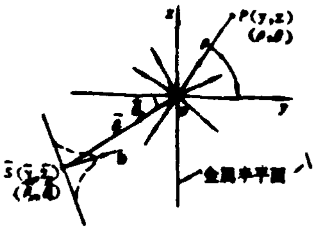


Figure 6: Edge diffraction of complex rays

key: 1 - metallic half plane

linear source to the complex space is made, then the complex ray diffraction field can be obtained.

$$\tilde{E}_d = \tilde{E}_i \tilde{D}(\theta, \tilde{\theta}_0) \frac{e^{jk_0\rho}}{\sqrt{\rho}}$$
$$= -\frac{\omega\mu_0}{\sqrt{j8\pi k_0 \tilde{\rho}_0 \rho}} \tilde{D}(\theta, \tilde{\theta}_0) e^{jk_0(\tilde{\rho}_0+\rho)} \tag{21}$$

where $\tilde{\theta}_0$ is the complex incident angle at the edge of the half plane, θ is the diffraction angle at the observation point, and $\tilde{D}(\theta,\tilde{\theta}_0)$ is the complex diffraction coefficient

$$\tilde{D}(\theta, \tilde{\theta}_0) = -\frac{1}{\sqrt{j2\pi k_0}} \frac{\sqrt{1-\sin\theta}\sqrt{1-\sin\tilde{\theta}_0}}{\sin\tilde{\theta}_0 - \sin\theta} \tag{22}$$

Obviously, if the observation point is located within the transitional region of the reflection interface or the shadow interface ($\tilde{\theta}_0 \to \theta$), then the above equation loses its applicability. When this is the case, then in the wave spectrum integration formula, the saddle point is very close to the supporting point and the simple geometrical diffraction theory can not be applied and the uniform diffraction theory and related equations should be used for the analysis of the complex space.

The complex ray theory has been used in the analysis of various diffraction problems involving waves such as the curved-edge diffraction of the antenna of reflectors.[15]

VI. Expansion of Complex Rays and Superposition of Complex Source Points[16-19]

Based on the principles of complex ray theory, we can extend the Wilkings-Feiner's principle and its Gilhoff mathematical expression to the complex space[16,17] and develop a new wave expansion method.

Considering the two-dimensional structure shown in figure 7 and assuming $z=z'$ denotes the Wilkings plane, then the wave source distribution function on this plane $f(y')$ is

$$f(y') = A(y')e^{ik_0\phi(y')}, \quad -\infty < y' < \infty \tag{23}$$

The field at observation point P can be expressed by the Gilhoff equation if the integration expression of the source distribution is known

$$E = -\frac{i}{4}\int_{-\infty}^{\infty} H_0^{(1)}(k\rho) f(y') dy' \tag{24}$$

where

$$\rho = \sqrt{(y-y')^2 + (z-z')^2} \tag{25}$$

Obviously, $f(y')$ is the weighted function of the source distribution. After Fourier transformation, equation (24) can be expressed in terms of the integration of plane wave spectrum

$$E = \frac{i}{2}\int_{-\infty}^{\infty} \frac{F(\eta)}{\sqrt{1-\eta^2}} e^{ik(\eta y + \sqrt{1-\eta^2}\, z)} d\eta \tag{26}$$

where $F(\eta)$ is the plane wave spectrum function corresponding to the field distribution $f(y')$.

If the Wilkings plane is extended to the complex space or if the sub-wave source is extended to the complex Wilkings source, then from (24) one can obtain

$$E = -\frac{i}{4}\int_{-\infty}^{\infty} H_0^{(1)}(k\tilde{\rho}) \tilde{W}(y') dy' \tag{27}$$

where $\tilde{\rho}$ is given by equation (3), $\tilde{W}(y')$ denotes the weighted function of the superposition of complex source fields (sometimes called the expansion coefficient of complex ray). Since complex source field is a Gaussian-type

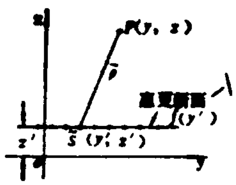


Figure 7: Expansion of complex rav

key: 1 - Wilkings plane

wave field with fixed direction and the energy is concentrated around the axis of the wave front, the integration limits in equation (27) can be reduced from $(-\infty, \infty)$ to a smaller range (y_1', y_2'). Also the discrete complex source field can be used to replace the continuous integration in equation (27) and, therefore, simplify the numerical process. Furthermore, from the complex expansion of the sub-wave sources, the characteristics of the field transitional region can be changed,[12,13] and the solution of the transitional field region can be accomplished through the choice of appropriate parameters and the direct application of the superposition of complex source fields and the singularities of the field can be made smooth without the introduction of complicated transitional functions.[18]

In order to apply the complex ray expansion equation (27), the weighted function $\widetilde{W}(y')$ must first be solved and then the appropriate free parameter for expansion should be chosen. These parameters are the ones such as Wilkings plane position z', modulus and direction of wave vector b, expansion range (y_1', y_2'), discrete source distance $\Delta y'$, and computer threshold value a_o. There have been detailed discussion on the complex ray expansion of cylindrical waves,[17,19] and the results have been applied to the reflection at plane interfaces.[18]

When $b \to 0$, the complex source field transforms to the real source field, and the expansion of complex rays transforms to the general Wilkings principle, when $b \to \infty$, the complex source field transforms to the plane wave radiation and the integration of complex source field transforms to the integration of plane wave spectrum. Hence, it can be shown that the expansion of complex source points is a more general form of wave field expansion than the source distribution integration and plane wave spectrum integration. The latter two cases can be viewed as the special cases of the first case.

7. Complex Ray Analysis of Radar Cross Section [20-22]

Based on the theoretical definition of target radar cross section (RCS)

$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{|E_s|^2}{|E_i|^2} \qquad (28)$$

one can see that the calculation of the radar cross section can be regarded as the calculation of the scattering wave amplitude at the receipt point $|E_s|$ if the incident wave amplitude $|E_i|$ is given. Therefore, in principle, all the methods used to analyze scattering of electromagnetic field can be used in the calculation of radar cross section. Since the Gaussian wave of the complex source is a very good simulation of the major wave packet of the radar antenna, the complex ray theory can be used to obtain the scattering field at the target and the single-station or double-station radar cross sections.

Figure 8 shows the calculational results of the cross section of an intermediate medium single-station radar cross section. [20] Except for the complex ray reflection and refraction on the surface of the medium, diffraction occurs at the edge of the rounded plate and the contribution from the diffraction should be included in the calculation if the diameter of the rounded plate is not large. In figure 8, the solid line is the integration results based on physical optics and dotted line is the calculational results based on complex ray theory. The distance of the observation point is taken as $R=10^{12}\lambda$. From this figure, we can see that when the incident angle is less than 50°, within the range of the major

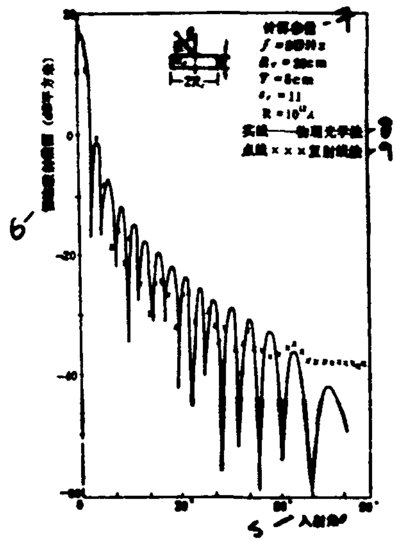


Figure 8: The medium circular plate single-station RCS calculational results

key: 5 - incident angle

6 - Radar cross section (db square meter)

7 - parameters used in calculation

8 - solid line — physical optics method

9 - points — x x x complex ray method

petal and the near petal, the difference in the results based on these two methods is less than 3db.

For the large-diameter concave cavity structure such as the gas inlet and outlet duct, if the radar cross section is calculated based on the traditional geometrical optics methods, then it is required to form a set of incident rays on the diameter surface and the distance between these rays should be less than 0.2λ. Obviously, a lot of computer time would be necessary to analyze the reflection of a few tens even hundreds of geometrical rays. If the analysis is conducted in the guided-wave fashion, then since the dimension of the wave guide is far greater than that of the radar waves, the expansion and analysis of a few hundreds high order modes is still not easy. If the complex ray theory is used in expansion and near-axis approximation is used in simplification of the problem, then tracing of a few reflection paths of the complex rays will be sufficient to establish the field distribution on the lip surface of gas inlet duct or the field strength at the reception point can be determined and then the radar cross section of the target can be calculated. The RCS analytical results of a curved gas inlet duct has been completed.[21] The results based on complex ray expansion were compared with those based on other methods.

The radar cross section of antenna and antenna cap can also be calculated by the complex ray theory.[22] The structures of antenna and antenna cap with low RCS can be optimized in this way.

VIII. Concluding Remarks

The complex ray theory has been proved to be an efficient way of analysis of high frequency field scattering. This paper discusses the application of this theory under the conditions of uniform and layered medium. These are just some simple conditions. However, its application is not limited by these conditions. In the non-uniform, dissipated, or directionally-conducting media, the complex ray theory still has very important applications. Using the complex ray theory, not only can the radar cross sections of the metallic parts such as the body and wings of the vehicle be calculated, the reflection and transmission of the radar cap and cabin hoods can also be analyzed. Not only can the scattering contribution due to the key scattering parts such as antenna and gas inlet duct be calculated, but also the effect of RCS reduction after application of wave-absorbing materials can be analyzed. So far, this topic has been under intensive study worldwide and, in some areas, significant accomplishments have been made.

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