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相控阵雷达天线的优化设计与研究

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[摘 要] 高时空分辨率和快速扫描速度是相控阵天气雷达的特点。它能为预报员提供覆盖整个区域的三维流场信息,并能快速响应,更有利于中小规模恶劣天气过程的观测。弧形阵列天线具有独特的空间结构和波束形成方法,可以在更大程度上获得距离和方位方向的空间频谱宽度。扫描速度和旁瓣性能是雷达系统的重要指标。本文在改变径向孔径辐射函数的基础上,通过频率扫描模式,采用不等功分器方案,通过混合加权法获得低旁瓣。计算机仿真验证了该方法的可行性和有效性。
[关键词] 弧形阵列天线；频率扫描；低旁瓣；混合加权法
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Optimization Design and Research of Phased Array Radar Antennas

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[Abstract] high spatial-temporal resolution and fast scanning speed are the characteristics of phased array weather radar. It can provide forecasters with three-dimensional flow field information covering the whole area, and can respond quickly, which is more conducive to the observation of small and medium-sized severe weather processes. The arc array antenna has a unique spatial structure and beam forming method, which can obtain the spatial spectrum width in the range and azimuth directions to a greater extent. Scanning speed and sidelobe performance are important indexes of radar system. On the basis of changing radial aperture radiation function, low sidelobe is obtained by frequency scanning mode, unequal power divider scheme and hybrid weighting method. Computer simulation proves the feasibility and effectiveness of this method.
[Key words] arc array antenna; Frequency scanning; Low side lobe; Mixed weighting method

引言

相控阵天线的波束优化问题一直以来都是研究人员关注的重点问题[1]。扫描过程中波束的质量影响着系统探测的准确性,最关键的就是方向图的旁瓣问题[2-3]。Arc array antenna has the characteristics of being able to select the exciting array element flexibly according to the desired beam direction, which is more convenient to complete the 360° space beam scanning[3].In addition, it has the advantage of using beam-forming technology to realize low side-lobe, beam scanning and multi-beam forming[4-7].

旁瓣会对主瓣接收的信息产生干扰而降低信噪比,如果在扫描过程中不对旁瓣进行抑制也就无法准确定位目标位置.Especially for the arc antenna array with large Angle scanning, it has a low side lobe scanning beam, so as to ensure the accuracy of the radar system in locating and tracking the detected target,as well as its own concealment.

在很多情况下,为了提高角分辨率,需要牺牲一些天线增益来换取窄波束,而天线主瓣的宽度主要与阵列天线孔径的大小有关.So as to keep the aperture size of the arc array antenna un-changed, the width of the main lobe of antenna is not affected, but a lower antenna side-lobe level can be obtained, the reasonable allocation and selection can be realized by the combination weighting method of

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amplitude and phase weighting to the array excitation size and phase configuration.

相控阵天线的阵列向分辨率不随波束范围增大而降低有较好的一致性,有利于观测平台周围成像观测分辨率保持相对稳定。阵列天线的副瓣性能是雷达系统的一个重要指标,为了获得低副瓣特性,必须充分考虑馈线网络的复杂性和天线阵元间的互耦影响。

本文研究了弧形阵列天线方位波束扫描的实现方法。根据信号频率的变化,铁电材料的介电常数是不同的。采用频率扫描法实现方位小角波束的灵活扫描。本文所述的低副瓣弧形天线阵的幅相加权方法可以通过馈电网络的结构设计,为阵列中的每个单元形成合理的功率分布。通过对阵列元素进行混合幅度和相位加权,获得低旁瓣辐射方向图。

1 理论分析

1.1辐射模式

由如图1几何关系所示,阵列天线的第i号阵元与第0号阵元间的圆心角大小可以表示为：

$$\varphi_i = \frac{\phi \cdot 2\pi i}{360M} \quad (i = 0,1,2,\cdots,M-1) \tag{1}$$

M is the total number of the arc array antenna elements, ϕ represents the aperture Angle of the arc array antenna is the Angle of the circular center corresponding to the array along the arc direction.

第号阵元的位置坐标向量表示为：

$$\mathbf{P_i} = \left(x_i, y_i, z_i\right) = \left(R\cos\varphi_i, R\sin\varphi_i, 0\right) \tag{2}$$

R is the arc radius of arc array antenna.

目标方向为$\left(\gamma,\theta\right)$,波达方向矢量可以表示为：

$$\mathbf{r} = \left(\sin\theta\cos\gamma, \sin\theta\sin\gamma, \cos\theta\right) \tag{3}$$

第i号阵元的空间相位差可由点积法得：

$$\psi_i = \frac{2\pi}{\lambda}\mathbf{r}\cdot\mathbf{P_i} = \frac{2\pi}{\lambda}R\sin\theta\cos(\gamma-\varphi_i) \tag{4}$$

当阵列主波束最大值指向$\left(\gamma_0,\theta_0\right)$时,第$i$号阵元相位差可表示为：

$$\alpha_i = -\frac{2\pi}{\lambda}R\sin\theta_0\cos(\gamma_0-\varphi_i) \tag{5}$$

Arc antenna array directional graph function can be expressed as:

$$F\left(\varphi,\gamma_0\right) = \sum_{i=0}^{M-1} A_i \exp\left\{jkR\left[\cos\left(\gamma_0-\varphi_i\right)-\cos\left(\gamma-\varphi_i\right)\right]\right\} \tag{6}$$

A_i is the No. i element weight amplitude, $k = 2\pi/\lambda$, λ is the wavelength of the signal.

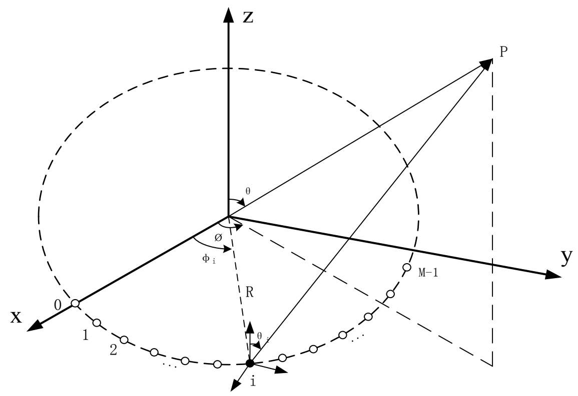

Figure 1 Schematic Diagram of Radiation Model of Arc Array Antennas

1.2频率扫描

According to the electromagnetic field theory, the electromagnetic field in the rectangular waveguide system changes according to the law of $e^{-\gamma z}$, and the dispersion equation can be expressed as:

$$K_c^2 = K^2 + \gamma^2 \tag{7}$$

上式中,K_c为截止波数,K为工作波数,γ为传播常数；

$$K_c = 2\pi f_c\sqrt{\mu\varepsilon} \tag{8}$$

$$K = 2\pi f\sqrt{\mu\varepsilon} \tag{9}$$

$$\gamma = \alpha + j\beta \tag{10}$$

上式中,f_c为截止频率、f为工作频率、μ为磁导率、ε为介电常数、α为衰减常数、β为相移常数；

The propagation constant in the further rectangular waveguide can be expressed as:

$$\gamma = j2\pi f\sqrt{\mu\varepsilon}\cdot\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2} \tag{11}$$

上式中,λ_c为截止波长,λ为工作波长；

The characteristic impedance of TE and TEM waves in the rectangular waveguide can be expressed as:

$$Z = \frac{j\omega\mu}{\gamma} \tag{12}$$

The relative dielectric constant of ferroelectric

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materials can be obtained by using the propagation constant and normalized characteristic impedance, which can be expressed as:

$$\varepsilon_r(\gamma,\overline{Z}_c)=\left(\frac{\lambda_0}{\lambda_c}\right)^2-j\frac{\lambda_0}{2\pi}\cdot\frac{\gamma}{\overline{Z}_c}\cdot\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2} \tag{13}$$

λ_0 为自由空间波长，λ_c 为波导中截止波长，γ 为归一化传播常数，$\overline{Z}_c$ 为归一化特征阻抗。

By the ferroelectric material is filled in the rectangular waveguide to realize omnidirectional beam scanning by frequency scanning. The frequency scanning model is shown in Figure 3.

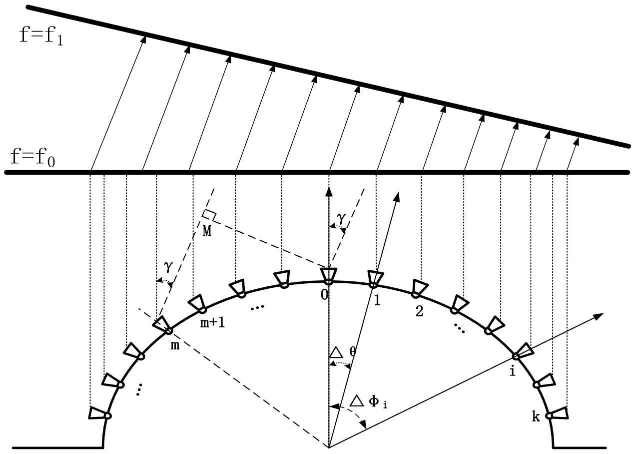

Figure 3 Schematic Diagram of Frequency Scanning

1.3振幅加权

$S(f)$ 为信号 $s(t)$ 的频谱，$H(f)$ 表示滤波器的频率响应特性，滤波器输出端的频谱为：

$$S_0(f)=S(f)H(f) \tag{14}$$

通过在滤波器中施加一个加权网络，从而用附加幅度和相位失真的方法来降低滤波器输出信号波形的副瓣，可以表示为：

$$W(f)=A(f)e^{-j\phi(f)} \tag{15}$$

$A(f)$ 为加权网络幅频特性，$\phi(f)$ 为加权网络相频特性。

The spectrum of the output signal of the filter can be expressed as:

$$S_w(f)=S_0(f)W(f)=S(f)H(f)W(f) \tag{16}$$

The output waveform of the filter can be expressed as:

$$S_w(t)=\int_{-\infty}^{\infty}S_0(f)W(f)e^{j2\pi ft}df \tag{17}$$

The schematic diagram of the amplitude-phase mixed weighting process of arc array antenna is shown in Figure 4.

发射天线的幅度加权过程，首先进行发射信号功率分配是通过不等功分网络，在每一个发射天线阵元通道上设置发射信号功率放大器，通过调整放大器输出电平来完成。根据天线可逆原理，由于采用收发共用天线，发射天线幅度加权实现方法同样适用于接收天线。另外，通过在接收天线每一个阵元通道上设置低噪声放大器，从而各个阵元接收到的信号先经过低噪声放大器，再经由移相器和衰减器进行功率相加。

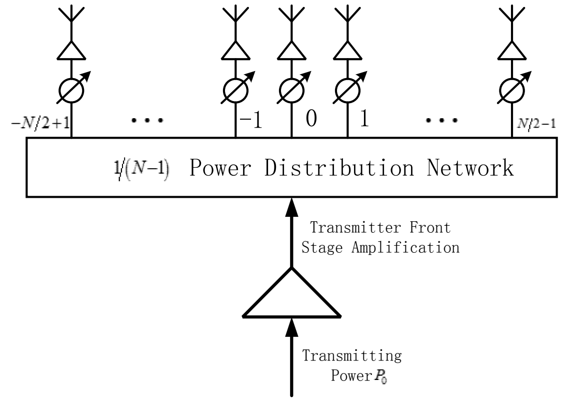

Figure 4 Schematic Diagram of Amplitude-Phase Mixed Weighting Process

加权方法中有效辐射阵元馈电网络部分采用的是不等功率分配方案，通过不等分功分器将发射信号输入功率按一定比例分配给各个辐射阵元。

The impedance of the input port of the unequal power work divider is, Z_0 and the characteristic impedance value of the output port $\lambda/4$ branch line can be expressed as:

$$Z_{out1}=Z_0\sqrt{K\left(1+K^2\right)} \tag{18}$$

$$Z_{out2}=Z_0\frac{1}{K}\sqrt{K+\frac{1}{K}} \tag{19}$$

上式中 K 为输出端口功率分配比例，P_0 功分器输入端口的输入功率，P_{out1} 和 P_{out2} 为输出端口的输出功率，满足关系如下：

$$P_{out2}=K^2P_{out1} \tag{20}$$

It is necessary add isolation resistance near the load end on the branch line to meet the isolation degree of output port, the resistance value can be expressed as:

$$R=Z_0\left(K+1/K\right) \tag{21}$$

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1.4相位加权

在目标方向上相控阵天线相位加权可以通过频率扫描方式来实现,在天线系统常规波束扫描控制信号基础上添加相位加权控制信号给阵列中的有效辐射阵元,从而改变其阵元激励电流的相位,可在幅度加权的基础上进一步降低天线波束的副瓣电平,因此为降低天线副瓣提供了更大的灵活性。

The spatial phase difference between antenna array elements in the desired target direction γ can be expressed as:

$$\Delta\varphi = \frac{360}{\phi}\cdot\frac{Md_c}{\lambda}\left[\sin\theta_i\sin\gamma + (1-\cos\theta_i)\cos\gamma\right] \qquad (22)$$

ϕ 为天线的孔径角, M 为阵元总数, d_c 为阵列上阵元间的圆弧向间距, λ 为信号波长, θ_i 为第个阵元对应的圆周角, γ 为目标期望方向。

The phase difference within the array between arc array antenna elements can be expressed as:

$$\Delta\varphi_B = \frac{2\pi l}{\lambda}\cdot\sqrt{1-(\lambda/2a)^2} \qquad (23)$$

l 为阵列天线两个阵元之间传输波导长度, a 为波导的宽边尺寸。

The phase relation of phase weighting by frequency scanning can be expressed as:

$$\frac{360}{\phi}\cdot\frac{Md_c}{\lambda}[\sin\theta_i\sin\gamma+(1-\cos\theta_i)\cos\gamma] = \frac{2\pi l}{\lambda}\cdot\sqrt{1-(\lambda/2a)^2} - 2\pi M \qquad (24)$$

$$\gamma = \arcsin\left[\frac{\pi\phi\cdot\sqrt{1-(\lambda/2a)^2}}{360Md_c}\cdot\frac{1}{\sin(\theta_i/2)}\cdot\left(l-\frac{M\lambda}{\sqrt{1-(\lambda/2a)^2}}\right)\right]-\frac{\theta_i}{2} \qquad (25)$$

As shown in equation (25),changing the signal frequency $f(f=c/\lambda)$ could control beam direction of the arc array antenna to γ ,so as to realize the phase weighting.

阵元相位调制情况较复杂,靠近阵列波束指向方向位置的数值较小,甚至可能进行0相位调制,由于阵列波束指向方向往阵列方位向两侧边缘延伸,因而大数值相位调制的阵元会逐渐增加,甚至会出现现场强抵消,等同于成为无效阵元的情形。

Phase of the antenna array is modulated by changing the signal frequency. Phase change of array element is superimposed on phase shift determined by antenna beam direction. The direction of beam is still determined by control signal of phase shifter but the phase weighted control signal caused by the change of signal frequency is added to wave control signal.

2 结论

随着科学技术的进步,现代雷达需要对目标进行探测、跟踪、识别、目标特征分析等技术要求越来越高。追求更高的增益、更强的方向性、更窄的波束宽度成为研究的热点。相控阵天线具有能够根据期望波束指向灵活选择激励阵元,比较方便完成全方位空间扫描波束形成等特点,还可以通过波束形成技术实现低副瓣、波束扫描、多波束形成的优势,能够通过对阵列中的阵元方向图进行叠加、选取阵元个数、阵元位置、幅相权值调整等方法来对有用信号进行针对性接收,对干扰信号有效抑制,提高信噪比,获得符合期望特征的方向图综合等研究前景。

相控阵雷达在气象探测方面有其独特的优势。天线是雷达系统的重要组成部分。基于频率扫描模式和混合加权模式的相控阵雷达优化设计和研究具有重要意义。在弧形阵列天线的辐射方向图中,在幅相混合加权后,旁瓣分布不会像在均匀激励下那样呈现出规则的衰减趋势,这主要是由于混合加权单元的激励分布具有不确定的非周期特性,等间距角分布单元的渐进相位不是固定常数。因此,在混合加权后元件在主瓣外相互抵消的子瓣区域,不可能保持均匀激励的规则分布特性。事实上,为了保持主瓣附近的旁瓣电平不变,混合加权是以主瓣附近低电平为代价提高远旁瓣电平并降低天线增益。

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