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Near-Field Antenna Measurements

Calculations and Facility Design

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ISSN 1869-1730 ISSN 1869-1749 (electronic)
Springer Aerospace Technology
ISBN 978-981-33-6435-6 ISBN 978-981-33-6436-3 (eBook)
https://doi.org/10.1007/978-981-33-6436-3

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Questions of determination of antenna parameters on the basis of measurement results of field amplitude–phase distribution on scanning surface in the near field of these antennas are reviewed. The study contains electrodynamic basis of near-field measurements and ready to use formulas to determine antenna parameters, based on measurement of amplitude–phase field distribution on flat and spherical scanning surfaces. Recommendations on how to write fast and efficient MATLAB (Octave) code, enabling to implement these formulas, are given. Measurement error estimation is carried out. The description of purpose designed facilities for measurement of amplitude–phase distribution of the field on flat scanning surfaces in the near-field zone of the studied antennas is given. The questions related to laboratory and flight tests of antennas are considered.

The book is intended for engineers and highly qualified specialists, whose activities are related to experimental testing of radio characteristics of complex antenna systems, and can also be used as a textbook for senior students in the field of "radioelectronics" and "radiophysics".

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2019

Introduction

Development of information technologies and mathematical modeling methods enabled scientists and specialists to use the obtained results to expand the discipline related to evaluation of antenna characteristics, based on measurements in the near field. Development of antennas for ground-based, ship-based, space-based, and airborne radio-electronic systems is a complex and expensive process. Testing of antenna parameters in the course of their development takes a long time. Developers have to constantly evaluate these parameters, when changing the antenna design due to the need to take into account the impact of carrier object elements and external destabilizing effects on these parameters. Implementation of the technologies related to antenna parameter evaluation on the basis of characteristics, measured in the near field, in practical activities of R&D centers and industrial enterprises not only increases the competitiveness of developed antenna products, but also allows to win new international markets. Using the near-field facility, professionals are given the opportunity to practically assess the impact of carrier object elements on alteration of antenna characteristics, thus allowing not only to consider the diffraction problems, but also to establish on-board antenna parameters, taking into account provision of stable radio communication link.

The monograph is based on the results of the authors' research activities in the course of development of antennas and antenna systems for a wide range of carrier objects (aircraft, mobile ground systems, etc.). One of the essential features of this monograph is that the proposed presentation of the issues is focused on both scientists and designers of radio engineering systems. The monograph includes an introduction, list of symbols and abbreviations, and six chapters. Reference literature is given at the end of each chapter.

Chapter 1 is dedicated to the definition and classification of main radio characteristics of antennas.

Chapter 2 provides a brief overview of methods of radio characteristic measurement of antennas.

Chapter 3 is dedicated to antenna characteristic calculation on the basis of measurement results of field amplitude–phase distribution on plane scanning surface.

Chapter 4 is dedicated to the study of characteristics of the planar near-field facility.

Chapter 5 is dedicated to the calculation of antenna characteristics on the basis of measurement of amplitude–phase field distribution on spherical scanning surface.

Chapter 6 is dedicated to mechanical, climatic, and flight antenna testing.

The monograph was developed by the team of contributors, consisting of:

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This monograph will be useful for radio specialists and for radiophysicists, whose activities are associated with antenna development.

Contents

Symbols and Abbreviations

AUT	Antenna under test
D	Directivity
DFT	Discrete Fourier transform
EM	Electromagnetic
FFT	Fast Fourier transform
G	Gain
G_R	Gain realized
Γ	Complex reflection coefficient
LAN	Local area network
L_{RET}	Return loss
PWS	Planar wave spectrum
RF	Radio frequency
RP	Radiation pattern
3D RP	Three-dimensional radiation pattern
UHF	Ultrahigh frequency
VSWR	Voltage standing wave ratio
η	Efficiency
Z_A	Complex antenna impedance

Chapter 1
Radio Characteristics of Antennas

1.1 The Role of Antennas in Radio Systems

Any radio line designed to transmit information or energy through free space contains transmitting and receiving antennas.

A simplified block diagram of such a radio line is shown in Fig. 1.1. It consists of a transmitter (1), a transmitting antenna (3), a transmission line segment connecting the output of the transmitter to the input of the transmitting antenna (2), a free space in which electromagnetic waves propagate (4), a receiving antenna (5), a receiver (7), and a transmission line segment connecting the output of the receiving antenna to the input of the receiver (6).

The main tasks solved by transmitting antennas are the following:

(1) conversion of the energy of high-frequency currents excited by the transmitter at the antenna input into the energy of electromagnetic waves emitted by the antenna into free space;
(2) energy beaming by excited electromagnetic waves, i.e., ensuring the required dependence of the power flux density of these waves on the direction in which they leave the antenna.

The main tasks solved by receiving antennas are the following:

(1) conversion of the energy of electromagnetic waves incident on the antenna into the energy of high-frequency currents excited by these waves at the antenna output;
(2) directed reception of energy of electromagnetic waves incident on the antenna, i.e., ensuring the required dependence of the electromotive force induced at the output terminals of the antenna on the direction from which these waves incident on it.

Summarizing the above, one can say that the antennas match the transmitter and receiver with the free space and perform directed transmission and directed reception of energy carried by electromagnetic waves.

V. S. Kalashnikov et al., *Near-Field Antenna Measurements*, Springer Aerospace Technology, https://doi.org/10.1007/978-981-33-6436-3_1

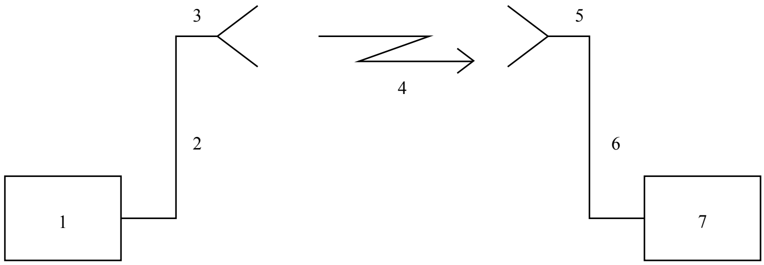

Fig. 1.1 Block diagram of the radio line

Transmitting and receiving antennas increase the efficiency of the radio line, allowing for a fixed transmitter power and a fixed receiver sensitivity to adjust the maximum range of its stable operation.

The quality of the transmitting and receiving antennas is assessed by a number of quantitative characteristics that can be calculated and measured. These characteristics are called “radio antenna characteristics,” or simply “antenna parameters.”

The introduction of these parameters, for which the calculation formulas and measurement methods are defined, provides a compact form for the presentation of a technical task for the development of antennas and a justified selection of antenna types intended to solve specific technical problems.

Antenna parameters associated with the energy of high-frequency currents excited in the antenna by the transmitter (when operating in the transmitting mode) or incident electromagnetic waves (when operating in the receiving mode) are called internal antenna parameters.

The antenna parameters associated with the energy of emitted (when operating in the transmitting mode) or received (when operating in the receiving mode) electromagnetic waves are called external antenna parameters.

1.2 The Structure of Electromagnetic Fields Excited by the Antenna

1.2.1 Types of Variable Electromagnetic Fields Excited by the Antenna in the Surrounding Space

The antenna excites two types of variable electromagnetic fields in the surrounding space, propagating and non-propagating ones.

Propagating variable electromagnetic fields take energy from the antenna and irrevocably carry it into the surrounding space. The period average value of the power flux density carried by these fields is always greater than zero. These fields are called radiation fields or electromagnetic waves.

Non-propagating alternating electric and magnetic fields are concentrated near the antenna and only exchange energy with each other and with the antenna. The average value of the power flux density carried by these fields over a period is always zero. These fields are called reactive fields or induction fields.

The main parameters of an electromagnetic (EM) field are strength, intensity, power, phase, polarization, and frequency. Let us recall these parameters [1–3].

EM field strength is a value that characterizes the amplitude of the vector of the electric or magnetic component of the EM field at a certain point in space.

EM field intensity is the square of the EM field strength.

EM field power is the amount of energy of the EM field that passed through some surface per unit of time.

The power flux density of the EM field is the power of the EM field that passed through a unit area in the direction perpendicular to this area.

The phase of an EM field is the angle of the phase shift between the oscillations of the EM field at a given point and at a conventional point of origin at the same time.

Wavefront (phase front) is the surface of equal phases of the electromagnetic field.

The polarization of the EM field is a characteristic of the EM field that determines the behavior of the electric field intensity vector in the transverse plane (perpendicular to the direction of propagation of the EM field) for a period of time equal to the period of oscillations.

The frequency of EM field is the frequency of oscillations of its electric or magnetic component.

1.2.2 Near-Field and Far-Field Regions of the Antenna

Depending on the structure of the electromagnetic field excited by the antenna, the space in which it exists can be divided into several regions (zones). Let us examine the location of these zones by the example of an aperture antenna focused at infinity.

Adjacent to the antenna surface is the near-field region of the antenna, which is divided into two sub-regions: the reactive near-field region and the radiative near-field region.

The area directly adjacent to the antenna surface is the reactive near-field region, in which the strength of these fields significantly exceeds the strength of the radiation fields. However, due to their physical nature, their intensity decreases inversely proportional to the second or even third degree of distance from the antenna surface (depending on the type of antenna). At the same time, the intensity of the radiation fields in this region is almost independent of the distance to the antenna surface. The conventional outer boundary of the zone of reactive fields, after which they can practically be neglected in comparison with radiation fields, is at a distance λ/π from the antenna surface.

The first part of the radiative near-field region, the aperture zone, begins from the reactive near-field region and extends to a distance of approximately $0.62 \cdot D \cdot (D/\lambda)^{0.5}$

(where D is the maximum linear size of the antenna and λ is its operating wavelength). In this area, the reactive fields are negligible, the front of the propagating electromagnetic wave is quasi-plane (almost non-divergent projecting ray), the field strength is almost independent of the distance to the antenna, and the distribution of the field amplitudes replicates the form of the distribution of amplitudes in the antenna aperture.

The second part of the radiative near-field region, the Fresnel region, is the area of space with conventional boundaries from $0.62 \cdot D(D/\lambda)^{0.5}$ to $2D^2/\lambda$. In the Fresnel region, the relative angular distribution of the field amplitude (radiation pattern) starts to form, but the shape of this distribution depends on the distance to the antenna. There are two reasons for this: first, the phase relationships between the fields from different antenna elements change with distance, and second, the ratio of field amplitudes from different antenna elements also changes with distance. As the observation point moves away from the antenna (along the radius), the amplitude of the field first oscillates and then decays steadily. In the infinite distance limit, this attenuation is inversely proportional to the first power of the distance. In addition, as the observation point moves further away, the relative phase and amplitude relationships between the fields from the individual antenna elements asymptotically approach fixed values, and the angular distribution of the field no longer depends on the distance. Although this position, strictly speaking, is achieved only when the observation point is moved to infinity, with certain assumptions, it is possible to find the outer boundary of the Fresnel zone. For most aperture antennas, this boundary is determined by the distance $2D^2/\lambda$.

The far-field region of the antenna extends from a distance of $2D^2/\lambda$ to infinity. In the far zone, the ratio of amplitudes and phases of the field from different parts of the antenna does not depend on the distance to the antenna and is determined only by the angular position of the observation point. When the observation point moves around a directional antenna, a stable interference pattern is observed, which is an alternation of maxima and minima of the field strength. This pattern is an amplitude radiation pattern (RP) of the antenna (see clause 1.4). The section of the RP between adjacent minima is called a lobe of the RP. Usually, a distinction is made between the main and the side lobes of the RP, and they are characterized by their maximum field value (absolute or relative) and angular width at a given level (usually at levels -3, -10 dB, or at the level of the minima that define the lobe; ideally, this level is $-\infty$ dB). The angular distribution of the field in the far region (the shape of the radiation pattern) does not depend on the distance to the antenna, the amplitude of the field descending proportionally to the first degree of the distance from the antenna, and the vectors $\boldsymbol{E}$ and $\boldsymbol{H}$ being mutually perpendicular and located in a transverse plane with respect to the direction of propagation. The phase front of the electromagnetic wave in the far region is spherical (within small space angles it is flat).

The internal parameters of the transmitting antennas are related to the reactive and radiated electromagnetic fields excited by the antenna.

The external parameters of the transmitting antennas are related only to the radiated electromagnetic fields (electromagnetic waves) excited by the antenna.

1.3 Internal Parameters of Transmitting Antennas

The internal parameters of the transmitting antenna characterize it as an energy consumer and assess the degree of matching of the antenna input with the transmission line connecting it to the transmitter (the antenna input is understood as the terminals to which the transmission line between the transmitter and the antenna is connected). The internal parameters of the transmitting antenna include the complex input impedance, the efficiency (η), the reflection coefficient (Γ), the standing wave ratio (VSWR), and return loss (L_{RET}).

1.3.1 The Balance of Active and Reactive Power in the Antenna

The active power coming from the transmitter to the antenna is partially reflected from its input and partially passes into the antenna. The active power that passes is partially spent on active losses in the antenna, and the remaining part is transferred to the electromagnetic waves excited by the antenna and radiated into the surrounding space.

Let us introduce the following notation:

P_{TRM} is the power from the transmitter arrived to the antenna input.
P_{REF} is the power reflected from antenna input.
P_{A} is the power accepted by the antenna.
P_{L} is the power of active losses caused by the flow of the conduction and displacement currents excited by the electromagnetic field of the antenna in the metal and dielectric elements of the antenna structure.
P_{R} is the power transferred by the antenna to the electromagnetic waves excited by it (radiated power).

A graphical representation of the active power balance at the input of the transmitting antenna is shown in Fig. 1.2.

The power of P_{TRM} is divided into P_{A} and P_{REF} ($P_{\mathrm{TRM}} = P_{\mathrm{A}} + P_{\mathrm{REF}}$).

The power of P_{A} is divided into P_{L} and P_{R} ($P_{\mathrm{A}} = P_{\mathrm{L}} + P_{\mathrm{R}}$), hence:

$$P_{\mathrm{TRM}} = P_{\mathrm{L}} + P_{\mathrm{REF}} + P_{\mathrm{R}} \tag{1.1}$$

The presence or absence of reactive power at the antenna input is related to the balance of energy stored by reactive electric and magnetic fields excited in the near zone of the antenna. Over time, these fields exchange energy, completing a full cycle of exchange in a period of time equal to the period of excited oscillations. If the maximum amount of energy that electric and magnetic reactive fields can store is not equal to each other, the source (transmitter) is also involved in the exchange of