

# RF MODULE

REFERENCE  
GUIDE

**VERSION 3.5 a**

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# C O N T E N T S

## Chapter 1: Introduction

Typographical Conventions . . . . .	2
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## Chapter 2: Application Mode Reference

<b>Application Mode Variables</b>	<b>6</b>
<b>Electromagnetic Waves</b>	<b>8</b>
Common Variables for the Application Modes . . . . .	8
Electromagnetic Waves (3D) . . . . .	14
In-Plane Waves Application Mode . . . . .	15
Electromagnetic Waves Application Modes (Axial Symmetry, 2D) . . . . .	17
Perpendicular Waves Application Modes(2D) . . . . .	20
Boundary Mode Analysis Application Modes (3D) . . . . .	23
Boundary Mode Analysis Application Modes (2D) . . . . .	26

## Chapter 3: Programming Reference

<b>The Programming Language</b>	<b>30</b>
The Application Structure . . . . .	30
<b>Application Mode Programming Reference</b>	<b>39</b>
3D Electromagnetic Waves . . . . .	40
In-Plane and Axisymmetric Waves . . . . .	46
Perpendicular Waves . . . . .	54
Boundary Mode Analysis . . . . .	57

## Chapter 4: Function Reference

<b>Summary of Commands</b>	<b>62</b>
<b>Commands Grouped by Function</b>	<b>63</b>
S-Parameter Computation . . . . .	63
File Exchange . . . . .	63
sparametermatrix . . . . .	64
spiceimport . . . . .	65
touchwrite . . . . .	66
<b>INDEX</b>	<b>67</b>

# Introduction

The RF Module 3.5a is an optional package that extends the COMSOL Multiphysics® modeling environment with customized user interfaces and functionality optimized for the analysis of electromagnetic waves.

This particular module solves problems in the general field of electromagnetic waves, such as RF and microwave applications, optics, and photonics. The application modes included here are fully multiphysics enabled, making it possible to couple them to any other physics application mode in COMSOL Multiphysics or the other modules. For example, to analyze stress-optical effects in a waveguide, you would first do a plane strain analysis using the Structural Mechanics Module followed by an optical mode analysis show the resulting split of the fundamental modes.

The underlying equations for electromagnetics are automatically available in all of the application modes—a feature unique to COMSOL Multiphysics. This also makes nonstandard modeling easily accessible.

The documentation set for the RF Module consists of the *RF Module User's Guide*, the *RF Module Model Library*, and the book you are reading, the *RF Module Reference Guide*. This book contains reference information such as application mode implementation details, information about command-line

programming, and details about the command-line functions that are specific to the RF Module (for example, a function for S-parameter extraction).

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**Note:** The full documentation set is available in electronic formats—PDF and HTML—through the COMSOL Help Desk after installation.

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### *Typographical Conventions*

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All COMSOL manuals use a set of consistent typographical conventions that should make it easy for you to follow the discussion, realize what you can expect to see on the screen, and know which data you must enter into various data-entry fields. In particular, you should be aware of these conventions:

- A **boldface** font of the shown size and style indicates that the given word(s) appear exactly that way on the COMSOL graphical user interface (for toolbar buttons in the corresponding tooltip). For instance, we often refer to the **Model Navigator**, which is the window that appears when you start a new modeling session in COMSOL; the corresponding window on the screen has the title **Model Navigator**. As another example, the instructions might say to click the **Multiphysics** button, and the boldface font indicates that you can expect to see a button with that exact label on the COMSOL user interface.
- The names of other items on the graphical user interface that do not have direct labels contain a leading uppercase letter. For instance, we often refer to the Draw toolbar; this vertical bar containing many icons appears on the left side of the user interface during geometry modeling. However, nowhere on the screen will you see the term “Draw” referring to this toolbar (if it were on the screen, we would print it in this manual as the **Draw** menu).
- The symbol **>** indicates a menu item or an item in a folder in the **Model Navigator**. For example, **Physics>Equation System>Subdomain Settings** is equivalent to: On the **Physics** menu, point to **Equation System** and then click **Subdomain Settings**. **COMSOL Multiphysics>Heat Transfer>Conduction** means: Open the **COMSOL Multiphysics** folder, open the **Heat Transfer** folder, and select **Conduction**.

- A **Code** (monospace) font indicates keyboard entries in the user interface. You might see an instruction such as “Type 1.25 in the **Current density** edit field.” The monospace font also indicates code.
- An *italic* font indicates the introduction of important terminology. Expect to find an explanation in the same paragraph or in the Glossary. The names of books in the COMSOL documentation set also appear using an italic font.





## Application Mode Reference

This chapter provides listings of the application mode variables that you have access to in the RF Module's application modes.

# Application Mode Variables

The application modes in the RF Module define a large set of variables. The purpose of this reference chapter is to list all the variables that each application mode define. Other information, like the theoretical background for the application mode, can be found in chapter “The Application Modes” on page 129 of the *RF Module User’s Guide*.

The *Application Mode Variables* section lists all variables that are available in postprocessing and when formulating the equations. You can use any function of these variables when postprocessing the result of the analysis. It is also possible to use these variables in the expressions for the physical properties in the equations.

The application mode variable tables are organized as follows:

- The **Name** column lists the names of the variables that you can use in the expressions in the equations or for postprocessing. The indices  $i$  and  $j$  (using an italic font) in the variable names can mean any of the spatial coordinates. For example,  $E_i$  means either  $E_x$ ,  $E_y$ ,  $E_z$  in 3D when the spatial coordinates are  $x$ ,  $y$ , and  $z$ . In 2D axisymmetry  $E_i$  stands for either  $E_r$  or  $E_z$ . The variable names of vector and tensor components are constructed using the names of the spatial coordinates. For example, if you use  $x1$ ,  $y1$ , and  $z1$  as the spatial coordinate names, the variables for the vector components of the electric field are  $E_{x1}$ ,  $E_{y1}$ , and  $E_{z1}$ .

In a COMSOL Multiphysics model, the variable names get an underscore plus the application mode name appended to the names listed in the tables. For example, the default name of the Electrostatics application mode is `emes`. With this name the variable for the  $x$  component of the electric field is `Ex_emes`.

- The **Analysis** column specifies for which type of analysis the variable is defined. The available analysis types are, for example, static, transient, harmonic, and eigenfrequency. The available analysis types are application-mode dependent. Some variables are defined differently depending on the analysis type, and others are only available for some analysis types.
- The **Constitutive Relation** column indicates the constitutive relation for which the variable definition applies. The abbreviations used are defined in the table below.

ABBREVIATION	CONSTITUTIVE RELATION
epsr	$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$
P	$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$

ABBREVIATION	CONSTITUTIVE RELATION
D <sub>r</sub>	$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} + \mathbf{D}_r$
m <sub>r</sub>	$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$
M	$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$
B <sub>r</sub>	$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r$

- The **Material Parameters** column appears in the tables for the electromagnetic waves application modes. It indicates if the refractive index  $n$  or the relative permeability  $\epsilon_r$ , the conductivity  $\sigma$ , and the relative permeability  $\mu_r$  are used as material parameters in the expression for the variable.
- The **Description** column gives a description of the variables.
- The **Expression** column gives the expression of the variables in terms of other physical quantities. In these expressions, the subscripts  $i$  and  $j$  of vector and tensor components stand for one of the spatial coordinates. For example,  $\mathbf{E}_i$  is either  $\mathbf{E}_x$ ,  $\mathbf{E}_y$ , or  $\mathbf{E}_z$ . When two equal subscripts appear in an expression this implies a summation. For example  $\sigma_{ij} \mathbf{E}_j = \sigma_{ix} \mathbf{E}_x + \sigma_{iy} \mathbf{E}_y + \sigma_{iz} \mathbf{E}_z$ .

# Electromagnetic Waves

A number of variables and physical quantities are available for postprocessing and for use in equations and boundary conditions. They are all given in the tables below.

See page 6 for a description of the notation used in these tables. The *up* and *down* subscripts indicate that the variable should be evaluated on the geometrical up or down side of the boundary. A letter *t* in front of a vector quantity for a boundary variable means the tangential vector on boundaries.

## *Common Variables for the Application Modes*

All the components of the electric and magnetic field quantities are available for postprocessing and for use in equations and boundary conditions. The different energy quantities are also available.

### **APPLICATION SCALAR VARIABLES**

The application-specific variables in this mode are given in Table 2-1.

TABLE 2-1: COMMON APPLICATION MODE SCALAR VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
lambda0	harmonic, mode analysis, $\lambda_0$ is input	free space wavelength	$\lambda_0$
lambda0	harmonic, mode analysis, $v$ is input	free space wavelength	$\frac{1}{v\sqrt{\epsilon_0\mu_0}}$
lambda0	eigenfrequency	free space wavelength	$2\pi/k_0$
omega	harmonic, mode analysis	angular frequency	$2\pi v$
omega	eigenfrequency	angular frequency	$\text{Im}(-\lambda)$
nu	harmonic, mode analysis, $\lambda_0$ is input	frequency	$\frac{1}{\lambda_0\sqrt{\epsilon_0\mu_0}}$
nu	harmonic, mode analysis, $v$ is input	frequency	$v$
nu	eigenfrequency	frequency	$\frac{\omega}{2\pi}$

TABLE 2-1: COMMON APPLICATION MODE SCALAR VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
k0	harmonic, mode analysis, eigenfrequency	free space wave number	$\omega\sqrt{\epsilon_0\mu_0}$
c0		speed of light	$\frac{1}{\sqrt{\epsilon_0\mu_0}}$
epsilon0		permittivity of vacuum	$\epsilon_0$
mu0		permeability of vacuum	$\mu_0$
damp	eigenfrequency	damping coefficient	$\delta = \text{Re}(\lambda)$
Qfact	eigenfrequency	quality factor	$\frac{\omega}{2 \delta }$

### APPLICATION SUBDOMAIN VARIABLES

The subdomain variables are given in Table 2-2. Note that, depending on the application mode, some field components may be zero. Suitable simplifications are then made on constitutive relations and expressions.

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
k	harmonic, mode analysis			wave number	$k_0\sqrt{\mu_r\left(\epsilon_r - j\frac{\sigma}{\omega\epsilon_0}\right)}$
k	eigenfrequency			wave number	$k_0\sqrt{\mu_r\epsilon_r}$
c				phase velocity	$\frac{c_0}{\sqrt{\mu_r\epsilon_r}}$
Z_wave				wave impedance	$c_0\mu_0\mu_r$
mur		n		relative permeability	1
mur <sub>ij</sub>		n		relative permeability, $x_i x_j$ component	1
mur		epsr	M	relative permeability	1

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
mur		epsr	mur, Br	relative permeability	$\mu_r$
mur <sub>ij</sub>		epsr	mur, Br	relative permeability, $x_i x_j$ component	$\mu_{rij}$
mu				permeability	$\mu_0 \mu_r$
mu <sub>ij</sub>				permeability, $x_i x_j$ component	$\mu_0 \mu_{rij}$
n		n		refractive index	$n$
n <sub>ij</sub>		n		refractive index, $x_i x_j$ component	$n_{ij}$
n		epsr		refractive index	$\sqrt{\epsilon_r}$
n <sub>ij</sub>		epsr		refractive index, $x_i x_j$ component	$(\sqrt{\epsilon_r})_{ij}$
epsilon <sub>r</sub>		n		relative permittivity	$n^2$
epsilon <sub>rij</sub>		n		relative permittivity, $x_i x_j$ component	$n_{ik} n_{kj}$
epsilon <sub>r</sub>		epsr	P	relative permittivity	1
epsilon <sub>r</sub>		epsr	epsr, Dr	relative permittivity	$\epsilon_r$
epsilon <sub>rij</sub>		epsr		relative permittivity, $x_i x_j$ component	$\epsilon_{rij}$
epsilon				permittivity	$\epsilon_0 \epsilon_r$
epsilon <sub>ij</sub>				permittivity, $x_i x_j$ component	$\epsilon_0 \epsilon_{rij}$
sigma		n		electric conductivity	0
sigma <sub>ij</sub>		n		electric conductivity, $x_i x_j$ component	0
sigma		epsr		electric conductivity	$\sigma$

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
$\sigma_{ij}$		epsr		electric conductivity, $x_i x_j$ component	$\sigma_{ij}$
delta	harmonic, mode analysis			skin depth	$\frac{1}{\text{Re}(\sqrt{j\omega\mu(\sigma + j\omega\epsilon)})}$
$P_i$	transient	epsr	P	electric polarization, $x_i$ component	$P_i$
$P_i$	transient	epsr	Dr, epsr	electric polarization, $x_i$ component	$D_i - \epsilon_0 E_i$
$D_{ri}$	transient	epsr	epsr	remnant displacement, $x_i$ component	0
$D_{ri}$	transient	epsr	P	remnant displacement, $x_i$ component	$P_i$
$D_{ri}$	transient	epsr	Dr	remnant displacement, $x_i$ component	$D_{ri}$
$M_i$	transient	epsr	M	magnetization, $x_i$ component	$M_i$
$M_i$	transient	epsr	mur, Br	magnetization, $x_i$ component	$\frac{B_i}{\mu_0} - H_i$
$B_{ri}$	transient	epsr	mur	remnant flux density, $x_i$ component	0
$B_{ri}$	transient	epsr	M	remnant flux density, $x_i$ component	$\mu_0 M_i$
$B_{ri}$	transient	epsr	Br	remnant flux density, $x_i$ component	$B_{ri}$
$E_i$	<b>E</b> dependent variable			electric field, $x_i$ component	$E_i$

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
$E_i$	<b>H</b> dependent variable			electric field, $x_i$ component	$-\frac{j}{\omega\epsilon_0} \left( \epsilon_r - j \frac{\sigma}{\omega\epsilon_0} \right)_{ij}^{-1} (\nabla \times \mathbf{H})_j$
$E_i$	transient			electric field, $x_i$ component	$\frac{\partial A_i}{\partial t}$
normE				electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}^*}$
$D_i$				electric displacement, $x_i$ component	$\epsilon_{ij} E_j$
normD				electric displacement, norm	$\sqrt{\mathbf{D} \cdot \mathbf{D}^*}$
$B_i$	<b>H</b> dependent variable			magnetic flux density, $x_i$ component	$\mu_{ij} H_j$
$B_i$	<b>E</b> dependent variable			magnetic flux density, $x_i$ component	$\frac{j}{\omega} (\nabla \times \mathbf{E})_i$
$B_i$	transient			magnetic flux density, $x_i$ component	$(\nabla \times \mathbf{A})_i$
normB				magnetic flux density, norm	$\sqrt{\mathbf{B} \cdot \mathbf{B}^*}$
$H_i$	<b>H</b> dependent variable			magnetic field, $x_i$ component	$H_i$
$H_i$	<b>E</b> dependent variable or transient			magnetic field, $x_i$ component	$\frac{\mu_{rij}^{-1} B_j}{\mu_0}$
normH				magnetic field, norm	$\sqrt{\mathbf{H} \cdot \mathbf{H}^*}$
Weav	harmonic, mode analysis, eigenfrequency			time average electric energy	$\frac{1}{4} \text{Re}(\mathbf{E} \cdot \mathbf{D}^*)$
Wmav	harmonic, mode analysis, eigenfrequency			time average magnetic energy	$\frac{1}{4} \text{Re}(\mathbf{B} \cdot \mathbf{H}^*)$



TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Wav	harmonic, mode analysis, eigenfrequency			time average total energy	$W_e^{av} + W_m^{av}$
Qav	harmonic, mode analysis, eigenfrequency			time average resistive heating	$\frac{1}{2}\text{Re}(\sigma \mathbf{E} \cdot \mathbf{E}^* - j\omega \mathbf{E} \cdot \mathbf{D}^*)$
Qmav	harmonic, mode analysis, eigenfrequency			time average magnetic hysteresis losses	$\frac{1}{2}\text{Re}(j\omega \mathbf{H} \cdot \mathbf{B}^*)$
Po <sub>iav</sub>	harmonic, mode analysis, eigenfrequency			time average power flow $x_i$ component	$\frac{1}{2}\text{Re}(\mathbf{E} \times \mathbf{H}^*)_i$
normPoav	harmonic, mode analysis, eigenfrequency			time average power flow, norm	$\sqrt{\mathbf{S}^{av} \cdot \mathbf{S}^{av*}}$
We	transient			electric energy	$\frac{1}{2}(\mathbf{E} \cdot \mathbf{D})$
Wm	transient			magnetic energy	$\frac{1}{2}(\mathbf{B} \cdot \mathbf{H})$
W	transient			total energy	$W_e + W_m$
Q	transient			resistive heating	$(\sigma \mathbf{E} - \frac{\partial \mathbf{D}}{\partial t}) \cdot \mathbf{E}$
Po <sub>i</sub>	transient			power flow $x_i$ component	$(\mathbf{E} \times \mathbf{H})_i$
normPo	transient			power flow, norm	$\sqrt{\mathbf{S} \cdot \mathbf{S}^*}$
dr_guess				default guess for width in radial direction	$\Delta_r$
R0_guess				default guess for inner radius	$R_0$
S <sub>i</sub>				infinite element $x_i$ coordinate	$s_i$

TABLE 2-2: COMMON APPLICATION MODE SUBDOMAIN VARIABLES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Sd <sub>i_guess</sub>				default guess for width along $x_i$ coordinate	$\Delta_i$
dVol				Volume integration contribution	$dV$

### APPLICATION BOUNDARY VARIABLES

The boundary variables are given in the table below.

TABLE 2-3: COMMON APPLICATION MODE BOUNDARY VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
normJs		surface current density, norm	$\sqrt{\mathbf{J}_s \cdot \mathbf{J}_s^*}$
nPoav		normal power flow	$\mathbf{n} \cdot \mathbf{S}^{av}$
Qs	transient	surface resistive heating	$\mathbf{J}_s \cdot \mathbf{tE}$
Qsav	harmonic, eigenfrequency, mode analysis	time average surface resistive heating	$\frac{1}{2} \text{Re}(\mathbf{J}_s \cdot \mathbf{tE}^*)$
deltabnd	harmonic, eigenfrequency, mode analysis, impedance cond.	skin depth	$\frac{1}{\text{Re}(\sqrt{j\omega\mu(\sigma + j\omega\epsilon)})}$
dVolbnd		Area integration contribution	$dA$

### *Electromagnetic Waves (3D)*

The tables in this section list the variables that differ from those in the section “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for 3D Electromagnetic Waves.

### APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in “Application Scalar Variables” on page 8.

### APPLICATION MODE SUBDOMAIN VARIABLES

No differences exist between the list of variables in “Application Subdomain Variables” on page 9.

### APPLICATION BOUNDARY VARIABLES

The boundary variables are given in Table 2-4.

TABLE 2-4: APPLICATION MODE BOUNDARY VARIABLES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
$J_{Si}$	<b>H</b> dependent variable	surface current density, $x_i$ component	$-\mathbf{n} \times \mathbf{tH}$
$J_{Si}$	<b>E</b> dependent variable, transient	surface current density, $x_i$ component	$\mathbf{n}_{\text{up}} \times (\mathbf{tH}_{\text{down}} - \mathbf{tH}_{\text{up}})$
$tH_i$	<b>H</b> dependent variable	tangential magnetic field, $x_i$ component	$tH_i$
$tH_i$	<b>E</b> dependent variable or transient	tangential magnetic field, $x_i$ component	$H_i - (\mathbf{n} \cdot \mathbf{H})n_i$
normtH		tangential magnetic field, norm	$\sqrt{\mathbf{tH} \cdot \mathbf{tH}^*}$
$tE_i$	<b>E</b> dependent variable	tangential electric field, $x_i$ component	$tE_i$
$tE_i$	<b>H</b> dependent variable	tangential electric field, $x_i$ component	$E_i - (\mathbf{n} \cdot \mathbf{E})n_i$
$tE_i$	transient	tangential electric field, $x_i$ component	$\frac{\partial}{\partial t} tA_i$
normtE		tangential electric field, norm	$\sqrt{\mathbf{tE} \cdot \mathbf{tE}^*}$

### *In-Plane Waves Application Mode*

The tables in this section list the variables that differ from those in the section “Common Variables for the Application Modes” on page 8. If you do not find a

variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for In-Plane Waves.

See page 6 for a description of the notation used in the tables.

### APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in “Application Scalar Variables” on page 8.

### APPLICATION MODE SUBDOMAIN VARIABLES

The variables for hybrid-mode waves is simply the sum of the variable sets from TE waves and TM waves.

TABLE 2-5: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TE WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Ez	harmonic, eigenfrequency			electric field, z component	$E_z$
Ez	transient			electric field, z component	$\frac{\partial A_z}{\partial t}$
Bx	harmonic, eigenfrequency			magnetic flux density, x component	$\frac{j}{\omega} \frac{\partial E_z}{\partial y}$
By	harmonic, eigenfrequency			magnetic flux density, y component	$-\frac{j}{\omega} \frac{\partial E_z}{\partial x}$
Bx	transient			magnetic flux density, x component	$\frac{\partial A_z}{\partial y}$
By	transient			magnetic flux density, y component	$-\frac{\partial A_z}{\partial x}$

TABLE 2-6: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
H <sub>z</sub>	harmonic, eigenfrequency			magnetic field, z component	$H_z$
H <sub>z</sub>	transient			magnetic field, z component	$\mu_{rij}^{-1} \frac{B_z}{\mu_0}$

TABLE 2-6: APPLICATION MODE SUBDOMAIN VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	MAT. PARAMS	CONST. REL.	DESCRIPTION	EXPRESSION
Bz	harmonic, eigenfrequency			magnetic flux density, z component	$\mu H_z$
Bz	transient			magnetic flux density, z component	$\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}$

### APPLICATION MODE BOUNDARY VARIABLES

The variables for hybrid-mode waves is simply the sum of the variable sets from TE waves and TM waves.

TABLE 2-7: APPLICATION MODE BOUNDARY VARIABLES, IN-PLANE TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
JSZ		surface current density, z component	$n_{xup}(H_{ydown} - H_{yup}) -$ $n_{yup}(H_{xdown} - H_{xup})$

TABLE 2-8: APPLICATION MODE BOUNDARY VARIABLES, IN-PLANE TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
JSZ	transient	surface current density, z component	$n_{xup}(H_{ydown} - H_{yup}) -$ $n_{yup}(H_{xdown} - H_{xup})$

### *Electromagnetic Waves Application Modes (Axial Symmetry, 2D)*

The tables in this section list the variables that differ from those in the section “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no mode analysis is available for Axisymmetric Waves.

See page 6 for a description of the notation used in the tables.

### APPLICATION SCALAR VARIABLES

No differences exist between the list of variables in “Application Scalar Variables” on page 8.

### APPLICATION MODE VARIABLES

The expressions for the refractive index and relative permittivity differ depending on which of the two is given as input in the equation.

The subdomain variables for axisymmetric TE and TM waves are given below in Table 2-9 and Table 2-10. The variables for hybrid-mode waves is simply the sum of the two tables.

TABLE 2-9: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Ephi	harmonic, eigenfrequency	electric field, $\varphi$ component	$E_{\varphi}$
Ephir	harmonic, eigenfrequency	electric field, $r$ derivative of $\varphi$ component	$\frac{\partial E_{\varphi}}{\partial r}$
Ephiz	harmonic, eigenfrequency	electric field, $z$ derivative of $\varphi$ component	$\frac{\partial E_{\varphi}}{\partial z}$
Aphi	transient	magnetic potential, $\varphi$ component	$A_{\varphi}$
Aphir	transient	magnetic potential, $r$ derivative of $\varphi$ component	$\frac{\partial A_{\varphi}}{\partial r}$
Aphiz	transient	magnetic potential, $z$ derivative of $\varphi$ component	$\frac{\partial A_{\varphi}}{\partial z}$
Aphit	transient	magnetic potential, time-derivative of $\varphi$ component	$\frac{\partial A_{\varphi}}{\partial t}$
Ephi	transient	electric field, $\varphi$ component	$\frac{\partial A_{\varphi}}{\partial t}$
Br	harmonic, eigenfrequency	magnetic flux density, $r$ component	$-\frac{j}{\omega} \frac{\partial E_{\varphi}}{\partial z}$
Bz	harmonic, eigenfrequency	magnetic flux density, $z$ component	$\frac{j}{\omega} \left( \frac{E_{\varphi}}{r} + \frac{\partial E_{\varphi}}{\partial r} \right)$

TABLE 2-9: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Br	transient	magnetic flux density, $r$ component	$-\frac{\partial A_\phi}{\partial z}$
Bz	transient	magnetic flux density, $z$ component	$\frac{A_\phi}{r} + \frac{\partial A_\phi}{\partial r}$

TABLE 2-10: APPLICATION MODE SUBDOMAIN VARIABLES, AXISYMMETRIC TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Hphi	harmonic, eigenfrequency	magnetic field, $\phi$ component	$H_\phi$
Hphir	harmonic, eigenfrequency	magnetic field, $r$ derivative of $\phi$ component	$\frac{\partial H_\phi}{\partial r}$
Hphiz	harmonic, eigenfrequency	magnetic field, $z$ derivative of $\phi$ component	$\frac{\partial H_\phi}{\partial z}$
Hphi	transient	magnetic field, $\phi$ component	${}_{\mu_{rij}}^{-1} B_j$
Bphi	harmonic, eigenfrequency	magnetic flux density, $\phi$ component	$\mu H_\phi$
Bphi	transient	magnetic flux density, $\phi$ component	$\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r}$

### APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for axisymmetric TE and TM waves are given in Table 2-11 and Table 2-12. The variables for hybrid-mode waves is simply the sum of the two tables.

TABLE 2-11: APPLICATION MODE BOUNDARY VARIABLES, AXISYMMETRIC TE WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
Jsp $\phi$		surface current density, $\phi$ component	$n_{zup}(H_{rdown} - H_{rup}) - n_{rup}(H_{zdown} - H_{zup})$

TABLE 2-12: APPLICATION MODE BOUNDARY VARIABLES, AXISYMMETRIC TM WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
J <sub>sphi</sub>	transient	surface current density, $\varphi$ component	$n_{zup}(H_{rdown} - H_{rup}) - n_{rup}(H_{zdown} - H_{zup})$

### *Perpendicular Waves Application Modes(2D)*

The tables in this section list the variables that differ from those in the section “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that no harmonic or transient analysis is available for Perpendicular Waves.

See page 6 for a description of the notation used in the tables.

### APPLICATION SCALAR VARIABLES

The application-specific variables in this mode are given in Table 2-13.

TABLE 2-13: APPLICATION MODE SCALAR VARIABLES, PERPENDICULAR WAVES

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
beta	mode analysis	propagation constant	$\text{Im}(-\lambda)$
beta	eigenfrequency	propagation constant	$\beta$
neff		effective mode index	$\beta/k_0$
dampz	mode analysis	attenuation coefficient	$\delta_z = \text{Re}(-\lambda)$
dampz	eigenfrequency	attenuation coefficient	$\delta_z = \text{Re}(j\beta)$
dampzdB		attenuation, dB scale	$20\delta_z \log e$



### APPLICATION MODE SUBDOMAIN VARIABLES

The subdomain variables for TM waves, TE waves, Hybrid-mode waves H-field formulation, and Hybrid-mode waves E-field formulation are listed in four tables below in the given order.

TABLE 2-14: APPLICATION MODE VARIABLES, PERPENDICULAR TM WAVES

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Ex	mode analysis		electric field, x component	$\frac{j\beta}{(\sigma + j\omega\epsilon)} H_y$
Ex	eigenfrequency		electric field, x component	$\frac{\beta}{\omega\epsilon} H_y$
Ey	mode analysis		electric field, y component	$-\frac{j\beta}{(\sigma + j\omega\epsilon)} H_x$
Ey	eigenfrequency		electric field, y component	$-\frac{\beta}{\omega\epsilon} H_x$
Ez			electric field, z component	$E_z$
Hx	mode analysis		magnetic field, x component	$\frac{\sigma + j\omega\epsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial y}$
Hx	eigenfrequency		magnetic field, x component	$\frac{j\omega\epsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial y}$
Hy	mode analysis		magnetic field, y component	$\frac{\sigma + j\omega\epsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial x}$
Hy	eigenfrequency		magnetic field, y component	$\frac{j\omega\epsilon}{k^2 - \beta^2} \frac{\partial E_z}{\partial x}$

TABLE 2-15: APPLICATION MODE VARIABLES, PERPENDICULAR TE WAVES

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Hx			magnetic field, x component	$-\frac{\beta}{\omega\mu} E_y$
Hy			magnetic field, y component	$\frac{\beta}{\omega\mu} E_x$
Hz			magnetic field, z component	$H_z$

TABLE 2-15: APPLICATION MODE VARIABLES, PERPENDICULAR TE WAVES

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
Ex			electric field, x component	$-\frac{j\omega\mu}{k^2 - \beta^2} \frac{\partial H_z}{\partial y}$
Ey			electric field, y component	$\frac{j\omega\mu}{k^2 - \beta^2} \frac{\partial H_z}{\partial x}$

TABLE 2-16: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, MAGNETIC FIELD DEPENDENT VARIABLE

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
H <sub>z</sub>	two-component		magnetic field, z component	$-\frac{j}{\beta\mu_{rzz}} (\nabla_t \cdot \mu_{rt} \mathbf{H}_t)$
H <sub>z</sub>	three-component formulation		magnetic field, z component	$\alpha h_z$

TABLE 2-17: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, ELECTRIC FIELD DEPENDENT VARIABLE

NAME	ANALYSIS	MAT. PARAMS	DESCRIPTION	EXPRESSION
E <sub>z</sub>	two-component		electric field, z component	$-\frac{j}{\beta\epsilon_{rzz}} (\nabla_t \cdot \epsilon_{rt} \mathbf{E}_t)$
E <sub>z</sub>	three-component formulation		electric field, z component	$\alpha e_z$

### APPLICATION BOUNDARY VARIABLES

The boundary variables for TM waves, TE waves, Hybrid-mode waves H-field formulation, and Hybrid-mode waves E-field formulation are listed in four tables below in the given order.

TABLE 2-18: APPLICATION MODE VARIABLES, PERPENDICULAR TM WAVES

NAME	DESCRIPTION	EXPRESSION
JSZ	surface current density, z component	$n_{xup}(H_{ydown} - H_{yup}) -$ $n_{yup}(H_{xdown} - H_{xup})$

TABLE 2-19: APPLICATION MODE VARIABLES, PERPENDICULAR TE WAVES

NAME	DESCRIPTION	EXPRESSION
JSX	surface current density, $x$ component	$-n_y H_z$
JSy	surface current density, $y$ component	$n_x H_z$
JSZ	surface current density, $z$ component	$n_y H_x - n_x H_y$

TABLE 2-20: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, MAGNETIC FIELD DEPENDENT VARIABLE

NAME	DESCRIPTION	EXPRESSION
JSX	surface current density, $x$ component	$-n_y H_z$
JSy	surface current density, $y$ component	$n_x H_z$
JSZ	surface current density, $z$ component	$n_y H_x - n_x H_y$

TABLE 2-21: APPLICATION MODE VARIABLES, PERPENDICULAR HYBRID-MODE WAVES, ELECTRIC FIELD DEPENDENT VARIABLE

NAME	DESCRIPTION	EXPRESSION
JSX	surface current density, $x$ component	$n_{yup}(H_{zdown} - H_{zup})$
JSy	surface current density, $y$ component	$n_{xup}(H_{zdown} - H_{zup})$
JSZ	surface current density, $z$ component	$n_{xup}(H_{ydown} - H_{yup}) - n_{yup}(H_{xdown} - H_{xup})$

### *Boundary Mode Analysis Application Modes (3D)*

Below is the variables listed that differ from the list of common variables in “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list

below, it can be in the list of common variables. Note that only mode analysis is available for Boundary Mode Analysis in 3D.

See page 6 for a description of the notation used in the tables.

### APPLICATION SCALAR VARIABLES

The application-specific variables in this mode are given in the following table.

TABLE 2-22: APPLICATION MODE SCALAR VARIABLES, BOUNDARY MODE ANALYSIS

NAME	ANALYSIS	DESCRIPTION	EXPRESSION
beta		propagation constant	$\text{Im}(-\lambda)$
neff		effective mode index	$\beta/k_0$
dampz		attenuation coefficient	$\delta_z = \text{Re}(-\lambda)$
dampzdB		attenuation, dB scale	$20\delta_z \log e$

### APPLICATION MODE BOUNDARY VARIABLES

The boundary variables for TM waves, TE waves, and Hybrid-mode waves are listed in three tables below in the given order.

TABLE 2-23: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, TM WAVES

NAME	MAT. PARAMS	DESCRIPTION	EXPRESSION
tE <sub>i</sub>		tangential electric field, $x_i$ component	$\frac{j\beta}{(\sigma + j\omega\epsilon)}(\mathbf{n} \times \mathbf{H}_t)_i$
En		electric field, normal component	$j\dot{e}_n$
tD <sub>i</sub>		tangential electric displacement, $x_i$ component	$\epsilon tE_i$
Dn		electric displacement, normal component	$\epsilon E_n$
tH <sub>i</sub>		tangential magnetic field, $x_i$ component	$\frac{\sigma + j\omega\epsilon}{k^2 - \beta^2}(\nabla_t \times \mathbf{n}E_n)_i$
tB <sub>i</sub>		tangential magnetic flux density, $x_i$ component	$\mu tH_i$

TABLE 2-24: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, TE WAVES

NAME	MAT. PARAMS	DESCRIPTION	EXPRESSION
tH <sub>i</sub>		tangential magnetic field, $x_i$ component	$-\frac{\beta}{\omega\mu}(\mathbf{n} \times \mathbf{E}_t)_i$
H <sub>n</sub>		magnetic field, normal component	$jh_n$
tB <sub>i</sub>		tangential magnetic flux density, $x_i$ component	$\mu H_i$
B <sub>n</sub>		magnetic flux density, normal component	$\mu H_n$
tE <sub>i</sub>		tangential electric field, $x_i$ component	$\frac{j\omega\mu}{k^2 - \beta^2}(\nabla_t \times \mathbf{n}H_n)_i$
tD <sub>i</sub>		tangential electric displacement, $x_i$ component	$\epsilon E_i$

TABLE 2-25: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, HYBRID MODE WAVES

NAME	DEP. VAR.	MAT. PARAMS	DESCRIPTION	EXPRESSION
tH <sub>i</sub>	<b>H</b>		tangential magnetic field, $x_i$ component	$th_i/\beta$
tH <sub>i</sub>	<b>E</b>		tangential magnetic field, $x_i$ component	$-\frac{\beta}{\omega\mu}(\mathbf{n} \times \mathbf{E}_t)_i - \frac{j}{\omega\mu}(\nabla_t \times \mathbf{n}E_n)_i$
H <sub>n</sub>	<b>H</b>		magnetic field, normal component	$jh_n/k_0$
H <sub>n</sub>	<b>E</b>		magnetic field, normal component	$-\frac{j}{\omega\mu}\mathbf{n} \cdot (\nabla_t \times \mathbf{E}_t)$
tB <sub>i</sub>			tangential magnetic flux density, $x_i$ component	$\mu H_i$
B <sub>n</sub>			magnetic flux density, normal component	$\mu H_n$
tE <sub>i</sub>	<b>H</b>		tangential electric field, $x_i$ component	$\frac{\beta}{\omega\epsilon_c}(\mathbf{n} \times \mathbf{H}_t)_i + \frac{j}{\omega\epsilon_c}(\nabla_t \times \mathbf{n}H_n)_i$
tE <sub>i</sub>	<b>E</b>		tangential electric field, $x_i$ component	$te_i/\beta$

TABLE 2-25: APPLICATION MODE VARIABLES, BOUNDARY MODE ANALYSIS, HYBRID MODE WAVES

NAME	DEP. VAR.	MAT. PARAMS	DESCRIPTION	EXPRESSION
En	<b>H</b>		electric field, normal component	$\frac{j}{\omega\epsilon_c} \mathbf{n} \cdot (\nabla_t \times \mathbf{H}_t)$
En	<b>E</b>		electric field, normal component	$je_n/k_0$
tDi			tangential electric displacement, $x_i$ component	$\epsilon \mathbf{E}_i$

### *Boundary Mode Analysis Application Modes (2D)*

The tables in this section list the variables that differ from those in the section “Common Variables for the Application Modes” on page 8. If you do not find a variable in the list below, it can be in the list of common variables. Note that only mode analysis is available for Boundary Mode Analysis in 2D.

See page 6 for a description of the notation used in the tables.

#### **APPLICATION SCALAR VARIABLES**

See the corresponding section for “Boundary Mode Analysis Application Modes (3D)” on page 23.

#### **APPLICATION MODE BOUNDARY VARIABLES**

The boundary variables for TM waves, and TE waves are listed in two tables below in the given order.

TABLE 2-26: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D TM WAVE.

NAME	SETTING	DESCRIPTION	EXPRESSION
tEx		tangential electric field, $x$ component	$\frac{\beta n_y}{\epsilon\omega - j\sigma} H_z$
tEy		tangential electric field, $y$ component	$\frac{-\beta n_x}{\epsilon\omega - j\sigma} H_z$
normtE		tangential electric field, norm	$\sqrt{\mathbf{E} \cdot \mathbf{E}^*}$
En		normal electric field	$\frac{-1}{\sigma + j\omega\epsilon} (\nabla_T \times \mathbf{n}H_z)$

TABLE 2-26: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D TM WAVE.

NAME	SETTING	DESCRIPTION	EXPRESSION
tDi		electric displacement, $x_i$ component	$\epsilon E_i$
normtD		tangential electric displacement, norm	$\sqrt{\mathbf{D} \cdot \mathbf{D}^*}$
Dn		normal electric displacement	$\epsilon E_n$
H <sub>z</sub>		magnetic field, $z$ component	$H_z$

TABLE 2-27: APPLICATION MODE VARIABLES. BOUNDARY MODE ANALYSIS 2D, TE WAVE

NAME	SETTING	DESCRIPTION	EXPRESSION
tH <sub>x</sub>		tangential magnetic field, $x$ component	$-\frac{\beta n_y}{\omega \mu} E_z$
tH <sub>y</sub>		tangential magnetic field, $y$ component	$\frac{\beta n_x}{\omega \mu} E_z$
normtH		tangential magnetic field, norm	$\sqrt{\mathbf{H} \cdot \mathbf{H}^*}$
H <sub>n</sub>		normal magnetic field	$\frac{j}{\omega \mu} \nabla_t \times \mathbf{n} E_z$
tB <sub>i</sub>		tangential magnetic flux density, $x_i$ component	$\mu t H_i$
normtB		tangential magnetic flux density, norm	$\sqrt{\mathbf{B} \cdot \mathbf{B}^*}$
B <sub>n</sub>		normal magnetic flux density	$\mu H_n$
E <sub>z</sub>		electric field, $z$ component	$E_z$





## Programming Reference

This chapter, which is a complement to the *COMSOL Multiphysics MATLAB Interface Guide*, describes how to use the application modes provided by the RF Module in command-line modeling.

# The Programming Language

Earlier in this documentation, the examples use the COMSOL Multiphysics graphical user interface for solving problems with the RF Module. Although this user interface provides a convenient environment for modeling many problems, it can sometimes be useful to work with a programming tool.

A summary of the application structure, and how application objects are used for a convenient transformation of application mode data to PDE and boundary coefficients, is presented in the following section.

For details on specific functions, see the chapter “Function Reference” on page 61 in this manual and the “Command Reference” chapter of the *COMSOL Multiphysics Reference Guide*.

## *The Application Structure*

---

The process of performing a simulation using the application modes available through the RF Module includes the correct setup of the application structure. The application structure contains the necessary information for the model setup in several fields. This section describes the application structure in the context of the RF Module. See also the section “Application Structures” on page 54 in the *COMSOL Multiphysics MATLAB Interface Guide*. Most fields have corresponding entries in the FEM structure, described in the section “Specifying a Model” on page 3 in the *COMSOL Multiphysics MATLAB Interface Guide*. The following table gives an overview of the fields in the application structure.

FIELD	DESCRIPTION
<code>appl.mode</code>	Application mode class
<code>appl.dim</code>	Cell array of dependent variable names
<code>appl.sdim</code>	Cell array of spatial coordinates
<code>appl.border</code>	Assembly on interior boundaries; turn on/off assembly on interior boundaries
<code>appl.name</code>	Application mode name
<code>appl.var</code>	Cell array or structure with application-specific scalar variables.
<code>appl.assign</code>	Assigned variable names

FIELD	DESCRIPTION
<code>appl.assignsuffix</code>	Suffix to append to all application mode variable names
<code>appl.equ</code>	Structure containing domain properties
<code>appl.bnd</code>	Structure containing boundary conditions
<code>appl.edg</code>	Structure containing edge conditions
<code>appl.pnt</code>	Structure containing point conditions
<code>appl.prop</code>	Application mode specific properties

Most of these fields have default values and need not be specified when solving a problem using the programming language. The function `multiphysics` transforms the application structure data to the FEM structure to generate the complete set of equations; see the entry for `multiphysics` on page 351 of the *COMSOL Multiphysics Reference Guide* for details.

The application mode specific names of the fields in the structures in the table above can be found in the chapter “Application Mode Programming Reference” on page 39.

#### APPLICATION MODE CLASS

The application modes are specified via a corresponding class name.

To specify the class, write the name of the class as a string, for example,

```
appl.mode.class = 'InPlaneWaves' ;
```

which specifies that the In-Plane Waves application mode will be used.

Some application modes, for example the In-Plane Waves application mode, can be used both for Cartesian and axisymmetric problems. The default is to use Cartesian coordinates. To specify an axisymmetric problem, use

```
appl.mode.class = 'AxisymmetricWaves' ;
appl.mode.type = 'axi' ;
```

#### DEPENDENT VARIABLES

The `dim` field in the application structure states the names of the dependent variables, and hence gives the dimension of the corresponding PDE system. If the `dim` field is missing, the corresponding standard names of the electromagnetic field quantities solved for are used. Note that in some axisymmetric modes, there is a variable transformation in the equations solved. In those modes, the default name of the dependent variable name has `dr` added to the name of the electromagnetic quantity, since the dependent variable is divided by  $r$ .

The default names of the dependent variables in the In-Plane Waves application mode is 'Ez'.

You can set a new name of the dependent variable by typing

```
appl.dim = {'E'};
```

### **SPATIAL COORDINATES**

The names of the spatial coordinates are given in `fem.sdim`. However, `fem.sdim` only gives the names of the spatial coordinates of the geometry: one variable in 1D, two variables in 2D, and three variables in 3D. To specify all three spatial coordinates, use `appl.sdim`. The additional spatial coordinates are used when giving names to vector component variables.

For example, in 2D Cartesian coordinates

```
fem.sdim = {'x1' 'y1'};  
appl.sdim = {'x1' 'y1' 'z1'};
```

defines the spatial coordinates  $x_1, y_1, z_1$ .

In cylindrical coordinates

```
fem.sdim = {'r' 'z'};  
appl.sdim = {'r' 'phi' 'z'};
```

defines the spatial coordinates  $r, \phi, z$ .

The coordinates defined both in `fem.sdim` and `appl.sdim` should match.

### **APPLICATION NAME**

This field is used for giving the application a name. If no name is specified, a default name is used.

```
appl.name = 'antenna';
```

### **APPLICATION MODE PROPERTIES**

Some application modes define properties to, for example, specify which type of analysis to perform or which dependent variables to use. These are specified in the `appl.prop` structure. For example, the In-Plane Waves application mode defines the field `appl.prop.analysis`, which specifies if a transient, time-harmonic, or eigenfrequency analysis should be performed. For instance,

```
appl.prop.analysis = 'harmonic';
```

indicates time-harmonic analysis.

The default element type used for domains and boundaries can be specified in the `appl.prop.elemdefault` field. For example, you can write

```
appl.prop.elemdefault='Lag1';
```

to obtain linear Lagrange elements.

#### **APPLICATION SCALAR VARIABLES**

For scalar variables that are valid in the whole model, such as permittivity and permeability of vacuum and angular frequency, the values can be specified in the `appl.var` field. Note that only predefined variable names can be used in this field.

For the In-Plane Waves application mode, the variables can be set as

```
appl.var.epsilon0 = 1;  
appl.var.mu0 = 1;  
appl.var.nu = 100;
```

The `appl.var` field can also be specified as a cell array,

```
appl.var = {'epsilon0' 1 'mu0' 1 'nu' 100};
```

The default values in the In-Plane Waves application mode in the harmonic formulation are

```
appl.var.epsilon0 = 8.854187817e-12;  
appl.var.mu0 = 4*pi*1e-7;  
appl.var.nu = 1e9;
```

#### **ASSIGNED VARIABLE NAMES**

To avoid duplicate variable names, you can use the `appl.assign` field to state the relation between the assigned name of a variable available in postprocessing and in the PDE and boundary coefficients on one hand, and the default name that is used in the COMSOL Multiphysics and RF Module algorithms on the other. This field is thus only necessary when you solve a multiphysics problem where variable name conflicts may arise.

If you want to use the variable name `w` for the intrinsic variable `omega` in the Perpendicular Currents Quasi-Statics application mode, all you have to enter is

```
appl.assign.omega = 'w';
```

An alternative syntax uses a cell array where the intrinsic and new variable names are listed pairwise:

```
appl.assign = {'omega' 'w'};
```

The odd-index entries in the `assign` field state the default application scalar variable names or the postprocessing variable names; these are listed for all application modes in the chapter “Application Mode Reference” on page 5 of this manual. The even-index entries in `appl.assign` are the variable names that you want to use for the physical entities when modeling.

There is also a field `appl.assignsuffix`, which can be used to add a suffix to the name of all application mode variables. Variables appearing in `appl.assign` will take the given assigned name, while the others will get the suffix added to their names.

### DOMAIN PROPERTIES

The application structure field `appl.equ` is used for specifying electromagnetic properties that will be transformed into PDE coefficients. For example the In-Plane Waves application mode defines the fields

```
appl.equ.epsilonr
appl.equ.mur
appl.equ.sigma
appl.equ.n
appl.equ.matparams
appl.equ.magconstrel
appl.equ.elconstrel
appl.equ.P
appl.equ.Dr
appl.equ.Br
appl.equ.M
```

Now consider an example with two materials. To use other values than the default for the physical properties, enter them as follows.

Scalars such as `sigma` are given as a cell array with the values,

```
appl.equ.sigma={'5.9e7' '0'};
```

Vectors such as `M` are given as a nested cell array with the vector components as elements in the inner cell array,

```
appl.equ.M={{'0' '0'} {'0' '500'}};
```

In the 3D case, the vector has three components,

```
appl.equ.M={{'0' '0' '0'} {'0' '500' '0'}};
```

Tensors or matrix variables are given as cell arrays with the tensor components,

```
appl.equ.mur={{'1' '2'; '3' '4'} {'5' '6' '7' '8'}};
```

This example shows two ways of writing a 2-by-2 tensor. The first tensor is written row by row with a semicolon separating the rows,

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$$

while the second tensor is written column by column,

$$\begin{bmatrix} 5 & 7 \\ 6 & 8 \end{bmatrix}$$

There are a number of short-hand ways of writing a tensor. In 2D  $\{ '1' \ '2' \}$  is a diagonal tensor

$$\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

$\{ '1' \ '2' \ '3' \}$  is a symmetric tensor

$$\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix}$$

and  $\{ '1' \ '2' \ '3' \ '4' \}$  is the full tensor

$$\begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix}$$

Similarly in 3D  $\{ '1' \ '2' \ '3' \}$  is a diagonal tensor

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$$

$\{ '1' \ '2' \ '3' \ '4' \ '5' \ '6' \}$  is a symmetric tensor

$$\begin{bmatrix} 1 & 2 & 4 \\ 2 & 3 & 5 \\ 4 & 5 & 6 \end{bmatrix}$$

and  $\{ '1' \ '2' \ '3' \ '4' \ '5' \ '6' \ '7' \ '8' \ '9' \}$  is the full tensor

$$\begin{bmatrix} 1 & 4 & 7 \\ 2 & 5 & 8 \\ 3 & 6 & 9 \end{bmatrix}$$

### Constitutive Relations

In the static and quasi-static application modes three different constitutive relations between both the  $\mathbf{D}$  and  $\mathbf{E}$  fields and the  $\mathbf{B}$  and  $\mathbf{H}$  fields can be used. To specify which ones to use, use the fields `appl.equ.elconstrel` and `appl.equ.magconstrel`. Their values are listed in the table below.

CONSTITUTIVE RELATION	VARIABLE	VALUE
$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$	<code>elconstrel</code>	<code>epsr</code>
$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$	<code>elconstrel</code>	<code>P</code>
$\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E} + \mathbf{D}_r$	<code>elconstrel</code>	<code>Dr</code>
$\mathbf{B} = \mu_0 \mu_r \mathbf{H}$	<code>magconstrel</code>	<code>mur</code>
$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$	<code>magconstrel</code>	<code>M</code>
$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B}_r$	<code>magconstrel</code>	<code>Br</code>

### Refractive Index and Relative Permittivity

The material data can be given either by the refractive index or the three properties relative permittivity, relative permeability and conductivity. To specify which of the two to use, use the field `appl.equ.matparams`. It takes the value `n` for refractive index and the value `epsr` for the other three properties. For example,

```
appl.equ.matparams = {'n' 'epsr'};
appl.equ.n = {'1.2' '1'};
appl.equ.epsilonr = {'1' '2'};
appl.equ.sigma = {'0' '1e4'};
appl.equ.mur = {'1' '1.1'};
```

specifies the refractive index  $n = 1.2$  for the first domain and  $\epsilon_r = 2$ ,  $\sigma = 10^4$  S/m, and  $\mu_r = 1.1$  for the second one.

### BOUNDARY CONDITIONS

The boundary conditions for the simulation is given in the `appl.bnd` field. First you have to select which type of boundary condition you want at each boundary. This is done using the field `appl.bnd.type`. Then some boundary conditions requires certain boundary variables to be set, unless the default value is sufficient. Note that not all types of boundary conditions require a boundary variable.



For example, the boundary variables defined by the In-Plane Waves application mode are

```
appl.bnd.type
appl.bnd.epsilonrbnd
appl.bnd.murbnd
appl.bnd.siglabnd
appl.bnd.nrbnd
appl.bnd.E0
appl.bnd.Esz
appl.bnd.portnr
appl.bnd.inport
appl.bnd.Pport
appl.bnd.rectmodetype
appl.bnd.usermodetype
appl.bnd.modespec
appl.bnd.betaTE
appl.bnd.betaTM
appl.bnd.modenum
appl.bnd.betaport
appl.bnd.nucutoff
appl.bnd.curoffforbeta
appl.bnd.applmode
appl.bnd.wavetype
appl.bnd.srcpnt
appl.bnd.eta
appl.bnd.kdir
appl.bnd.nu0
appl.bnd.srctype
appl.bnd.Js0
appl.bnd.A0
appl.bnd.matparams
appl.bnd.H0
```

The variables are specified using the same form for scalars, vectors, and tensors as above for the subdomain variables.

### **DOMAIN GROUPS**

Often you have a model with several subdomains having the same physical properties and many boundaries where you want to apply the same boundary condition. To simplify the notation, the index vectors in the fields `equ.ind` and `bnd.ind` are used. Consider this example:

```
appl.equ.sigma = {'5.9e7' '0'};
appl.equ.ind = [1 2 1 1 1];
```

Here you have five subdomains. Subdomain 2 is nonconducting, whereas the other four subdomains have the electric conductivity  $5.9 \cdot 10^7$  S/m.

Here is another example where three different boundary conditions are applied to six boundaries:

```
appl.bnd.type = {'tH0' 'H' 'A'};  
appl.bnd.A0 = {[ ] [ ] '100'};  
appl.bnd.H0 = {[ ] {'10' '5'} [ ]};  
appl.bnd.ind = [1 2 2 2 3 3];
```

This specifies the magnetic field at Boundaries 2–4, the magnetic potential at Boundaries 5 and 6 and electric insulation at Boundary 1. Note that the perfect magnetic conductor condition does not need any boundary variable to be defined and that we have set the variables to an empty vector where the value is ignored.

There is an alternative syntax for the index vector using a cell array of numeric vectors instead of a single numeric vector as in the examples above. In this case the numeric vectors in the cell array list the domains having the same settings. For example,

```
appl.equ.ind = {[1 3 4 5] 2};
```

is equivalent to

```
appl.equ.ind = [1 2 1 1 1];
```

and

```
appl.bnd.ind = {1 [2 3 4] [5 6]};
```

is equivalent to

```
appl.bnd.ind = [1 2 2 2 3 3];
```

# Application Mode Programming Reference

This reference chapter tabulates the application mode dependent fields of the application structure. For each application mode these are the following sections:

- *Dependent variables*—gives the variables in `app1.dim`. In the COMSOL Multiphysics graphical user interface (GUI) you find these variables in the **Dependent variables** edit field in the Model Navigator.
- *Application mode class and name*—specifies the values to use in `app1.mode` and gives the default value of `app1.name`. In the GUI, `app1.name` appears in the **Application mode name** edit field in the Model Navigator.
- *Scalar variables*—specifies the variables in `app1.var`. The corresponding GUI dialog box is the **Application Scalar Variables** dialog box.
- *Properties*—specifies all fields in `app1.prop`, for example which type of analysis to perform or which elements to use. In the GUI you find the properties in the **Application Mode Properties** dialog box.
- *Subdomain/Boundary/Edge/Point Variables*—specifies the variables available in `app1.equ`, `app1.bnd`, `app1.edg`, `app1.pnt`. The GUI dialog boxes corresponding to these fields are the **Subdomain Settings**, **Boundary Settings**, **Edge Settings**, and **Point Settings** dialog boxes, respectively.
- *Boundary Conditions*—specifies which type of boundary conditions are available and which boundary variables are significant for each boundary condition. In the user interface, the boundary condition types correspond to the items in the **Boundary condition** list in the **Boundary Settings** dialog box.

See also the section “The Programming Language” on page 30 for a general discussion of the various fields in the application structure.

## 3D Electromagnetic Waves

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### DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.dim	{'Ex' 'Ey' 'Ez' 'Hx' 'Hy' 'Hz' 'Ax' 'Ay' 'Az' 'scEx' 'scEy' 'scEz' 'schx' 'schy' 'schz' 'psi'}	Electric and magnetic field, magnetic potential and divergence condition variable

All ten dependent variables have to be specified, including the seven that are not in use.

### APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	ElectromagneticWaves	
appl.name		rfl

### SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength

### PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	harmonic   eigen   trans	harmonic	Analysis type, harmonic propagation, eigenfrequency or transient propagation
appl.prop.solvefor	E   H	E	Which field to use as dependent variable, electric or magnetic
appl.prop.inputvar	nu   lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.eigtype	lambda   freq	freq	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or the eigenfrequency. This property only applies when working in the user interface.
appl.prop.divcond	on   off	off	Divergence condition active or not.
appl.prop.elemdefault	Vec1   Vec2   Vec3	Vec1	Default element type, vector elements.

### SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma	expression   cell array of expressions	0	Electric conductivity
appl.equ.mur	expression   cell array of expressions	1	Relative permeability
appl.equ.epsilonr	expression   cell array of expressions	1	Relative permittivity
appl.equ.n	expression   cell array of expressions	1	Refractive index
appl.equ.matparams	n   epsr	epsr	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
appl.equ.M	cell array of expressions	0	Magnetization
appl.equ.Br	cell array of expressions	0	Remanent flux density
appl.equ.P	cell array of expressions	0	Electric polarization
appl.equ.Dr	cell array of expressions	0	Remanent displacement

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.magconstrel	mur   M   Br	mur	Magnetic constitutive relation
appl.equ.elconstrel	epsr   P   Dr	epsr	Electric constitutive relation

### BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.bnd.H0	cell array of expressions	0	Magnetic field
appl.bnd.Js0	cell array of expressions	0	Surface current density
appl.bnd.E0	cell array of expressions	0	Electric field
appl.bnd.A0	cell array of expressions	0	Magnetic potential
appl.bnd.eta	expression	1	Surface impedance
appl.bnd.Es	cell array of expressions	0	Surface electric field
appl.bnd.sigmapnd	expression   cell array of expressions	0	Electric conductivity
appl.bnd.murbnd	expression cell array of expressions	1	Relative permeability
appl.bnd.epsilonrbnd	expression   cell array of expressions	1	Relative permittivity
appl.bnd.nrbnd	expression   cell array of expressions	1	Refractive index
appl.bnd.lrsouce	E   H   EH	E	Source field for the low-reflecting boundary condition, electric, magnetic, or general

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.bnd.mbsource	E   H	E	Source field for the matched boundary condition, electric or magnetic
appl.bnd.beta	expression	0	Propagation constant
appl.bnd.matparams	n   epsr	epsr	Indicates if the material in the impedance boundary condition is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
appl.bnd.portnr	expression	1	Port number.
appl.bnd.inport	0   1	0	Wave excitation at this port
appl.bnd.modespec	userdef   rect   circular   coaxial   numeric	userdef	Mode specification
appl.bnd.rectmodetype	TE   TM	TE	Mode type for rectangular port
appl.bnd.usermodetype	TE   TM   TEM	TE	Mode type for user defined mode
appl.bnd.nummodetype	auto   TE   TM   TEM	auto	Mode type for numeric port
appl.bnd.modenum	expression	10	Mode number for rectangular port
appl.bnd.circmodenum	expression	11	Mode number for circular port
appl.bnd.nu0	expression	0	Reference frequency
appl.bnd.nucutoff	expression	0	Cutoff frequency
appl.bnd.cutoffforbeta	cutoff   beta	beta	Should the cutoff frequency of beta and nu0 be specified

<b>FIELD</b>	<b>VALUE</b>	<b>DEFAULT</b>	<b>DESCRIPTION</b>
<code>appl.bnd.applmode</code>	expression	0	The application mode to pick numeric data from
<code>appl.bnd.sparammethod</code>	field   energy	field	Method to calculate S-parameter output data
<code>appl.bnd.type</code>	string	E0   cont	The type of boundary condition

`appl.bnd.type` takes the default value E0 on exterior boundaries and cont on interior boundaries.



## BOUNDARY CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field	H	H0	Magnetic field
Surface current	Js	Js0	Surface current density
Perfect magnetic conductor	H0		
Electric field	E	E0	Electric field
Magnetic potential	A	A0	Magnetic potential
Perfect electric conductor	E0		
Continuity	cont		
Low-reflecting	NR	H0 E0 Irsource	Magnetic field Electric field E/H/both as source
Matched boundary	M	E0 H0 beta mbsource	Electric field Magnetic field Propagation constant E or H as source
Impedance boundary condition	IM	Es matparams nbnd sigmabnd murbnd epsilonbnd	Surface electric field Input parameters Refractive index Conductivity Relative permeability Relative permittivity
Transition boundary condition	sIM	Es eta	Surface electric field Surface impedance
Port	port	portnr inport modespec rectmodetype usermodetype nummodetype  modenum nu0 nucutoff cutoffforbeta applmode	Port number Wave excitation at port Mode specification Mode type for rect. Mode type for userdef Mode type for num. Mode number Reference frequency Cutoff frequency Cutoff or beta, nu0 Appl. mode with data

The **Type** column indicates the possible values for `app1.bnd.type`.

## EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.edg.I0	expression	0	Current
appl.edg.type	string	cont	The type of edge condition

## EDGE CONDITIONS

DESCRIPTION	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Current	I	I0	Current
Perfect electric conductor	E0		
Continuity	cont		

### *In-Plane and Axisymmetric Waves*

## DEPENDENT VARIABLES

Variables for In-Plane Waves.

FIELD	DEFAULT	DESCRIPTION
appl.dim	{ 'Ez' 'Hz' 'Ax' 'Ay' 'Az' }	Electric and magnetic field, $z$ components and magnetic potential

Variables for Axisymmetric Waves.

FIELD	DEFAULT	DESCRIPTION
appl.dim	{ 'Ephi' 'Hphi' 'Ar' 'Aphi' 'Az' }	Electric and magnetic field, $\phi$ components, Magnetic potential vector $\phi$ component

All variables must be given, including the once that are not used when doing TE or TM wave analysis.

## APPLICATION MODE CLASS AND NAME

Class and name for In-Plane Waves.

FIELD	VALUE	DEFAULT
appl.mode.class	InPlaneWaves	
appl.name		rfwe   rfwh   rfweh

Class and name for Axisymmetric Waves.

FIELD	VALUE	DEFAULT
appl.mode.class	AxisymmetricWaves	
appl.name		rfwe   rfwh   rfweh

The default for appl.name is rfwe for TE waves, rfwh for TM waves, and rfweh for hybrid waves.

## SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength

## PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	harmonic   eigen   trans	harmonic	Analysis type, harmonic propagation, eigenfrequency, transient propagation
appl.prop.field	TE   TM   TETM	TE	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.inputvar	nu   lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.eigtype	lambda   freq	freq	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or the eigenfrequency. This property only applies when working in the user interface.
appl.prop.elemdefault	Vec1   Vec2   Vec3   Vec1_lag1   Vec2_lag2   Vec3_lag3   Lag1   Lag2   Lag3   Lag4   Lag5	Vec2   Vec2_lag2   Lag2	Default element type. Vector elements or Lagrange elements of order 1 to 5.
appl.prop.weakconstr	off   ideal   non-ideal	off	The type of weak constraints to use.

#### SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma	expression   cell array of expressions	0	Electric conductivity
appl.equ.mur	expression   cell array of expressions	1	Relative permeability
appl.equ.epsilonr	expression   cell array of expressions	1	Relative permittivity
appl.equ.n	expression   cell array of expressions	1	Refractive index
appl.equ.matparams	n   epsr	epsr	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
appl.equ.M	cell array of expressions	0	Magnetization
appl.equ.Br	cell array of expressions	0	Remanent flux density

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.P	cell array of expressions	0	Electric polarization
appl.equ.Dr	cell array of expressions	0	Remanent displacement
appl.equ.magconstrel	mur   M   Br	mur	Magnetic constitutive relation
appl.equ.elconstrel	epsr   P   Dr	epsr	Electric constitutive relation

#### BOUNDARY VARIABLES

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.H0		cell array of expressions	0	Magnetic field
appl.bnd.Js0z	In-Plane	expression	0	Surface current density
appl.bnd.Js0phi	Axisymmetric	expression	0	Surface current density
appl.bnd.E0		cell array of expressions	0	Electric field
appl.bnd.A0		cell array of expressions	0	Magnetic potential
appl.bnd.eta		expression	1	Surface impedance
appl.bnd.Esz	In-Plane	expression	0	Surface electric field
appl.bnd.Esphi	Axisymmetric	expression	0	Surface electric field
appl.bnd.sigtabnd		expression   cell array of expressions	0	Electric conductivity
appl.bnd.murbnd		expression   cell array of expressions	1	Relative permeability
appl.bnd.epsilonrbnd		expression   cell array of expressions	1	Relative permittivity
appl.bnd.nrbnd		expression   cell array of expressions	1	Refractive index

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.lrsource		E   H   EH	E	Source field for the low-reflecting boundary condition, electric, magnetic, or general
appl.bnd.betaTE		expression	0	Propagation constant for TE waves
appl.bnd.betaTM		expression	0	Propagation constant for TM waves
appl.bnd.betaport		expression	0	Propagation constant in Port boundary condition
appl.bnd.matparams		n   epsr	epsr	Indicates if the material in the impedance boundary condition is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.
appl.bnd.portnr		expression	1	Port number.
appl.bnd.inport		0   1	0	Wave excitation at this port
appl.bnd.modespec	In-Plane	userdef   analytic   numeric	userdef	Mode specification
appl.bnd.modespec	Axisymmetric	userdef   cylindrical   coaxial   numeric	userdef	Mode specification
appl.bnd.rectmodetype		TE   TM	TE	Mode type for rectangular port
appl.bnd.usermodetype		TE   TM	TE	Mode type for user defined mode
appl.bnd.modenum		1   2   3   4   5   6   7   8   9   10	1	Mode number for analytic port
appl.bnd.nu0		expression	0	Reference frequency
appl.bnd.nucutoff		expression	0	Cutoff frequency

FIELD	APPL. MODE	VALUE	DEFAULT	DESCRIPTION
appl.bnd.cutoffforbeta		cutoff   beta	beta	Should the cutoff frequency of beta and nu0 be specified
appl.bnd.applmode		expression	0	The application mode to pick numeric data from
appl.bnd.type		string	E0   cont	The type of boundary condition

appl.bnd.type takes the default value E0 on exterior boundaries and cont on interior boundaries.

### BOUNDARY CONDITIONS

The variables H0 and E0 are always vectors of length 3, also in the TE and TM cases when not all vector components are used in the boundary conditions.

DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Magnetic field		TE	H	H0 (in-plane components)	Magnetic field
Magnetic field		TM	H	H0 (out-of-plane component)	Magnetic field
Magnetic field (exterior boundaries)		hybrid	H	H0	Magnetic field
Magnetic field (interior boundaries)		hybrid	HH0	H0 (out-of-plane component)	Magnetic field
Surface current	In-Plane	TE, hybrid	Js	Js0z	Surface current density
Surface current	Axisymmetric	TE, hybrid	Js	Js0phi	Surface current density
Perfect magnetic conductor			H0		
Electric field		TE	E	E0 (in-plane components)	Electric field
Electric field		TM	E	E0 (out-of-plane component)	Electric field
Electric field (exterior boundaries)		hybrid	E	E0	Electric field

DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Electric field (interior boundaries)		hybrid	EE0	E0 (out-of-plane component)	Electric field
Magnetic potential		TE	A	A0 (out-of-plane components)	Magnetic potential
Magnetic potential		TM	A	A0 (in-plane component)	Magnetic potential
Magnetic potential		hybrid	A	A0	Magnetic potential
Perfect electric conductor			E0		
Electric and magnetic field		hybrid	EH	H0 E0 (out-of-plane components)	Magnetic field Electric field
Neutral		hybrid	n		
Continuity			cont		
Low-reflecting		TE	NR	E0 (out-of-plane component)	Electric field
Low-reflecting		TM	NR	H0 (out-of-plane component)	Magnetic field
Low-reflecting		hybrid	NR	H0 E0 Irsource	Magnetic field Electric field E/H/both as source
Matched boundary		TE	M	E0 (out-of-plane component) betaTE	Electric field Propagation constant
Matched boundary		TM	M	H0 (out-of-plane component) betaTM	Magnetic field Propagation constant



DESCRIPTION	APPL. MODE	WAVE TYPE	TYPE	APPLICABLE VARIABLES	VARIABLE DESCRIPTION
Matched boundary		hybrid	M	H0 (out-of-plane component) E0 (out-of-plane component) betaTE  betaTM	Magnetic field  Electric field  propagation constant TE waves propagation constant TM waves
Impedance boundary condition			IM	Es matparams nbnd sigmabnd murbnd epsilonbnd	Surface electric field Input parameters Refractive index Conductivity Relative permeability Relative permittivity
Transition boundary condition			sIM	Es eta	Surface electric field Surface impedance
Port			port	portnr inport  modespec rectmodetype usermodetype  modenum nu0 nucutoff cutoffforbeta applmode	Port number Wave excitation at port Mode specification Mode type for analytic Mode type for userdef Mode number Reference frequency Cutoff frequency Cutoff or beta, nu0 Appl. mode with data
Axial symmetry			ax		

The **Type** column indicates the possible values for `appl.bnd.type`.

#### POINT VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
<code>appl.pnt.I0</code>	expression	0	Current

**DEPENDENT VARIABLES**

FIELD	DEFAULT	DESCRIPTION
appl.dim	{ 'Ex' 'Ey' 'Ez' 'Hx' 'Hy' 'Hz' 'ex' 'ey' 'ez' 'hx' 'hy' 'hz' }	Electric and magnetic field

All twelve variables must be given, including the ones that are not used. The table below shows which variables that are used in each equation:

FORMULATION	VARIABLES	DESCRIPTION
TE	H <sub>z</sub>	Magnetic field, <i>z</i> component
TM	E <sub>z</sub>	Electric field, <i>z</i> component
Three-component formulation, <b>H</b> dependent variable, mode analysis	H <sub>x</sub> , H <sub>y</sub> , h <sub>z</sub>	Magnetic field, in-plane components, $H_z = \alpha h_z$
Three-component formulation, <b>H</b> dependent variable, eigenfrequency	H <sub>x</sub> , H <sub>y</sub> , h <sub>z</sub>	Magnetic field, in-plane components, $H_z = \alpha h_z$
Two-component formulation, <b>H</b> dependent variable	H <sub>x</sub> , H <sub>y</sub>	Magnetic field, <i>x</i> and <i>y</i> components
Three-component formulation, <b>E</b> dependent variable, mode analysis	E <sub>x</sub> , E <sub>y</sub> , e <sub>z</sub>	Electric field, in-plane components, $E_z = \alpha e_z$
Three-component formulation, <b>E</b> dependent variable, eigenfrequency	E <sub>x</sub> , E <sub>y</sub> , e <sub>z</sub>	Electric field, in-plane components, $E_z = \alpha e_z$
Two-component formulation, <b>E</b> dependent variable	E <sub>x</sub> , E <sub>y</sub>	Electric field, <i>x</i> and <i>y</i> components

## APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	PerpendicularWaves	
appl.name		rfwev   rfwhv   rfwv

The default value for `appl.name` is `rfwev` for TE waves, `rfwhv` for TM waves, and `rfwv` for hybrid mode waves.

## SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength
appl.var.beta	30	Propagation constant

## PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.analysis	mode   eigen	mode	Analysis type, mode analysis or eigenfrequency
appl.prop.field	TE   TM   TETM	TETM	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.solvefor	E   H	H	Which field to use as dependent variable
appl.prop.comps	2   3	3	Which field components to use as dependent variables, in-plane or all three components
appl.prop.inputvar	nu   lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.eigtype	lambda   freq   propconst   modeind	modeind   freq	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or some other quantity. This property only applies when working in the user interface.
appl.prop.elemdefault	Vec1_lag1   Vec2_lag2   Vec3_lag3   Lag1   Lag2   Lag3   Lag4   Lag5	Vec2_lag2   Lag2	Default element type. Vector or Lagrange elements of order 1 to 5.

### SUBDOMAIN VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.equ.sigma	expression   cell array of expressions	0	Electric conductivity
appl.equ.mur	expression   cell array of expressions	1	Relative permeability
appl.equ.epsilonr	expression   cell array of expressions	1	Relative permittivity
appl.equ.n	expression   cell array of expressions	1	Refractive index
appl.equ.matparams	n   epsr	epsr	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.

## BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.bnd.type	string	E0   H0   cont	Boundary condition type

appl.bnd.type takes the default value E0 on exterior boundaries except in the two-component magnetic field formulation when it takes the default H0. On interior boundaries the default value is cont.

## BOUNDARY CONDITIONS

DESCRIPTION	TYPE
Perfect magnetic conductor	H0
Perfect electric conductor	E0
Continuity	cont

The **Type** column indicates the possible values for appl.bnd.type.

## *Boundary Mode Analysis*

## DEPENDENT VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.dim	{'en' 'hn' 'ex' 'ey' 'ez' 'hx' 'hy' 'hz'}	Electric and magnetic field

All eight variables must be given, including the ones that are not used.

## APPLICATION MODE CLASS AND NAME

FIELD	VALUE	DEFAULT
appl.mode.class	BoundaryModeAnalysis	
appl.name		r fwb

## SCALAR VARIABLES

FIELD	DEFAULT	DESCRIPTION
appl.var.epsilon0	8.854187817e-12	Permittivity of vacuum
appl.var.mu0	4*pi*1e-7	Permeability of vacuum

FIELD	DEFAULT	DESCRIPTION
appl.var.nu	1e9	Frequency
appl.var.lambda0	0.3	Free space wavelength

### PROPERTIES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.prop.field	TE   TM   TETM	TETM	Which type of waves to handle, TE, TM, or hybrid waves
appl.prop.solvefor	E   H	H	Which field to use as dependent variable
appl.prop.inputvar	nu   lambda	nu	Which property to use when characterizing the wave, the frequency or wavelength.
appl.prop.eigtype	lambda   propconst   modeind	modeind	Should the parameters to the eigenvalue solver be given in terms of the eigenvalue or some other quantity. This property only applies when working in the user interface.
appl.prop.elemdefault	Vec1_lag1   Vec2_lag2   Vec3_lag3   Lag1   Lag2   Lag3   Lag4   Lag5	Vec2_lag2   Lag2	Default element type. Vector or Lagrange elements of order 1 to 5.

### BOUNDARY VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
appl.bnd.sigma	expression	0	Electric conductivity
appl.bnd.mur	expression	1	Relative permeability
appl.bnd.epsilonr	expression	1	Relative permittivity

FIELD	VALUE	DEFAULT	DESCRIPTION
app1.bnd.n	expression	1	Refractive index
app1.bnd.matparams	n   epsr	epsr	Indicates if the material is specified in terms of the refractive index or in terms of the permittivity, permeability, and conductivity.

#### EDGE VARIABLES

FIELD	VALUE	DEFAULT	DESCRIPTION
app1.edg.type	string	cont	The type of edge condition

#### EDGE CONDITIONS

DESCRIPTION	TYPE
Perfect magnetic conductor	H0
Perfect electric conductor	E0
Continuity at interior edges	cont

The **Type** column indicates the possible values for app1.edg.type.





# Function Reference

This chapter complements the Command Reference chapter of the *COMSOL Multiphysics Reference Guide* by giving detailed reference information about the additional functions for command-line modeling that come with the RF Module.

# Summary of Commands

`sparametermatrix` on page 64

`spiceimport` on page 65

`touchwrite` on page 66

# Commands Grouped by Function

## *S-Parameter Computation*

<b>FUNCTION</b>	<b>PURPOSE</b>
sparametermatrix	Compute the full S-parameter matrix using the port boundary conditions defined in the model.
touchwrite	File export to the Touchstone format

## *File Exchange*

<b>FUNCTION</b>	<b>PURPOSE</b>
spiceimport	Import a SPICE netlist as system of ODEs

**Purpose** Compute the full S-parameter matrix using the port boundary conditions defined in the model.

**Syntax** `S = sparametermatrix(fem, ...)`

**Description** `S = sparametermatrix(fem, ...)` computes the S-parameter matrix **S** from the model stored in the `fem` structure.

By default, `sparametermatrix` searches for all port boundary conditions and activates all of them, setting each port to input.

If the model in `fem` has *N* ports, `sparametermatrix` computes a *N*-by-*N* S-parameter matrix **S**. A parametric sweep results in a *N*-by-*N*-by-*M* matrix, where *M* is the number of parameters returned by the solver.

Table 4-1 contains the valid property/value pairs for the `sparametermatrix` function.

TABLE 4-1: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
Scale	lin   db	lin	dB or linear scale

`Solver` is a string that states which solver to use. The default solver is `femlin`.

Property value pairs not recognized by `sparametermatrix` are passed on as solver parameters to the solver.

**See Also** `femsolver`, `posteval`, `postint` (in the *COMSOL Multiphysics Command Reference*)

**Purpose** Import an electric circuit from a netlist in the SPICE format.

**Syntax** `fem = spiceimport(filename,...)`

**Description** `fem = spiceimport(filename,...)` reads the netlist `filename` and return an ode structure representing the circuit in the file.

Table 4-2 contains the valid property/value pairs for the `spiceimport` function.

TABLE 4-2: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
Fem	FEM structure		Model to add circuit to
ac	off   on	off	Time harmonic analysis
Suffix	string	cir	Suffix for circuit variables

If the `fem` argument is not supplied `spiceimport` will just add the ode to a new `fem` structure, only containing a point geometry.

More details about the SPICE import can be found in the section “SPICE Circuit Import” on page 85 of the *RF Module User’s Guide*.

**Cautionary** The script is mainly intended for small and simplified circuits coupled to a finite element model.

The SPICE import does not support small-signal models of any semiconductor device models. In a time-harmonic simulation you can only connect sources and passive devices.

- Purpose** File export to the Touchstone format.
- Syntax** `ok = touchwrite(filename, freq, data, ...)`
- Description** `ok= touchwrite(filename, freq, data,...)` exports the frequency-dependent data from an S-parameter analysis stored in `freq` and `data` to a file named `filename`. A full path can be specified in `filename`. Otherwise, the file is placed in the current directory. The argument `data` is an N-by-N-by-length(`freq`) matrix, where N is the number of ports in the analysis. The function `sparametermatrix` can compute the S-parameter data.

Table 4-3 contains the valid property/value pairs for the `touchwrite` function.

TABLE 4-3: VALID PROPERTY/VALUE PAIRS

PROPERTY NAME	PROPERTY VALUE	DEFAULT	DESCRIPTION
Format	DB   MA   RI	MA	The format used for the complex notation in the file
Frequnit	Hz   kHz   MHz   GHz	GHz	The unit used for the frequency
Parameter	S   Y   Z   H   G	S	The parameter type stored in the data argument
Zref	double value	50	The reference impedance in ohms

The format can be specified as pairs of magnitude and angle (MA), magnitude in dB and angle (DB), or as real and imaginary parts (RI).

- See Also** `sparametermatrix`

# I N D E X

- A**
  - appl.assign 33
  - appl.assignsuffix 34
  - appl.bnd 36
  - appl.bnd.ind 37
  - appl.dim 31
  - appl.equ 34
  - appl.equ.ind 37
  - appl.mode 31
  - appl.name 32
  - appl.prop 32
  - appl.prop.elemdefault 33
  - appl.var 33
  - application mode
    - Boundary Mode Analysis (2D) 26
    - Boundary Mode Analysis (3D) 23
    - Electromagnetic Waves (3D) 14
    - Hybrid-Mode Waves (2D axi) 17
    - TE Waves (2D axi) 17
    - TE Waves (2D) 20
    - TM Waves (2D axi) 17
  - application mode class 31
  - application mode properties 32
  - application mode variable 6
  - application scalar variable 33
  - application structure 30
    - axisymmetric 31
    - boundary field 36
    - dimension field 31
    - element property field 33
    - index vector 37
    - mode field 31
    - name field 32
    - property field 32
    - scalar variable field 33
    - subdomain field 34
    - variable name field 33
  - assigned variable name 33
- B**
  - boundary coefficients 37
  - boundary condition 36
  - Boundary Mode Analysis
    - application modes (2D) 26
    - application modes (3D) 23
  - boundary variables 36
- C**
  - cemlumped 64
- D**
  - domain groups 37
  - domain properties 34
- E**
  - Electromagnetic Waves
    - application mode (3D) 14
    - application modes (2D axi) 17
  - electromagnetic waves 8
    - perpendicular 20
- H**
  - Hybrid-Mode Waves (2D) 20
- I**
  - index vector 37
- L**
  - lumped parameter matrix 64
- M**
  - material properties 34
  - multiphysics 31
- P**
  - PDE coefficients 34
  - port 64
  - programming language 30
- S**
  - subdomain settings 34
- T**
  - TM Waves (2D) 20
  - typographical conventions 2
- V**
  - variables
    - application mode 6
    - application scalar 33
    - assigned names 33
    - boundary 36

