

Chapter 11

VERSION 6.4S (Second-order module)

WAMIT Version 6.4S designates a program which extends the capabilities of WAMIT Version 6.4 to include the analysis of the second-order hydrodynamic interaction between waves and one or more structures. V6.4S has all of the capabilities of V6.4, with the exceptions listed below. The extended capabilities of V6.4S include evaluation of the sum- and difference-frequency components of the second-order forces and moments (Quadratic Transfer Functions, or QTF), the second-order hydrodynamic pressure on the body and in the fluid domain, the second-order wave elevation and the second-order Response Amplitude Operator (RAO), in the presence of bichromatic and bidirectional waves. The second-order forces ¹ can be evaluated by both indirect and direct methods, analogous to the linear forces evaluated from Haskind relations and from diffraction pressure. The structures can be freely floating, submerged, constrained or fixed.

The second-order solutions are not available in the situations listed below: i) the generalized mode (NEWMDS) option is not allowed, ii) fixed/free modes option is not allowed, iii) walls are not allowed and iv) the zero-thickness structure is not allowed. The effect of the external constraints can be accounted for partially when the second-order RAO is evaluated. Specifically, only the effect of the constraints which is linearly proportional to the second-order motion RAO can be accounted for using the external force matrices of the Alternative 2 format of the FRC file. Quadratic terms which include the effect of the constraints due to the linear RAO are not included.

- The major updates in V6.4S from the previous version, V6.1S, are as follow.
 1. Second-order analysis can be made for vessels with internal tanks with free surfaces.
 2. The method using control surfaces, implemented for the evaluation of the mean drift forces, is extended for the evaluation of the quadratic forces. Using this option, the quadratic forces may be evaluated more accurately than using the conventional pressure integration.

¹It is understood forces include both forces and moments throughout this chapter.

3. In V6.1S, when ILOWHI=1, the second-order forcing terms are evaluated on the centroids of flat panels approximating the body and free surfaces. In V6.4S, they are evaluated on the centroids of subdivided areas on the exact body and free surfaces without approximation.
4. Various options of geometry definitions can be used to describe the free surface geometry.
5. V6.4S is compiled using Intel Fortran V12.1. It is available in a 64-bit executable form, eliminating the limit of the usage of RAM inherent in 32-bit Windows applications.

The rest of this chapter describes the input and output of V6.4S which differ from those of V6.4. It is recommended to review the previous chapters, if users are not familiar with V6.4. The description of the theoretical background of the second-order analysis can be found in References [9], [17], [26] and other documents cited therein.

All input files for V6.4 are required in order to run V6.4S. These include CFG, GDF, POT, FRC, optional FNames.WAM as well as optional SPL when ILOWHI=1. These files can be used without modifications, when the linear quantities and mean drift force are evaluated. To evaluate the second-order quantities, new parameters must be added to the CFG (or CONFIG.WAM) and FRC files. In addition, up to three new files must be prepared. These are the Potential Control File 2 (PT2), the Free Surface Geometry Data File (FDF) and the Spline Control File (FDF.SPL). Extensions, .pt2, .fdf and _fdf.spl are reserved for these three additional input files. The filename of FDF.SPL should be the same as the corresponding FDF filename. For example, for a FDF file with the complete filename *example.fdf*, the corresponding FDF.SPL file should be named as *example_fdf.spl*. The filenames of PT2 and FDF, including the extensions, may be specified in FNames.WAM, in order to avoid interactive input of these filenames during execution of WAMIT.

New parameters in the CFG and FRC files and the parameters in the new input files are described next.

11.1 THE CONFIGURATION FILE (CFG)

The parameter **I2ND** must be specified to evaluate the second-order solution.

I2ND=0: Do not compute the second-order solution (0 is the default value).

I2ND=1: Compute the second-order solution for the sum- and difference-frequencies listed in the PT2 file.

When I2ND=1, the dimension of the **NOOUT** array parameter in the CFG file must be increased from 9 to 16. The last 7 indices, between 10 and 16, correspond to seven second-order quantities described in the next section. For example, by specifying

NOOUT=1 1 1 1 0 1 1 1 1 1 1 0 1 1 1

all available linear and second-order quantities are output in the OUT file except options 5 and 13 which correspond to the linear and the second-order pressure and velocity on the body surface.

ISOR=1 must be specified, when **ILOWHI**=0 and **I2ND**=1. Otherwise, execution of the program is aborted with an appropriate error message.

- **NPTANKFS** is an integer array specifying indices of the panels or patches on the free surface over each internal tank. This parameter is specified in the same manner as **NPTANK** (see Sections 3.7 and 10.7). Thus the data in this array are in pairs, denoting the first and last index of the panels or patches on the tanks. If **NBODY**>1, the body number of each body which contains internal tanks must be appended to the parameter name such as **NPTANKFS**(**IB**), where **IB** is the body index.

11.2 THE FORCE CONTROL FILE (FRC)

The input parameters in the FRC files are described in Chapters 3 and 8. For the second analysis, the dimension of the array **IOPTN**, on the second line of the FRC files, should be increased to 16 from 9. The last 7 elements of the **IOPTN** array correspond to second-order hydrodynamic parameters.

The first two lines of the FRC file are shown below.

```
header
IOPTN(1) . . . IOPTN(9) IOPTN(10) IOPTN(11) IOPTN(12) . . . IOPTN(16)
.
.
```

The **IOPTN** array can be specified on one line or on multiple lines without space between the lines. When **I2ND**=0, only the first 9 elements are read in the program and it is not necessary to specify the last 7 elements. If all 16 elements are specified with 0 for the last 7 elements, the last 7 elements must be on the same line with **IOPTN**(9).

Descriptions of the output options and numeric file names for **I**=10, . . . , 16 are as follows (Descriptions of the output options, corresponding to **IOPTN**(**I**) for **I**=1, . . . , 9, can be found in Section 3.3.):

Option	Description	File name
10	Quadratic second-order forces by pressure integration	<i>frc.10s, frc.10d</i>
■ 10	Quadratic second-order forces by control surface integration	<i>frc.qcs, frc.qcd</i>
11	Total second-order forces by indirect method	<i>frc.11s, frc.11d</i>
12	Total second-order forces by direct method	<i>frc.12s, frc.12d</i>
13	Second-order hydrodynamic pressure on the body	<i>frc.13s, frc.13d</i>
14	Second-order hydrodynamic pressure in the fluid	<i>frc.14s, frc.14d</i>
15	Second-order wave elevation	<i>frc.15s, frc.15d</i>
16	Second-order response amplitude operator	<i>frc.16s, frc.16d</i>

The last letters, ‘s’ and ‘d’, of the numeric filenames signify that the files contain the output for sum-frequencies and difference-frequencies, respectively.

The evaluation and output of the above quantities are in accordance with the following choice of the corresponding index:

IOPTN(I) = 0 : do not output parameters associated with option I.

IOPTN(I) = 1 : do output parameters associated with option I.

IOPTN(16) may have an additional value as listed below:

IOPTN(16) = 0 : do not output the second-order RAO.

IOPTN(16) = 1 : do output the second-order RAO computed using the ‘indirect’ exciting force.

IOPTN(16) = 2 : do output the second-order RAO computed using the ‘direct’ exciting force.

- When IOPTN(10)=1 and ICTRSURF=0, the quadratic forces are evaluated by direct pressure integration only. The corresponding numeric output files are .10s and .10d. When IOPTN(10)=1 and ICTRSURF=1, the quadratic forces are evaluated by control surface integration in addition to pressure integration. These forces are contained in the numeric output files .qcs and .qcd.

The total second-order forces, in the output options 11 and 12, are the sum of the quadratic forces evaluated in option 10 and the second-order hydrodynamic forces due to the second-order velocity potential. The latter is denoted as the second-order potential forces. The second-order potential forces are evaluated by ‘indirect’ method in the output option 11 and by ‘direct’ method in the output option 12. As they are the same forces computed by different approaches, they must converge to each other. The descriptions of two methods can be found in References [9] and [17].

Depending on the value of the parameter ICTRSURF, the total forces in the output options 11 and 12 contain the quadratic forces by pressure integration (when ICTRSURF=0) or by control surface integration (when ICTRSURF=1).

When IOPTN(14)=1 or IOPTN(15)=1, the number of field points NFIELD and their Cartesian coordinates XFIELD should be specified in the FRC file. When IOPTN(15)=1, the second-order wave elevation is computed for the field points on the free surface. A point is considered on the free surface, if its vertical distance from the free surface, normalized by ULEN, is less than 10^{-6} .

When two linear wave periods are the same, the quadratic forces for the difference frequency are the same as the mean drift forces. The second-order potential forces and the second-order RAO are trivial in this case.

11.3 THE POTENTIAL CONTROL FILE 2 (PT2)

The PT2 file contains two sets of parameters. One specifies pairs of linear waves, identified by their periods and wave headings, for which the second-order solution is computed. The other specifies mode indices for which the second-order forces and RAOs are output.

The input data in the Potential Control File 2 (PT2) are shown below:

```
header
IRAD2(1) IDIF2(1)
MODE2(1,1) MODE2(2,1) MODE2(3,1) MODE2(4,1) MODE2(5,1) MODE2(6,1)
IRAD2(2) IDIF2(2)
MODE2(1,2) MODE2(2,2) MODE2(3,2) MODE2(4,2) MODE2(5,2) MODE2(6,2)
.
.
IRAD2(NBODY) IDIF2(NBODY)
MODE2(1,NBODY) MODE2(2,NBODY) MODE2(3,NBODY) ... MODE2(6,NBODY)
IXSUM IXDIF
NSUMP
IPER(1) JPER(1) NBETA2(1)
IBETA(1,1) JBETA(1,1)
.
IBETA(1,NBETA2(1)) JBETA(1,NBETA2(1))
.
.
.
IPER(NSUMP) JPER(NSUMP) NBETA2(NSUMP)
IBETA(NSUMP,1) JBETA(NSUMP,1)
.
IBETA(NSUMP,NBETA2(NSUMP)) JBETA(NSUMP,NBETA2(NSUMP))
NDIFP
IPER(NSUMP+1) JPER(NSUMP+1) NBETA2(NSUMP+1)
IBETA(NSUMP+1,1) JBETA(NSUMP+1,1)
.
IBETA(NSUMP+1,NBETA2(NSUMP+1)) JBETA(NSUMP+1,NBETA2(NSUMP+1))
.
.
.
IPER(NPER2) JPER(NPER2) NBETA2(NPER2)
IBETA(NPER2,1) JBETA(NPER2,1)
.
IBETA(NPER2,NBETA2(NPER2)) JBETA(NPER2,NBETA2(NPER2))
```

IRAD2(N) and **IDIF2(N)** are indices used to specify the components of the radiation and diffraction problems to be solved at the specified second-order frequencies. The following

options are available depending on the values of IRAD2(N) and IDIF2(N):

IRAD2(N)=1 Solve for the radiation velocity potentials due to all six rigid-body modes of motion of N-th body

IRAD2(N)= 0 Solve the radiation problem only for those modes of motion specified by setting the elements of the array MODE2(I)=1 (see below).

IRAD2(N)=-1 Do not solve the radiation problem due to the motion of N-th body.

IDIF2(N)=1: Solve for all diffraction components.

IDIF2(N)=0: Solve for the diffraction components required to evaluate the second-order forces in the modes specified by MODE2(I)=1.

IDIF2(N)=-1: Do not solve for the second-order diffraction problem.

MODE2(I) is a six-element array of indices, assigned for each body, where I=1,2,3,4,5,6 correspond to the surge, sway, heave, roll, pitch and yaw. Each of these six elements should be set equal to 0 or 1. The components of the second-order diffraction and radiation solutions corresponding to the modes with MODE2(I)=1 are computed and the second-order forces and RAOs for these modes are output.

IXSUM, IXDIF are indices choosing how to specify the list of pairs of the linear waves for which the second-order solutions are computed.

IXSUM=0: Do not compute the sum-frequency second-order solution.

IXSUM=1: Compute the sum-frequency second-order solution only for selected combinations of the wave periods and headings listed below.

IXSUM=2: Compute the sum-frequency second-order solution for all combinations of the wave periods and headings (PER and BETA) listed in the POT file.

IXDIF=0: Do not compute the difference-frequency second-order solution.

IXDIF=1: Compute the difference-frequency second-order solution only for selected combinations of the wave periods and headings listed in the PT2 file.

IXDIF=2: Compute the difference-frequency second-order solution for all combinations of the wave periods and headings (PER and BETA) listed in the POT file.

When IXSUM and IXDIF are 0 or 2, no additional input parameters are required in the PT2 file. When IXSUM=1 or IXDIF=1, additional input parameters follow right after IXSUM or IXDIF in the format shown above.

NSUMP is the total number of combinations of wave periods for which the sum-frequency solution is evaluated.

NDIFP is the total number of combinations of wave periods for which the difference-frequency solution is evaluated.

In the PT2 file above, NSUMP+NDIFP is denoted by NPER2 in brief.

IPER, JPER are indices which identify the periods of two linear waves in the array PER in the POT file. As many as NSUMP pairs of IPER and JPER should follow after the

parameter NSUMP and NDIFP pairs of IPER and JPER after the parameter NDIFP.

NBETA2 is the total number of wave-heading pairs for each pair of period combination, IPER and JPER.

IBETA, JBETA are indices which identify the wave headings of two linear waves in the array BETA in the POT file.

11.4 FREE SURFACE DATA FILE (FDF)

A FDF file must be prepared, unless IOPTN(I)=0 for I=11,12,... and 16.

The FDF file is used to input all requisite geometric data of the free surface exterior to the bodies for the integration of the quadratic forcing over the entire free surface. When the bodies have internal tanks with free surfaces, the geometric data of the internal free surface may be included in the FDF file.

To perform the integration efficiently, different quadrature schemes are used depending on the proximity of the domain to the bodies. The free surface is divided into three regions using two circles of radii, **RINNER** and R_{part} where $RINNER \leq R_{part}$. Both circles are centered at the origin of the global coordinates system. Three regions are denoted by the **inner region, intermediate region** and **far-field**. The inner region is inside a circle of radius RINNER and exterior to the bodies. It also includes the free surface in internal tanks. The intermediate region is the annulus between RINNER and R_{part} . The far-field is the entire free surface outside a circle of radius R_{part} . Use of the intermediate region is optional and, when it is omitted, $R_{part}=RINNER$.

The geometry of the inner region can be represented in the similar manner as the body geometries in the GDF file. An important difference is the free surface geometry should be defined in terms of **global coordinates system**. When ILOWHI=0, the region is represented by an ensemble of quadrilateral panels specified by the horizontal coordinates of the vertices of the panels. When ILOWHI=1, the patches on the inner region can be described by B-splines, explicit formulae or using MultiSurf models. The vertical coordinates of the panels or patches are assigned in the program and they are not required. They are set to zero for the exterior free surface and to the highest vertical coordinates of the panels or patches on each tank wall.

The intermediate region can be represented with one or more sub-annuli of equal width. Specifically, the intermediate region is defined by three input parameters as described in detail later in this section. They are RINNER, **NAL** and **DELR** where NAL is the number of sub-annuli and DELR is the width of sub-annuli. The outer circle of the intermediate region is determined by $R_{part}=RINNER+NAL*DELR$. The integration of the free surface forcing over each sub-annulus is performed using the Gauss Chebyshev quadrature in the azimuthal direction and the Gauss Legendre quadrature in the radial direction.

In the far-field, exterior to a circle of radius R_{part} , integration is performed in a semi-analytic manner using asymptotic approximations of the integrand.

Except the parameters defining the inner region, other input parameters are common for all formats of the FDF file. These common parameters of the FDF file are described below.

```
header  
RINNER  
(line 3)  
NAL DELR NCIRE NGSP  
(line 5)  
.  
.
```

The parameters on lines 3, 5 and below are relevant to the definition of the inner region using panels or patches. These parameters differ between different geometric representations of the inner region and they are described in the subsequent sections.

header denotes a one-line ASCII header dimensioned CHARACTER 72. This line is available for the user to insert a brief description of the file.

RINNER is the dimensional radius of the inner circle with the center at the origin of the global coordinates system. RINNER is in the same unit as the length ULEN in the GDF file.

NAL is the total number of sub-annuli of same thickness (or width) on the intermediate annular region. When NAL=0, the parameters DELR, NCIRE and NGSP are not required.

DELR is the dimensional width of a sub-annulus, in the same unit as ULEN.

NCIRE is the integer exponent of 2. The number of nodes is equal to $2^{\text{NCIRE}} + 1$ in the azimuthal integration based on Gauss-Chebyshev quadrature.

NGSP is the number of nodes used for the Gauss-Legendre quadrature in radial direction on each sub-annulus.

When NBODY=1, the geometric data in the inner region of the FDF file should contains one quadrant of, a half of, or the entire free surface depending on the symmetry of the problem. When NBODY > 1, the entire inner region should be included in the FDF file regardless of the symmetry of the individual bodies. Same interpretation is applied to the parameter NCIRE which assigns the number of nodes on a quarter of, a half of or the whole circumference.

A guidance to estimate RINNER, NAL and DELR is provided in Section 11.8. To determine appropriate values of NCIRE and NGSP, it is advised to increase these parameters until the computational results are consistent. To determine proper vaules for NCIRE and NGSP on a sub-annulus, the panels or patches in the inner region may be omitted. Though the computational results are not physically correct because the free surface forcing in the inner region is ignored, they can be used to efficiently determine adequacy of NCIRE and NGSP parameters for the integration of the forcing in the intermediate region.

In the following sections, various formats of the FDF file are presented.

11.5 FDF FOR THE LOW-ORDER METHOD (ILOWHI=0)

Three options are available to describe the inner region for ILOWHI=0 as shown below.

11.5.1 INNER REGION REPRESENTED BY PANELS

In this option, the inner region of the free surface is represented by an ensemble of connected four-sided facets in a similar manner as the body surface is represented by panels. Three major differences to the GDF file are i) the vertical coordinates of the free surface are assigned in the program and they should not be included in the FDF file, ii) there is no preference in the vertex ordering and both clockwise and anti-clockwise direction is acceptable and iii) the format to specify the coordinates of the vertices is different.

The complete data in the FDF file are listed below.

```
header
RINNER
NPF NTCL
NAL DELR NCIRE NGSP
VERX(1,1) VERX(2,1) VERX(3,1) VERX(4,1)
VERY(1,1) VERY(2,1) VERY(3,1) VERY(4,1)
.
.
.
VERX(1,NPF) VERX(2,NPF) VERX(3,NPF) VERX(4,NPF)
VERY(1,NPF) VERY(2,NPF) VERY(3,NPF) VERY(4,NPF)
```

The descriptions of the parameters on lines 1, 2 and 4 can be found in Section 11.4.

NPF is the total number of free surface panels in the inner region.

NTCL is the total number of line segments of equal length on the inner circle of radius RINNER.

VERX(K,I), K=1,2,3,4 is the dimensional x coordinate of the K-th vertex of the I-th panel, in the global coordinates system.

VERY(K,I), K=1,2,3,4 is the dimensional y coordinate of the K-th vertex of the I-th panel, in the global coordinates system

- When the internal tanks are present and the panels on the internal free surface are also specified in the global coordinates system.

■ 11.5.2 AUTOMATIC DEFINITION OF INNER REGION

In this option, the inner region is defined automatically without specifying panels. To invoke this option, -1 should be specified for **NPF**. It is followed by a real parameter **SCALE**. The complete input data are as follow.

```
header
RINNER
-1 SCALE
NAL DELR NCIRE NGSP
```

The descriptions of the parameters on lines 1, 2 and 4 can be found in Section 11.4.

NPF=-1 should be specified to activate automatic subdivision of the inner region into panels.

SCALE is a real number used as a scaling factor of the size of the panels in the inner region relative to the average length of the waterline panels on the body. For example, if **SCALE**=1.5, the length scale of free surface panels will be 1.5 times the average length of the sides of the body panels which form the waterlines.

When there are multiple waterlines, the average length of waterline segments should be smaller than a half of the minimum distance between two waterlines in order to use this option. This requires sufficiently small waterline panels on the body, when the gap between the waterlines are small. In this case, a large value of **SCALE** may be used to avoid unnecessarily small free surface panels on the inner region.

■ 11.5.3 INNER REGION REPRESENTED BY MULTISURF MODELS

MultiSurf users may create a MultiSurf model, MS2, containing the inner region of the free surface, and discretize the inner region and inner circle with an appropriate distribution of panels and the line segments. The number of panels and line segments correspond to the parameters **NPF** and **NTCL** described in the previous section.

The panel vertices and the parameters **NPF** and **NTCL** may be exported to a FDF file, from MultiSurf, in the format described in Section 11.5.1. Alternatively the name of MultiSurf model, a .ms2 file, can be specified in the FDF file instead of the panel vertices. This format will be referred to as the short form FDF file. In order to use the short form, it is required to install rg2wamit.dll and rgkernel.dll as explained in Appendix C.

The short form FDF input file should be in the following format:

```
header
RINNER
-2 NTCL
NAL DELR NCIRE NGSP
1 (NLINES)
(path) filename.ms2
```

The descriptions of the parameters on lines 1, 2 and 4 can be found in Section 11.4.

NPF=-2 should be specified on the 3rd line as shown above.

NLINES on the 5th line is the number of subsequent lines on which the name of the .ms2 file containing the inner region of the free surface and other relevant parameters of the

model.

filename.ms2 on the 6th line is the name of a MultiSurf model.

When a short form FDF file is used, the geometric data of the MultiSurf model is exported to an auxiliary file *fdf_ms2.fdf*, where *fdf* denotes the name of the short form FDF file. This file contains the panel vertices and all other input parameters in the FDF file in the format shown Section 11.5.1.

■ 11.6 FDF FOR THE HIGHER ORDER METHOD (ILOWHI=1)

When ILOWHI=1, the geometry of the inner region of the free surface can be represented by B-splines, MultiSurf models, or explicit analytical formulae. The first part of the FDF file, shown below, is identical for all representations.

```
header
RINNER
NPATCHF NTCLH
NAL DELR NCIRE NGSP
IFSDEF PANSIZF
```

The description of the parameters **RINNER**, **NAL**, **DELR**, **NCIRE** and **NGSP** and the header line can be found in Section 11.4 and other parameters are described below.

NPATCHF is the total number of patches on the inner region.

NTCLH is the total number of segments of equal arc-length on the inner circle. A conservative estimation of required NTCLH is to divide the circumference of the inner circle of radius RINNER with PANSIZF, which is described below, or the average length of the subdivisions on the body surface.

IFSDEF is an integer parameter which is used to specify the manner in which the geometry of the inner region is defined.

IFSDEF < 0: The geometry of the inner region is represented explicitly by a special subroutine containing analytic formulae, with optional data in the FDF file.

IFSDEF = 1: The geometry of the inner region is represented by B-splines, with corresponding data in the FDF file.

IFSDEF = 2: The geometry of the inner region is defined by inputs MultiSurf models.

PANSIZF PANSIZF is a real parameter.

PANSIZF > 0 : A positive PANSIZF denotes the length scale of the panel subdivision of the patches in the inner region. Automatic subdivision is carried out in the similar manner as PANLE_SIZE is used for the subdivision of the patches on the body surface. In general, PANSIZF should be comparable to PANLE_SIZE.

PANSIZF < 0 : A negative PANSIZF denotes that the subdivision of the patches in the inner region is made using the parameters specified in the *fdf_fdf.spl* file. The *fdf_fdf.spl* file is described in Section 11.7.

11.6.1 INNER REGION REPRESENTED BY B-SPLINES (IFSDEF=1)

Each patch of the inner region is represented by B-spline, in an analogous manner to the representation of the body surface (IGDEF=1). The panel subdivision (knot vector), the order of the B-splines and the coefficients of the B-splines for x and y coordinates in terms of the global coordinates system are specified as follow.

```

header
RINNER
NPATCHF NTCLH
NAL DELR NCIRE NGSP
1 PANSIZF
NUF(1) NVF(1)
KUF(1) KVF(1)
VKNTUF(1,1) ... VKNTUF(NUA(1),1)
VKNTVF(1,1) ... VKNTVF(NVA(1),1)
XCOEF(1,1) XCOEF(2,1)
XCOEF(1,2) XCOEF(2,2)
.
.
.
XCOEF(1,NB(1)) XCOEF(2,NB(1))
.
.
.
NUF(NPATCHF) NVF(NPATCHF)
KUF(NPATCHF) KVF(NPATCHF)
VKNTUF(1,NPATCHF) ... VKNTUF(NUA(NPATCHF),NPATCHF)
VKNTVF(1,NPATCHF) ... VKNTVF(NVA(NPATCHF),NPATCHF)
XCOEF(1,1) XCOEF(2,1)
XCOEF(1,2) XCOEF(2,2)
.
.
.
XCOEF(1,NB(NPATCHF)) XCOEF(2,NB(NPATCHF))

```

The descriptions of the parameters **RINNER**, **NAL**, **DELR**, **NCIRE** and **NGSP** and the header line are in Section 11.4. The description of **PANSIZF** can be found in Section 11.6. Other parameters are described below.

IFSDEF=1 is assigned on line 5. This signifies the B-spline representation of the patches in the inner region of the free surface.

NUF(I) and **NVF(I)** are the numbers of panel subdivisions in the u and v coordinates, respectively, on I -th patch.

KUF(I) and **KVF(I)** are the orders of B-splines in the u and v coordinates, respectively, on I -th patch.

VKNTUF(J,I) is the B-spline knot vector in u on patch I . $J=1,2,\dots,NUA(I)$
 $NUA(I)=NUF(I)+2*KUF(I)-1$.

VKNTVF(J,I) is the B-spline knot vector in v on patch I . $J=1,2,\dots,NVA(I)$
 $NVA(I)=NVF(I)+2*KVF(I)-1$.

XCOEF(1,K) and **XCOEF(2,K)** are the components of the vector coefficient similar to \mathbf{X}_{ij} in equation (6.6). These are defined in terms of the single array index K , where $K=1,2,\dots,NB(I)$. Here $NB(I)$ is the total number of coefficients on patch I , given by the relation $NB(I)=(NUF(I)+KUF(I)-1)\times(NVF(I)+KVF(I)-1)$.

The coefficient corresponding to the vertical coordinate **XCOEF(3,K)** may be included in the FDF file, if it is on the same line with **XCOEF(1,K)** and **XCOEF(2,K)** and followed by a line breaker. However, **XCOEF(3,K)** is not used in the program. Instead, the vertical coordinates are set to 0 for the exterior free surface and to the highest Z-coordinates of the patches in each tank.

11.6.2 INNER REGION REPRESENTED BY EXPLICIT FORMULAE (IFSDEF < 0)

This option may be used when the geometry of the inner region can be defined by explicit formulae. The formulae required to define the inner region must be coded in FORTRAN, as subroutines in the file FDEXACT.F. Subroutines already provided in this file may be useful to understand the appropriate procedures for developing new subroutines. This file can be compiled separately as a .dll file, FDEXACT.DLL, and linked with WAMIT at runtime, following the same procedure to modify GEOMXACT.DLL, as described in Section 6.9.

In general, these subroutines contain generic patterns or shapes of the inner region without specific dimensions or other conditions ("parameters"). Parameters specific for each problem under consideration may be written in the FDF files and input to the subroutine at runtime. For example, the inner region for vertical cylindrical columns may be represented by an annulus extending from the circular intersection of the column with the free surface to the outer circle of radius RINNER. The radii of the smaller and larger circles of annulus may be specified in the FDF file as input parameters and the corresponding subroutine in FDEXACT.F may have READ statements to read these parameters.

The format of the FDF file is as follows:

```
header  
RINNER
```

```

NPATCHF NTCLH
NAL DELR NCIRE NGSP
IFSDEF PANSIZF
NLINES
line 1
line 2
.
.
.
line NLINES

```

The descriptions of the parameters **RINNER**, **NAL**, **DELR**, **NCIRE** and **NGSP** and the header line are in Section 11.4. The description of **IFSDEF** and **PANSIZF** can be found in Section 11.6.

NLINES is the number of lines containing parameters. The parameters should be specified on the following **NLINES** lines in the same format in **READ** statements in the subroutine. Continuing with above example of an annular inner region, if two radii of the annulus are denoted by **RI** and **RO**, with $RI < RO$, the following formula represents the first quadrant of the inner region.

$$T = \frac{\pi}{4}(u + 1) \text{ and } R = \frac{(RO - RI)}{2}(v + 1) + RI, \quad \text{for } -1 \leq u, v \leq 1$$

$$X = R \cos T \text{ and } Y = R \sin T$$

As shown in this example, the domain of parametric coordinates u and v must be $(-1.,1)$, in the expressions of the explicit formulae for each patch.

11.6.3 INNER REGION REPRESENTED BY MULTISURF (IFSDEF = 2)

The inner region may be represented using MS2 geometry database files from MultiSurf in the similar manner as the body geometries are represented. In order to use this option, it is required to install `rg2wamit.dll` and `rgkernel.dll`. The MS2 files should include the entire inner region described in the global coordinates system. The vertical coordinates of the free surface specified in the MS2 files are ignored in WAMIT and they are automatically set to zero for the exterior free surface or to the vertical coordinates of the free surfaces in the internal tanks.

The FDF input file takes the following format in the simplest form.

```

header
RINNER
NPATCHF NTCLH
NAL DELR NCIRE NGSP
2 PANSIZF
3

```

```
(path) fdf.ms2
*
0 0 0
```

The first four lines and the real parameter **PANSIZF** on line 5 are explained in Sections 11.4 and 11.6.

IFSDEF=2 is assigned on line 5, signifying the use of the MS2 file. Line 6 contains an integer specifying the number of subsequent lines to be read from the .fdf file. Line 7 contains the name of the .ms2 file. The asterisk (*) on line 7 is a default specifier to indicate that all visible surfaces in the .ms2 file are to be included; alternatively if only a subset of these surfaces are submerged these may be designated by following the instructions in Appendix C. Line 8 includes three integer parameters with default values zero, which may be used to control the accuracy of the geometry evaluation in RGKernel, and also to modify the convention regarding the direction of the unit normal. Further information is contained in Appendix C.

NPATCHF can be specified as 0. Use of this option is recommended, to avoid errors in counting surfaces or patches. In the case the number of patches is evaluated from the MultiSurf model, and the user does not need to input **NPATCHF** separately. If **NPATCHF** > 0 is input by the user, the number of MultiSurf patches used in the solution will be limited to **NPATCHF**.

■ 11.6.4 AUTOMATIC DEFINITION OF INNER REGION

In this option, the inner region is defined automatically without specifying the patches by the users.

To invoke this option, a negative integer should be specified for **NPATCHF** and it should be followed by a real parameter **PANSIZF** as described below. The complete input data are as follow.

```
header
RINNER
-1 PANSIZF
NAL DELR NCIRE NGSP
```

The descriptions of the parameters **RINNER**, **NAL**, **DELR**, **NCIRE** and **NGSP** and the header line are in Section 11.4.

NPATCHF=-1 should be specified on the 3rd line as shown above.

PANSIZF **PANSIZF** is a real parameter.

PANSIZF > 0 : A positive **PANSIZF** denotes the length scale of the subdivision of the patches in the inner region. It is used for automatic subdivision in the similar manner as **PANLE_SIZE** is used for the body surface.

PANSIZF < 0 : A negative **PANSIZF** denotes that the subdivision of the patches in the

inner region is made using the parameters specified in the *fdf_fdf.spl* file. This file must be prepared by the user. The *fdf_fdf.spl* file is described in a section below.

When there are multiple waterlines, the current option may not be used in the following situation. When the smallest rectangles drawn around each waterline, with the sides parallel to two horizontal axes of the global coordinates system, if any of these rectangles are overlapped, the current option can not be used. In this case, users may rotate the positions of the bodies, around the origin of the global coordinates system, to avoid the overlapping of the rectangles. If that is not possible, other options for the FDF file should be used.

11.7 OPTIONAL SPLINE CONTROL FILE (ILOWHI=1)

The optional `_FDF.SPL` file may be used to specify the panel subdivision on each patch in the inner region of the free surface in the similar manner as `SPL` is used for the body surface. In general, the size of the panels on the inner region of the free surface should be comparable to the panels on the body surface. If the `_FDF.SPL` file is used, `PANSIZF<0` must be specified in the FDF file and `_FDF.SPL` file must have the same filename as the FDF file, with the extension '`_fdf.spl`'.

The complete data in the `_FDF.SPL` file are as follow.

```
header
NU(1) NV(1)
NU(2) NV(2)
.
.
NU(NPATCHF) NV(NPATCHF)
```

NU and **NV** are the numbers of subdivision along the *u* and *v* coordinates of each patch in the inner region.

11.8 SPECIAL TOPICS ON FDF

11.8.1 PARTITION CIRCLE AND INNER CIRCLE

As noted in Section 11.4, the radius of the partition circle, $R_{part} = RINNER + NAL \times DELR$, should be sufficiently large such that the asymptotic expansion of the potentials is valid outside of the circle. An appropriate estimation of the radius of the partition circle, R_{part} , is $O(h)$ (h =water depth) for shallow water and $O(\lambda)$ (λ = longest wavelength involved) for deep water ($h \gg \lambda$). The actual constant of proportionality R_{part}/λ may have to be substantially larger than one to achieve accuracy in deep water (see Reference [9] and [12]).

As the Gauss quadrature over the intermediate region is more efficient than the piecewise integration in the inner region, the smaller `RINNER` is, the integration of the forcing is

more efficient in general. However, if the inner circle of radius RINNER is too close to the body, Gauss quadrature may not be efficient due to the influence of the Rankine sources. If the farthest radial distance of the body surface from the origin of the global coordinates system is denoted as R_{body} , the following table shows the required number of nodes in the azimuthal integration of the influence of Rankine source as RINNER varies. In the table, $NCIR=2^{NCIRE} + 1$ is the number of nodes of the Gauss-Chebyshev quadrature between $[0, 2\pi]$. A recommended procedure to determine RINNER is i) first to select the parameter NCIRE which would be dependent on the wavelengths of the linear and second-order waves and ii) find RINNER from the table.

$R_{body}/RINNER$	NCIRE	NCIR
0.1	3	9
0.4	4	27
0.5	5	33
0.8	6	65
0.9	7	129
0.95	9	257

When field quantities are evaluated on the free surface, such as the second-order wave elevation, similar consideration applies. The maximum radial distance to the field points should be sufficiently smaller than RINNER. Above table can be used to estimate RINNER after replacing R_{body} with the maximum radial distance to the field points.

Unlike the piecewise integration in the inner region, inadequate values of NCIRE and NGSP for the integration over the intermediate region may produce the computational results with gross error. It is recommended to examine the dependence of the computational results to these parameters.

11.8.2 RESTRICTION ON VERY LONG WAVES

When $k_i R$, $k_j R$ or $k_2^\pm R$ is less than BOUND in the DATA statement of subroutine FARFS.F and RHSFFS.F, the program will continue to run but neglect the integration over the outer region in the total second-order exciting forces. Here R is the partition radius and k_i , k_j and k_2^\pm are wavenumbers associated with the frequencies ω_i , ω_j and $\omega_i \pm \omega_j$. This case may be encountered when a very long wavelength is involved in the difference-frequency solution. If this occurs a warning message will appear in the log file. To avoid this condition the user may increase the partition radius.

In V6.4S, BOUND is set to 10^{-3} . Depending on the range of the double-precision floating-point decimal exponent of the computing system, the source code users can modify this value as follows. On the system where the exponent is in the range $\pm 64 \times n$, the recommended value of BOUND is 10^{-n} .

11.8.3 APPROXIMATION WITHOUT FREE SURFACE FORCING

An approximated second-order solution may be obtained excluding the contribution of the free surface forcing to the second-order scattering potential. As significant computational effort is required to account to the free surface forcing, the approximated solution can be evaluated efficiently. However, since the quality of the approximation depends on the problem, it must be used with discretion. In particular, this option is not recommended for the sum-frequency solution.

By specifying a negative number for the parameter RINNER in the FDF file, the effect of the free surfacing is omitted in the second-order solution. An example of the FDF file is shown below.

```
header
```

```
-1
```

```
where RINNER = -1 is specified.
```

11.8.4 AUXILIARY OUTPUT FILES

When $IPLATDAT > 0$ in the .cfg file, *fdf_pan.dat* and *fdf_pat.dat* are output for the inner region of the free surface in the same way *gdf_pan.dat* and *gdf_pat.dat* are for the body geometry. The latter files are explained in Section 10.6. These files contain the vertex coordinates of the free surface panels or subdivisions in a format suitable for input to plotting programs such as Tecplot. This facilitates the use of perspective plots to illustrate and check the FDF inputs or automatic representation of the inner region.

When $ILOWGDF > 0$ and $ILOWHI=1$ in the .cfg file, *fdf_low.fdf* is output in the similar way *gdf_low.gdf* is output. The data in *fdf_low.fdf* has the same definitions of the free surface geometry in *fdf.fdf* but in the FDF format for $ILOWHI=0$.

11.9 FNAMES.WAM

When FNAMES.WAM is used to list the input files, the PT2 and FDF file names can be specified in addition to input files for V6.4 as shown in an example below.

```
FNAMES.WAM:
```

```
test.cfg
```

```
test.gdf
```

```
test.pot
```

```
test.frc
```

```
test.pt2
```

```
test.fdf
```

If all second-order output options are suppressed, PT2 and FDF can be omitted. If all second-order output options are suppressed except option 10, FDF can be omitted.

11.10 DEFINITIONS OF OUTPUT

The second-order forces and other quantities evaluated by WAMIT V6.4S are output in a standard nondimensional form as described below. All second-order output satisfies symmetry relations $F_{ij}^+ = F_{ji}^+$ and $F_{ij}^- = F_{ji}^{-*}$. Here $+$ and $-$ denote sum and difference frequency quantities, respectively, ij or ji ordered pair of frequency indices and $*$ the complex conjugate. In the difference frequency output F_{ij}^- , $\omega_i \geq \omega_j$ is assumed. When $\omega_i < \omega_j$ the indices are interchanged within the program and F_{ji}^- is output (F_{ij}^- can be obtained from the symmetry relation).

1. The second-order wave forces and moments at sum- and difference-frequencies are defined as

$$\bar{F}^+ = \frac{F^+}{\rho g L A_i A_j} \quad \text{and} \quad \bar{F}^- = \frac{F^-}{\rho g L A_i A_j^*}$$

$$\bar{M}^+ = \frac{M^+}{\rho g L^2 A_i A_j} \quad \text{and} \quad \bar{M}^- = \frac{M^-}{\rho g L^2 A_i A_j^*}$$

where $L=UEN$ is the characteristic body length, and $A_{i,j}$, g and ρ represent the complex first-order incident-wave amplitudes, gravitational acceleration and fluid density, respectively.

2 The second-order hydrodynamic pressure at sum- and difference-frequencies is defined as

$$\bar{p}^+ = \frac{p^+}{\rho g A_i A_j / L} \quad \text{and} \quad \bar{p}^- = \frac{p^-}{\rho g A_i A_j^* / L}$$

3. The second-order wave elevation at sum- and difference-frequencies is defined as

$$\bar{\eta}^+ = \frac{\eta^+}{A_i A_j / L} \quad \text{and} \quad \bar{\eta}^- = \frac{\eta^-}{A_i A_j^* / L}$$

4. The second-order response amplitude operator at sum- and difference-frequencies is defined as

$$\bar{\xi}_k^+ = \frac{\xi_k^+}{A_i A_j / L^n} \quad \text{and} \quad \bar{\xi}_k^- = \frac{\xi_k^-}{A_i A_j^* / L^n}$$

where $n = 1$ for the translational modes $k = 1, 2, 3$ and $n = 2$ for the rotational modes $k = 4, 5, 6$

11.11 NUMERIC OUTPUT FILES

For each of the seven options of the second-order hydrodynamic output, separate output files of numeric data are generated as listed in Section 11.2. The data in these numeric

output files are listed in the following format:

OPTN.10s, OPTN.qcs, OPTN.11s and OPTN.12s:

PER(i) PER(j) BETA(i) BETA(j) I MOD(\bar{F}_{ij}^+) PHS(\bar{F}_{ij}^+) Re(\bar{F}_{ij}^+) Im(\bar{F}_{ij}^+)

OPTN.10d, OPTN.qcd, OPTN.11d and OPTN.12d:

PER(i) PER(j) BETA(i) BETA(j) I MOD(\bar{F}_{ij}^-) PHS(\bar{F}_{ij}^-) Re(\bar{F}_{ij}^-) Im(\bar{F}_{ij}^-)

OPTN.13S:

PER(i) PER(j) BETA(i) BETA(j) M K MOD(\bar{p}^+) PHS(\bar{p}^+) Re(\bar{p}^+) Im(\bar{p}^+)

OPTN.13D:

PER(i) PER(j) BETA(i) BETA(j) M K MOD(\bar{p}^-) PHS(\bar{p}^-) Re(\bar{p}^-) Im(\bar{p}^-)

OPTN.14S:

PER(i) PER(j) BETA(i) BETA(j) L MOD(\bar{p}^+) PHS(\bar{p}^+) Re(\bar{p}^+) Im(\bar{p}^+)

OPTN.14D:

PER(i) PER(j) BETA(i) BETA(j) L MOD(\bar{p}^-) PHS(\bar{p}^-) Re(\bar{p}^-) Im(\bar{p}^-)

OPTN.15S:

PER(i) PER(j) BETA(i) BETA(j) N MOD($\bar{\eta}^+$) PHS($\bar{\eta}^+$) Re($\bar{\eta}^+$) Im($\bar{\eta}^+$)

OPTN.15D:

PER(i) PER(j) BETA(i) BETA(j) M MOD($\bar{\eta}^-$) PHS($\bar{\eta}^-$) Re($\bar{\eta}^-$) Im($\bar{\eta}^-$)

OPTN.16S:

PER(i) PER(j) BETA(i) BETA(j) I MOD($\bar{\xi}^+$) PHS($\bar{\xi}^+$) Re($\bar{\xi}^+$) Im($\bar{\xi}^+$)

OPTN.16D:

PER(i) PER(j) BETA(i) BETA(j) I MOD($\bar{\xi}^-$) PHS($\bar{\xi}^-$) Re($\bar{\xi}^-$) Im($\bar{\xi}^-$)

Here I is the mode index, M is the index of a quadrant or half when the body has two or one planes of symmetry, respectively, K is the index of the panels on the body and L is the index of the field points.

Only the second-order hydrodynamic pressure is output in .13s and .13d. The second-order quadratic hydrostatic pressure, \bar{P}_{sq}^\pm , normalized in the same manner as the hydrodynamic pressure, can be calculated from the following expression.

$$\bar{P}_{sq}^{\pm} = \frac{1}{4}[(\bar{\xi}_{4_i}\bar{\xi}_{6_j}^{\pm} + \bar{\xi}_{4_j}\bar{\xi}_{6_i}^{\pm})x + (\bar{\xi}_{5_i}\bar{\xi}_{6_j}^{\pm} + \bar{\xi}_{5_j}\bar{\xi}_{6_i}^{\pm})y - (\bar{\xi}_{4_i}\bar{\xi}_{4_j}^{\pm} + \bar{\xi}_{6_i}\bar{\xi}_{6_j}^{\pm})z]$$

where $\bar{\xi}$ is the normalized linear RAO and $\bar{\xi}^-$ is the complex conjugate of $\bar{\xi} = \bar{\xi}^+$. The subscripts i and j denote the frequency indices and x, y and z are the coordinates of a point on the body surface normalized by the parameter ULEN in the GDF file.

The hydrostatic pressure due to the second-order RAO can be calculated from the following expression where $\bar{\xi}^{\pm}$ is the normalized second-order RAO.

$$\bar{P}_{sp}^{\pm} = -(\bar{\xi}_3^{\pm} + \bar{\xi}_4^{\pm} \times y - \bar{\xi}_5^{\pm} \times x)$$

11.12 INSTALLATION AND SETUP

The WAMIT software includes the main executable program **wamit.exe**, the DLL files listed below, a complete set of input files for the standard test runs TESTn (n=01,02, ...), and the formatted output files TESTn.OUT for these test runs. The PC-executable Version V6.4S-PC includes additional dynamic link library files (DLL) which must be installed in the same directory (i.e. ‘folder’) as the executable file **wamit.exe**, or in a different folder which is included in the system path. If these DLL files are missing the program will not run, regardless of the inputs and options specified. The required DLL files include special WAMIT DLL files and also special Intel or Microsoft DLL files. The five required WAMIT DLL files are

- geomxact.dll
- newmodes.dll
- fdexact.dll
- rg2wamit.dll
- rg2wamit2.dll

The extended Version including the capability to input MultiSurf models requires one additional DLL file, rgkernel.dll, and two extended versions of rg2wamit.dll and rg2wamit2.dll. Version 6.4S-PC is compiled using Intel Visual Fortran (IVF), Version 12.1. The following DLL files are required to run executable code compiled with IVF:

- libifcoremd.dll
- libmmd.dll
- libiomp5md.dll
- msvcr100.dll
- svml dispmd.dll

These DLL files are distributed by Intel and may be redistributed to all users. Copies of these files are included with each distribution of WAMIT. Users may encounter a problem on some older PC systems, indicated by the runtime error message ‘The system cannot execute the specified program’. This problem can be overcome by downloading and installing the Microsoft Visual C++ 2005 Redistributable Package, which is available from Microsoft.

Before installing the software a new main directory (folder) should be made. The recommended name is `c:\wamitv6`, but the user may prefer to use a different drive or directory name, with a maximum length of 40 characters for the string. The software must be unzipped using a local utility, and all unzipped files should be saved in the directory `c:\nwamitv7` and in subdirectories corresponding to those in the zip file. If a different drive or directory name is used, this must be specified as `USERID PATH` in the configuration file, as explained in Section 3.7. The text file `readme.txt` includes an outline of the directory tree and files contained in the zip file. If any difficulties are encountered during installation and testing the user should confirm that the subdirectories and files correspond to the description in `readme.txt`.