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BALTRIM v.1

Thomas M. Gaffney

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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T. M. Gaffney
Enduring Weapons Systems Engineering
Sandia National Laboratories
Livermore, CA 94551

ABSTRACT

BalTrim is an Excel® spreadsheet designed to calculate the inertial mass properties and ballast trim weight for either an assembled reentry vehicle (RV) or reentry body (RB). With this application, the user enters known mass properties and global coordinates for each subcomponent of the assembly, and BalTrim calculates the mass properties of the total assembly. Then, using the assembly mass properties, BalTrim calculates the necessary amount of ballast trim weight required to dynamically and statically balance the assembly mass properties. The final mass properties and trim ballast weight calculated with BalTrim agree with physically measured values.

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BalTrim v.1

Mass Properties Spreadsheet

1. Introduction

BalTrim is a spreadsheet template for use in Microsoft Excel® that serves as a modern implementation of the BALSUM program, developed by C.J. Mauck in 1968 [1]. The name BalTrim is an abbreviation stemming from the main function of this spreadsheet, which is to calculate the necessary amount of ballast trim weight required to dynamically and statically balance the inertial mass properties of an assembled Reentry Vehicle (RV) or Reentry Body (RB). The details as well as limitations of BalTrim are the focus of this report. Therefore, it is recommended that all users read this report before implementing BalTrim.

The original version of BALSUM was developed using FORTRAN IV, which provided limited functionality. Therefore, the program code for BALSUM has been translated and programmed into a spreadsheet format referred to as BalTrim. The decision to use a spreadsheet application stems from the ease with which the original program code is adapted for use within a spreadsheet, and because spreadsheet applications are readily available on a variety of computing platforms. As a result, more users have direct access to BalTrim, and the graphical user interface of BalTrim makes this application convenient to use. Similarly, users may view their results using a word processor or a variety of other spreadsheet applications, as well as store their results electronically for future updates. For those reasons, BalTrim is more versatile than the original BALSUM program.

BalTrim was developed primarily for use in recording and tabulating the mass properties of an assembled reentry vehicle or reentry body. For that reason, the weight and the inertial mass properties must be known for each subcomponent, and the location of each subcomponent's center of gravity must be known relative to the assembly's global coordinate origin. BalTrim also was developed around the use of a left-hand coordinate system, since the majority of re-entry vehicles and re-entry bodies use a left-hand coordinate system. Therefore, to be consistent with BalTrim, the weapon assembly must have a global left-hand coordinate system. Additional details regarding the implementation BalTrim are described in the following sections.

2. Spreadsheet Capabilities

This spreadsheet is programmed to perform the following calculations:

1. Summation of mass properties including weight, moments of inertia (I_{xx} , I_{yy} , I_{zz}), and products of inertia (I_{xy} , I_{xz} , I_{yz}).
2. Calculation of ballast trim weights at known radii in two trim planes.
3. Computation of the full assembly's mass properties including trim ballast weights. Note that if the ballast weights are to be incorporated in a specific subassembly, then the mass properties of the subassembly may be computed with the ballast weights included as a separate spreadsheet. The results would then be entered as a single component with the final spreadsheet analysis.
4. Conversion of results to SI Units.

3. System of Units

Dimensions and Units

BalTrim reports calculated results using the English system of units. However, the user may also view the results in SI units by selecting the worksheet tab labeled 'SI Units' or by clicking the scroll arrows on the BalTrim toolbar. All calculated values are labeled with the appropriate units.

At this point, a cautionary note is necessary regarding weight. Within BalTrim, the weight of each component or subassembly may be substituted for mass in order to calculate the assembly mass properties. This is common practice, since a known mass standard is used to calibrate the weight scale. If the scale is correctly calibrated, then one pound-mass registers a weight equal to one pound-force. For that reason, weight is used interchangeably with mass. For reference, the quantities for mass and length as well as moments and products of inertia are reported herein using the following English system of units:

Mass	Pound-mass (lbm)
Weight (force).....	Pound-force (lbf)
Length	inch (in)
Moments of inertia	Pound-mass - inches ² (lbm-in ²)
Products of inertia	Pound-mass - inches ² (lbm-in ²)

In the SI system of units, these scalar quantities have the following units:

Mass	Kilogram (kg)
Weight.....	Newton (N)
Length	meter (m)
Moments of inertia	Kilogram - meter ² (kg-m ²)
Products of inertia	Kilogram - meter ² (kg-m ²)

4. Basic Formulations and Equations

The mass properties of an assembly or subassembly are calculated within BalTrim using the following equations. A comprehensive derivation for these equations is available in many engineering solid mechanics texts [2,3,4].

Total mass of the assembly, M_{total} , is defined by Eq 1.1 as the sum of all the individual mass elements.

$$M_{\text{total}} = \sum_i^n m_i \quad (1.1)$$

Where m_i is the mass of each individual item, and n is the total number of components in the summation.

The first moment of mass, Mm_{nt_i} , about a point at the origin of a rectangular coordinate system is calculated with Eqs 2.1-2.3, for each coordinate axis.

$$Mm_{nt_x} = \sum_i^n x_i m_i \quad (2.1)$$

$$Mm_{nt_y} = \sum_i^n y_i m_i \quad (2.2)$$

$$Mm_{nt_z} = \sum_i^n z_i m_i \quad (2.3)$$

Here, x_i , y_i , and z_i are the coordinate vectors representing the distance of each mass m_i from the origin of the global rectangular coordinate system.

Mass moments of inertia for the assembly are calculated with Eqs 3.1-3.3 about the global coordinate system origin (0, 0, 0) by summing moments of inertia for each component.

$$I_{xx_{000}} = \sum_i^n m_i (y_i^2 + z_i^2) + I_{xx_i} \quad (3.1)$$

$$I_{yy_{000}} = \sum_i^n m_i (x_i^2 + z_i^2) + I_{yy_i} \quad (3.2)$$

$$I_{zz_{000}} = \sum_i^n m_i (x_i^2 + y_i^2) + I_{zz_i} \quad (3.3)$$

Here, I_{xx_i} , I_{yy_i} , and I_{zz_i} are the known mass moments of inertia for each component about its own center of gravity. The values for x_i , y_i , and z_i are the coordinate vectors from the assembly coordinate system origin to the component's center of gravity.

Products of inertia for the assembly are calculated with Eqs 3.4-3.6 about the global coordinate system origin (0,0,0) by summing the individual products of inertia for each component.

$$I_{xy_{000}} = \sum_i^n m_i (x_i y_i) + I_{xy_i} \quad (3.4)$$

$$I_{xz_{000}} = \sum_i^n m_i (x_i z_i) + I_{xz_i} \quad (3.5)$$

$$I_{yz_{000}} = \sum_i^n m_i (y_i z_i) + I_{yz_i} \quad (3.6)$$

Here I_{xy_i} , I_{xz_i} , and I_{yz_i} are the products of inertia for each individual component about its respective center of gravity. Again, the values for x_i , y_i , and z_i are the coordinate vectors from the global coordinate system origin to the component's center of gravity.

Using the first moments of mass and the total assembly's mass, it is possible to calculate the center of gravity ($\bar{X}$, $\bar{Y}$, $\bar{Z}$) for the entire assembly with Eqs 4.1-4.3.

$$\bar{X} = \frac{Mm_{nt_x}}{M_{total}} \quad (4.1)$$

$$\bar{Y} = \frac{Mm_{nt_y}}{M_{total}} \quad (4.2)$$

$$\bar{Z} = \frac{Mm_{nt_z}}{M_{total}} \quad (4.3)$$

Next, the mass moments inertia and products of inertia for the assembly, about the center of gravity, are calculated by applying the parallel axis theorem. This is accomplished by substituting the center of gravity coordinates for $\bar{Y}$ and $\bar{Z}$ from Eqs 4.2 and 4.3 into the parallel axis equation for $I_{xx_{000}}$ to produce Eq 5.1.

$$I_{xx_{000}} = I_{xx_{cg}} + (Mm_{nt_z}\bar{Z} + Mm_{nt_y}\bar{Y}) \quad (5.1)$$

Now substitute Mm_{nt_z} and Mm_{nt_y} into Eq 5.1, and then rearrange Eq 5.1 to yield Eq 5.2. The mass moment of inertia about the X-axis at the center of gravity for the assembly is now defined by Eq 5.2. Note that subtracting the term in parentheses on the right side of Eq 5.2 indicates that we are translating from the origin to the system's center of gravity.

$$I_{xx_{cg}} = I_{xx_{000}} - M_{total}(\bar{Z}^2 + \bar{Y}^2) \quad (5.2)$$

Similar equations are used to calculate I_{yy} and I_{zz} about the assembly's center of gravity.

$$I_{yy_{cg}} = I_{yy_{000}} - M_{total}(\bar{X}^2 + \bar{Z}^2) \quad (5.3)$$

$$I_{zz_{cg}} = I_{zz_{000}} - M_{total}(\bar{X}^2 + \bar{Y}^2) \quad (5.4)$$

The products of inertia for the total assembly also are determined by employing the parallel axis theorem as shown in Eqs 5.5-5.7.

$$I_{xy_{cg}} = I_{xy_{000}} - M_{total}(\overline{XY}) \quad (5.5)$$

$$I_{xz_{cg}} = I_{xz_{000}} - M_{total}(\overline{XZ}) \quad (5.6)$$

$$I_{yz_{cg}} = I_{yz_{000}} - M_{total}(\overline{YZ}) \quad (5.7)$$

Notice that the mass properties of the assembly are first determined about a global coordinate system that is defined as station (0,0,0). This is necessary since the system's center of gravity is unknown at the outset. Once the mass properties are known about the origin, it is possible to calculate the center of gravity for the assembly, and then using the parallel axis theorem, transfer the mass properties to the assembly's center of gravity.

Also notice that the above calculations as well as BalTrim assume that each component's mass properties are defined about a local coordinate system that is aligned with the global coordinate system. If an assembled component's mass properties are known about a local coordinate system that is rotated relative to the assembly's coordinate system, then the component's mass properties must be transformed into the assembly's coordinate system. Often, this may be accomplished with the aid of a 3-D CAD modeling program. Otherwise, the user will have to perform the necessary second order tensor transformations using equations commonly found in engineering dynamics texts [5]. Remember that the order in which rotational transformations are taken about each axis is important, and they must comply with, in this case, the positive left-hand rule and clockwise rotation. For example, if the first transformation is due to rotation about the x-axis, the next transformation must be about the y-axis, and the final transformation will be about the z-axis.

Finally, the amount of ballast required to produce both static and dynamic equilibrium for the assembly is calculated by solving a system of simultaneous equations. The system of

simultaneous equations employed by BalTrim to solve for the ballast trim weights are provided in Appendix A.

5. Using BalTrim

Opening the Worksheet

The first worksheet in BalTrim is a title page, which contains three selection buttons as shown in Figure 1. The first selection button 'View Coordinate System Axes' will transfer the user to the Coordinate System Definition worksheet. The second selection button 'View Data Entry Form' will transfer the user to the Data Entry worksheet. Alternatively, the user may use the worksheet tabs near the bottom of the worksheet or the scroll arrows on the BalTrim toolbar

Figure 1. Front Page for BalTrim.

to switch between worksheets. The third button will launch the floating BalTrim toolbar, which also launches automatically when the BalTrim spreadsheet is first opened. Hence, this third button, 'Activate Toolbar', is provided as a means to recover the toolbar, after it has been dismissed by the user.

The BalTrim floating toolbar is equipped with seven buttons. The first two arrow buttons allow the user to scroll continuously between different worksheets. The third button on the toolbar takes the user directly to the Data Entry Worksheet. The fourth button inserts a new row into the data entry form, and the fifth button deletes the selected row. Note, the user should only use the 'delete component' button on the toolbar while they are viewing the Data Entry Worksheet. Otherwise, they may unwittingly delete a row of data. The sixth and seventh buttons on the BalTrim toolbar allow the user to cut and paste selected cells in the data entry region without deleting the cell's formatting. The last key on the toolbar will dismiss the toolbar. The user may further dock the toolbar on the window frame to keep it out of the working window.

Coordinate Definition Worksheet

The coordinate definition worksheet is available to modify or define a particular weapon assembly's coordinate system. In addition, it provides a graphical representation of the coordinate system for the assembly. This worksheet also contains two buttons that allow the user to switch between the Front Page and Data Entry worksheets.

As an aid to the user, BalTrim automatically performs a check to determine whether the user's coordinate system definition complies with the left-hand rule or whether two axes have the same label. If the user's coordinate system does not adhere to the left-hand rule or if the user

enters the same label for two axes, then BalTrim will not allow the user to switch to the Data Entry worksheet until that problem is corrected.

The default coordinate system for BalTrim is shown in Figure 2, and it is a left-hand coordinate system. The user may redefine the coordinate system by clicking on each pull-down dialog box and selecting the appropriate axis label for the coordinate axis. Note that changing the axes labels only changes the column headings on the Data Entry worksheet. It does not alter any of the equations used to compute mass properties or transpose columns of existing data. Therefore, the user must enter each component's mass properties in accord with the column headings and coordinate system definition.

Figure 2. Default Coordinate System Definition for BalTrim.

Also, there are two restrictions with defining the coordinate axes. First, the user cannot change the 0° or 90° axis orientation as shown in Figure 2. These two angular labels are fixed because of their association with trigonometric functions. Second, the user's assembly coordinate system axes must align with the axes shown in Figure 2, because BalTrim is not programmed to perform rotational coordinate transformations. In other words, the user may not input mass properties defined about an assembly coordinate system that is rotated at, for example, a 45° angle orientation to the coordinate system shown in Figure 2.

With regard to the assembly's coordinate system origin, the user may define the coordinate origin either at the nose-tip or at the virtual apex of the cone angle. Origin location will not affect the programmed equations. However, it will affect data entry as well as the calculated results. So the user must choose the origin location at the outset and consistently enter longitudinal coordinates relative to that defined coordinate system origin.

Data Entry

The mass properties for more than 10,000 components or subassemblies may be entered into the Data Entry Worksheet. The user must also enter the radius as well as the coordinate location along the longitudinal axis for each of two trim plane stations. These trim plane stations are referred to as the forward station and aft station. If only one trim plane is available, then BalTrim cannot calculate the amount of trim ballast weight or the correct location for the trim weight in order to statically and dynamically balance the total assembly. Therefore, the RV assembly must be equipped with two trim plane stations of known radii and axial location in order to solve for the ballast trim weights using simultaneous equations.

When viewing the BalTrim Data Entry worksheet as shown Figure 3, there are three important features. The first feature is a tabulated listing of the calculated results for mass properties, which are shown in the box frames near the top of the worksheet. Notice that the worksheet windowpane is split to allow the user to scroll up and down in the data entry region, while still enabling the user to view calculated results. The second feature is the data entry region, which is highlighted in green to indicate user input. The third feature is a series of column headings, which are automatically defined by setting the coordinate system axis labels. Therefore, changing the axis labels on the coordinate system definition sheet will automatically change the column headings, but it will not modify the equations or transpose data entry columns.

Calculated Mass Properties Using Entered Data										Tot_Mass= 57.85 lbm	
X_cg=	10.543 in	lxx_@cg=	584.65 lb-in ²	lxy_@cg=	6.52 lb-in ²						
Y_cg=	0.028 in	lyy_@cg=	708.46 lb-in ²	lxz_@cg=	-2.90 lb-in ²						
Z_cg=	-0.076 in	lzz_@cg=	707.41 lb-in ²	lyz_@cg=	-1.20 lb-in ²						

Calculated Mass Properties with Trim Weight Solution										Tot_Mass= 59.28 lbm	
X_cg=	10.491 in	lxx_@cg=	605.46 lb-in ²	lxy_@cg=	0.00 lb-in ²						
Y_cg=	0.000 in	lyy_@cg=	778.19 lb-in ²	lxz_@cg=	0.00 lb-in ²						
Z_cg=	0.000 in	lzz_@cg=	764.33 lb-in ²	lyz_@cg=	-8.85 lb-in ²						

Trim Ballast Location:

fwd_trim_wt=	0.824 lbm	fwd_ang=	92.4 deg.	fwd_rad=	1.75 in
aft_trim_wt=	0.614 lbm	aft_ang=	118.0 deg.	aft_rad=	5.4 in

Front Page View Coordinate Axes Insert New Component Row Delete Selected Component Row

fwdstation	3.50 in
fwdrad (R1)	1.75 in
aftstation	15.00 in
aftad (R2)	5.40 in

Data Entry Fields (English Units)

Do not delete the first row of data, instead overwrite existing data contained in the first row.

cmpnt name	itm No.	Mass	Xcoord	Ycoord	Zcoord	bxcmp	lyycmp	lzzcmp	bxcmp	bxcmp	lyzcmp
brick	1	4.9	12	0.5	-0.75	20.42	11.84	11.84	0	0	0
cube	2	1.11	7	-0.75	-0.625	0.94	0.94	0.94	0	0	0
small_cone	3	0.115	1.75	0	0	0.02	0.03	0.03	0	0	0
large_cone	4	51.72	10.5	0	0	558.61	659.47	659.47	0	0	0
		0	0	0	0	0	0	0	0	0	0

Figure 3. Data Entry Worksheet for BalTrim.

<i>fwdstation</i>	3.50	in	Data Entry Fields (English Units)	Do not delete the first row of data, instead overwrite existing data contained in the first row.								
<i>fwdrad (R1)</i>	1.75	in										
<i>aftstation</i>	15.00	in										
<i>aft rad (R2)</i>	5.40	in										
<i>cmpnt name itm No. Mass Xcoord Ycoord Zcoord boxcmp lyycmp lzzcmp bycmp bzcmp lyzcmp</i>												
brick	1	4.9	12		0.5	-0.75	20.42	11.84	11.84	0	0	0
cube	2	1.11	7		-0.75	-0.625	0.94	0.94	0.94	0	0	0
small_cone	3	0.115	1.75		0	0	0.02	0.03	0.03	0	0	0
large_cone	4	51.72	10.5		0	0	558.61	659.47	659.47	0	0	0
		0	0		0	0	0	0	0	0	0	0

Figure 4. Data Entry Fields for BalTrim.

While viewing the Data Entry worksheet, the data entry fields for each row in the shaded area of Figure 4 are defined as follows:

Column B	Name of component or subassembly
Column C	Component item number (optional)
Column D	Component mass (or weight)
Column E	i-axis coordinate location for component center of gravity relative to the global coordinate system origin.
Column F	j-axis coordinate location for component center of gravity relative to the global coordinate system origin.
Column G	k-axis coordinate location for component center of gravity relative to the global coordinate system origin.
Column H	Mass moment of inertia Iii for component about its center of gravity.
Column I	Mass moment of inertia Ijj for component about its center of gravity.
Column J	Mass moment of inertia Ikk for component about its center of gravity.
Column K	Product of inertia Iij for component about its center of gravity.
Column L	Product of inertia Iik for component about its center of gravity.
Column M	Product of inertia Ijk for component about its center of gravity.

Data in Column B between rows 19-22 are for the trim plane location and radii:

Row 19	Global i-axis coordinate location of the forward trim plane
Row 20	Radius of the forward trim plane
Row 21	Global i-axis coordinate location of the aft trim plane
Row 22	Radius of the aft trim plane

To enter a component's mass properties, simply click on a cell in the green shaded area and enter the information. To insert a new row for each additional component, the user must

click on the 'Insert New Component Row' button. This button is located above the split windowpane as well as on the BalTrim toolbar. It is imperative that the user select BalTrim's 'Insert New Component Row' button rather than just arbitrarily inserting rows; because this button employs a macro to copy hidden equations into specific cells. The new row will be inserted wherever the current cell selection is within data entry region. Inserting extra blank rows also makes it easier to rearrange the data using the copy and paste functions, but is not necessary. Do not use the 'cut' option on Excel's 'Edit' pull-down menu to move or remove data, because this also deletes the cell's formatting. Instead, use the 'cutcell' and 'pastecell' selections on 'Edit' pull-down menu. These buttons execute subroutines to copy, clear, and paste cell data while preserving the cell's formatting.

Similarly, to delete a row properly, use BalTrim's 'Delete Selected Component Row' button provided rather than the 'delete' option on Excel's 'Edit' pull-down menu. This will ensure that hidden formulas are properly deleted, and that cells below the deleted row are correctly shifted up one row. A final note on deleting rows. Do not delete the first row in the data entry region, as this will destroy hidden formulas that are copied by BalTrim's 'Insert New Component Row' button. Instead, simply overwrite mass properties data in the first row.

On the other hand, if the user would like to retain a particular component's mass properties for accounting reasons, but remove its contribution to the assembly mass properties, then they must insert a negating copy. In other words, the user must insert a new blank row, copy the component's mass properties to the blank row, then change the signs to their opposite value for mass, moments of inertia, and products of inertia. Center of gravity values retain their sign. The results will recompile automatically with the contribution of that component zeroed

out. If Excel does not recompile automatically, then activate the 'Automatic-calc' option on the 'Tools/Options' menu of Excel, or press the F9 function key.

Output Information

The calculated results are reported in two separate title boxes, which are contained in the upper windowpane of the Data Entry Worksheet. A similar table of results is provided with SI units, and may be viewed by selecting the SI Units worksheet tab. As shown in Figure 5, the upper title box lists the calculated mass properties of the assembly based on the input component data. The lower title box reports the calculated trim ballast weights necessary to balance the assembly and their respective locations. The lower title box also reports the final calculated mass properties of the assembly including the calculated trim weights. Note that if the user has already included known trim weight mass properties as part of a subassembly or as a component, then refer to the mass properties listed in the upper title box labeled 'Calculated Mass Properties Using Entered Data'. The reason is that the lower title box reports calculated mass properties including whatever additional trim ballast weight is necessary to balance the

Calculated Mass Properties Using Entered Data				Tot_Mass=	57.85 lbm
X_cg=	10.543 in	lxx_@cg=	584.65 lb-in ²	lxy_@cg=	6.52 lb-in ²
Y_cg=	0.028 in	lyy_@cg=	708.46 lb-in ²	lxz_@cg=	-2.90 lb-in ²
Z_cg=	-0.076 in	lzz_@cg=	707.41 lb-in ²	lyz_@cg=	-1.20 lb-in ²

Calculated Mass Properties with Trim Weight Solution				Tot_Mass=	59.28 lbm
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Y_cg=	0.000 in	lyy_@cg=	778.19 lb-in ²	lxz_@cg=	0.00 lb-in ²
Z_cg=	0.000 in	lzz_@cg=	764.33 lb-in ²	lyz_@cg=	-8.85 lb-in ²
Trim Ballast Location:					
fwd_trim_wt=	0.824 lbm	fwd_ang=	92.4 deg.	fwd_rad=	1.75 in
aft_trim_wt=	0.614 lbm	aft_ang=	118.0 deg.	aft_rad=	5.4 in

Figure 5. Results Table for Calculated Mass Properties.

assembly. With that in mind, the user could manually iterate on a final ballast solution, by entering actual trim weight mass properties, and solving for any additional ballast weight necessary to balance the assembly.

To preview printer output, select the 'print preview' option on Excel's 'File' pull-down menu. Note that print areas have been pre-defined for hardcopy output of the results as well as the entered mass properties data. Similarly, print areas have been pre-defined for the coordinate system worksheet and SI units worksheet. The user may adjust these print areas. Though it should not necessary, because each time the user inserts a new row for data entry, the print area for the data entry region expands accordingly.

Accuracy

The accuracy of this mathematical tool is only as good as the input data. Ideally, accurate mass properties for each component will be measured at a qualified facility using equipment with a high degree of accuracy. However, this is not always possible for assemblies. Therefore, the mass properties and center of gravity may be determined in most cases mathematically. Hence, the results from BalTrim will depend upon the accuracy of physically measured data, assumptions used with calculated component mass properties, and the number of significant figures used while entering input data. With that in mind, the overall accuracy of the results from this spreadsheet are sufficient to predicate a ballast trim weight solution.

For reference, the values calculated with this spreadsheet are comparatively close to physically measured values. For example, centers of gravity calculated with BalTrim agree to within three significant figures of the measured centers of gravity. The difference is attributed to tolerance stack-up and measurement errors. Along with that, the calculated amount of ballast

trim weight necessary to balance the assembly agree with physically measured results to within two decimal places. In many situations, this is sufficient to reduce the products of inertia and position the center of gravity to within acceptable limits. However, the user should not completely rely on BalTrim results. These values should be viewed as an approximation and the assembly should be dynamically balanced at a qualified facility using certified equipment.

6. References

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APPENDIX A

Equations Used to Compute
Ballast Trim Weights for
a Weapon Assembly

Nomenclature:

I_{xx_asm}	=	mass moment of inertia about global x-axis at assembly center of gravity
I_{yy_asm}	=	mass moment of inertia about global y-axis at assembly center of gravity
I_{zz_asm}	=	mass moment of inertia about global z-axis at assembly center of gravity
I_{xy_asm}	=	product of inertia about global x & y axes at assembly center of gravity
I_{xz_asm}	=	product of inertia about global x & z axes at assembly center of gravity
I_{yz_asm}	=	product of inertia about global y & z axes at assembly center of gravity
asm_mass	=	total weapon assembly weight (pre-ballast)
x_o	=	preballast assembly center of gravity location along global x-axis
y_o	=	preballast assembly center of gravity location along global y-axis
z_o	=	preballast assembly center of gravity location along global z-axis
fwd_rad	=	radius of forward ballast plane for ballast placement
aft_rad	=	radius of aft ballast plane for ballast placement
x_{pln1}	=	location along global x-axis of ballast plane 1
x_{pln2}	=	location along global x-axis of ballast plane 2

Unknown variables:

aft_wt	=	the weight of aft ballast weight
fwd_wt	=	the weight of forward ballast weight
fwd_y	=	location along global y-axis of forward ballast weight
fwd_z	=	location along global z-axis of forward ballast weight
aft_y	=	location along global y-axis of aft ballast weight
aft_z	=	location along global z-axis of aft ballast weight

To balance the assembly, it is necessary to solve six equations for six unknowns. These six simultaneous equations are shown as Eqs A.1-A.6. To arrive at these equations, start by generating Eqs A.1 and A.2 using dynamic equilibrium. Notice that Eqs A.1 and A.2 are derived by transferring the product of inertia terms to ballast plane 1. This eliminates the product of inertia term due to trim weight number 1 and simplifies the solution.

$$0 = I_{xy\_asm} + asm\_mass * y_o * (x_o - x_{pln1}) + aft\_wt * aft\_y * (x_{pln2} - x_{pln1}) \quad (A.1)$$

$$0 = I_{xz\_asm} + asm\_mass * z_o * (x_o - x_{pln1}) + aft\_wt * aft\_z * (x_{pln2} - x_{pln1}) \quad (A.2)$$

Next, Eqs A.3 and A.4 are derived for the ballast weight locations using the Pythagorean theorem and known radii for each ballast plane station.

$$\text{aft\_rad}^2 = \text{aft\_z}^2 + \text{aft\_y}^2 \quad (\text{A.3})$$

$$\text{fwd\_rad}^2 = \text{fwd\_z}^2 + \text{fwd\_y}^2 \quad (\text{A.4})$$

Eqs A.5 and A.6 are derived from static equilibrium for the assembly by summing moments about the assembly's postballast center of gravity, which will equal zero for $\bar{y}$ and $\bar{z}$.

$$0 = \text{fwd\_wt} * \text{fwd\_y} + \text{aft\_wt} * \text{aft\_y} + \text{asm\_mass} * y_o \quad (\text{A.5})$$

$$0 = \text{fwd\_wt} * \text{fwd\_z} + \text{aft\_wt} * \text{aft\_z} + \text{asm\_mass} * z_o \quad (\text{A.6})$$

Solving the above simultaneous equations will yield the weight for both trim weights and their correct location on each of their respective trim planes. As an aid to the user these values are reported in BalTrim as an angle whose arc is subtended on the radial trim plane.

Now that the ballast weights and their respective locations are known, it is necessary to compute the final mass properties of the overall assembly with the ballast weights included. This is accomplished by applying Eqs 1.1 through 5.7 in Section 4 of this report. Again, the final calculated mass properties with trim weights are tabulated and reported on the Data Entry worksheet of BalTrim.

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