Fairing Separation Analysis Using SepTOOL

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Acknowledgments

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1.0   Introduction

This document describes the relevant equations programmed in spreadsheet software, SepTOOL, developed by ZIN Technologies, Inc. (ZIN) to determine the separation clearance between a launch vehicle payload fairing and remaining stages. The software uses closed form rigid body dynamic solutions of the vehicle in combination with flexible body dynamics of the fairing, which is obtained from flexible body dynamic analysis or from test data, and superimposes the two results to obtain minimum separation clearance for any given set of flight trajectory conditions. Using closed form solutions allows SepTOOL to perform separation calculations several orders of magnitude faster compared to numerical methods which allows users to perform real time parameter studies. Moreover, SepTOOL can optimize vehicle performance to minimize separation clearance. This tool can evaluate various shapes and sizes of fairings along with different vehicle configurations and trajectories. These geometries and parameters are inputted in a user friendly interface. Although the software was specifically developed for evaluating the separation clearance of launch vehicle payload fairings, separation dynamics of other launch vehicle components can be evaluated provided that aerodynamic loads acting on the vehicle during the separation event are negligible.

This document describes the development of SepTOOL providing analytical procedure and theoretical equations whose implementation of these equations is not disclosed. Realistic examples are presented, and the results are verified with ADAMS (MSC Software Corporation) simulations. It should be noted that SepTOOL is a preliminary separation clearance assessment software for payload fairings and should not be used for final clearance analysis.

2.0   Background

The SepTOOL spreadsheet software is an effective tool to assess the separation clearance of payload fairings. It combines flexible body dynamics of the fairing from other sources with closed form rigid body dynamic solutions of the vehicle and the fairing. SepTOOL calculates all the rigid body dynamics of the vehicle and the fairing including the transfer of linear and angular momentum during the separation event. The rigid body dynamics of the entire vehicle and fairing are tracked and combined with the flexible body dynamics of the fairing to determine the clearance between the fairing and the vehicle/payload. The input of flexible body dynamics lets users to input either flexible body dynamics analysis results from numerical analysis codes or test data. This capability allows SepTOOL to evaluate the separation of already qualified fairings on different vehicles or different trajectories. The user inputs the fairing's dynamic behavior into SepTOOL as point-wise displacement (x, y, z) versus time (t) data. SepTOOL evaluates one point on the fairing at a time but is capable of assessing every point on the fairing regardless of location.

SepTOOL can assess the separation clearance for various vehicle geometries and vehicle flight parameters, as described in Section 3.0, User Input. The vehicle flight parameters include angle of attack, pith rate, yaw rate, and roll rate. The implementation of these parameters as well as the input is discussed in subsequent sections.

3.0   User Input (Zalewski 2014)

SepTOOL is divided into several tabs, each dealing with a different aspect of the calculations, to enhance the user friendliness of the software. The first tab provides the version number and developer contact information (Figure 1).

In the second tab, the user inputs fairing and vehicle geometry information, such as stage lengths, stage diameter, center of gravity locations, and fairing thickness (Figure 2). The fairing diameter is inputted later with the nose contour in the fairing OML tab. Flexible inputs allow for different vehicle configurations to be implemented into SepTOOL. By entering a zero in the appropriate geometry section, as shown in Figure 2, makes that section ignored in the calculations. Hence, any vehicle geometry can be defined in SepTOOL using these inputs as depicted in Figure 3 to Figure 5.
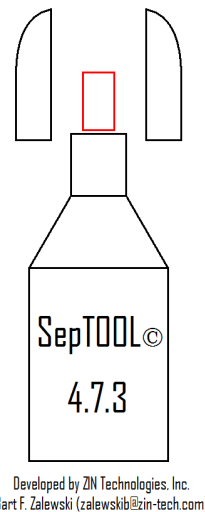

Figure 1.—SepTOOL's first tab—banner page.

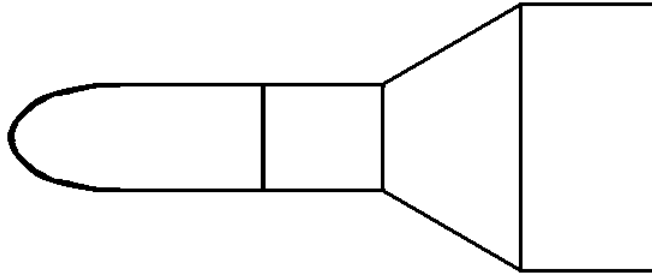Figure 2.—SepTOOL's second tab—geometry input.

Figure 3.—Increasing vehicle diameter configuration.

Figure 4.—Decreasing vehicle diameter configuration.

Figure 5.—Constant vehicle diameter configuration.

It is recommended that all petals are checked for a given vehicle position axis orientation (θ), shown in red, and the corresponding Angle of Attack, shown in yellow, in order to ensure clearance.

Angle of Attack (AoA) (deg)
0.0

Pitch Rate (deg/s)
0.0

Yaw Rate (deg/s)
0.0

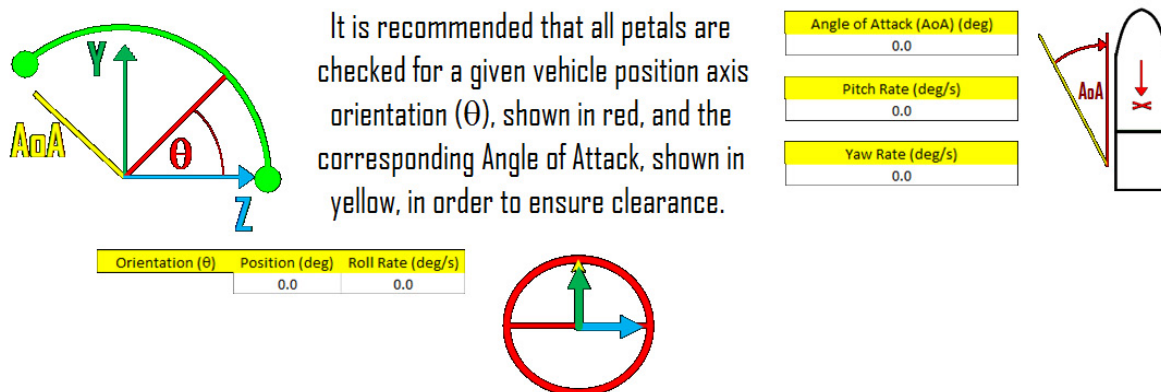| Orientation (θ)	Position (deg)	Roll Rate (deg/s)
	0.0	0.0

Figure 6.—SepTOOL's third tab—flight parameters.

Vehicle flight parameters are entered in the third tab as shown in Figure 6. These include angle of attack, as well as pitch, yaw, and roll rates. The orientation of the fairing petal with respect to the vehicle axis or launch tower axis (θ) is also prescribed in this tab in order to define the correct vehicle flight path with respect to the separation plane of the fairing (Figure 7).

In the fourth tab, vehicle acceleration and clearance evaluation timeline are defined (Figure 8). The start time definition is necessary to avoid clearance calculations just as the fairing begins to separate from the vehicle when it is still within the clearance envelope. If the start time was not defined, the minimum clearance margin would be either zero or negative. Figure 9 shows the start time of the clearance margin calculation on a typical separation trace. SepTOOL automatically calculates the clearance margin. Vehicle acceleration may be optimized to minimize separation clearance as described later in this section.

The fifth tab provides a figure depicting fairing displacement relative to the vehicle and a summary of all the inputs (Figure 10). The figure is formatted for use in presentations or reports.
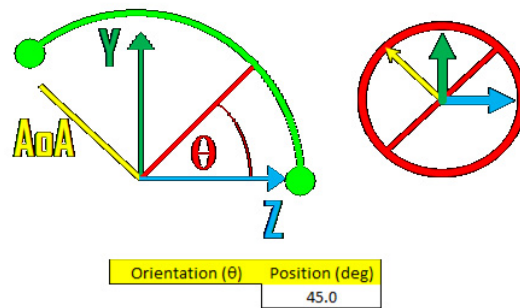
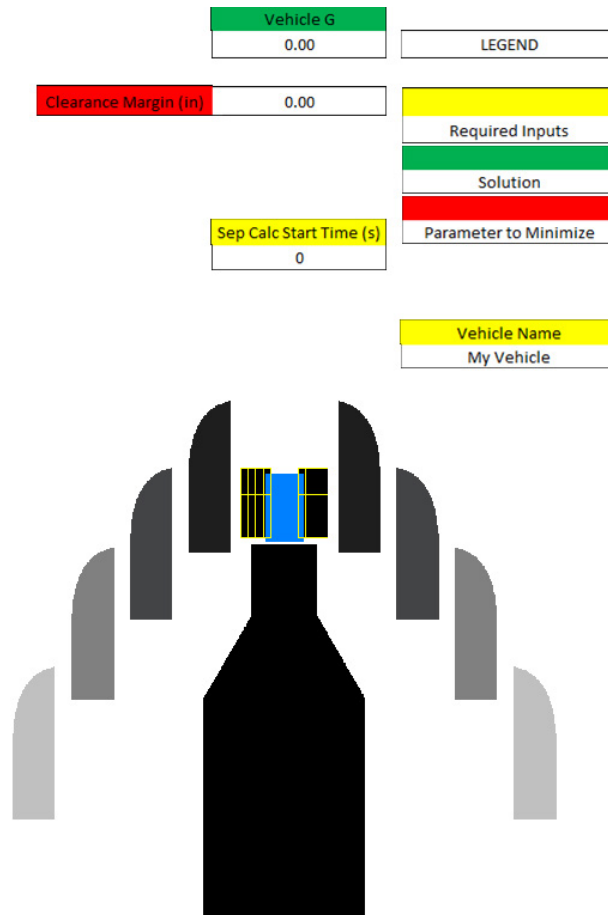Figure 7.—Fairing position angle (θ) with respect to the vehicle shown with graphical feedback

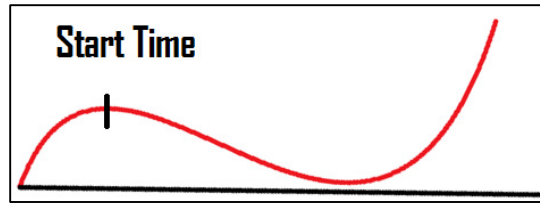Figure 8.—SepTOOL's fourth tab—vehicle acceleration and clearance margin

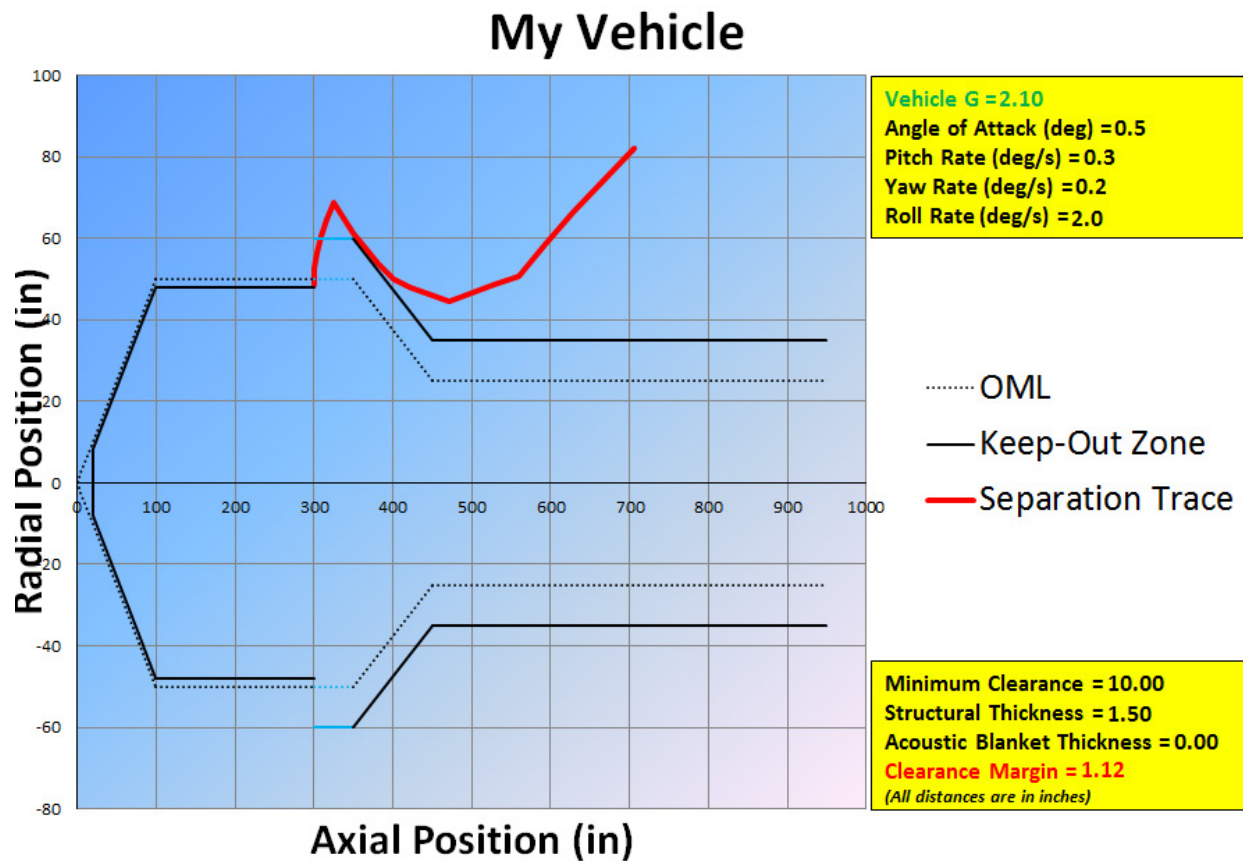Figure 9.—Separation trace schematic and clearance calculation start time

Figure 10.—SepTOOL's fifth tab—separation trace

The user inputs the fairing flexible body dynamics into the sixth tab of SepTOOL (Figure 11). The data is entered in column format (time, x-displacement, y-displacement, z-displacement) and can come from either a numerical analysis or test results.

In the seventh tab, shown in Figure 12, the user defines the detailed geometry of the fairing outer mold line (OML) and the payload envelope. The payload envelope lies within the fairing, and fairing contact with it is not permitted. The inputs consist of a point-wise description of the fairing nose geometry, its functional interpolation using fifth degree polynomial, and the offset of the payload envelope from the fairing's OML, which is computed normal to the fairing surface. The fairing nose geometry input is entered in column format (node number, x-position, y-position, z-position).

The fairing diameter is defined from the fairing nose input data, and together with the second tab, which defines the barrel length of the fairing, fully describes the fairing geometry along with the payload envelope as shown in Figure 10. The fifth tab shows the vehicle and fairing OML in dashed line, and the clearance envelope in solid line (Figure 10). A fifth degree polynomial interpolation was used to check

the inputted fairing OML against several known fairing geometries yielding satisfactory results. The interpolation coefficients are manually entered in the designated cells on the top right in Figure 12.

The eighth tab describes optimization capabilities of SepTOOL with Microsoft Excel Solver (Microsoft Corporation) installation and its setup for vehicle acceleration optimization (Figure 13).

	Node	101200	
t (sec)	DX (in)	DY (in)	DZ (in)
Coordinates	-153.75	0	101
0	0	0	0
0.0125	0	-4.6273	1.86992
0.025	0	-10.4013	5.16531
0.0375	0	-16.9041	9.81427
0.05	0	-23.5241	15.5724
0.0625	0	-29.6808	19.8156
0.075	0	-35.9374	25.2699
0.0875	0	-41.4665	27.7863
0.1	0	-46.7463	30.5506
0.1125	0	-51.7863	33.226
0.125	0	-56.0608	33.1657
0.1375	0	-59.7058	31.5446
0.15	0	-63.0005	29.1283
0.1625	0	-66.0413	25.9913
0.175	0	-69.2853	23.3976
0.1875	0	-72.7861	22.5269
0.2	0	-75.8627	20.0095
0.2125	0	-79.0027	18.0049
0.225	0	-81.7976	15.438
0.2375	0	-84.3603	12.3089
0.25	0	-86.9091	9.10751

Figure 11.—SepTOOL's sixth tab—flexible body dynamics input

Figure 12.—SepTOOL's seventh tab providing payload envelope

The SepTOOL has a capability of sizing vehicle acceleration by varying 'Vehicle G' to meet the clearance requirements. In order to access that capability, the user may need to install a Solver Add-in. The Solver Add-in can be readily installed by typing in "solver add-in" in Excel Help search window and following the installation instructions. After successful installation the Solver should show up on the Data tab as shown below.

Double clicking on the Solver would open up a Solver Parameters window with the appropriate cells filled out as shown to the left. In case these entries are empty, please fill the Set Target Cell window with cell S4 and the By Changing Cells window with cell S2. Then press Solve to size the vehicle performance.
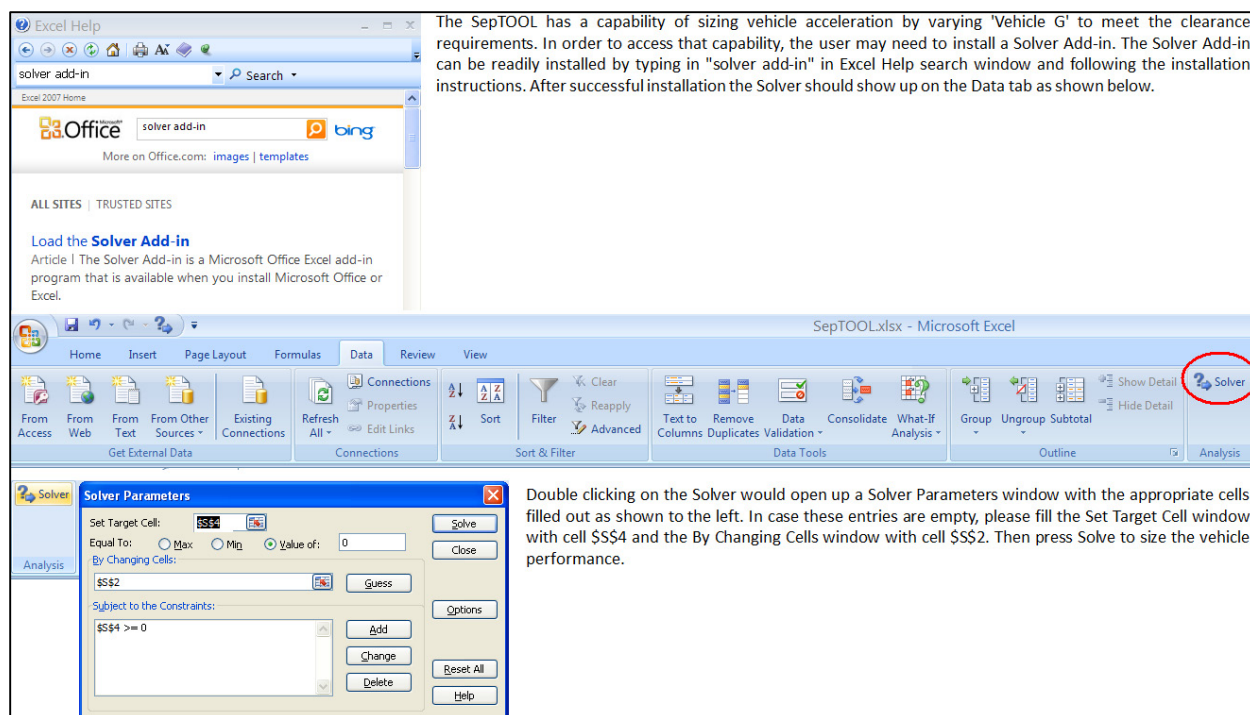
Figure 13.—SepTOOL's eighth tab providing optimization instructions

This spreadsheet was developed by ZIN Technologies, Inc. While ZIN thoroughly reviewed the spreadsheet calculations, we realize that there could be potential errors and bugs. The user is ultimately responsible for the usage of this software and we would appreciate reporting any errors and/or bugs to the developer such that SepTOOL can be improved. The developer is not responsible for any changes to the software made by the user.

Figure 14.—SepTOOL's disclaimer

The ninth tab provides a disclaimer of SepTOOL usage (Figure 14).

4.0 Theoretical Displacement Equations

SepTOOL accounts for all of the rigid body motions of the vehicle relative to fairing as well as the effect of separation on the linear and angular momentum of the fairing. The displacement of the vehicle due to its acceleration is given by the basic dynamic equation, Equation (1) (Hibbeler 1998), where the initial velocity and the initial displacement are equal for both the vehicle and the fairing. The instant after separation the vehicle is still accelerating, but the fairing is not. The acceleration term is the only one left in Equation (1) resulting in Equation (2).

These equations assume vertical acceleration. The following symbols will be used in subsequent equations and Figure 15 to Figure 17.

AoA angle of attack
I_i mass inertia of a body
S height of the adapter stage
a vehicle acceleration
g gravitational acceleration
h_1 height of the point for which the separation data is inputted with respect to the bottom of the fairing
h_2 height of the upper stage
r_1 upper radius of the adapter stage
r_2 lower radius of the adapter stage
t time

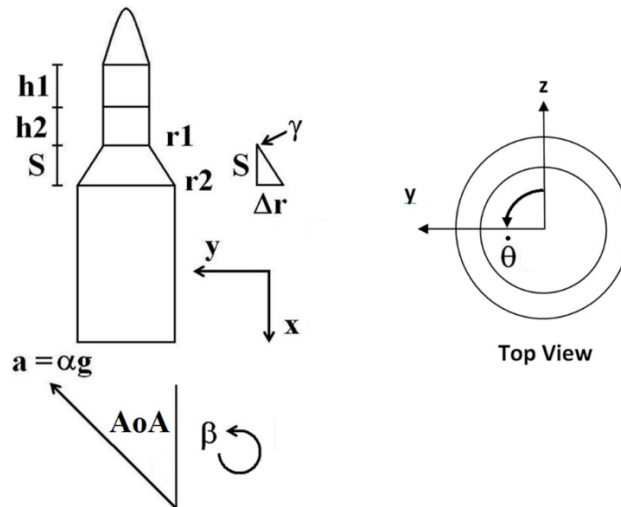| v	velocity
x_i	vertical displacement for an ith component of the total x-displacement
y_i	horizontal displacement for an ith component of the total y-displacement
z_i	horizontal displacement for an ith component of the total z-displacement
Δr	difference between the adapter stage radii computed as $\Delta r = r_2 - r_1$ also $\Delta r = S \tan(\gamma)$
ΔD	horizontal fairing clearance distance computed as $\Delta D = sqrt(dy^2 + dz^2)$ where 'dy' and 'dz' are relative positions of the inputted fairing separation data
α	scalar multiple of g's
β	pitch rate
φ	yaw rate
γ	adapter stage taper angle computed as $\gamma = atan(\Delta r / S)$
$\dot{\theta}$	roll rate
θ	position angle
ω_i	rotational velocity such as pitch yaw, or roll

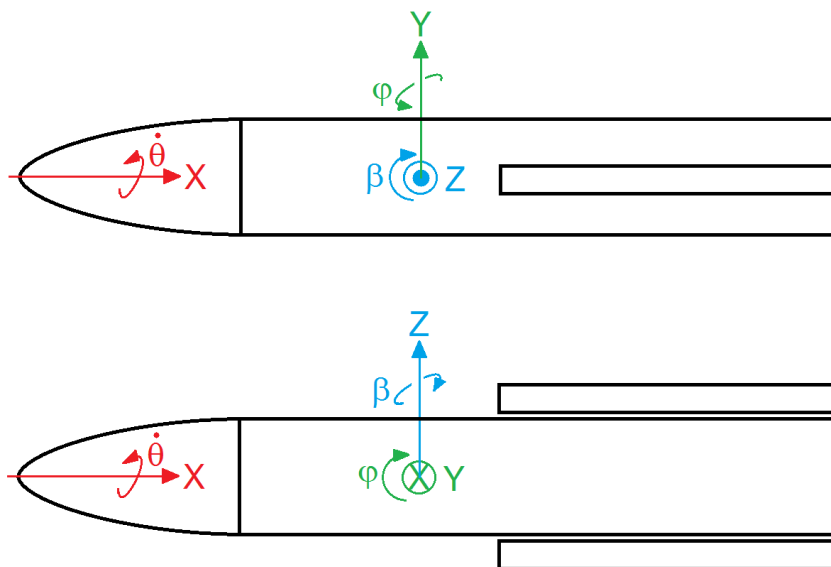Figure 15.—Definition of the variables with respect to fairing geometry

Figure 16.—Fairing rotational axes

Figure 17.—Fairing separation
distance in the radial direction

$$x(t) = \frac{1}{2}a\,t^2 + v_0 t + x_0 \tag{1}$$

$$x(t) = \frac{1}{2}a\,t^2 \tag{2}$$

The separation distance of the fairing from the vehicle, shown in Equation (3), must account for the vehicle's continued rotation along the pitch and yaw axes. The roll rotation occurs around the axis of the vehicle and does not influence that fairing displacement.

$$x_1 = \frac{1}{2}a\,t^2\cos(AoA + \beta t)\cos(\varphi) \tag{3}$$

At the time of separation, the relative motion of the fairing petals is due to rotation about the petal's center of gravity produced by pitch, yaw, and roll rates. However, due to the transfer of angular momentum, the vehicle rotation (pitch, yaw and roll) also contributed to the motion of the fairing petals. Given that 'R' is the distance between the petal center of gravity and the center of gravity of the entire vehicle, the angular momentum during separation is described as (Hibbeler 1998):

$$I_{Total}\omega_{Total} = I_{Vehicle}\omega_{Vehicle} + 2I_{Petal}\omega_{Petal} + 2mR \times \omega_{Petal} \times R \tag{4}$$

The linear velocity due to the rotation is $\omega_{Petal} \times R$, where 'm' is the fairing petal mass. Equation (5) defines the total mass inertia (Hibbeler 1998):

$$I_{Total} = I_{Vehicle} + 2\left(I_{Petal} + mR^2\right) \tag{5}$$

Assuming that the vehicle angular velocity, before and after separation, remains the same, Equation (5) is substituted into Equation (4) to yield:

$$I_{Total}\omega_{Vehicle} = I_{Total}\omega_{Vehicle} - 2\left(I_{Petal} + mR^2\right)\omega_{Vehicle} + 2\left(I_{Petal} + mR^2\right)\omega_{Petal} \tag{6}$$

Simplifying Equation (6) leads to $\omega_{Vehicle} = \omega_{Petal}$. The term ω represents pitch, yaw, and roll. Hence the fairing petal rotates around its own center of gravity with the same angular velocity as the vehicle, which rotates around its own center of gravity. In addition, there is a tangential velocity due to vehicle's angular velocity. In order to account for displacement of any point on the petal, the rotation of that point with respect to the petal center of gravity must be considered. Pitch, yaw, and roll must be considered simultaneously. The process is obtained as follows.

The point on the petal is first defined with respect to the petal by subtracting the petal's center of gravity coordinates from the location of that point. Then the pitch and yaw axes are defined based on the orientation of the fairing axis with respect to the vehicle axis (see Section 3.0, Figure 6 and Figure 7):

$$P = y\cos(\theta) - z\sin(\theta) \tag{7}$$

9

$$Y = y\sin(\theta) + z\cos(\theta) \tag{8}$$

Each point then undergoes a transformation that rotates that point according to pitch, yaw, and roll (Murray 2013). For simplicity cosine is represented by 'c' and sine by 's'.

$$\begin{vmatrix} x^{New} \\ P^{New} \\ Y^{New} \end{vmatrix} = \begin{vmatrix} c(\beta t)c(\varphi t) & s(\varphi t)c(\dot\theta t)+s(\beta t)c(\varphi t)s(\dot\theta t) & s(\varphi t)s(\dot\theta t)-s(\beta t)c(\varphi t)c(\dot\theta t) \\ -c(\beta t)s(\varphi t) & c(\varphi t)c(\dot\theta t)-s(\beta t)s(\varphi t)s(\dot\theta t) & c(\varphi t)s(\dot\theta t)+s(\beta t)s(\varphi t)c(\dot\theta t) \\ s(\beta t) & -c(\beta t)s(\dot\theta t) & c(\beta t)c(\dot\theta t) \end{vmatrix} \begin{vmatrix} x \\ P \\ Y \end{vmatrix} \tag{9}$$

The point coordinates are then rotated back from the pitch and yaw axes to the fairing coordinate system as:

$$y^{New} = P^{New}\cos(\theta) + Y^{New}\sin(\theta) \tag{10}$$

$$z^{New} = -P^{New}\sin(\theta) + Y^{New}\cos(\theta) \tag{11}$$

The center of gravity (c.g.) coordinates of the petal are added to bring the coordinate system back to the point on the fairing. These coordinates are then used to account for vehicle rotation and tangential velocity. The x-displacement due to vehicle rotation relative to the petal is given as (Murray 2013):

$$x_2 = x^{New}\cos(\beta t)\cos(\varphi t) + y^{New}\big[\sin(\beta t)\cos(\dot\theta t)+\cos(\beta t)\sin(\varphi t)\sin(\dot\theta t)\big]\ldots$$
$$+ z^{New}\big[\sin(\beta t)\sin(\dot\theta t)-\cos(\beta t)\sin(\varphi t)\cos(\dot\theta t)\big] \tag{12}$$

The x-displacement component due to tangential velocity given petal's c.g. coordinates is given as:

$$x_3 = c.g.y\big[\beta\cos(\theta)+\varphi\sin(\theta)\big]t + c.g.z\big[\beta\sin(\theta)+\varphi\cos(\theta)\big]t \tag{13}$$

From Equations (10) to (11), the y-displacement component due to vehicle rotation relative to the petal is given as:

$$y_1 = y^{New}\cos(\theta) + z^{New}\sin(\theta) \tag{14}$$

The y-displacement component due to tangential velocity with respect to the petal's c.g. coordinates is given as:

$$y_2 = c.g.x\big[\beta\cos(\theta)+\varphi\sin(\theta)\big]t + c.g.z\,\dot\theta\,t \tag{15}$$

The additional y-displacement component due to the vehicle's acceleration perpendicular to its axis is given as:

$$y_3 = \frac{1}{2}a\,t^2\big[\cos(AoA+\beta t)\sin(\varphi)\sin(\theta+\dot\theta)+\sin(AoA+\beta t)\cos(\theta+\dot\theta)\big] \tag{16}$$

From Equations (10) to (11), the z-displacement component due to vehicle rotation relative to the petal is given as:

$$z_1 = -y^{New}\sin(\theta) + z^{New}\cos(\theta) \tag{17}$$

The z-displacement component due to tangential velocity given petal's c.g. coordinates is given as:

$$z_2 = \mathrm{c.g.x}\left[-\beta\sin(\theta) + \varphi\cos(\theta)\right]t - \mathrm{c.g.y}\,\dot{\theta}\,t \tag{18}$$

The additional z-displacement component due to the vehicle's acceleration perpendicular to its axis is given as:

$$z_3 = \frac{1}{2}a\,t^2\left[\cos(AoA + \beta t)\sin(\varphi)\cos(\theta + \dot{\theta}) - \sin(AoA + \beta t)\sin(\theta + \dot{\theta})\right] \tag{19}$$

These displacements are all appropriately combined to obtain the complete three dimensional displacement field of the fairing petal with respect to the vehicle. The following section describes the numerical checks that SepTOOL performs for this displacement.

5.0   Clearance Assessment (Zalewski 2014)

SepTOOL compares the previously described displacement field to the vehicle geometry in order to compute clearance. The software first checks whether the point that is being assessed for clearance is within the geometry of the vehicle. The previously defined nose, see Section 3.0, was interpolated as a fifth degree polynomial in order for SepTOOL to track its shape during all time steps, which are defined from the flexible body dynamics input. Hence due to vehicle and petal dynamics and a continuously defined fairing shape, SepTOOL is able to compute the normal distance from the nose to the point as clearance. The cut-off of the payload envelope defined in the second tab, see Figure 2 'Nose Envelope Top X-Coordinate', is incorporated as an upper limit. The software then changes the clearance calculation to the nearest vehicle stage where the diameter is constant. If any stage length is set to zero, that clearance calculation gets ignored. Clearance from the adapter is calculated in the same manner as the clearance from the nose. The normal vector is computed between the point and the adapter based on adapter geometry. If there is no adapter, that clearance calculation is ignored. If the adapter is straight, no diameter change, the adapter is treated like a stage. The core stage is treated as a stage with constant diameter to which clearance is calculated.

6.0   SepTOOL Limitations

SepTOOL calculates accurate rigid body dynamics of both the vehicle and the fairing petal to determine impact of these dynamics on clearance. The flexible body dynamics of the fairing petal due to separation force only are captured outside of SepTOOL environment using numerical methods or test data. However, there is an additional secondary displacement component that is not accounted and whose impacts are negligible for reasonable angular velocities such as pitch, yaw, and roll. That secondary effect is the flexible body deformation of the petal due to its own angular velocities after separation event. These constant angular velocities create a centripetal acceleration of each point on the petal with respect to its center of gravity. These point-wise accelerations along with point-wise masses result in a distributed inertial force that deforms the petal. This deformation is minor but it would still be present if the fairing petals were released without a force and displaced based on vehicle trajectory parameters alone. Since accounting for these displacements would require either functional or matrix form stiffness and mass information about the entire fairing petal, this calculation is outside of SepTOOL's capability. The verification problems compared with ADAMS simulations show that for typical angular velocities of the vehicle, the angular velocity induced deformation is negligible. The difference is noticeable at unrealistically high angular velocities that launch vehicles should never experience in a normal trajectory.

7.0   SepTOOL Solver (Zalewski 2014)

SepTOOL has a capability of optimizing vehicle acceleration for minimum clearance. The optimization is based on a built-in Excel solver, and the setup is explained on tab eight in the software.

The solver varies the vehicle acceleration and thus changes all appropriate clearance calculations to minimize the clearance. Clearance can also include a minimum clearance margin as prescribed. Minimizing clearance allows the user to calculate the acceleration threshold needed for the petal to clear the vehicle. This becomes important especially in the preliminary stages of design where trajectories can vary. Experienced Excel users can also adjust the solver setup to optimize all the flight parameters for minimum clearance.

8.0   SepTOOL Verification with ADAMS

SepTOOL was verified against ADAMS simulations in order to improve the maturity level of the software and test its capabilities. Five analysis cases were performed, all with a separation force on an existing fairing (point-wise data from ADAMS was used in SepTOOL for flexible body dynamics input to ensure accurate comparison between the two):

1) Straight Line Acceleration
2) Acceleration at an Angle of Attack with Fairing Orientation
3) Realistic Pitch Rate
4) Unrealistically Large Pitch Rate
5) Combined Case

Case 1 only involved straight line 1.7979838634 g acceleration in addition to the separation force applied on the petals. The results shown in Figure 18 depict SepTOOL's accuracy for this test case for the worst case bottom petal corner.

In addition to the separation force on the petal, Case 2 involved 2 g vehicle acceleration at 8° angle of attack with the vehicle axis being oriented at −65.1° from the fairing axis. Figure 19 shows the ADAMS and SepTOOL results for this case for the worst case bottom petal corner.
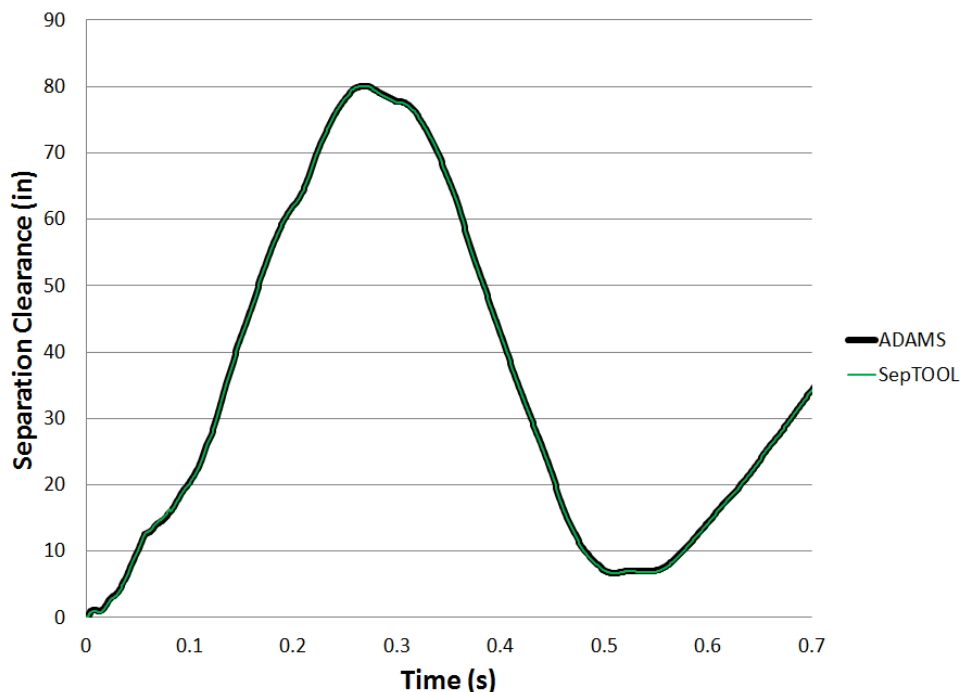

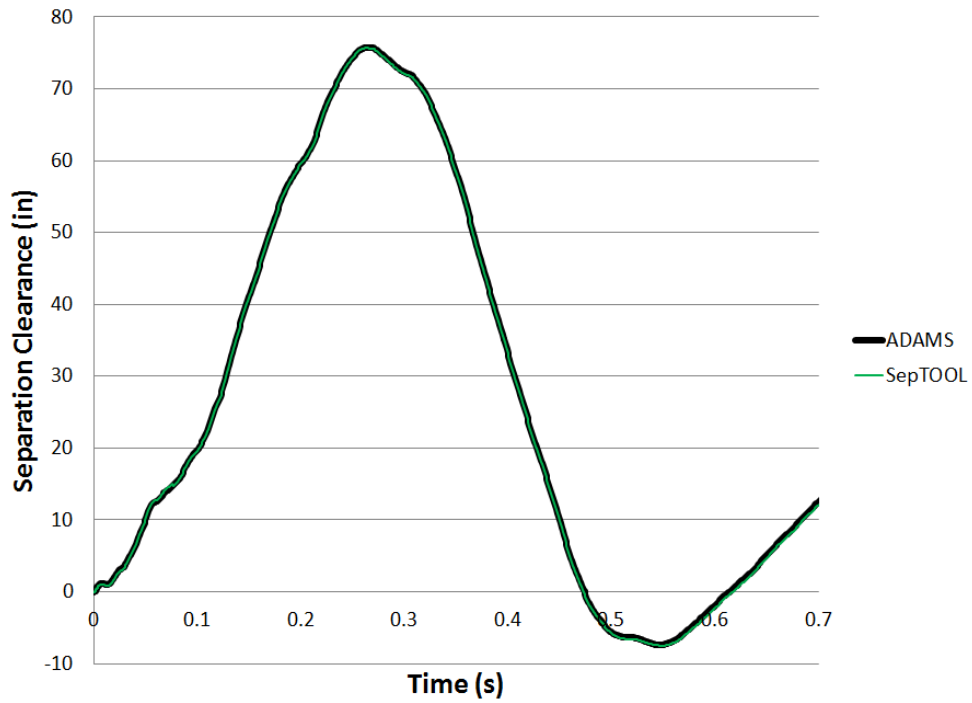Figure 18.—Case 1 separation clearance trace

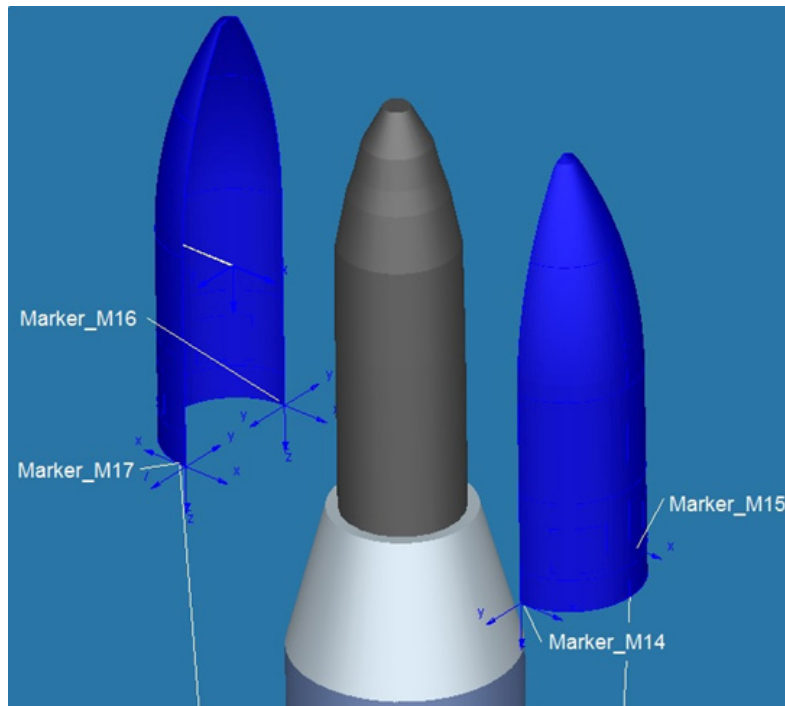Figure 19.—Case 2 separation clearance trace

Figure 20.—Petal bottom corner labels

Case 3 and 4 illustrate the accuracy of SepTOOL considering a separation force applied on the petal and a pitch rate. Case 3 considers a typical 1°/sec pitch, while Case 4 illustrates SepTOOL's limitations by considering a large and unrealistic 10°/sec pitch. Figure 21 and Figure 22 show ADAMS and SepTOOL clearance traces for the respective cases for both bottom corners for both petals (Figure 20) M14, M15, M16, and M17.
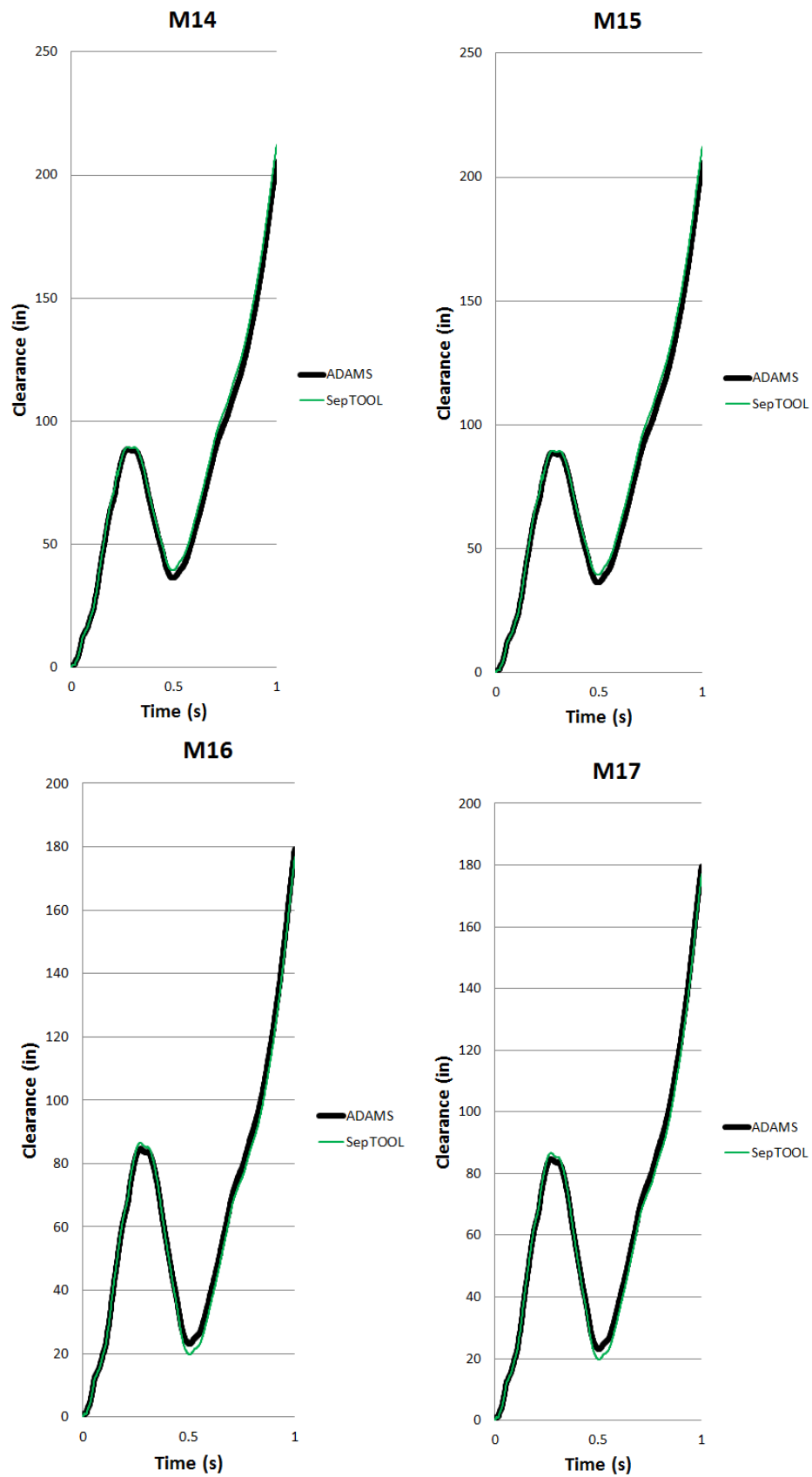
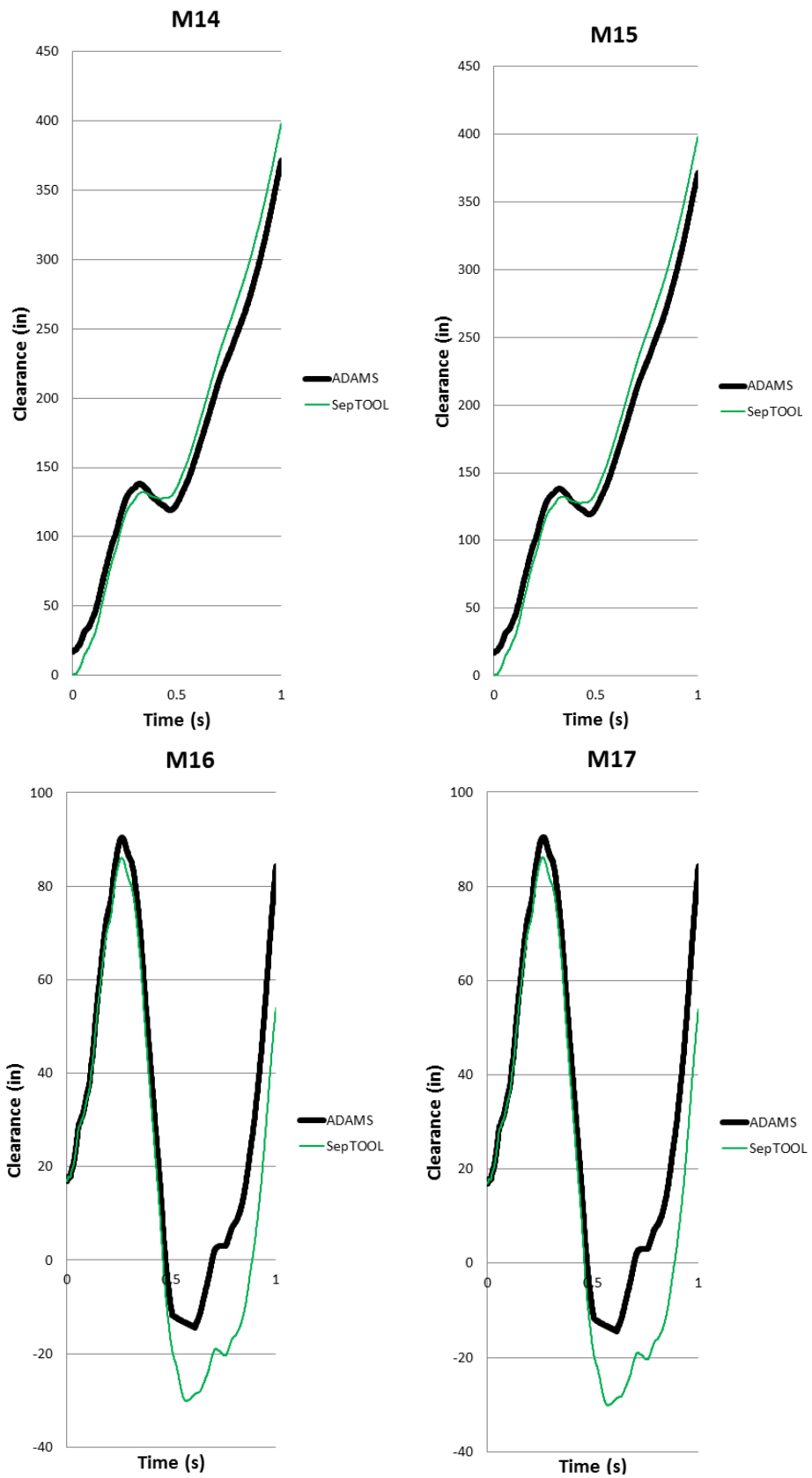Figure 21.—Case 3 separation clearance traces

Figure 22.—Case 4 separation clearance traces

Case 5 combines typical vehicle trajectory parameters in a comprehensive case. It considers separation force, 2.2 g vehicle acceleration at a 0.5° angle of attack, 0.5°/sec pitch rate, 0°/sec yaw rate, 1.5°/sec roll rate, and –17° vehicle orientation. Separation clearance traces for all bottom petal corners (Figure 20) are compared between ADAMS and SepTOOL (Figure 23).
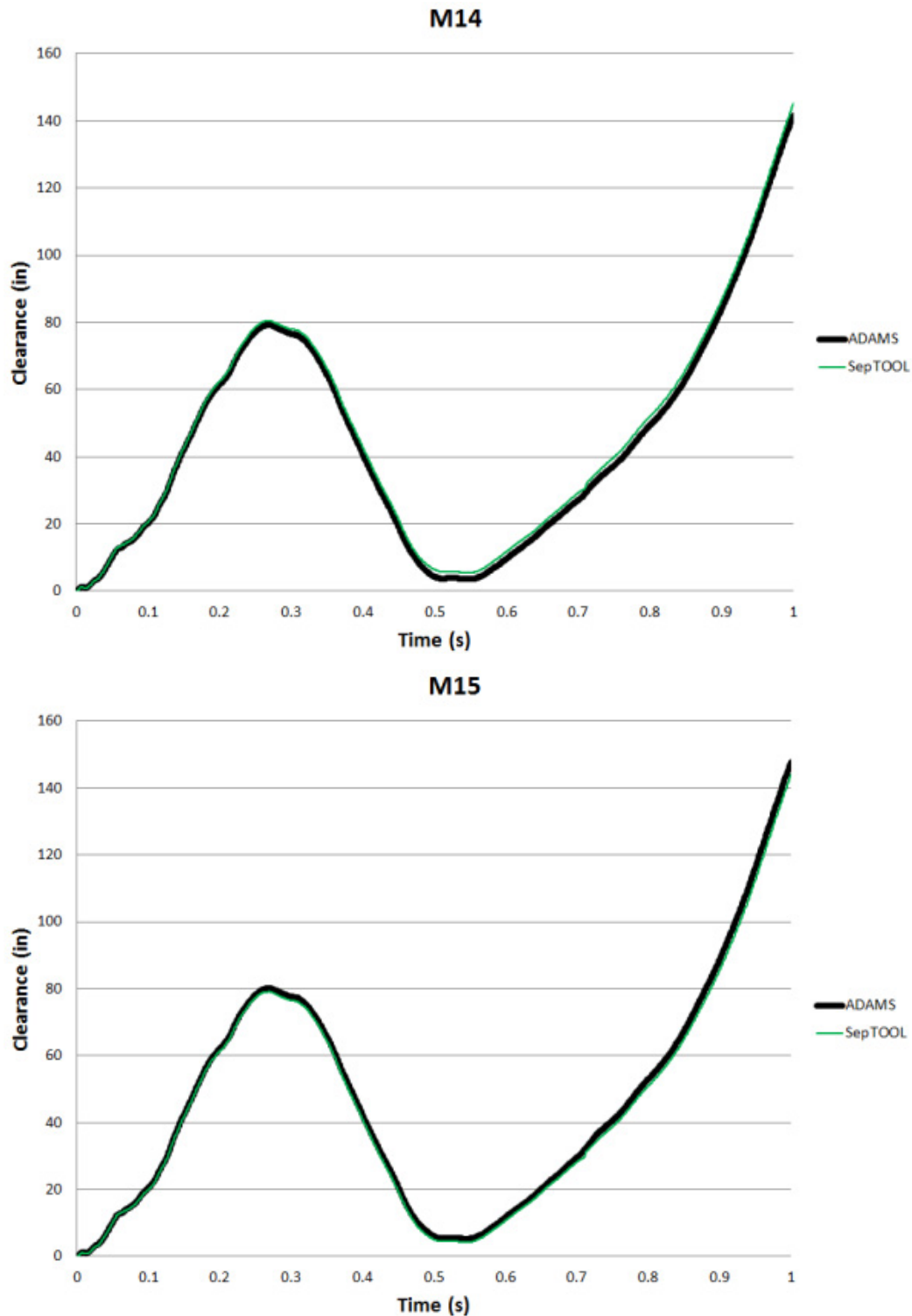

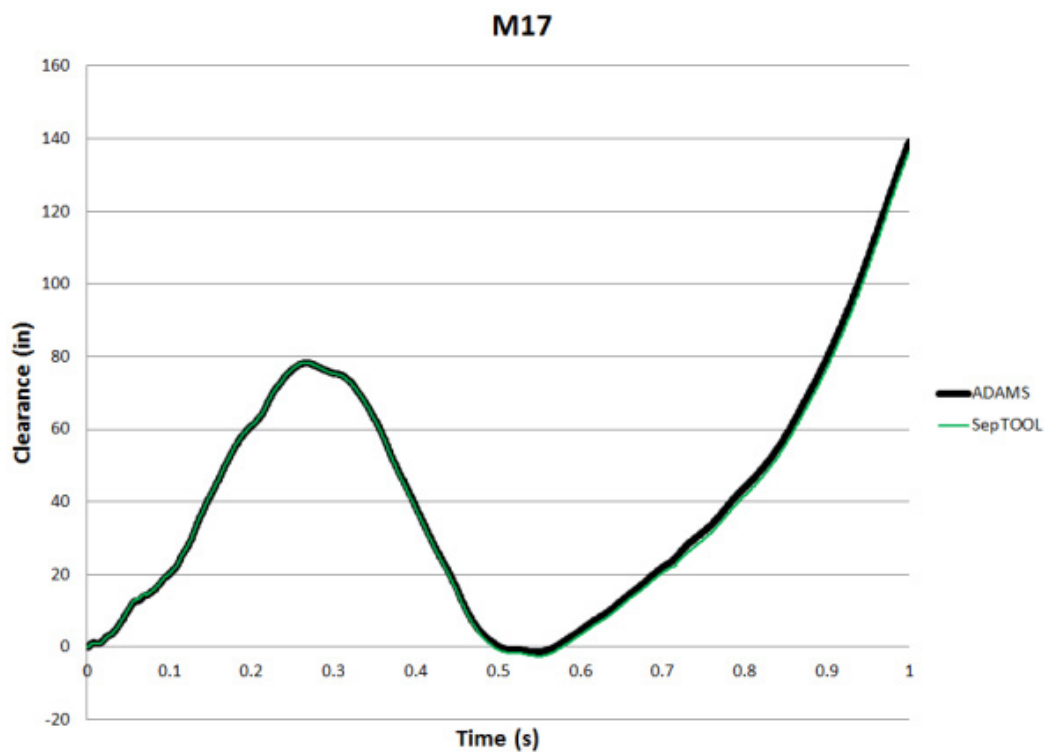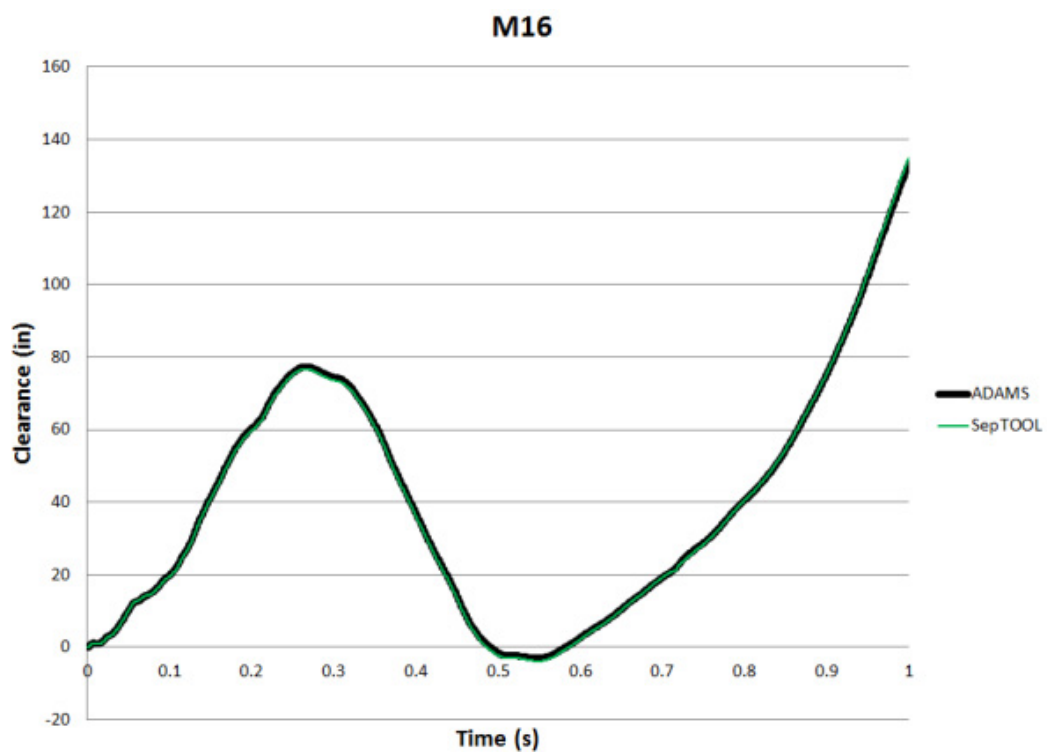Figure 23.—Case 5 separation clearance traces

M16

M17

Figure 23.—Concluded.

9.0   Conclusion

Spreadsheet software SepTOOL was developed to efficiently analyze clearance during fairing separation. The software was verified with ADAMS and yielded accurate results for reasonable and typical launch vehicle trajectory parameters. This document describes the theoretical background and the user interface as well as limitations of the software. SepTOOL allows users to perform accurate rapid separation analyses and vary vehicle trajectory parameters in real time. Because of the speed of the calculations, trade studies using different parameters can be performed much faster than using numerical methods, where for each change in parameter; a user needs to rerun the entire analysis. SepTOOL is several orders of magnitude faster than numerical codes and provides reasonable accuracy.

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