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MULTIBODY PARACHUTE FLIGHT SIMULATIONS FOR PLANETARY ENTRY TRAJECTORIES USING "EQUILIBRIUM POINTS"

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ABSTRACT

A method has been developed to reduce numerical stiffness and computer CPU requirements of high fidelity multibody flight simulations involving parachutes for planetary entry trajectories. Typical parachute entry configurations consist of entry bodies suspended from a parachute, connected by flexible lines. To accurately calculate line forces and moments, the simulations need to keep track of the point where the flexible lines meet (confluence point). In previous multibody parachute flight simulations, the confluence point has been modeled as a point mass. Using a point mass for the confluence point tends to make the simulation numerically stiff, because its mass is typically much less that than the main rigid body masses. One solution for stiff differential equations is to use a very small integration time step. However, this results in large computer CPU requirements. In the method described in the paper, the need for using a mass as the confluence point has been eliminated. Instead, the confluence point is modeled using an "equilibrium point". This point is calculated at every integration step as the point at which sum of all line forces is zero (static equilibrium). The use of this "equilibrium point" has the advantage of both reducing the numerical stiffness of the simulations, and eliminating the dynamical equations associated with vibration of a lumped mass on a high-tension string.

INTRODUCTION

Many planetary entry systems employ a parachute system as a decelerator device from supersonic to subsonic velocities. Simulating the parachute portion of the planetary entry often involves modeling the parachute and the suspended bodies as individually attached rigid Six-Degree-Of-Freedom (6 DOF) bodies. The parachute and the suspended bodies are connected by flexible lines on these planetary entry configurations. In this model, the suspension lines meet at a confluence point. The Mars Exploration Rover (MER) mission uses a parachute system to slow down its descent and after chute deployment has one such confluence point (Fig. 1). In current MER simulations, confluence points are modeled using Three-Degree-Of-Freedom (3 DOF) point mass bodies. Due to its small mass, the confluence point is subject to rapid accelerations. The rapid accelerations make the simulations numerically stiff, requiring very small time increments on the order of 0.0001 second. This causes the simulation run times to significantly increase.[1] This is undesirable in Monte-Carlo simulations where fast turn-around is required to support trade studies. In previous multibody entry models,[1-3] line masses are lumped into the confluence points. In reality, this mass is distributed evenly along the suspension lines. Therefore, the vibrational modes will be those of a distributed mass system, as in a vibrating string. Thus, the vibrational modes introduced by the confluence point mass may not be realistic.

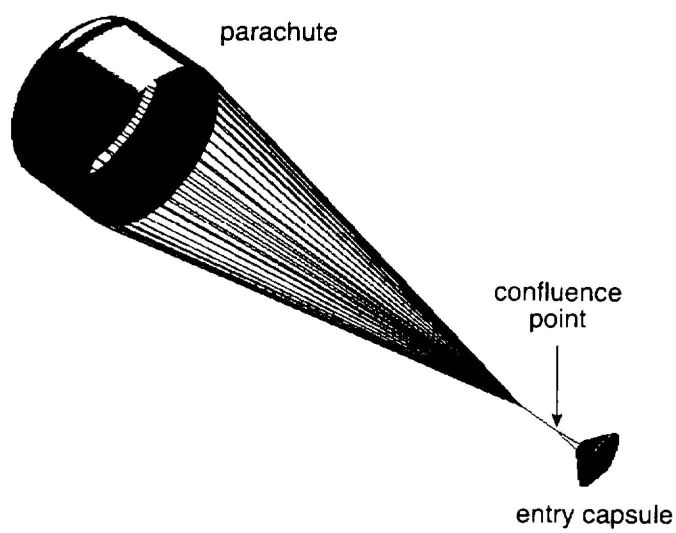


Figure 1 Vehicle entry configuration.

This paper outlines a method to eliminate confluence point masses, and introduces the "equilibrium point". The "equilibrium point" is defined as the point at which the sum of the line forces is zero, the point where the line forces are in equilibrium. This has the same effect as using a confluence point with an infinitely small mass, and allowing all the transients to die out. Instead of integrating the confluence point mass, the "equilibrium point" location is calculated at every time step. The solution is then used to calculate the line forces. This allows the simulations to run at a larger time step on the order of 0.01 second (100 times larger than without), and the high frequency vibrations caused by the small confluence mass are eliminated. This also reduces the number of differential equations to integrate.

SYMBOLS AND ABBREVIATIONS

MER	Mars Exploration Rover
POST	Program to Optimize Simulated trajectories
DOF	Degree of Freedom
$\hat{p}_i$	Position vector of the attach point per line
$\hat{p}_{ep}$	Position vector of the equilibrium point
e_i	Line strain per line
$\dot{e}_i$	Line strain rate per line
L_{0i}	Free length per line
$\hat{u}_i$	Unit vector in direction of the line
f_i	Magnitude of line force per line
$\hat{f}_i$	Line force vector per line
$\hat{f}_{ki}$	Line force vector due to stiffness per line
$\hat{f}_{ci}$	Line force vector due to damping per line
L_t	Line length in current time step
L_{t-1}	Line length in previous time step
$[x_i \quad y_i \quad z_i]$	Attach point coordinates
$[x_{ep} \quad y_{ep} \quad z_{ep}]$	Equilibrium point coordinates
Ixx	Moment of inertia about the roll axis
Iyy	Moment of inertia about the pitch axis
Izz	Moment of inertia about the yaw axis
C_D	Drag coefficient
Cp	Center of pressure
S_{ref}	Reference surface area
Ω	Mars gravitational constant
R_e	Mars equatorial radius
R_p	Mars polar radius
ω	Mars rotation rate
J	Mars gravity zonal harmonics

BACKGROUND

The underlying simulation used to test the "equilibrium points" concept is the Program to Optimize Simulated Trajectories II (POST II). POST II is the latest major upgrade to POST.[4] POST was originally developed for the Space Shuttle program to optimize ascent and entry trajectories. Over the years it has been upgraded and improved to include many new capabilities. POST II relies on most of the technical elements established by POST, but the executive structure has been reworked to take advantage of today's faster computers. The new executive routines allow POST II to simulate multiple bodies simultaneously, and to mix Three-Degree-Of-Freedom (3DOF) bodies with Six-Degree-Of-Freedom (6DOF) bodies in a single simulation. The already established and verified multiple body capability using confluence point masses allows POST II to simulate parachutes. This is done by connecting the spacecraft and the parachute by massless spring-dampers. The springs can be attached at any point on the body. No moments are applied except those due to force application away from the center of mass. Each line connects an attach point on one body to an attach point on another body and provides a tension-only force. When the lines are stretched, tension in the lines is determined as function of strain and strain rate. In the current multiple body POST II, the differential equations of motion for all bodies are explicitly integrated numerically, and the line forces are calculated based on relative position and velocity of the bodies attached.

APPROACH

First, the algorithm to calculate the "equilibrium point" is described. This algorithm needs to be robust since it has to solve the "equilibrium point" at every time step, and also be able to account for special cases, such as when the lines are slack. Although this capability has been added to POST II, it could be used with any multiple body simulation programs such as ADAMS.[5] To verify the current multiple body capability of POST II (without "equilibrium points"), a series of more than 35 tests of increasing complexity were performed. These tests were intended to prove that the POST II model was implemented correctly by evaluating its performance on problems that could be verified by other means. The test cases started with a simple vertical drop from rest of the fully deployed parachute and entry capsule and gradually increased in complexity to include parachute opening, non-zero initial conditions, line deployments, wind gusts, and other effects. The POST II model was compared to both MATLAB-based and ADAMS-based multi-degree-of-freedom simulations. In each case the agreement between the simulations was excellent. These tests have validated the general parachute model within POST II. Some of the validation is reported more fully in Reference 1. To verify the method using "equilibrium point" some of the same test cases are used, except the confluence point mass is replaced by the "equilibrium point", and the results are compared.

ALGORITHM

The "equilibrium point" is defined as the point at which the sum of all line forces is zero. Note that in the general case an arbitrary number of lines can be connected at the equilibrium point. In this algorithm the "equilibrium point" position is the unknown.

$$\hat{p}_{ep} = [x_{ep} \quad y_{ep} \quad z_{ep}]$$

The position of the attach point is fixed in each time step.

$$\hat{p}_i = [x_i \quad y_i \quad z_i]$$

Line strain is found by subtracting the position vectors, calculating the magnitude, and dividing by free length. The force is in the direction of the line connecting the end points.

$$e_i = \frac{| p_i - p_{ep} | - L_{0i}}{L_{0i}}$$

The unit vector in the direction of the line force is found by subtracting the position vectors and dividing by the magnitude.

$$\hat{u}_i = (\hat{p}_i - \hat{p}_{ep}) / | \hat{p}_i - \hat{p}_{ep} |$$

Force vector due to stiffness is found by the following equation:

$$\hat{f}_{ki} = L_{0i} K e_i \hat{u}_i$$

In calculating the damping force we do not have direct access to velocity of the "equilibrium point" in inertial space. Thus strain rate of the line is not readily available. Instead, the strain rate is approximated numerically by subtracting the line length from the previous time step and dividing by time increment. The direction of damping force is along the line, and opposite to the strain rate of the line.

$$\dot{e}_i = \frac{\frac{L_{t-1} - L_t}{dt}}{L_{0i}}$$

Force due to damping is then found using the following relationship:

$$\hat{f}_{ci} = L_{0i} C_i \dot{e}_i \hat{u}_i$$

The net line force is the sum of force due to stiffness and damping force

$$\hat{f}_i = L_{0i} K_i e_i \hat{u}_i + L_{0i} C_i \dot{e}_i \hat{u}_i$$

$$\hat{f}_i = L_{0i} (K_i e_i + C_i \dot{e}_i) \hat{u}_i$$

At the "equilibrium point" sum of all the line forces is equal to zero.

$$\sum_{i=1}^{n} \hat{f}_i = 0$$

At the initial guess for the "equilibrium point" there will most likely be a non—zero resultant force vector. The objective is to find a unique location in space where the summation all line forces is zero. The only variable here is the position of the "equilibrium point", and the output is the resultant force vector. This problem can be solved using one of many available methods for solving system of equations. Here, the Newton method is chosen to solve this system. In summary, the Newton method uses the slope of the output variable (in this case force vector), by varying the input variable (in this case the "equilibrium point" position vector) to converge to a point where the output is zero (static equilibrium).

RESULTS

As mentioned earlier, some of the same test cases used previously to verify multiple body capability of POST are used again to evaluate the "equilibrium point" solution. For a detailed description of the test cases see Reference 1. Test cases 2 and 3 are chosen for this study. Comparison is made between the solution using the "equilibrium position", and the solution utilizing the confluence point mass. All test cases are performed in a Mars environment. But this method can be applied to parachute entry simulations on any planet. A constant atmospheric density of 0.0135 kg/m^3 is assumed for all runs. Aerodynamic drag acts on the parachute only. Mars gravity and an oblate planet model have been used. The planet is assumed to be non-rotating. All simulations start at zero latitude and zero longitude at a height of approximated 8.4 kilometers. Tables 1, 2 and 3 summarize the inputs used.

Table 1
LINE PROPERTIES

Line	Parameter	Value
Single riser	L_0	1.832 m
	K	60,000 N/m
	C	600 N/(m/s)
Triple risers	L_0	0.71524 m
	K	47,000 N/m
	C	470 N/(m/s)

Table 2
PLANET MODEL

Parameter	Value
Ω	4.2828286853e^{13} m^3/s^2
R_e	3.393940e^6 m
R_p	3.376780e^6 m
ω	0.0 rad/s
J terms	0.0

Table 3
PARACHUTE AND ENTRY CAPSULE INPUTS

Body	Parameter	Value
Parachute	DOF	6
	Mass	16.0 kg
	Ixx	253.7 kg.m^2
	Iyy	1126.5 kg.m^2
	Izz	1126.5 kg.m^2
	C_D	0.46
	Cp	1.57 m
	S_{ref}	178.47 m^2
Backshell/lander	DOF	6
	Mass	761 kg
	Ixx	238.02 kg.m^2
	Iyy	179.13 kg.m^2
	Izz	212.51 kg.m^2

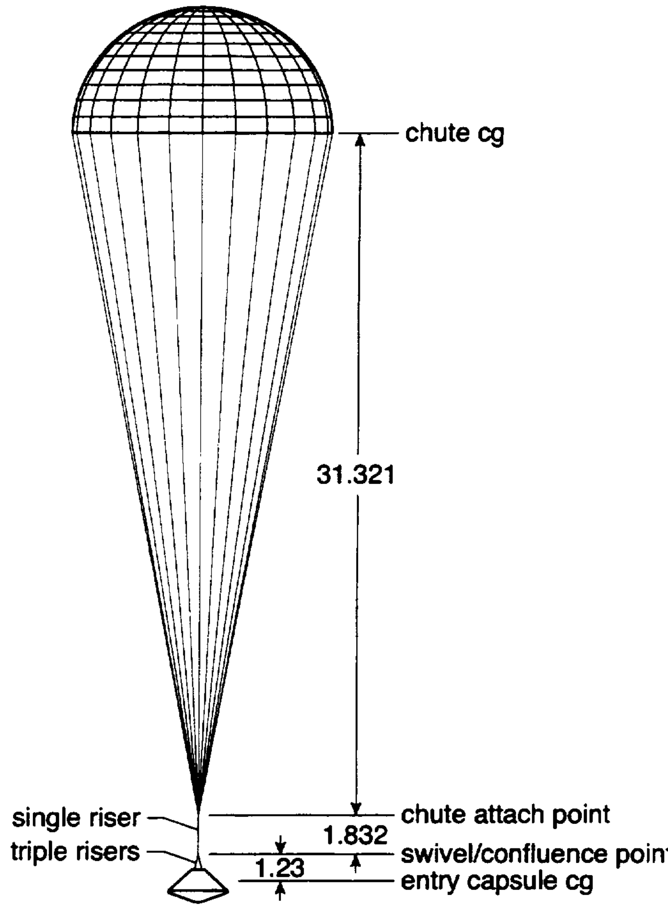
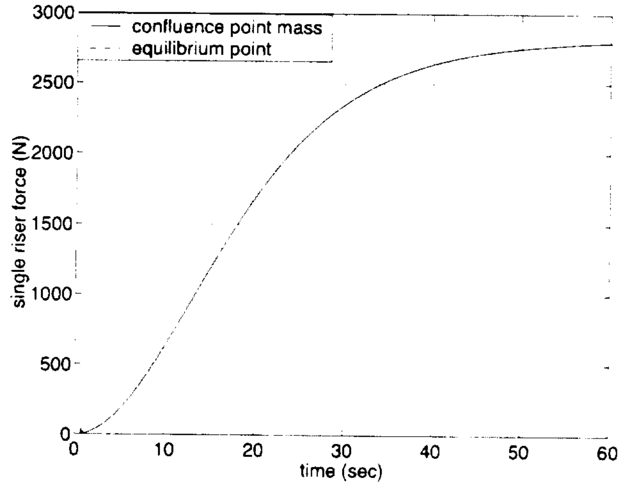
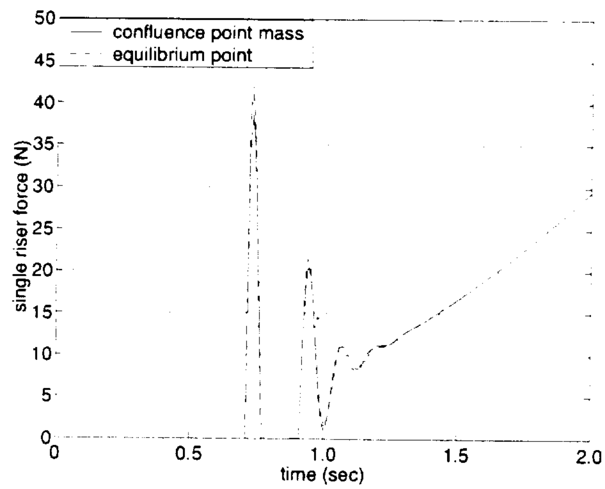


Figure 2 Test cases configuration.
Note: Dimensions are typical (not based on any specific Mars mission).

Test case 2 is repeated here with the "equilibrium point" and results are compared. In this test case a parachute system is dropped from rest. To introduce dynamics into the system we included a slack of one centimeter in the Single Riser (see Figure 2). Note that the aerodynamic drag acts on the parachute only. The entry capsule initially drops faster than the parachute. Eventually, the single riser runs out of slack, thus exciting the system. In this simulation it takes the system about sixty seconds to reach terminal velocity. It takes approximately two seconds for vibrational dynamics to damp out. Figure 3a is the plot of force in the Single Riser. Note that the simulation started with a one-centimeter slack in the Single Riser. It takes about 0.7 second for the slack to run out. The entry bodies then undergo an oscillatory motion. The oscillations damp out approximately 0.5 second after they start (Figure 3b). After this point, the line force gradually builds up until it reaches a steady state value. Note that in Figure 3a the curves are indistinguishable. In Figure 3b the differences become more visible. In the solution with the "equilibrium point", an integration time step of 0.01 second was used as opposed to 0.0001 second for the simulation using confluence point mass.



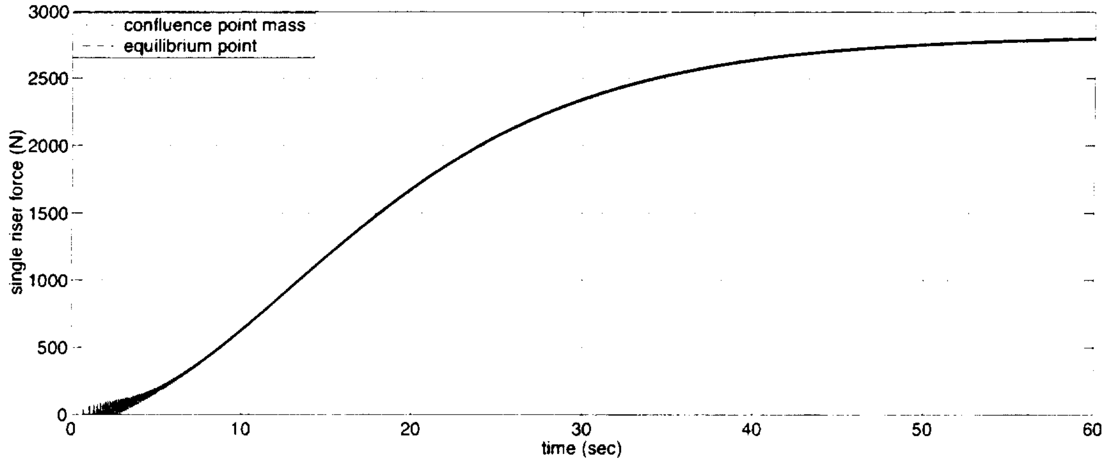
3a Entire simulation.



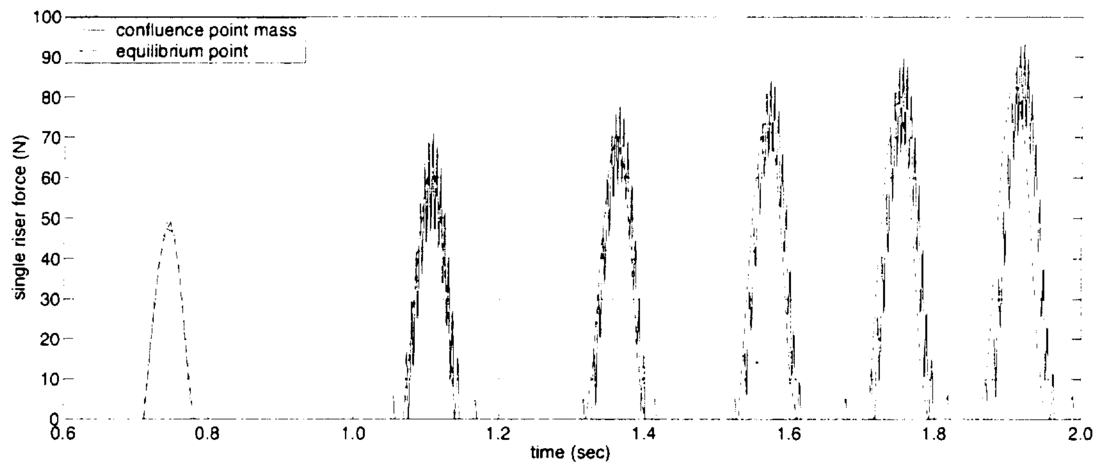
3b Initial two seconds.

Figure 3 Single Riser force.

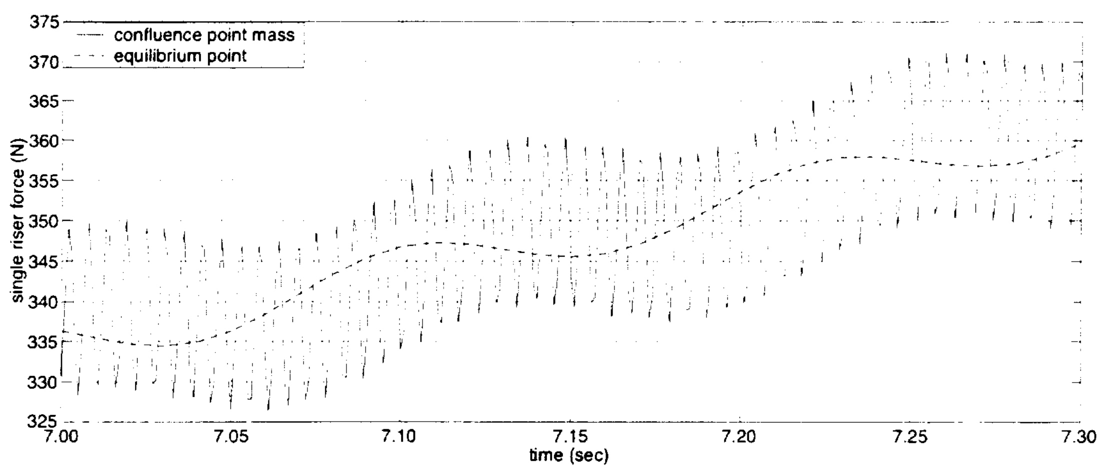
An interesting set of results is obtained by zeroing out line damping, and leaving all other inputs unchanged. The comparison of the Single Riser force is presented in Figure 4. In Figure 4a, the overall force-time history of the line appears to produce a good comparison. But a closer inspection shows that the model with confluence point mass has an additional high frequency mode (Figures 4b and 4c). This is caused by the confluence point mass vibrating back-and-forth in between the lines in tension. This example illustrate how the confluence point mass tends to introduce unwanted frequency contents into the simulation, and how it can be eliminated using the "equilibrium point".



4a Entire simulation.



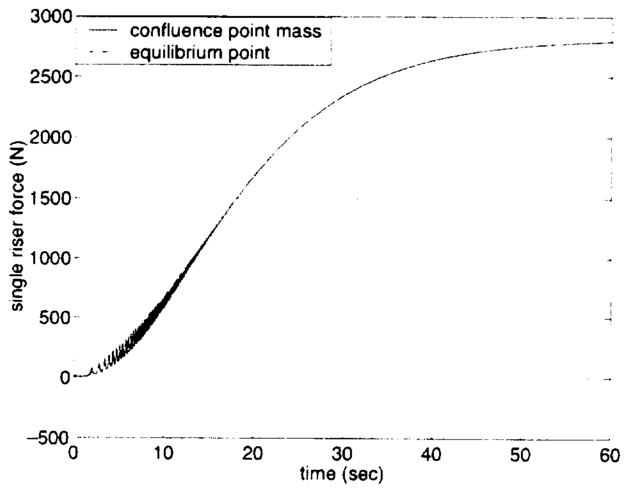
4b Initial two seconds.



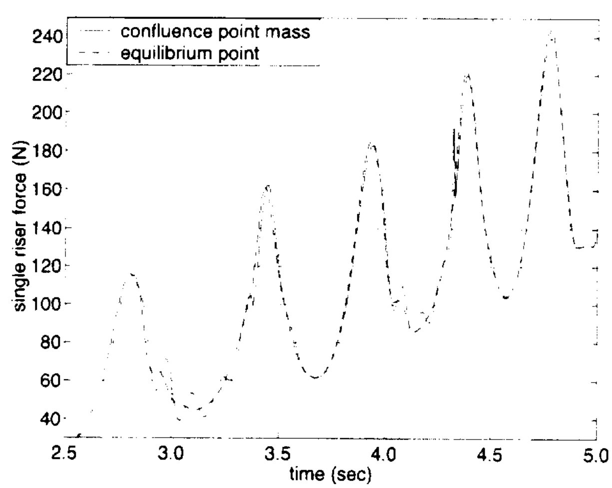
4c Midway range.

Figure 4 Single Riser force, no line damping.

The next test case is identical to the previous with the exception that the entry capsule is given an initial horizontal velocity of 1 m/s. In this test case, more degrees of freedom are excited, as opposed to the previous test case where the bodies were excited in the vertical direction only. Figure 5 shows the plot of the Single Riser line force as a function of time. The overall force curve shows good agreement (Figure 5a), but when observed in detail the model using confluence point mass has additional frequency contents caused by the point mass (Figure 5b). The simulation with confluence point mass ran using integration time step of 0.0001 second, and the simulation using "equilibrium point" used an integration time step of 0.01 second, resulting in substantial savings in run time (at least by a factor of ten).



5a Entire simulation



5b Midway range

Figure 5 Single Riser, non-zero initial conditions

CONCLUSION

Modeling the confluence points using a point mass is a numerical challenge for all the multibody parachute entry simulations (past and present). The method described in this paper reduces numerical stiffness associated with modeling the confluence point as a point mass. This method also eliminates unwanted high frequency oscillations caused by the confluence point mass. Reduced stiffness is desirable because it allows larger integration time steps which should lead to shorter run times. Also, by eliminating the confluence point mass, the simulation has fewer equations of motion to integrate. These speed enhancements are somewhat offset by the need to numerically solve for the "equilibrium point" position. Effectiveness of this scheme can be improved by refining numerical techniques used to solve for the "equilibrium point."

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